Australian Agricultural & Resource Economics Society (AARES)
National Conference 2010

Integration of biological, economic and sociological knowledge by Bayesian belief networks: the interdisciplinary evaluation of potential Baltic salmon management plan

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Integration of biological, economic and sociological knowledge by Bayesian belief networks: the interdisciplinary evaluation of potential Baltic salmon management plan

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Abstract

There is a growing need to evaluate fisheries management plans in a comprehensive interdisciplinary context involving stakeholders. In this paper we demonstrate a probabilistic management model to evaluate potential management plans for Baltic salmon fisheries. The analysis is based on several studies carried out by scientists from respective disciplines. The main part consisted of biological and ecological stock assessment with integrated economic analysis of the commercial fisheries. Recreational fisheries were evaluated separately. Finally, a sociological study was conducted aimed at understanding stakeholder perspectives and potential commitment to alternative management plans. In order to synthesize the findings from these disparate studies a Bayesian Belief Network (BBN) methodology is used.

The ranking of management options can depend on the stakeholder perspective. The trade-offs can be analysed quantitatively with the BBN model by combining, according to the decision maker's set of priorities, utility functions that represent stakeholders' views. We show how BBN can be used to evaluate robustness of management decisions to different priorities and various sources of uncertainty. In particular, the importance of sociological studies in quantifying uncertainty about the commitment of fishermen to management plans is highlighted by modelling the link between commitment and implementation success.

Keywords: Baltic salmon, bio-economic modelling, Bayesian Belief Network, expert knowledge, fisheries management, commitment and implementation uncertainty, management plan, recreational fisheries, stakeholders.

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1. Introduction

The recent shift in fisheries management has been towards a more inclusive practice that involves stakeholders in policy shaping (CEC, 2003). This paradigm shift is reflected in the demands of the European Commission for a broadly based scientific advice that takes account of ecosystem issues and environmental, social and economic aspects (CEC, 2003). New management plans developed by the European Commission should be based on comprehensive impact assessments. In such a pluralistic context, evaluating management strategies is a greater challenge. Not only the perception of the resource can be radically different from economic, biological or sociological perspectives, but also different stakeholders may desire radically different outcomes from a management regime. Bayesian Belief Network (BBN) (Jensen, 2001) is one of the methodologies developed that can demonstrate the implications of divergent stakeholders' ideas and values for fisheries management (Hammond and O'Brien, 2001; Haapasaari and Karjalainen, 2009; Haapasaari *et al.*, 2007).

In the management of anadromous species, such as salmon, that are harvested sequentially by various groups of fishers there are always conflicts of interest (Romakkaniemi *et al.*, 2003). Whereas offshore fishery may represent national interest against those of other countries on an international arena, coastal fishery carries local traditional values that are likely to be defended in an intra-national discourse. River fishery management, especially in cases where a river marks an international border, as does the Tornionjoki between Finland and Sweden, may have to address an even more complex set of socio-political issues, as there may be an even greater variety of users with distinct agendas: local vs. tourist fishermen, locals that are involved in tourism vs. those locals who do not see a greater number of outside fishermen as a benefit, fishermen from different countries, etc.

Overfishing of Baltic salmon and a subsequent stock declines have triggered an international response in the form of the Salmon Action Plan (SAP) that was initially overseen by the International Baltic Salmon Fisheries Commission (IBSFC). The plan's objectives are set for the period up to 2010. A new management plan is currently under consideration by the European Commission (EC). For the impact assessment conducted, in addition to the simulation of the biological and economic outcomes of different management options, a sociological analysis of the commitment of stakeholders to various management options was performed and an economic study of recreational fisheries were carried out, separately (Anon, 2009). There is clearly a need to synthesize and communicate all these results to decision makers and various stakeholders, and to be able to demonstrate how these results might be viewed from stakeholder perspectives. This task can be eased with the use of the BBN methodology – to facilitate the communication of the modelling results, and to represent a variety of perspectives.

In the field of environmental management, water management is particularly the area where BBNs have found advanced application (Varis *et al.*, 1990; Bromley *et al.*, 2005; Castelletti and Soncini-Sessa, 2007; Henriksen *et al.*, 2007; Martin de Santa Olalla *et al.*, 2007, Barton *et al.*, 2008). Castelletti and Soncini-Sessa (2007) explain the growing interest in the last decade for applying Bayesian Belief Networks to environmental problems by the "recognition that participation and uncertainty have a key role in integrated natural resource management and that there is a need for tools and methodologies that make it easier to handle them". Describing the study of involvement of stakeholders in the decision making process via BBNs to solve groundwater contamination problems, Henriksen *et al.* (2006) conclude that this methodology is particularly useful in allowing "stakeholder divergent values, interests and beliefs to be surfaced and negotiated in participatory process" where other approaches fail "due to lack of data, knowledge, or mutual trust between parties". Problems such as lack of information and trust among stakeholders are also major obstacles in achieving sustainable fisheries which a wider application of inclusive methodologies such as BBN could help to alleviate (Utne, 2006; Hammond and Ellis, 2001; Kuikka *et al.*, 1999; Haapasaari *et al*., 2007; Haapasaari and Karjalainen, 2009).

