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Seismic shifts from regulations: Spatial trade-offs in marine mammals and the value of information from hydrocarbon seismic surveying

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Abstract

Seismic surveys can increase hydrocarbon deposit information, lowering subsequent expected costs of hydrocarbon exploration. Survey noise, however, can interfere with marine mammals and fishes, reducing fitness. Ice-covered Arctic waters temporally constrain both surveying and marine mammal species; damage mitigation requires temporal and spatial planning. The survey noise externality is stronger than that for drilling (Erbe, 2012); there is additional cost to marine species' habitat versus drilling alone. We develop a spatially explicit bio-economic and Value-of-Information (VOI) model examining these tradeoffs and illustrate it for oil exploration decisions off the Western Greenlandic coast. We use cost-effectiveness to identify implicit thresholds for sound habitat quality conservation as a function of regulatory choices that have different impacts under different assumptions about the relative spatial values of marine mammal habitat maintenance.

Keywords: Value of Information (VOI); seismic surveys; marine mammals; marine habitat; marine noise pollution; hydrocarbon exploration;Arctic oil and gas exploration; evaluation of regulatory programs; spatial bio-economic modelling.

JEL codes: D83; Q35; Q53; Q57

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1 Introduction

The exploratory search for new oil and gas reservoirs in the face of increasing energy demand has pushed into increasingly challenging offshore marine environments. Exploratory drilling for oil offshore is expensive (T. Smith, 2007) and growing more so in these environments. Rising costs of exploratory actions, including not only drilling but also seismic surveying, stem in part from heightened uncertainties about the presence of hydrocarbon deposits and in part from external consequences to environmental amenities. These environmental amenities include marine mammals. Hydrocarbon exploration and marine mammals compete over the ocean as a sound transmission mechanism. This paper develops a spatially explicit bio-economic framework for examining this competition and the tradeoffs between the increased information accrued from seismic surveying and the damages surveying imposes on marine mammal populations.

Seismic surveys (henceforth surveys) present firms with one option for lower-cost pre-drilling information, but may also incur environmental costs for society. The Value of Information (VOI) to a firm from conducting a survey in a location depends upon whether the new information is likely to change any decision to conduct exploratory drilling. This likelihood is, in itself, a function of the uncertainty over the potential for recoverable hydrocarbons. Surveying reduces this uncertainty by improving estimates of both abundance and recoverability of hydrocarbons. Spillover effects from the information may also impact decisions in neighboring locations. The greater the probability that the new information affects drilling decisions in one's own or neighboring locations, the greater the value of surveying will be to the industry (Mason, 1986).

Marine mammal disruptions may occur from the noise of surveys. The greater the disruption to marine mammals is, the higher the costs to society of that information. Disruptions may affect the total numbers of marine mammals present in an area, the location of the marine mammals relative to human demand for them, or both. Impacts may also be cumulative and long lasting.[1]

While the effects of seismic surveying remain uncertain and contentious, several nations where seismic surveying interests are significant have already instituted regulations aimed at mitigation of survey sounds' impacts on marine mammals (Compton, Goodwin, Handy, & Abbott, 2008; Erbe, 2013). Regulatory interventions aimed at minimizing industry and external costs consider both spatial and temporal planning in aiming to improve social welfare, and may result in decisions to forego surveying in a given location, and therefore likely to forego drilling there. This particularly may hold true as long as the relatively new low cost terrestrial exploration opportunities for shale oil and gas continue.

Surveying is generally considered less destructive than exploratory drilling (Neff, Rabalais, & Boesch, 2005). The direct costs of a seismic survey are much lower than those of a drilling operation, and a survey reduces the probability of drilling in a dry spot (Pickering & Bickel, 2006). In general, then, environmental values have aligned with economic interests for surveying's potential gains. However, surveys' external effects in certain dimensions, for example noise pollution affecting marine mammals, are potentially significant and greater than those from exploratory drilling. The decision of whether to conduct new surveys as a step in the search for new oil and gas reservoirs should include the tradeoff between the value of the expected additional information gained and the damages from the noise pollution surveying imposes.

The debate over the environmental costs of seismic surveying has reignited in light of the US government's decision to open up significant portions of the US coast for hydrocarbon exploration. While most of the areas intended to open for hydrocarbon exploration have been surveyed, many of

[1] Cumulative impacts become even more relevant if 4D seismic surveying, which involves repeated surveying during production to better characterize the reservoir's flow capabilities and therefore optimize resource quantity extractions, becomes more prominent, or if firms are allowed to simultaneously conduct survey operations in neighboring areas.

the surveys are over three decades old. Technological change in the industry has increased the net benefits of surveying, as evidenced by the decreasing rate of 'dry holes' drilled since the turn of the century (Mason, 2016). This increasing success rate for exploration concretely lowers the costs of exploratory drilling; firms have an interest in conducting new surveys if they lower exploratory costs more than the cost of the surveying[2]. Environmental regulations drive up the costs of surveying and reduce their net expected benefit.

Furthermore, one expects that locations where surveying is curtailed will result in exploratory drilling shifting to areas with access to better and more recent information. Governments, seeking royalties, therefore have incentives to minimize regulations. Oil and gas interests at the state level are currently acting to pass legislation in the US Congress that is intended to reduce noise mitigation regulations in place under the Marine Mammal Act; H.R. 3133. The SEA Act of 2017 (H.R. 3133) was introduced to the US House of Representatives June 29, 2017, passed through the Committee on Natural Resources for consideration by the full House on January 10, 2018 (Representatives, 2018), and was reported upon and placed on the Union Calendar Nov. 16, 2018 (H. Rept. 115-1030)[3]. Regulations that explicitly weigh not only the economic tradeoffs, but also the risks to marine habitat, imply cost-effectiveness ratios (CERs) for the marine habitat these contested regulations aim to protect. Our analysis uncovers measures of these cost-effectiveness ratios where the cost of foregone information generates effects in the habitat impacts across space. While CERs cannot tell us whether regulation choices are efficient, the estimated values may serve as a starting point in debates about where and when surveying should be restricted.[4] These may be

[2] As an indication of the global industry for seismic surveying, there is a global fleet of approximately 100 survey vessels, about half of which are deployed at any given time (Research, 2018); about 40 of these vessels are 3D surveyors (Survey, 2018).

[3] Given the dissenting view expressed in the House Report (H. Rept. 115-1030), the change in the Congressional majority (Jan. 2019) makes it unlikely that the bill will be called to the floor.

[4] The use of Cost Effectiveness Analysis in economic evaluation is most developed within health economics (Drummond, Sculpher, Claxton, Stoddart, & Torrance, 2015) but its use in the conservation literature is increasing with growing understanding of the potential gains (Ansell, Freudenberger, Munro, & Gibbons, 2016).

particularly valuable in the absence of spatially explicit benefit estimations that include use and non-use values for the marine species. They may indeed serve as a stepping stone in further research to acquire or ground-truth such estimates that would enable a full-blown benefit-cost analysis.

While seismic surveying activity is global (Hildebrand, 2009: Fig 5), nowhere are the spatial and temporal constraints potentially as binding as in Arctic waters. This makes them a good testing ground for our bio-economic model. Increasing exploration in Arctic waters faces seasonal and spatial constraints for both the presence of valuable marine mammal populations and access to ice-free waters for surveying. High uncertainties over the potential returns on hydrocarbon exploration exist. In spite of promising estimates of Arctic hydrocarbon resources (Gautier et al., 2009), exploratory finds have been limited to date, oil prices have declined, and Shell Oil Company (Alaska North Slope), Cairn Energy (W. Greenland), and Statoil (Barents Sea) have all had significant disappointments in different parts of the Arctic in recent years. While Shell and Cairn have abandoned their Arctic claims, Statoil will continue to explore the Barents, and other firms may now be returning to the North Slope. In Figure 1, marine mammal habitats are overlaid on USGS estimates of the probability that there is at least one undiscovered oil and/or gas field with recoverable resources greater than 50 million barrels of oil equivalent (MMBOE) within Assessment Units above the Arctic circle (Gautier et al., 2009) to illustrate where the conflicts may be the strongest[5]. We focus on western Greenlandic waters (Baffin Bay), which provide habitat for walrus, seals, narwhal, beluga and bowhead whales as well as moderate potential for undiscovered hydrocarbons.

[5] Note that the well-developed fields in the Norwegian Sea have few marine mammals. This reduces its effectiveness as precedent.

