Noise Signals Value: Trading off marine mammals and seismic survey information

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Abstract

This paper explores competition over the ocean as a sound transmission medium between marine mammals and oil exploration activities. Seismic surveying uses underwater sound transmission to increase information regarding the presence or absence of hydrocarbon resources and therefore lowers expected costs of subsequent exploratory drilling and reduces additional search costs. However, this surveying may interfere with marine mammals' use of the medium and reduce fitness amongst these populations by shifting behavior away from optimal feeding, migration, and reproduction patterns. Seasonally ice-covered Arctic waters temporally constrain seismic surveying opportunities, so that spatial planning over the transmission medium's use is required to mitigate environmental damages. We develop a spatially explicit model to examine these tradeoffs on the Western Greenlandic coast. We find that important changes in the surveying plans take place when whales are taken into consideration.

Keywords: Value of Information; seismic surveys; bowhead whale (*Balaena mysticetus*); oil exploration; spatial model.

JEL codes: D83; Q35; Q53; Q57

1 Introduction

The exploratory search for new oil and gas reservoirs in the face of increasing energy demand has pushed into increasingly marginal areas. Exploration reached the Arctic in the late 1960s, and now it is pressing into one of the least hospitable of Arctic environments: off the coasts of Greenland. Geologists have speculated that large reserves exist in this area, although the amount is disputed (McGlade, 2012). Drilling for oil, however, is expensive, especially offshore, and in the Arctic even more so (Smith, 2007). Therefore oil companies would like to have a trustworthy estimate of the presence and volume of oil available in a location. Although a first estimate may be obtained from geologists, more reliable information can be obtained from seismic surveys (henceforth: survey).

Seismic surveys usually consist of a ship that pulls a series of air guns, 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 more detailed inferences about the surface and geological composition of the seafloor and thus the presence of oil (Deffenbaugh, 2002; Laws & Hedgeland, 2008).

In principle the development of seismic surveys created a win-win situation for both oil companies and the environment. The costs of a seismic survey are significantly lower than those of a drilling operation, and a survey reduces the probability of drilling in a dry spot (Pickering & Bickel, 2006). The environmental impacts and risks of a survey are generally lower than those associated with a drilling operation.

Despite the potential environmental advantages of surveys over drilling, surveys do have an environmental impact. Loud sounds may startle or scare fish and marine mammals, causing them to migrate, change feeding behavior, or move away. Such moves or migration costs 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).

These effects become especially important if the effects are cumulative due to multiple surveys in a short time span near each other. In that case animals may have to migrate multiple times. Similarly, if surveys take place near mating grounds, masking the mating calls, the breeding grounds lose their function. In non-ice covered seas, temporal restrictions may be sufficient to separate such competing uses of the ocean as a sound transmission medium. This is not possible, 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. In such cases, careful spatial planning can be used to mitigate the effects.

The spatial planning of drilling operations and seismic surveys has interdependent prospects –a survey in one location will reveal information on neighboring locations. Academics have turned their attention to developing optimized spatial surveying plans at the behest of firms interested in resource extraction (Bickel & Smith, 2006; Martinelli, Eidsvik, & Hauge, 2013; Martinelli, Eidsvik, Hauge, & Førland, 2011). Applications typically use Bayesian networks or Markov fields combined with dynamic programming or heuristic searches to select the best locations to maximize expected profits from drilling operations or surveys, as well as the best order (e.g. Bhattacharjya, Eidsvik, & Mukerji, 2010; Bickel & Smith, 2006; Martinelli, Eidsvik, & Hauge, 2013; Martinelli, Eidsvik, Hauge, & Førland, 2011). Incentives and efforts may differ due to strategic considerations based on the size of the leasehold and the regulatory framework; regulation mandating shared information can reduce redundant efforts, as could considering seismic noise impacts when determining lease size. We leave this discussion for subsequent work.

In addition, 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). To the best of our knowledge, however, there has not yet been an attempt to combine these two. In this paper we will formulate a model that optimizes the location of seismic surveys under environmental constraints. Our new contribution to the literature is therefore a model that allows explicit trade-offs between the value of information, as obtained from the surveys, and the protection of the environment.