In this paper we demonstrate how this methodology can be used in an interdisciplinary setting with an example of Baltic salmon. Four management options are evaluated using a stochastic bio-economic model under different scenarios for environmental conditions that can strongly influence recruitment success. Thus we incorporate ecological knowledge in the form of scenarios affecting recruitment and biological and epistemic uncertainty over the states of nature by using a Bayesian state-space estimation model as a simulation framework (Michielsens *et al.*, 2006). Using BBN methodology we synthesize available relevant knowledge from sociological, economic and biological studies and evaluate, from different stakeholder perspectives, the management options considered for the future Baltic salmon action plan.

2. Methods

In this section, first the two sub-studies, bio-economic and sociological, are briefly described. Then the BBN model that is used to synthesise the sub-studies is presented.

2.1 Bio-economic analysis

We constructed and used a bio-economic simulation model of the Baltic salmon fishery in order to: (1) evaluate historic performance of management (IBSFC SAP for the period of 1997-2007), (2) assess consequences of future management options, and (3) quantify the trade-offs under each proposed policy. The biological part of the model is identical to the population model currently used in the ICES Baltic Salmon and Trout Assessment Working Group (ICES, 2008; Michielsens et al., 2006). The economic part of the model accounts for four member states that are responsible for catching about 90% of the annual, commercial, salmon landings: Finland (FI), Sweden (SWE), Denmark (DK), and Poland (POL).

DG MARE proposed four management options in terms of fishing effort of commercial salmon fleet. Accordingly, in the bio-economic analysis for the future SAP the following effort scenarios were explored:

- *no particular change in the fishing effort (base-scenario)*
- *25% reduction in the fishing effort compared to base-scenario*
- *50% reduction in the fishing effort compared to base-scenario*
- *75% reduction in the fishing effort compared to base-scenario.*

The bio-economic model was used to simulate biological and economic (commercial fisheries) consequences of each of these four options with two scenarios for post-smolt survival; since it was concluded in recent stock assessments that uncertainty over juvenile mortality during the post-smolt stage is the leading cause of predicted abundance variability (ICES, 2008).

We analyze the economic impacts of different management options on commercial sea fisheries by calculating annual revenues (catch times price) and profits (revenues minus fishing costs) for every country and gear, under each option and environmental scenario. To measure economic performance over a period of time we use net present value of profits (NPV), assuming 5% discount rate, constant prices and fishing costs.

One of the most informative uses of the bio-economic modelling is the quantifying of trade-offs associated with different management options. In the Baltic salmon fishery these trade-offs consist of profits, ability to safeguard weak wild stocks, and catch allocation among recreational and commercial users of the resource. The model we have developed enables us to calculate profits, probabilities to meet biological management objectives for each river, and numbers of fish available to the recreational river fisheries. We use river abundance of salmon as an indirect measure of the potential recreational benefits.

Stochastic outputs of the bio-economic model are approximated by discrete distributions and used as inputs to the BBN model.

2.2 Sociological study

In the sociological study, four long-term management options for Baltic salmon stocks were evaluated from the viewpoint of stakeholders' commitment to them. Commitment refers to a general attitude or voluntary support to a management plan, and therefore is a usable concept to be applied when dealing with implementation uncertainty. The pledge to commit is informal or may even be implicit, but it leads to acceptance of management measures if stakeholders are convinced that the measures are in their own long-term interest. Commitment to a multi-annual plan implies that stakeholders consistently act in ways that support the management goal thus increasing the probability of achieving the ultimate objective of the plan, whereas if stakeholders do not commit, the biological, social, and economic effects may be less predictable (Haapasaari *et al.*, 2007; Haapasaari and Karjalainen, 2009). Hence, stakeholders' commitment is associated with implementation uncertainty in natural resource management.

We selected experts representing commercial fishers and recreational fishing sector in the Baltic Sea countries, and carried out a web questionnaire in which the experts were asked to evaluate alternative management plans, on behalf of their reference groups. The experts were full-time officials or persons elected to a position of trust in organizations related to salmon fishing, and thus considered capable to assess and express the views of the stakeholders belonging to their reference group. The questionnaire included both open and structured questions. The responses to the structured questions were converted into probabilities and used to build a BBN describing commitment, and the answers to the open questions were analyzed qualitatively to check the reliability of the BBN, and to interpret the results of it (Haapasaari and Karjalainen 2009).