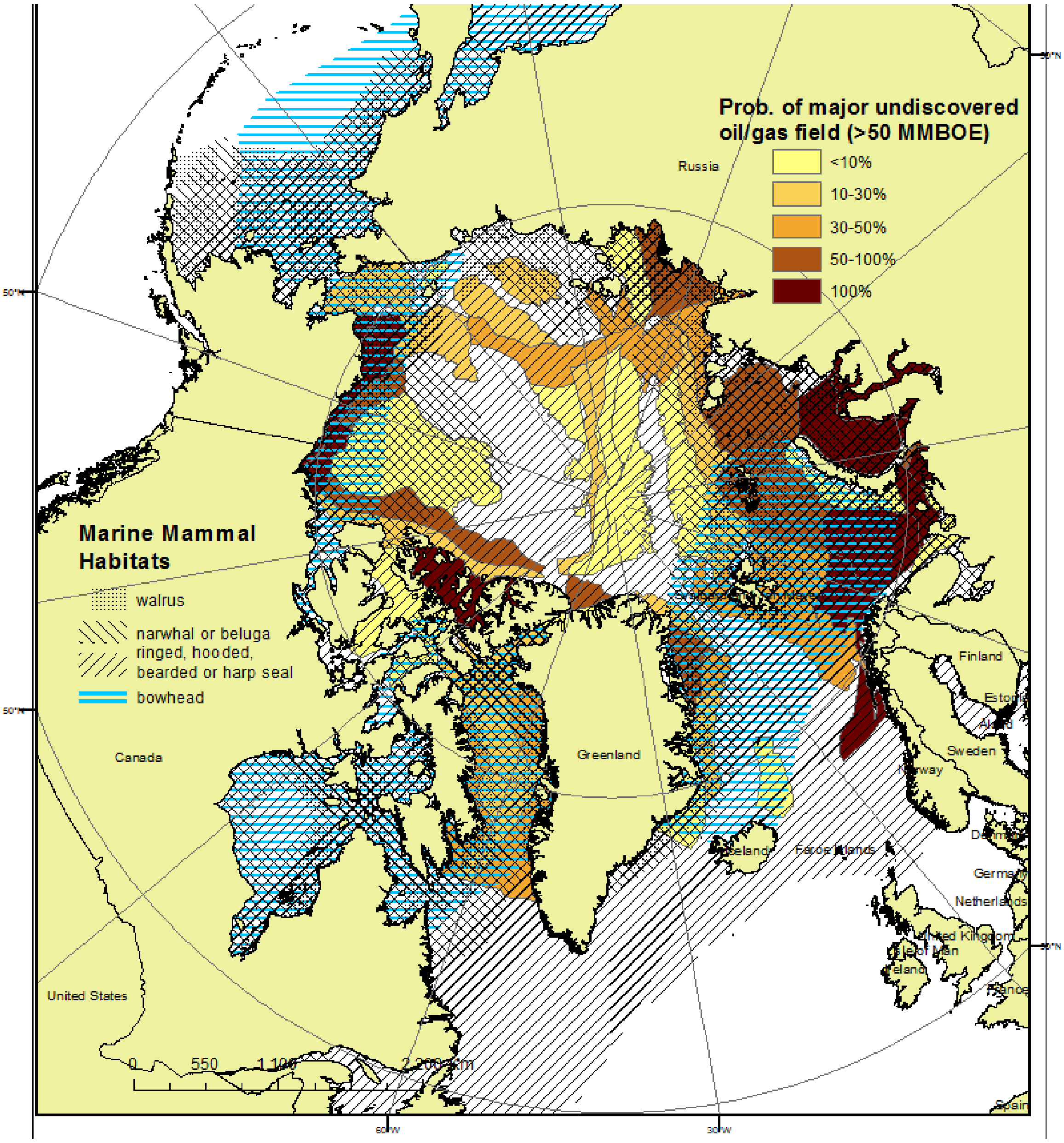

Figure 1: Marine mammal habitats overlaid on the probability of an undiscovered major oil/gas field (Assessment Unit containing >50 MMBOE) in Arctic waters. Data sources: USGS, IUCN Red List. Map created in ArcMap 10.3 by Brooks A. Kaiser. WGS 84/ Polar Stereographic Projection.

To the best of our knowledge, there has not yet been an attempt to combine the value of information of surveys with their effects on marine mammal habitat. Our spatially explicit bio-economic model identifies optimal locations for seismic surveys under environmental constraints. The new contribution to the literature is therefore a model that allows explicit trade-offs between the value of information and the protection of the environment. The combination of cost-effectiveness with VOI methodology adds flexibility to the economist's toolbox. Used together, one can better understand the tradeoffs inherent in competing uses of environmental space, even when the environmental impacts are uncertain or potentially minor compared to e.g. species extinction. Our case study, in which the window of opportunity for both seismic surveys and marine mammals is severely time-constrained due to seasonal ice coverage, renders spatial planning a necessity. Though the simulation focuses on extreme economic and ecological conditions that increase clarity, the model and results are generalizable to the remainder of the Arctic and to the broader global management problem of underwater noise pollution.

2 Information gathering in oil and gas exploration

2.1 Optimal search and value of information

There are several concepts that try to capture the reduction of uncertainty and its value to decision makers. The two most frequently employed ones are Normalized Expected Reduction in Entropy based on the entropy concept introduced by Shannon (1948), and the Value Of Information (VOI) introduced by Schlaifer (1959). The advantage of the latter as opposed to the former is that VOI captures the explicit value of the information, whereas normalized expected reduction in entropy merely describes the reduction in uncertainty (Bhattacharjya, Eidsvik, & Mukerji, 2010). Since seismic surveying reduces uncertainty about both the presence and the recoverable value of any hydrocarbon deposits, VOI is clearly advantageous.

Bratvold, Bickel, and Lohne (2009) review the use of the VOI in the past and present. They conclude that even though it was introduced in the oil and gas industry in 1960 (Grayson, 1960) it remained unused and generally misunderstood until recently. Conditions for successful information gathering are discussed in Appendix I. The literature addressing uses of VOI in hydrocarbon exploration is relatively recent, and mainly addresses drilling, rather than surveys. Mathematically speaking, however, the problems are closely related. For example, Pickering and Bickel (2006) show how the VOI of seismic information depends on the presence of a budget constraint regarding the number of wells that can be drilled. Initially, loosening the budget constraint increases the VOI of an exploratory drill because drilling locations can be chosen with more precision. As the budget increases further, however, the VOI goes down again, because drilling will occur in all viable locations ultimately anyway. The climatic conditions of the Arctic create a temporal constraint on the number of drilling operations or surveys that can be executed in any given season. The time investment of seismic surveying is therefore at a higher cost than in other locations. This should push VOI up in the same way that a budget constraint would do.

Bickel and Smith (2006) formulate a sequential model of drilling decisions where pairwise conditional probabilities of oil presence are available. They use these pairwise conditional probabilities to formulate a joint probability distribution over all prospects. They then use this joint probability function to solve the optimal drilling path across time and space using dynamic programming.[6] The presence of more information, in the form of conditional pairwise probabilities, allows for a more sophisticated VOI that includes an order for drilling and path dependent decisions. Given that the window of opportunity is short in the Arctic so that staggered options are not feasible within a season, and because we do not have information on pairwise conditional probabilities, we opt for a simpler approach.

[6] The spatial planning of drilling operations and seismic surveys has interdependent aspects: a survey or exploratory well in one location can reveal information on neighboring locations. Hendricks, Porter, and Boudreau (1987) show ways in which this increase in information translates to value; their comparison of auction activities concerning wildcat wells, which have surveys but do not have developed drilling in neighboring areas, with those concerning drainage wells, which do, shows that drainage wells result in higher bids, and higher net and gross profits. Higher bids also translate into higher rates of well drilling. Improved surveying technology is increasing benefits for both wildcat and drainage wells; our model need not only apply to the former. Incentives and efforts may differ due to strategic considerations based on the size of the leasehold and the regulatory framework. Regulation that mandates shared information can reduce redundant efforts, as can consideration of seismic noise impacts when determining lease size. We leave this discussion for subsequent work.

Bhattacharjya et al. (2010) develop a spatial model where the prior probabilities are correlated through a Markov field. They formulate an algorithm to calculate the VOI of an experiment and use it to explore its properties in the presence of spatial correlation. They show that if the decision maker can survey all locations, the VOI increases if the correlation becomes stronger, and if the accuracy of a test goes up. If the decision maker is budget constrained in his tests, however, the VOI may decrease with an increasing spatial correlation. In addition, the VOI may be higher for a budget-constrained decision maker than for an unconstrained decision maker. Regardless of financial budget, the time budget for Arctic exploration is smaller, suggesting that VOI may be higher, although patial correlation, if present, may decrease it.As shown in our results spatial correlation between marine mammal presence in contrast further constrains surveying and therefore would increase the VOI.