We proceed as follows: in section two we will shortly review the literature on optimal searching for oil and the effects of seismic surveys on marine species. Section three presents the theoretical model, a combination of an optimal search model and an ecological model. In section four we present a case study trading-off the value of information and whales. Finally, section five concludes.

2 Literature review

2.1 Optimal search, value of information and more

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 entropy merely describes the reduction in uncertainty (Bhattacharjya et al., 2010).

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 misunderstood until relatively recently. They also point to four important characteristics, introduced by Howard and Abbas (2016) that any information gathering (and by extension a survey) should be:

1. Observable
2. Relevant
3. Material
4. Economic

The first characteristic simply means that the test result can be registered. The second characteristic implies that the survey has the capability to change our prior estimates. The third characteristic 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 simply implies that the costs of the survey should not outweigh the benefits.

If a decision maker is neutral, the value of information is defined as the expected value with information minus the expected value without information. In case 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 prior probabilities, prospect value and the accuracy of the survey. However, 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.

The literature addressing these issues is relatively recent, and mainly addresses drilling, rather than surveys. However, mathematically speaking, 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, the VOI of a seismic survey goes up because drilling locations can be chosen with more precision. As the budget increases, however, the VOI goes down again as all locations will be drilled anyway. Additionally, the climatic conditions of the Arctic add 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 higher than in other locations. This should push VOI up in the same way as a budget constraint.

Bickel and Smith (2006) formulate a sequential model of drilling decisions where pairwise conditional probabilities 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 using dynamic programming.

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 a non-constrained decision maker.

A similar model is constructed by Martinelli et al. (2011), 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 (Martinelli et al., 2013) they extend the model to consider sequential decision making. Because the model is too large to solve by 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 algorithm takes the effect that possible results have on the future search path into account. This is similar, but not the same, as modeling the cumulative effect of seismic surveys on marine mammals.

2.2 The effect of seismic surveys on marine mammals

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

- Physical effects
- Perceptual effects (masking)
- Behavioral effects

Physical effects are direct effects on the animals, such as tissue damage and hearing loss. Perceptual effects are effects that are 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).

Directly measuring the effects of seismic surveys in a controlled experiment is typically infeasible and possibly unethical. Therefore the effects of surveys must typically be inferred from observational field studies, modeling, and extrapolation from either a few captive individuals or other species (Gordon et al., 2003; Southall et al., 2007c). Potential effects are therefore often highly uncertain and there are large gaps in the data that are available, historically, currently, and most probably in the future.

There is no direct evidence of physical effects of seismic surveys on marine mammals, but dynamite shockwaves are known to damage tissue and can even be lethal. However, as Gordon et al. (2003) point out, seismic surveys are unlikely to have such effects because the rising time (the time it takes for the signal to reach its maximum) is longer. The most prominent worry in terms of physical damage from seismic surveys is probably hearing loss, either permanently, referred to as “permanent threshold shifts” (PTS) or temporary, known as temporary threshold shifts (TTS). These are measured by the combination of the sound level at the source (sound pressure level) and the level at the receiver (exposure level). Again there is no direct evidence, but using models, data from captive animals, terrestrial species and threshold levels in humans, Southall et al. (2007b) report PTS criteria: 230 dB (decibel) re: 1 μPa (microPascal) as sound pressure level for cetaceans, and 198 dB re: 1 μPa for sound exposure.[1] For TTS criteria the sound pressure and exposure levels have to be lowered with six and 15 dB, respectively. Johnson et al. (2007) report the effects of a commercial seismic survey on gray whales. The company aimed for sound exposure levels for feeding gray whales of 163 dB or less, in order to not disturb them at all. The original planned survey

[1]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. Sound pressure level is the level emitted at the source, exposure level is the level received. Because sound loses energy with distance, exposure levels are lower than the level emitted at the source. The height of the sound is its frequency and expressed in Hertz (Hz.)

included 28 airguns with a volume of 3090 in^3, however after a calibration of the resulting distance that they would need to stay away from the feeding area, they decided to reduce the number of guns by half. The final survey included 14 airguns with a volume of 1640 in^3 and had sound pulses > 180 dB re: 1 µPa for distances <565 m. This indicates that direct damage is mainly an issue in close proximity to the survey, but less so further away. Longer distances are required however for no disturbing. The final configuration allowed to approach feeding gray whales up to 4 km (Johnson et al., 2007)