The commercial fishers saw restrictions expected to emerge from the management options as a potential risk to their livelihood and this issue was critical to them when assessing the alternative plans. The recreational fishing sector supported smolt production targets as high as possible to enable the development of tourist fishing industry.

However, the management options in the sociological study were not the same as effort reduction scenarios simulated in the bio-economic analysis; this inconsistency is due to the timing, the differences in approaches, and the fact that the studies were carried out independently and separately. Management options investigated in the sociological study included biological management objectives that were expressed as a set of targets referring to achieving 75% or 50% of the maximum smolt production by a particular date for individual rivers. The sociological study thus provided a link between management objectives and fishers commitment to a management regime based on those targets. Further, it suggested a relationship between fishers' commitment and fishers' readiness to implement effort reduction measures.

The results of this study have been summarized in a Bayesian Belief Network so that commitment determines the implementation error associated with management options investigated with the bio-economic simulation model.

2.3 Bayesian Belief Network Model

Bayesian Belief Network is constructed here by specifying the structural causal relationships, the prior probabilities for the causal nodes (implementation of management options, ecological scenario) and the full conditional probabilities for the affected nodes (recruitment, profits, river abundances) Figure 1. The conditional probabilities summarised in the recruitment, profits and river abundance nodes are derived from performing stochastic simulations with the bio-economic model under the different combinations of effort reduction and post-smolt survival scenarios, an example is given in Table 1.

Table 1. Discretized distributions of the recruitment in river Simojoki (in the year 2015), under the four different management options, assuming high post-smolt survival (favourable environmental conditions)**.**

Proportion of carrying capacity	*Discrete Probability Values*			
	No change in effort	25% reduction in effort	50% reduction in effort	75% reduction in effort
0-10%	0.014	0.006	0.004	0.005
10-25%	0.143	0.13	0.102	0.073
25 -50%	0.583	0.55	0.505	0.445
50- 75%	0.227	0.263	0.324	0.36
75% -up	0.033	0.051	0.065	0.117

The model includes two decision nodes (rectangular), seven stochastic variables (oval), and four utility nodes (diamond), Figure 1.

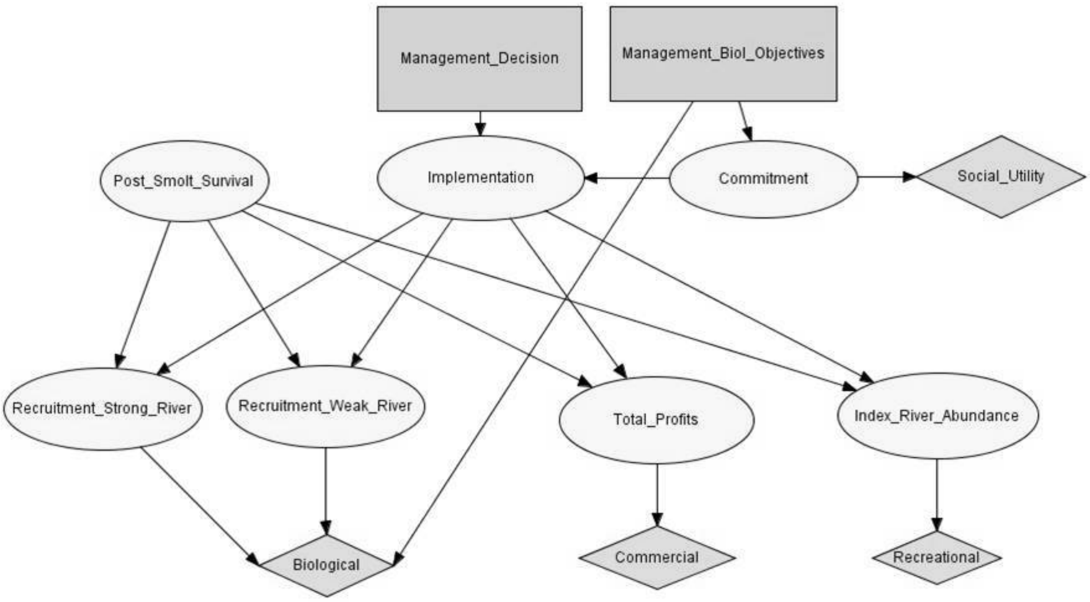

Figure 1. The Bayesian Belief Network for Baltic salmon, the rectangle represents decision node, oval nodes are random variables, and the utility functions are represented by the diamond shape.

2.3.1 Decision nodes

The decision nodes contain the alternative management decisions to be evaluated. 'Management Decision' includes the different options of fishery regulation in terms of reducing fishing effort. This was used as the control variable in the bio-economic simulation model. 'Management Biol. Objectives' were used in the sociological study. This node represents different management objectives expressed as a target proportion of smolts relative to the carrying capacity of the rivers (Uusitalo, 2005).