Martinelli, Eidsvik, Hauge, and Førland (2011) construct a similar model to explore drilling prospects in the North Sea. However, rather than a Markov field they use a Bayesian network to represent the conditional dependence between prospects. They characterize the optimal drilling locations, depending on a budget constraint. In a later paper, they extend the model to consider sequential decision making (Martinelli, Eidsvik, & Hauge, 2013). Because the model is too large to solve through dynamic programming they use a forward-looking algorithm and compare it with a myopic search. They show that such a forward-looking search strategy, combined with a Bayesian network, improves search strategies and produces search strategies that are very different from myopic searches. A forward-looking strategy takes into account that possible test outcomes affect the future search path. This does, however, require additional information on conditional probabilities. As the number of potential surveys is low in our model and we do not have information on conditional probabilities, we do not need a forward looking strategy A similar dynamic approach would be useful when modeling the cumulative effect of seismic surveys on marine mammals, but we leave such considerations for future research.

2.2 Spatial considerations

In non-ice covered seas, temporal restrictions may be sufficient to separate competing uses of the ocean as a sound transmission medium, except in cases of year-round presence of highly vulnerable marine mammal populations. The VOI costs in this case include the costs of the survey and any premium for surveying at a less economically preferred time. Temporal restrictions alone will not suffice, however, when the time window of opportunity for surveying must coincide with that of the migratory marine mammals or other seasonally constrained marine mammal behavior such as breeding, or if the area's marine mammal populations are resident rather than migratory. A current trend in surveying is '4D surveying' -- surveying continuously during production to map reservoir flows and changes; this is information that can be used to maximize output, but it increases the length and intensity of potential survey noise pollution. In these cases, the competing uses have to be spatially separated.

Solving such a problem fits into the literature of the economics of spatial-dynamic processes (M. D. Smith, Sanchirico, & Wilen, 2009), where standard analytical bio-economic models of costs and benefits often result in intractable complexities that require non-linear and non-continuous solution methods such as mixed integer non-linear programming (MINLP) (Kaiser & Burnett, 2010; Punt & Wesseler, 2017). These remain computationally challenging. Furthermore, the underutilized insights from Value of Information (VOI) analyses in the oil and gas industry (Bratvold et al., 2009; Eidsvik, Mukerji, & Bhattacharjya, 2015) provide complementary tools for assessing the tradeoffs in this class of problems. Careful spatial planning combined with VOI can be used to mitigate the effects of seismic surveys on populations of marine mammals (Douvere, 2009). More broadly, this methodology provides a framework for comparing the benefits of knowing more against the costs of acquiring that knowledge. The benefits of knowing more are intermediate environmental costs of production. As such, cost effectiveness analysis enables assessment of the tradeoff of these costs with the environmental effects.

2.3 The effect of seismic surveys on marine mammals and their habitat

The literature of the effects of anthropogenic noise on marine species, and the effect of seismic surveys in particular, has been expanding (e.g. Gordon et al., 2003; Hildebrand, 2009; Nowacek, Thorne, Johnston, & Tyack, 2007; Southall et al., 2007c). A November 2017 Environmental Assessment prepared by Matherne, Charpentier, and Kaller (2017) for the Bureau of Ocean Energy Management (BOEM) summarizes the industry perspective and acceptance of the basic premise that their activities may cause damages. More specifically, Kyhn et al (2019) identify changes in ambient noise measured during past seismic survey activities in the case study area and relate them to the potential for damages to marine mammals in the waters of Baffin Bay.

In short, loud sounds from surveys may startle or scare fish and marine mammals, causing them to migrate, change feeding behavior, or move away. Such deviations cost them valuable energy and may reduce their fitness and probability of survival. In addition, sound is an important communication mechanism for many marine mammals and fish, and the sounds of the survey may mask these communication messages (e.g. Di Iorio & Clark, 2010). In Appendix III, damages from anthropogenic noise are discussed in more detail; Arctic species of concern in W. Greenland are summarized in Table AIII.1. While specifics of damages remain highly uncertain, increasingly research is showing that Arctic marine mammals, including narwhal, beluga whales, and bowhead whales, are highly sensitive to marine noise (Erbe, 2012; Hauser, Laidre, & Stern, 2018; Wisniewska et al., 2014). Hauser et al (2018) creates a vulnerability index for overall risks from increasing anthropogenic activity in the Arctic that places narwhal, walrus, bowhead and beluga at the top of the list. Some impacts on these four species are considered sufficiently certain to warrant restrictions on noise activities, see Table AIII.1.

Recent analysis of past seismic activities in Baffin Bay, GL, indicate that these impacts are present and may affect a range of species, particularly baleen whales including bowhead (Kyhn et al., 2019). As the scientific understanding of these impacts remains limited, however, we do not attempt to exactly quantify the impacts on the species. Instead we assume only, following Kyhn et al (2019), that longer and louder exposures increases expected damages, and that a main effect is the temporary displacement of marine mammals from their preferred habitat[7].

3 Modelling the ecological and economic tradeoffs

3.1 Spatial setting

Consider a set N of cells in a marine area, denoted i. For each cell $i \in N$ there is a random binary variable X_i that denotes oil presence (1) or absence (0). The realization of X_i is known only after drilling, but the decision maker, for example the oil company that has leased the area, attaches a prior probability $p_i(X_i = 1)$ to each cell $i \in N$ that oil can be found there. Let us denote the net value of the reserve in cell i as v_i, that is, v_i is the value of the reserve, should oil be found at i. It includes the extraction costs, the price paid for the lease, as well as recoverable volume and expected price. Should an oil company decide to execute an explorative drill immediately after obtaining the license in cell i the expected payoff π_i of drilling is:

$$\pi_i = p_i(X_i = 1)v_i - c^d$$

[7] An outstanding question of import regards how cumulative impacts build relative to higher levels of disruption in any one period. There is some indication that for species whose primary response is strongly to leave the area at initial increases in noise levels, such as with narwhals and bowhead whales, the least damaging course of action when multiple overlapping surveys are desired is to conduct them all in one season, despite the higher noise levels, rather than to have lesser-intensity surveying over multiple seasons (Kyhn et al, 2019).

where we assume that the costs of drilling c^d is equal in all cells. This expected payoff can be negative, in which case the company would not decide to drill, based on this information only[8].

Similarly, each cell $i \in N$ has a quality of habitat H_i. In principle, H_i is species and time specific, but for now, we will only consider that marine mammal habitat for a single species, the bowhead whale, is improved when there is less disruption in the sound dimension of habitat quality.

3.2 The Value of Information from seismic surveying

Based on the previous assumptions, each cell has a prior value π_i. A seismic survey in cell *i* would reduce some of the uncertainty, and would result in an updated probability that reflected the results of the survey. The outcome of the test, however, is not completely conclusive and can be thought of as another random binary variable Y_i where $Y_i = 1$ is a positive, and $Y_i = 0$ a negative result. In principle v_i can be updated as well, but for now we consider v_i to be fixed.

For the risk-neutral decision maker, the value of the information of the survey in cell *i* equals the updated expected payoff minus the prior expected payoff. The updated expected payoff is calculated using Bayes' rule and depends on the precision of the test. Let $p(Y_i = 1|X_i = 1)$ be the sensitivity of the test, that is, the probability of a positive signal if there is oil, and similarly $p(Y_i = 0|X_i = 0)$ is the specificity of the test, that is the probability of a negative signal if there is no oil. Further, let $p(Y_i = \{0,1\})$ denote the overall probability of a negative (positive) test result at *i*. In that case the benefit of the survey W_i within cell *i* is:

$$W_i = p(Y_i = 1)\max\Big((p(X_i = 1|Y_i = 1)v_i - c^d), 0\Big) +$$

$$p(Y_i = 0)\max\Big((p(X_i = 1|Y_i = 0)v_i - c^d), 0\Big) - \max(\pi_i, 0)$$

This is the value of information (VOI) in the literature as discussed above. It depends on a) the posterior probabilities that oil is present in case of a positive test result ($p(X_i = 1|Y_i = 1)$) and

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[8] Negative expectations may come to be realized after obtaining the license, as pre-sale information is reconciled with newly revealed information from the bidding process itself (Porter, 1995).

the probability of its presence despite a negative test result ($p(X_i = 1|Y_i = 0)$), b) the general probabilities of getting a positive $p(Y_i = 1)$ or negative $p(Y_i = 0)$ test result, and c) the prior value of that cell ($\max(\pi_i, 0)$). If the separate X_i are correlated, as expected in the case of neighboring cells of seismic surveys, some or all cells in N may have updated posterior probabilities as well, and W_i is potentially larger. The risk-neutral decision maker is then interested in maximizing the total net value of the surveys, that is, s/he will want to solve:

$$\max Z = \sum_{i \in N} ((W_i - c_s) z_i),$$

where c_s are the costs of the individual surveys, which are considered equal across cells, and z_i is an indicator variable equal to 1 if a cell is surveyed, and 0 otherwise. The collection of (binary) survey decisions is a vector that we denote as $\mathbf{z}$. This maximization may be subject to constraints on budget and the impact on wildlife.