The second main issue is the potential masking of signals of marine mammals. Marine mammals use sound for a variety of purposes, among others echolocation and communication. Recently, there has been anecdotal evidence that sonar causes certain whales to strand, but the mechanism is unclear (Southall et al., 2007c). The masking of signals would mainly be a problem if it would result in reduced fitness of the individuals. This is, of course, a question that is difficult to answer. Moreover, the evidence of how the animals respond to masking is mixed. It is certainly clear that the frequency of surveys and the ones used by baleen whales (such as the blue whale) overlap. Di Iorio and Clark (2010) found that blue whales increase their vocalization rate 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 issue is that of behavioral changes. These changes are among the most variable ones and therefore the net effects on fitness and survival are rather uncertain. In addition, behavioral effects are very much dependent on the current activity (Southall et al., 2007c). 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) report ranges of more than 20 km for bowhead whales, 24 km for Gray whales, but only 3 km for Humpback whales. Other behavioral changes include increased diving or surfacing, course changes and behavior type change (e.g. from feeding to fleeing). Table 1 gives a general overview of the sensitivity of broad species groups to seismic surveys

Table 1: Sensitivity of groups marine mammals to seismic surveys

Species group	Criteria for injury (Sound pressure level in dB)	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	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.

3 Theoretical model

3.1 Preliminaries

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 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, as well as recoverable volume and expected price. Should an oil company decide to execute an explorative drill in cell i immediately the expected payoff π_i is:

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

where we assume that the costs of drilling c^d is equal in all cells.

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 a single species.

3.2 Seismic survey model

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, depending on the results of the survey. The outcome of the test, however, is not completely conclusive either 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.

If the decision maker is risk-neutral the value of the information of the survey in cell i is equal to 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 $p(Y_i = \{0,1\})$ denote the probability of a negative (positive) test result at i, and $p(X_i = \{0,1\}|Y_i = \{0,1\})$, the conditional or posterior probability, that oil is absent (present) in i if the test result is negative (positive). In that case the benefit of the survey W_i within cell i is:

$$W_i = p(y_i = 1)\max\Big(\big(p(x_i = 1|y_i = 1)v_i - c^d\big), 0\Big) + p(y_i = 0)\max\Big(\big(p(x_i = 1|y_i = 0)v_i - c^d\big), 0\Big) - \pi_i$$

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 result ($p(x_i = 1|y_i = 1)$) and 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 (π_i). If the separate X_i are correlated, some or all cells in N may have updated posterior probabilities as well, and W_i is potentially larger. A risk-neutral decision maker is then interested in maximizing the total net value of the surveys, that is, a risk-neutral decision maker will want to maximize:

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

where c_s are the costs of the individual surveys, which are considered equal across cells. This maximization may be subject to constraints on budget and the impact on wildlife.

3.3 The biological 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. 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 cell *i* and *j* are connected, we calculate the probability that individuals reach cell i from cell j as $r_{ij}H_j$. The complement of this probability is the probability that individuals do not reach cell *i* originating from *j*. By multiplying this complement over all $j \epsilon N \backslash i$ 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:

$$Q_i = 1 - \left(\prod (1 - r_{ij}H_j)\right) \quad \forall i.$$

However, instead of evaluating this form we follow Hof and Bevers (1998) and replace this equation with a linear approximation in the form of two equations:

$$Q_i \leq \sum d_{ij}H_j \quad \forall i \in N,$$

$$Q_i \leq H_i \quad \forall i \in N.$$

We then choose d_{ij} to approximate r_{ij} as closely as possible. 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:

$$A_i = Q_i \times n_i \quad \forall i \in N.$$

3.4 Integrating both models

As a first-order approximation we assume that the habitat quality H_i of cell *i* drops to 0 when a seismic survey is carried out. This does not just affect the cell where the survey is carried out, but potentially also any connected cells, as their Q_j drops, depending on which factor is limiting for them: habitat quality or connectivity.