3.3 The biological response model

The biological model builds on the work of Hof and Bevers (1998) and the extensions in Groeneveld (2004); Punt, Groeneveld, Van Ierland, and Stel (2009). As stated, each cell is characterized by a habitat suitability H_i where $0 \leq H_i \leq 1$, with 0 indicating no presence possible, and 1 a perfect quality. We assume that the habitat quality H_i of cell i drops when a seismic survey is carried out, and consequently H_i is a function of z_i. However, in addition to being suitable for a species, individuals of that species must also be able to reach a cell. Assuming random dispersal of the species and defining r_{ij} as the probability that an individual migrates from cell i to j, we calculate the probability that individuals reach cell i from cell j as $r_{ij}H_j(z_j)$. The complement of this probability is the probability that individuals do not reach cell i originating from j. Because we model species movement as random dispersal, the probability that individuals remain in their own cell i (r_{ii}) equals 0. By multiplying the complement of $r_{ij}H_j(z_j)$ over all $j \epsilon N$ we find the probability that cell i is not reached from any cell. The probability Q_i that cell i is reached is again the complement of that and can therefore be calculated as:

$$Q_i(\boldsymbol{z}) = 1 - \left(\prod_{i \in N} \left(1 - r_{ij} H_j(z_j)\right)\right) \quad \forall i.$$

Denoting the potential maximum number of individuals in a cell (when both H_i and Q_i are 1) as $n_{i,}$ the amount of individuals in cell i, A_i, can be calculated as:

$$A_i(\boldsymbol{z}) = \min\left(Q_i(\boldsymbol{z}), H_i(z_i)\right) \times n_i \quad \forall i \in N.$$

Consequently, carrying out a survey does not just affect the cell where the survey is carried out, but potentially also any connected cells, causing their Q_j to drop. If those Q_j's are or become the limiting factor the population in those cells decline.

3.4 Integrating the VOI and biological models

3.4.1 Aspatial restrictions on damages

To mitigate the effect of seismic surveys we consider two types of restrictive policy options in relation to the absence of restrictions on survey activities. The first policy – *population maintenance*– puts a minimum on the total number of individuals that should be present. That is, the policy maker solves:

$$\max_{\boldsymbol{z}} Z = \sum_{i \in N} ((W_i - c_s) z_i)$$

$$\text{subject to}$$

$$z_i \in \{0,1\} \ \forall\, i \in N$$

$$A^{tot} \leq \sum_{i \in N} A_i(\boldsymbol{z}).$$

In this scenario, the policy maker does not care about the location of the species, but just about its survival. The number A^{tot} in this case is likely to be a number of individuals that constitutes a viable population, or a population size that guarantees current (spatially undifferentiated) consumptive and non-consumptive uses can be satisfied.

3.4.2 Spatial restrictions on damages

A policy maker may also care, however, about the location of species, for example because of tourism or hunting possibilities. In that case, a more spatially explicit policy – *spatially differentiated population maintenance* – is required. We do not explicitly model preferences for sites, but mimic such a policy by specifying minimum numbers of individuals in the individual cells that can reflect higher or lower spatial demands:

$$\max_{\boldsymbol{z}} Z = \sum_{i \in N} ((W_i - c_s) z_i) \text{ subject to}$$

$$A_i^{min} \leq A_i \;\; \forall i \in N.$$

Note that the latter formulation is a general one; if A_i^{min} is set to 0 for all cells there is no restriction.

4 Simulation of W. Greenland Exploration

We parameterize the model with plausible best guesses from the literatures on hydrocarbon extraction and marine mammal abundance in Northern Baffin Bay, Greenland. The model returns spatially explicit estimated populations of marine mammals after any seismic surveying within the set of possible locations as well as the VOI generated by the surveying. We test the results' sensitivity to parameter choice in appendix V.

4.1 Representative species: Bowhead whale

4.1.1 Bowhead sensitivity to noise

We use the bowhead whale (*Balaena mysticetus*) as a representative species. The bowhead is thought to be vulnerable to seismic surveys. Blackwell et al. (2015) showed that the species has two behavioral thresholds: one where it increases its calls and a later one where it ceases its calls. This non-linear relationship clarifies earlier perceived inconsistencies with respect to displayed calling behavior of bowhead whales in response to noise (e.g. Greene Jr, Altman, & Richardson, 1999; Greene Jr, Richardson, & Altman, 1998). Moreover bowhead whales have been identified as a species of concern for earlier seismic surveys in this area (Kyhn et al., 2019; Wisniewska et al., 2014) and the species is known to migrate through the area during potential surveying time (Nielsen, Laidre, Larsen, & Heide-Jørgensen, 2015).

4.1.2 Spatial differences in demand for the presence of bowhead whales

The bowhead whale is also important from an economic point of view for the local community. Both harbor towns in the area, Qaanaaq in the North and Upernavik in the South (Figure 2), have a small whale watching industry, receive a small number of cruise ship visitors during the same ice-free period in question (between 1000 and 2500 per year in 2015-2017Grønlands Statistik, 2019), and therefore a clear incentive to keep bowhead whales present in the neighboring area. Finally the bowhead whale is hunted in very small amounts (8 over the last 20 years) by the native population of Greenland (International Whaling Commission, 2019), and Qaanaaq is a whaling town whose hunting waters include those around Pituffik. As such the continued presence of the whales also has a small direct use value but particularly a cultural use value[9]. Proximity to the shore and their indigenous communities therefore increases the consumptive and non-consumptive use values of the whale.

[9] The 8 bowheads were taken in the past 10 years, as estimated populations have risen. The cumulative harvest can be expected to grow as the population continues to recover (Laidre et al., 2015) and the quota is increased ((International Whaling Commission, 2019). Hunting of other whale species in Greenland has in recent times considerably higher, with 5001 whales taken in the last 30 years (International Whaling Commission, 2016). To the extent that results are transferable, we would expect the value here to be a lower bound estimate.

4.2 Baffin Bay Oil Exploration Area

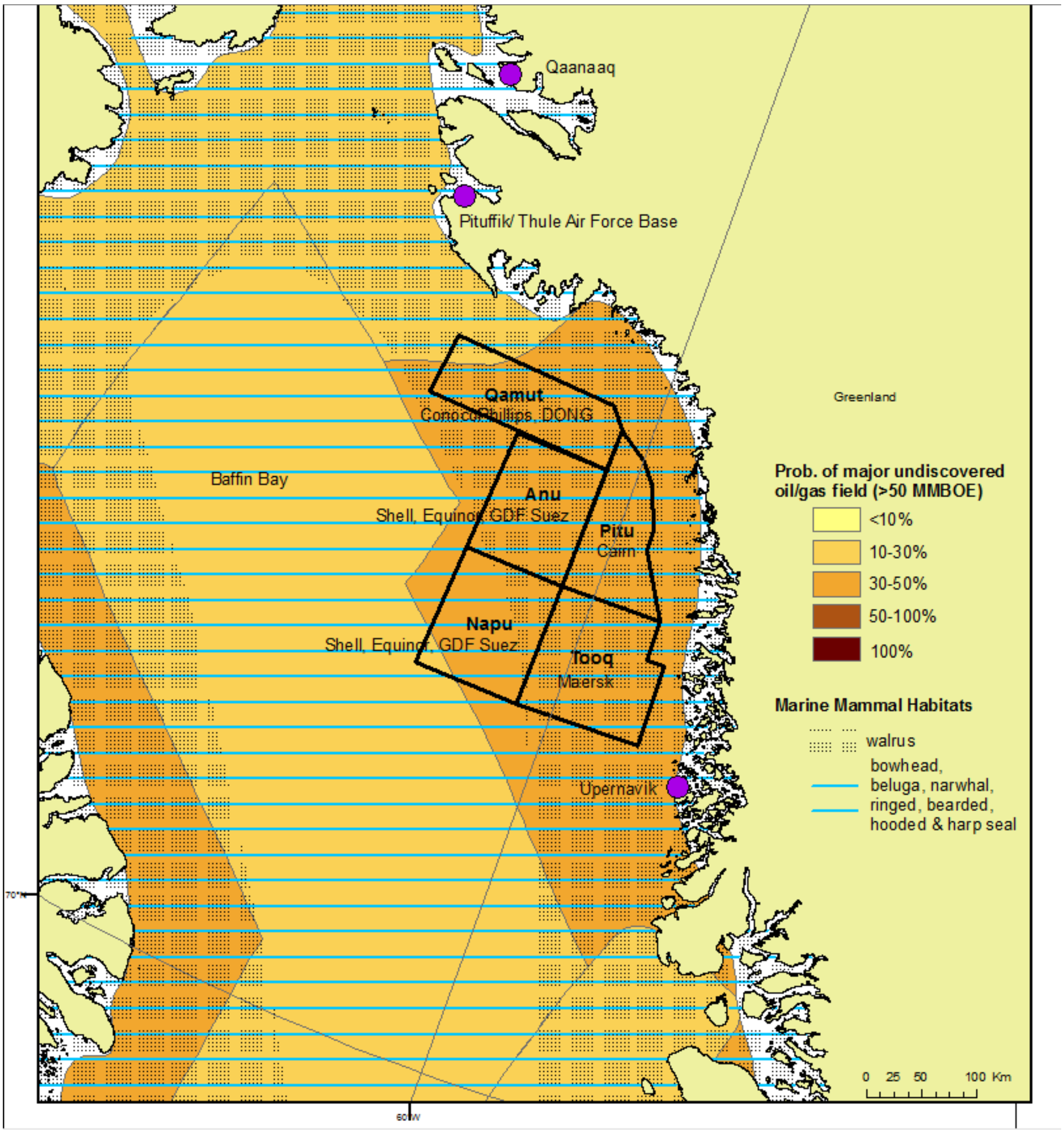

Figure 2: Baffin Bay hydrocarbon leased exploration areas. Data from Greenland National Petroleum Data, USGS, IUCN Red List. Map generated in ArcGIS 10.3 by Brooks A. Kaiser. WGS 84/ Polar Stereographic Projection.

As shown in the close-up of Baffin Bay in Figure 2, several large firms have acquired exploration leases in Baffin Bay. Each leaseholder must operate in partnership with NunaOil, Greenland's national oil company; the leases shown here involve 1/8 share ownership by NunaOil.. High oil prices in the 1970s led to the first seismic surveys in W. Greenland; periodic surveying since that time has resulted in 2D surveying for almost all West Greenlandic waters, but very little 3D surveying has occurred. To do seismic surveying in one of the blocks, the firms have to get permission from the government and carry out an environmental impact assessment (Mineral Licence and Safety Authority, 2015). Given the direct and indirect roles of Greenlandic interests in determining survey schedules, we assume that strategic interactions amongst the firms have limited ability to affect the timing of official Greenlandic choices over these surveys. Thus the government and its state-run oil enterprise are appropriate representatives of the main decision-makers.

Table 2: Assumed parameter values

	Location				
	Qamut	Anu	Pitu	Napu	Tooq
Oil parameters					
$p(X_i = 1)$	0.65	0.5	0.5	0.3	0.3
v_i (Million $)	150	200	100	100	300
c_d (Million $)	50	50	50	50	50
c_s (Million $)	5	5	5	5	5
$p(Y_i = 1\|X_i=1)$	0.8	0.8	0.8	0.8	0.8
$p(Y_i = 0\|X_i=0)$	0.9	0.9	0.9	0.9	0.9
Biological parameters					
H_i	0.4	0.6	0.9	0.4	1
n_i	800	900	1000	800	950
A_i	226	405	440	320	303

The assumed prior probabilities are (variations) taken from (Schenk, 2010) for the Northern and Southern part of West Greenland. Expected v_i are chosen to be comparable to the net values of a small sized fields from (Martinelli et al., 2011). The costs for an exploratory well are taken from (Martinelli et al., 2011) and increased by 150% to account for more difficult circumstances in Greenland compared to the North Sea. Costs for the survey are those quoted by Pickering and Waggoner (2006) for a 4D survey in the Norwegian sector of the North Sea. Habitat suitability for the bowhead whales from Aquamaps.org Kaschner (2013). The parameter values n_i have been calibrated such that the total abundance roughly matches half of the estimated stock in Greenland from Frasier et al. (2015): 3317/2=1658, the total population in our calibration is 1694.

Table 2 shows the assumed parameter values for the different regions (cells) and the results of the population model when no seismic survey takes place. In addition we assume that r_{ij} is a function of the number of neighboring cells, so that if there were only two neighbors, r_{ij} =0.5 whenever i and j share a border. The outside borders are considered as potential migration areas, but we do not explicitly model the population there. The probabilities of migration between any two exploration areas is based on adjacency to neighbors and "open water" (Figure 2) and presented in Table 3.

Finally, we assume that the habitat quality H_i of cell i drops to zero if a survey is carried out. This presents an upper bound to the losses in habitat quality, which we use as a worst-case estimate of damages from the noise pollution. This does not necessarily imply that all bowhead whales in the area die, but rather reflects that they use different migration routes and are no longer present in the area. This might particularly be the case with extended (e.g. 4D) surveying. We test the sensitivity of this assumption by investigating a number of smaller drops in habitat quality in the appendix.

Table 3: Migration probabilities in percent

From \ To	Qamut	Anu	Pitu	Napu	Tooq	Open Water	Total
Qamut	0	16.67	33.33	0	0	50	100
Anu	12.5	0	25	12,5	12.5	37.5	100
Pitu	25	25	0	25	25	0	100
Napu	0	12.5	12.5	0	12.5	62.5	100
Tooq	0	20	20	20	0	40	100

Probability of migration to open water outside the focal area is the sum of the individual open water cells in Figure 2 .

4.3 Outcomes

We present four sets of outcomes. In the first, no attention is paid to the whales (*no restrictive policy*). In the second, the policy maker sets a restriction of keeping 60% of the total number of whales in the area (*population maintenance policy*). In the third, the policy maker wishes to keep 60% of the whales close to shore in the areas of Pitu and Tooq, but does not place further restrictions (*spatially differentiated population maintenance policy*). In the fourth and final scenario we combine the two restrictions. The rationale behind these scenarios is that the multiple use values of the whales are tied to their proximity to the shore, both for consumptive and non-consumptive anthropogenic values. Biodiversity alone, on the other hand, would not require the presence of the whales in a given location; migration is not problematic if equally suitable habitat is available.

We use R (R Core Team, 2016) in combination with a genetic algorithm from the package GA (Scrucca, 2013) to solve this MINLP, implementing the restrictions through penalty functions. Although genetic algorithms in general are not guaranteed to find the optimal solution, in such small problems they are unlikely to miss it. The solutions are presented in Figure 3.

Figure 3: Visualization of scenario results. With no restrictions on noise (Panel (I)), four out of five areas create positive expected value from surveying; no whales remain in any cells. With only an overall population restriction (Panel (II)), $11.5 million in VOI benefits can be derived from surveying a single area, with 1034 bowheads remaining across the region. A spatial injunction on areas closer to shore (Panel (III)) results in two surveyed areas, $6 million in expected benefits, and only 701 remaining bowhead. A combined spatial and population maintenance scenario (Panel (IV)) results in only one surveyed area, $3.5 million in expected benefits, and 1285 bowhead remaining. Results are also shown in tabular form in Appendix 4.

4.3.1 No spatial or temporal restrictions

Panel (I) in Figure 3 characterizes the case where no mitigating restrictions are required. The whale population present in the area declines 100%; the total estimated population of whales is reduced to zero from a starting estimate of 1694 whales. Whale habitat quality and populations are implicitly valueless and the economic net benefits from surveying total $30 million. One area, Qamut, is not surveyed; it has a relatively high probability of containing oil but has a relatively small net value for that oil and therefore extra information gained by surveying it is not worth the cost. Still, the surveying in all other areas prevents whales from reaching or remaining in Qamut.

4.3.2 Population maintenance (aspatial)

Panel (II) in Figure 3 illustrates the case where restrictions exist for overall population maintenance but are not spatially explicit. These restrictions result in economic net benefits of only $11.5 million, but the whale population only falls to 1034, a reduced loss of 660 whales in the area vs. the no regulations case. Surveying only occurs in Tooq, where whale populations are driven to zero. In this case, the whale presence in Qamut does not change from the case of no surveying, and the reduction in whales in the remaining three areas is approximately 30% (see Table 4).