To mitigate the effect of seismic surveys we consider several policy options. One policy puts a minimum on the total number of individuals that should survive. That is, the policy maker maximizes:

$$\max Z \quad subject\ to$$

$$A^{tot} \leq \sum_{i \in N} A_i.$$

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 that case is likely to be a number of species that constitutes a viable population given current consumptive and non-consumptive uses.

A policy maker may also care about the location of species, for example because of tourism or hunting possibilities. In that case a more spatially explicit policy 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:

$$\max Z \;\; subject\ to$$

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

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 A simple illustration

We parameterize the model with plausible best guesses from the literatures on hydrocarbon extraction and marine mammal abundance in Baffin Bay, Greenland. We use the bowhead whale (*Balaena mysticetus*) as indicator species as it is thought to be vulnerable to seismic surveys and has been identified as a species of concern for earlier seismic surveys in this area (Wisniewska et al., 2014). In addition this species is hunted in very small amounts by the native population of Greenland. We test the result's sensitivity to parameter choice in an appendix.

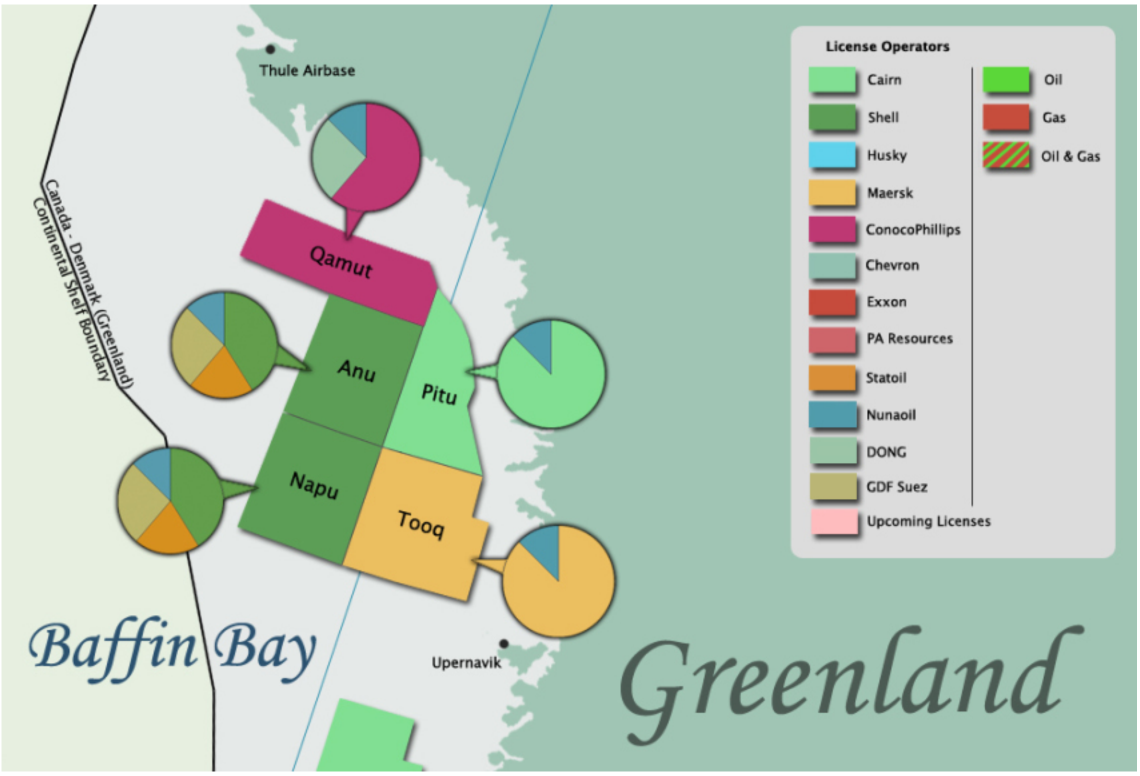

Figure 1: Oil licenses in Baffin Bay, Greenland. Picture by Jared Allen. Source: https://arcticecon.wordpress.com/2012/01/28/cairn-spreads-out-the-risk-farms-out-shares-to-statoil/

Figure 1 shows a picture of Baffin Bay, an area where potentially oil is located and several firms have obtained exploration licenses. Still, to do a seismic survey 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). We abstract from the firms' motives and assume that the government of Greenland plans these surveys. Table 1 shows the assumed parameter values for the different regions, and the results of the population model when no seismic survey takes place. In addition we assume that d_{ij} =0.35 whenever i and j share a border (diagonals are not included). We also assume that the bowhead whales cannot move out of the 5 areas.

Table 2: Assumed parameter values

	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

$p(X_i = 1 \mid Y_i=1)$	0.8	0.8	0.8	0.8	0.8
$p(X_i = 0 \mid Y_i=0)$	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	450	600	600	500	500
A_i	180	360	540	200	403

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 matches half of the estimated stock in Greenland from Frasier et al. (2015)

We present three sets of outcomes: one where there is no attention paid to the whales, one where the policy maker sets a restriction of keeping 80% of the total number of whales in the area and one where the policy maker wishes to keep 80% of the whales in Pitu and 90% in Tooq, but does not place further 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. The solutions are presented in Table 3.

Table 3: Results from the three scenarios

	Qamut	Anu	Pitu	Napu	Tooq	Totals
Scenario						
No restrictions						
Survey (yes/no)	No	Yes	Yes	Yes	Yes	4
Net Benefits (M$)	0	2.5	12.5	23.5	11.5	50
A_i	63	0	0	0	0	63
Total population						
Survey (yes/no)	No	No	No	Yes	No	1
Net Benefits (M$)	0	0	0	23.5	0	23.5
A_i	180	360	540	0	333	1413
Spatial restriction						
Survey (yes/no)	No	Yes	No	No	No	1
Net Benefits (M$)	0	2.5	0	0	0	2.5

A_i	180	0	483	200	403	1266

Looking at the solutions we see significant differences between the scenarios. The first thing to note is that in some cases it does not even pay to survey certain areas. 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. This is the case for example in Qamut, that has a relatively high probability of containing oil but has a relatively small net value and therefore extra information gained by surveying it is not worth the cost. We also see that the value of information does not necessarily increase with the net value of the reserve. The value of information for Napu is higher than that for Tooq even though they have the same probability of hitting oil. The reason is the different prior decisions: without further information Napu would not be drilled whereas Tooq would. The effect of the no restriction policy on the whales is that the surveyed area becomes inhabitable. In Qamut, which is not surveyd, the population is reduced due to the negative spill-over on habitat quality, but it is not completely wiped out.

Putting a 80% restriction on the total population alters the solution drastically. Now it is almost impossible to carry out a survey at all. The main reason is that the threshold is so high. Exploring only Napu keeps the number of whales just above the threshold, even when the effects of that in Tooq are included. Therefore in this scenario, a single survey is the optimal solution.

Putting restrictions on the populations in Pitu and Tooq also reduces the number of surveys by three. Again only a single survey is possible, but now it is only Anu that can be surveyed. The knock-on effect on the population in Tooq when surveying Napu is too large to allow surveys. 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. However, this scenario makes it all the more clear that if the value of the whales is also dependent on their location, much more care needs to be taken when planning the surveys.

5 Discussion and conclusion

From our example it is clear that space matters. The fact that whales move implies that just considering 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 then in others, as is implicitly assumed if we apply spatial restrictions in our model. What is a whale worth? That is a question that cannot be answered by this model, and it much depends on whom you ask, and when. However, it is clear that placing restrictions on when and where the surveys take place puts an implicit value on them.

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. Although the modeling of underwater sound has progressed significantly over the years, cumulative effects are not well captured yet (Wisniewska et al., 2014).