4.3.3 Spatially differentiated population maintenance

The results for the spatially restrictive regulations, in which certain cells must maintain populations above a certain percentage of their original populations, are shown in Panel (III) of Figure 3. Recall that here the requirement is that 60% of the population remain in Tooq and Pitu, due to their proximity to shore and greater expected value. In this case, there are fewer whales remaining overall – only 701 whales, but they are in greater numbers in the areas closest to human populations, especially in the case of Tooq. Tooq and Pitu retain about 70% of their whale presence, which is higher than the 60% requirement. Qamut retains 80%, but Anu and Napu lose their populations (See Table 4).

4.3.4 Combined restrictions

The final panel in Figure 3 shows the results when both 60% of the overall population, and spatially, 60% of the original population in Tooq and Pitu, must be maintained. Like the aspatial population maintenance restriction, this results in a single survey, but this time it occurs in lower-VOI Napu. The change in location is necessary as the spatial restriction alone is not sufficient to guarantee a total population that exceeds the 60% of the original population. The single survey results in a small drop in population in the neighboring cells, whereas Qamut is not affected at all (Table 4).

Table 4: Spatially differentiated losses in whale population in percentages, relative to no surveys

	Location					
Whale population change	*Qamut*	*Anu*	*Pitu*	*Napu*	*Tooq*	*Total*
percent loss, no regulation	100	100	100	100	100	100
percent loss, population maintenance	0	30	32	29	100	39
percent loss, spatial population maintenance	20	100	30	100	29	59
percent loss, combined restriction	0	6	7	100	11	24

4.3.5 Cost-Effectiveness Ratios

We use the results of our model to calculate incremental cost effectiveness ratios (ICERs) in which the effects are whales conserved and the costs are the VOI benefits foregone. This assumes a baseline action of surveying. The cost effectiveness ratios reported in Table 5are incremental as these are mutually exclusive; one can either survey or not survey a given location (Drummond et al., 2015).

Table 5: Incremental Cost Effectiveness Ratios for Seismic Survey Restrictions to Conserve Whales

Regulation:	Cost (C) mill$	Effect (E)	Δ C	Δ E	ICER (ΔC '$000 / ΔE)
No restrictions	0	0	-	-	
Aspatial population maintenance	18.5	1034	18.5	1034	17.9
~~Spatial population maintenance~~	~~24~~	~~701~~	~~5.5~~	~~333~~	
Combined restrictions	26.5	1285	8	251	31.9

We confirm the expectation that the aspatial population maintenance regulation allows greater flexibility and therefore less costly whale conservation compared to spatial constraints. While the cost per whale conserved in the population maintenance case is $17.9 thousand, the incremental cost rises to $31.9 thousand per whale conserved for the combined population and spatial maintenance requirements.

The limited spatial restrictions case, where Pitu and Tooq must maintain 60% of their populations but the other locations' populations are unrestricted, may be considered a dominated regulatory alternative – it costs more to achieve fewer effects – if the weights of all whales are equal. This is however contrary to the expectation of higher-valued whales in certain areas that provides the reasoning for the spatially differentiated regulation and the mixed public good nature of marine mammals (Kuronuma & Tisdell, 1993). We use this contradiction to pin down information about the conditions under which spatial differences in the relative benefits of the marine mammal habitat should make it worthwhile to employ spatially explicit policies vs. conditions where the differences in values may not be sufficiently substantial to warrant increased costs and damages.

We can answer how much higher the relative value of the Pitu and Tooq whales should be to make the spatially restrictive case at least equivalent to the no restrictions case in terms of the effects generated (whales whose habitat is preserved) by determining the relative weights of whales in Pitu and Tooq vs. elsewhere that just generates the same level of effects. This relative weight is just slightly over 2.5 times for our scenarios.[10] This provides a mechanism for explicitly considering how spatial distributions of resource amenities relate to spatial distinctions in the components of benefits in economic evaluation, particularly in cases where some components of the good (e.g. biodiversity) are both more difficult to measure and less sensitive to spatial concerns than others (e.g. access for tourism or hunting). Further, it supports the many findings that benefits transfer methods can be extremely tricky to use in meaningful ways (Lewis & Landry, 2017).

As shown, differing relative values for the whale populations in different cells change the true effects; a variety of outcomes can be expected from weighted effects that differ spatially.[11] The spatially explicit regulation to may in fact be cost effective under a wide range of relative weights. We choose not to select arbitrary weights for the whales to generate artificially constructed weighted cost effectiveness (cost-utility) ratios, instead we anticipate that our mechanism can be

[10] To solve the system, we assume that whales in Pitu and Tooq have the same, higher value over those in the other three areas, which have the same value as one another. Then let a be the relative increase in value for Tooq and Pitu whales and solve $734+300a = 180+521a$ for the point at which the spatially restrictive scenario generates at least as many effects (whale habitat preserved) as the population maintenance scenario. $a = 2.507$.

[11] Take as a different spatially explicit example the case where the three offshore areas and Pitu all have equal weighting, normalized to one. Then the number of 'effects' or whales conserved remains 1034 in the population maintenance case, regardless of the relative weighting of the whales in Tooq, because none are present there. If the relative weight for Tooq whales conserved is 2.6, then the number of effects generated by the spatial regulation rises to just over 1034. This methodology identifies a breakeven ratio between the relative values in Pitu and Tooq, but the ratio is also dependent on their relative value to the offshore cells. In the extreme, the offshore whales are given no value (as the limited spatial regulation implies), then the relative weighting does not need to favor Tooq; Pitu's whale population is already higher than it was under the population maintenance scenario.

used to elucidate when regulations should embrace spatially explicit restrictions vs. when it should not by illustrating the relative values needed to justify the trade-offs.

Whether or which of these additional costs should be undertaken depends upon the total value to society of the whales as well as the spatial distribution of these values. In a recent review of the literature, Lew (2015) finds average values for a variety of marine mammals. Though immediate comparisons are challenging for several reasons, including the facts that none of the over thirty species valued are the bowhead whale and there is no aggregation of value to the societal level, the results suggest that individual or household values are substantial. The cost per whale thresholds identified by the ICER analysis would likely be far exceeded by benefits in a full benefit-cost analysis. Annual payments for improved status of near-threatened Beluga whales in Canada, for example, range from $113.58-$355.73 per household (Boxall, Adamowicz, Olar, West, & Cantin, 2012).

4.4 Comparative analysis and discussion

Looking at the solutions we see significant differences between the scenarios, but similarities as well. For example, in all cases, it does not pay to survey Qamut. This is true even in the absence of the externalities imposed through damages to the whales. Even though the test is quite precise, the amount of information gained from the survey is so small, or the prospect so attractive, that it would be explored anyway.

We also see that the value of information does not necessarily increase with the net value of the reserve. The value of information for Pitu is higher than that for Anu, even though they have the same probability of hitting oil. The reason is the different prior decisions: without further information Pitu would not be drilled, whereas Anu would. The effect of the no restriction policy on the whales is that the area becomes inhabitable for them, and therefore is no longer occupied by the whales. Even in Qamut, which is not surveyed, no population is present due to the negative spill-over on habitat quality.

Putting a 60% restriction on the total population alters the solution dramatically. Now surveying options become considerably less flexible. Exploring Tooq, while leaving the other areas un-surveyed, keeps the number of whales just above the threshold. Pitu is more valuable for its potential gains from improved information, but because it is relatively well connected with the other focal areas, doing a survey here would reduce the population below the threshold. The same holds for doing an additional survey in one of the less valuable areas. Therefore, in this scenario, a single survey is the optimal solution.

Putting restrictions on the populations in Pitu and Tooq, but not the other locations, again reduces the number of surveys compared to the no-restrictions case; under this regulation, two areas can be surveyed. The value of the acquired information is, however, much lower. The spatial restriction makes the decision where to survey less flexible, even though the restriction is much lighter in terms of total number of whales that needs to be preserved. This scenario makes clear that if some or all of the value of the whales is dependent on their location, increased care needs to be taken when planning the surveys, and increased costs may be borne.

The latter can also be seen from the fact that the limited spatial regulation scenario is a dominated regulatory alternative. The ICERs measure the additional cost we will pay in foregone information value in order to implement an increasingly effective restriction on a per whale basis, compared to surveying with no restrictions. As the gain in whales conserved in the spatial scenario is smaller and the lost net benefits from information are larger, the regulatory alternative is dominated. In another light, this change in implied cost illuminates the importance of spatial differentiation in conservation efforts on both the demand and supply sides.