The model above can be criticized for its simplicity, but is not meant as actual policy advice. Rather it demonstrates the potential and possibilities for spatial planning that is so urgently needed in this area. 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 survey. 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. 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: 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

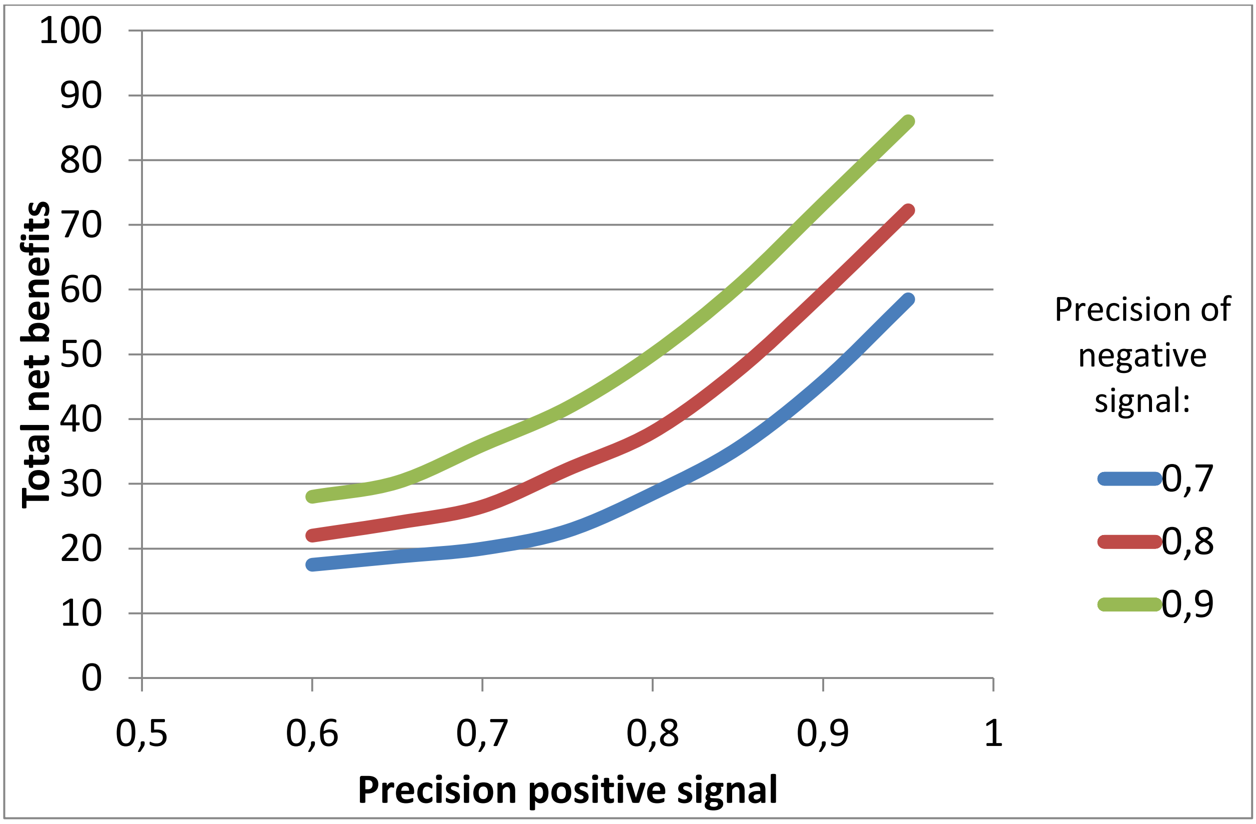

Figure 2: Net benefits of the surveys in the economic scenario as a function of the precision of the positive signal ($p(X_i = 1|Y_i=1)$)and the precision of the negative signal $p(X_i = 0|Y_i=0)$. The kinks in the line represent additional cells that are surveyed.

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						
Total population						
Survey (yes/no)	No	No	No	No	No	0
Net Benefits (M$)	0	0	0	0	0	0
A_i	171	276	348	200	230	1225
Spatial restriction						
Survey (yes/no)	No	No	No	No	No	0
Net Benefits (M$)	0	0	0	0	0	0
A_i	171	276	348	200	230	1225
d_{ij}=0.5						

Total population						
Survey (yes/no)	No	No	No	Yes	No	1
Net Benefits (M$)	0	0	0	23.5	0	0
A_i	180	360	540	0	475	1555
Spatial restriction						
Survey (yes/no)	No	Yes	No	Yes	No	2
Net Benefits (M$)	0	2.5	0	23.5	0	0
A_i	180	0	540	0	475	1195