When both overall population and distributional restrictions are combined the number of surveys falls to one again, but now the surveyed area is Napu. This area has a low whale population when no surveys take place, and the spillover damage to whale populations in the neighboring cells is small. As a result compared to the no restriction scenario we gain a large number of whales, so that while it is more costly than the aspatial restrictions, it does gain more conservation effects.

These results are in part driven by the severe effect of the survey on habitat quality. In Appendix V we show that the difference between the last three scenarios disappears if the reduction in habitat quality is 75% or less, rather than the 100% we use here. A lower reduction in habitat quality would also allow more strict constraints, as the current ones are relatively mild. This would restore the difference between the scenarios.

5 Conclusions

It is clear that both space and information matter. Our example highlights this, and adds to ways in which information about differences in costs and values across space and time can be both gathered and used. The mobile nature of whales implies that considering only the local effect of seismic surveys is not enough; the effect in a larger area has to be considered. This is especially true if the whales are more valuable in certain locations than in others. This is implicitly assumed if we apply spatial restrictions in our model. While this paper cannot answer what a whale is worth, it identifies the implicit cost society is willing to pay per whale when different types of noise mitigating regulations are attached to seismic surveying. Further, it demonstrates how the when and where of the potential surveying shifts these opportunity costs as a function of both the marine mammals at risk and the potentially discovered value of information pertaining to hydrocarbon deposits.

In the temporally and spatially constrained situation simulated here, the overall level of conservation from either restrictive policy can increase the whale population by a factor of about 20. The spatially restrictive policy, however, reflects a much higher (and more accurate) opportunity cost and thus a much greater implicit value is imputed for the specifically located whales when such restrictions are implemented. Note that this can result in lower overall whale populations, because location matters more than overall quantities – both for the potential oil and the potential whale habitat.

Previous conservation literature (e.g. Ando, Camm, Polasky, & Solow, 1998) has often interpreted these differentiated spatial opportunity costs as an opportunity for cheaper conservation by conserving where it is least costly. Our work rather aims to strengthen the arguments that spatial considerations may justify higher cost conservation when both the opportunity costs and the conservation demands are spatially differentiated (as in e.g. Ando & Shah, 2010).

An additional reason to place a large emphasis on spatial planning in this area is that the time window in which surveys and other economic activity can be carried out is limited (see e.g. Halpin and Cleary (2014)). Due to this limited time frame, seismic surveys will typically have to be carried out at approximately the same time when the whales migrate through the area. Although the modeling of underwater sound has progressed significantly over the years, cumulative effects are not yet well captured (Wisniewska et al., 2014), and in such a time-constrained window of opportunity the surveys will have to be more concentrated and hence their effects cumulative.

The model above can be criticized for its simplicity, but is not meant as specific policy advice. Rather it demonstrates the potential and possibilities for spatial planning that is so urgently needed in this area. The value of information allows for a specific and clear measurement of the opportunity costs, and in combination with a biological model allows for explicit trade-offs between oil and conservation. The model can easily be extended both on the biological and economic side.

From the biological side, the response functions can be improved; from the economic side we could consider budget or environmental constraints on drilling and spatial correlation between surveyed areas. The latter will most probably increase the value of information in certain areas, and by extension also the implicit value of the whales should their presence prevent surveys. In contrast, it would decrease the value of information in other areas and if these areas are valuable whale habitat then the improvement of geological models may actually constitute a win-win situation. It would contribute valuable information for oil exploration and leave more whale habitat intact.

A related issue is that of private information of the surveys. As shown in the map of Baffin Bay the exploration blocks are in the hands of several oil firms. If these do not share their information every firm has to do its own surveys. However, as this information is valuable, the firms have every incentive to keep the information private, thus exacerbating the problem of multiple surveys in the same area having cumulative effects. In part this may be solved by requiring the data to be public, but this would reduce the value of the information and the incentives to survey in the first place. The value of private seismic information and the tension with requiring that information to be public is perfectly illustrated by the court case of Geophysical Service Incorporated (GSI) versus several public institutions in Canada, which it claims have infringed GSI's copyright (e.g. http://business.financialpost.com/news/energy/canadas-top-oil-firms-governments-grabbed-seismic-data-property-geophysical-services-inc-claims). There might even be strategic incentives to do extra surveys in an area to misinform or credibly threaten competition. Our example is simplified by the co-ownership of NunaOil in all exploration leases, so that we leave this area for future research.

In any case, it should be clear that the spatial dimension is pivotal when making decisions about seismic surveys, in order to make clear trade-offs and find the value of the noise.

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Appendix 1: VOI in hydrocarbon exploration

(Bratvold et al., 2009) point to four important characteristics, introduced by Howard and Abbas (2016) that any information gathering (and by extension a survey) should exhibit. They should be: 1) Observable, 2) Relevant, 3) Material, and 4) Economic.

The first characteristic, observability, means that the test result can be registered. The second characteristic, relevance, implies that the survey has the capability to change our prior beliefs. The third characteristic, material impact goes a step further; not only should the survey be able to change our prior beliefs, but such a change should also have an effect on the actions undertaken. The final characteristic, economically rational, implies that the costs of the survey should not outweigh the benefits.

Appendix II: Risk neutrality and VOI

If a decision maker is risk neutral, the value of information is defined as the expected value of a prospect with information minus the expected value of a prospect without information. In cases where the decision maker is not risk neutral, additional adjustments have to be made to account for the risk-changes and a utility function of the decision maker has to be modeled explicitly.

When the decision maker is neutral, the VOI is relatively straightforward to calculate for a single survey using Bayes' rule, provided one has information on 1) prior probabilities, 2) prospect value, 3) the accuracy of the test, both in terms of true positives (sensitivity) and true negatives (specificity). The calculation of the VOI becomes increasingly difficult if multiple prospects are to be surveyed, especially in the presence of budget constraints, spatial correlation or sequential decision making.

Appendix III: Seismic surveys and damages to marine mammals from anthropogenic noise

Seismic surveys usually consist of a ship pulling a series of air guns, which are cylinders that release a sound pulse in a timed manner under a fixed angle. The ship also pulls a number of recorders that record the echo of these sound pulses. The echo provides information that can be used to make inferences about the surface and geological composition of the seafloor, and the presence of oil (Deffenbaugh, 2002; Laws & Hedgeland, 2008).

Erbe (2012: Figure 1) confirms that, amongst hydrocarbon exploration techniques including surveying and exploratory drilling, typical air gun arrays create the greatest potential impact on marine mammals as they have the highest power spectrum density. The power spectrum density is the power in the signal per unit of frequency (in dB re 1μPa^2/Hz @1m)[12] from relevant anthropogenic noises at any frequency (Hz) from 10 to 10,000. Air gun arrays' densities (~150-210 dB) are consistently higher than pile-driving activities (~145-190), with more than 40 dB difference at lower frequencies, and average about 60 dB higher than drilling caisson activities (~105-145). As dB is a logarithmic scale, the environmental costs of the survey in terms of noise pollution are higher than those of drilling would be.

Gordon et al. (2003) classify the effects of anthropogenic noise, and of seismic surveys in particular, on marine mammals in three types: 1) Physical, 2) Perceptual (masking) and 3)

[12] Sound is essentially differences in pressure over time. Its loudness is measured in decibel (dB), a logarithmic scale that expresses the ratio between the pressure caused by the sound source and the reference level pressure. In air the reference level is 20 μPa (Fahy, 2001), in fluids the reference level is 1 μPa. The height of the sound is its frequency and expressed in Hertz (Hz).

Behavioral effects. Physical effects are direct effects on the animals, such as tissue damage and hearing loss. Perceptual effects are effects caused by changed perceptions, such as the masking of sounds by noise. Behavioral effects are changes in behavior by the sounds, such as startle reactions, diving or switching between behavior types (Gordon et al., 2003).

The anticipated damages become worse if they are cumulative, such as with multiple surveys in a short time span near each other. This is because animals must move away from ideal habitat multiple times, or stay away longer. Firms should find longer surveying to become more attractive with increased adoption of 4D surveying, a tool that may be most attractive in new exploration (wildcat) areas where little is known of reservoir conditions or behavior. Similarly, if surveys take place near mating grounds, masking the mating calls, the breeding grounds lose their function. Moreover, if a single survey typically takes place over several weeks (e.g. the survey described in Johnson et al., 2007 took 8-10 weeks), then the noise pollution is even more likely to have cumulative effects.

Directly measuring the effects of seismic surveys is typically infeasible and the effects of surveys must be inferred from observational field studies, modeling, and extrapolation from data on either a few captive individuals or other species (Gordon et al., 2003; Southall et al., 2007c). Potential effects are therefore often highly uncertain. While there is no direct evidence of physical effects of seismic surveys on marine mammals, Southall et al. (2007b) use models, data from captive animals, terrestrial species and threshold levels in humans to determine the criteria for the most widely considered, those of hearing loss damages; their results are summarized in Table 1, second column.

A second dimension of damages is the potential masking of marine mammals' signals. Marine mammals use sound for a variety of purposes, among others echolocation and communication. The signal masking becomes problematic if it results in reduced fitness of the individuals. The evidence of how animals respond to masking is mixed. It is certainly clear that the frequency of surveys and the frequencies used by baleen whales (such as the blue whale) overlap. Di Iorio and Clark (2010) found that blue whales increase their vocalization rate in the presence of surveys, most likely to compensate for the masking. However, reactions such as no changes or cessation of singing have also been observed (e.g. Castellote, Clark, & Lammers, 2012; Madsen, Møhl, Nielsen, & Wahlberg, 2002)

The final concern is that of behavioral changes. These changes are among the most variable ones and therefore the net effects on fitness and survival are uncertain. In general whales seem to try to avoid loud noises but the range where effects are observed depends very much on the species (Gordon et al., 2003). Table 1, third column gives a general overview of the sensitivity of broad species groups to seismic surveys.

Table AIII.1: Sensitivity of groups marine mammals to seismic surveys

Species group	Criteria for permanent injury (Sound pressure level in dB)[a]	Sensitivity in behavioral disturbance
Low-Frequency Cetaceans (e.g. Baleen whales)	230 dB	Moderate responses
Mid-Frequency Cetaceans (e.g. Toothed whales, Dolphins)	230 dB	Minor responses
High-Frequency Cetaceans (e.g. Porpoises)	230 dB[b]	Unknown
Pinnipeds (e.g. seals)	218 dB	Minor responses

Data summarized from Southall et al. (2007a, 2007b). Frequency refers to the communication frequency spectrum of the species. [a]The thresholds for temporary injury are 6dB lower. [b]Later research indicates that this threshold may be even lower (202 dB) (NOAA, 2015).

Appendix IV: Results from the four scenarios

	Qamut	Anu	Pitu	Napu	Tooq	Totals
Survey Regulations						
No restrictions						
Survey (yes/no)	No	Yes	Yes	Yes	Yes	4
Net Benefits (M$)	0	2.5	12.5	3.5	11.5	30
Population (A_i)	0	0	0	0	0	0
Population maintenance						
Survey (yes/no)	No	No	No	No	Yes	1
Net Benefits (M$)	0	0	0	0	11.5	11.5
Population (A_i)	226	282	300	226	0	1034
Spatially differentiated population maintenance						
Survey (yes/no)	No	Yes	No	Yes	No	2
Net Benefits (M$)	0	2.5	0	3.5	0	6
Population (A_i)	180	0	307	0	214	701
Combined restrictions						
Survey (yes/no)	No	No	No	Yes	No	1
Net Benefits (M$)	0	0	0	3.5	0	3.5
Population (A_i)	226	379	411	0	269	1285

Appendix V: Sensitivity analysis of parameters

We present a number of alternative outcomes for relevant scenarios under different parameter values. We show the effect of the survey precision net benefits in the economic scenario, and the effect of the connectivity parameter on the outcomes in the population and spatial restriction scenarios.

Varying the precision of the survey

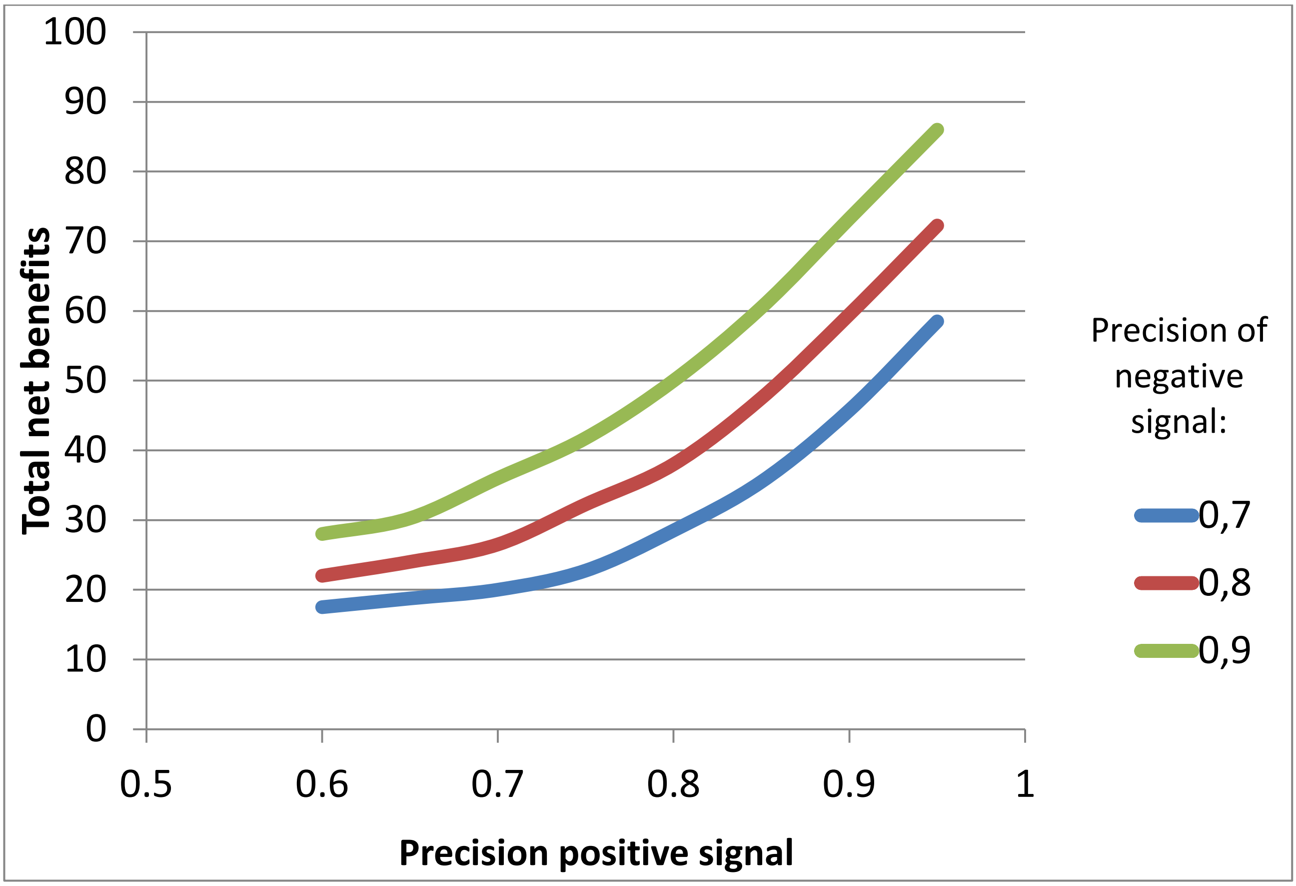

Figure 4: Net benefits of the surveys in the economic scenario as a function of the precision of the positive signal ($p(X_i = 1|Y_i=1)$) and the precision of the negative signal $p(X_i = 0|Y_i=0)$. The kinks in the line represent additional cells that are surveyed.

Varying the connectivity between cells (d_{ij}) in the spatial scenario

Note that varying the d_{ij} also alters the original population, so the results cannot directly be compared. We still show the results to clarify the effect of this parameter. The restrictions are still relative, e.g. 80% of the total population that would have existed if d_{ij}=0.2 and no surveys take place.

d_{ij}=0.2						
Population maintenance						
Survey (yes/no)	No	No	No	No	No	0
Net Benefits (M$)	0	0	0	0	0	0
Population (A_i)	171	276	348	200	230	1225
Spatially differentiated population maintenance						
Survey (yes/no)	No	No	No	No	No	0
Net Benefits (M$)	0	0	0	0	0	0
Population (A_i)	171	276	348	200	230	1225
d_{ij}=0.5						
Population maintenance						
Survey (yes/no)	No	No	No	Yes	No	1
Net Benefits (M$)	0	0	0	23.5	0	0
Population (A_i)	180	360	540	0	475	1555
Spatially differentiated population maintenance						
Survey (yes/no)	No	Yes	No	Yes	No	2
Net Benefits (M$)	0	2.5	0	23.5	0	0
Population (A_i)	180	0	540	0	475	1195

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