2.3.2 Affected nodes

The stochastic variable 'Post-smolt survival' reflects the uncertainty related to the survival of juvenile salmon during their first year at sea. It has only two uncertain states: high or low survival. These two scenarios were simulated in bio-economic model under different fishing effort levels supplying conditional probabilities for the affected nodes: "Recruitment strong river", "Recruitment weak river", "Total_Profits" and "Index_River_Abundance". These stand for, respectively: probability to meet management objectives in terms of recruitment by 2015 in Tornionjoki and Simojoki, NPV of total commercial profits for 2009-2015, and spawner abundance for 2015 in

Tornionjoki which is chosen as an index river. These rivers were chosen because of their respective recovery patterns: Tornionjoki, a major salmon river in the Baltic, has seen its stock recover strongly, while Simojoki river salmon stock, which is thought to be more susceptible to overexploitation, has experienced much weaker recovery when the fishing pressure decreased.

2.3.3 Commitment and Implementation nodes

Interrupting the causal link between the decisions nodes and the affected nodes are the nodes "commitment" and "implementation". This represents the real world problem of imperfect implementation of management decisions. The observations from the sociological study that quantified the relationship between management objectives and fisher's commitment are summarised in the "commitment" node. Commitment implies that the actors are willing to behave according to the agreed-upon course, and thus is a major factor influencing the implementation success of a management plan (Haapasaari *et al*., 2007, Haapasaari and Karjalainen, 2009). Thus the actual, or realised, fishing effort reductions expressed in the "implementation" node depend on both the management decision and the state of commitment of fishermen.

The relationship between commitment uncertainty and implementation uncertainty is constructed based on expert opinion grounded in sociological research. The probabilistic relationship between commitment and implementation of a management decision is defined in Table 2.

Table 2. Implementation error as a function of commitment, the table below specifies the probability of effort reduction depending on the management decision and the degree of commitment.

	Committed				*Somewhat Committed*				*Slightly Not Committed*				*Not Committed*			
	none	-25%	-50%	-75%	none	-25%	-50%	-75%	none	-25%	-50%	-75%	none	-25%	-50%	-75%
No change in the actual fishing effort	1.0	0.0	0.0	0.0	0.9	0.2	0.1	0.0	1.0	0.8	<u>0.3</u>	0.1	1.0	1.0	1.0	1.0
Effort is reduced by 25%	0.0	1.0	0.0	0.0	0.1	0.8	0.3	0.2	0.0	0.2	<u>0.6</u>	0.5	0.0	0.0	0.0	0.0
Effort is reduced by 50%	0.0	0.0	1.0	0.0	0.0	0.0	0.6	0.3	0.0	0.0	<u>0.1</u>	0.3	0.0	0.0	0.0	0.0
Effort is reduced by 75%	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.5	0.0	0.0	<u>0.0</u>	0.1	0.0	0.0	0.0	0.0

In the ideal situation stakeholders would be completely committed, leading to perfect implementation of effort reduction target decided by management – we explore this situation in a sensitivity analysis. However, in reality management decisions rarely get the full support of stakeholders. We hypothesise that the more ambitious is the effort reduction target, the more dependent on commitment is the success of implementation. We assumed that the more committed fishers are the higher is the probability that the management decision will be implemented successfully. Implementation error in BBN depends on the ambitiousness of the effort reduction targets: greater cuts are less likely to be achieved than minor effort reductions (Table 2).

In case that the stakeholders are not at all committed, BBN assumes that no change occurs with regard to their fishing behaviour, no matter what kind of management decision is made (Table 2). If, for example, the fishermen are 'slightly not committed' and the management decide on a 50% reduction in effort (bold and underlined column, table 2), there is only a 10% chance that the effort will actually be reduced by half, 60% chance that the effort will be reduced by a quarter, and a 10% chance that no effort reduction will occur.

2.3.4 Utility functions

Utility functions as implemented in BBN are functions of random variables in the network – (utility) values are assigned to each state (or a combination of states) of variable(s) upon which utility depends. If more than one utility function is defined in the network, BBN software calculates the sum of expected utilities (the sum of expectations of functions of random variables) under each choice in the decision module that is represented by a rectangle (Figure 1). In order for the sum of expected utilities to have meaning, utilities must be expressed in the same units. For example, valuation studies can help define utilities for management costs, fishing costs, and "conservation" in terms of units of currency. But it might be more difficult to translate other utilities, such as "commitment" into monetary terms.

Alternatively, all utility functions can be normalized and combined or compared on a unitless scale – this is what we chose to do in this paper, because it is equivalent to giving each stakeholder interest the same prior weight and it avoids problems such as extrapolating from river specific study of recreational benefits to the entire Baltic. For example, the commercial utility function can be derived based on the assumption that fishermen prefer higher profits, Figure 2.

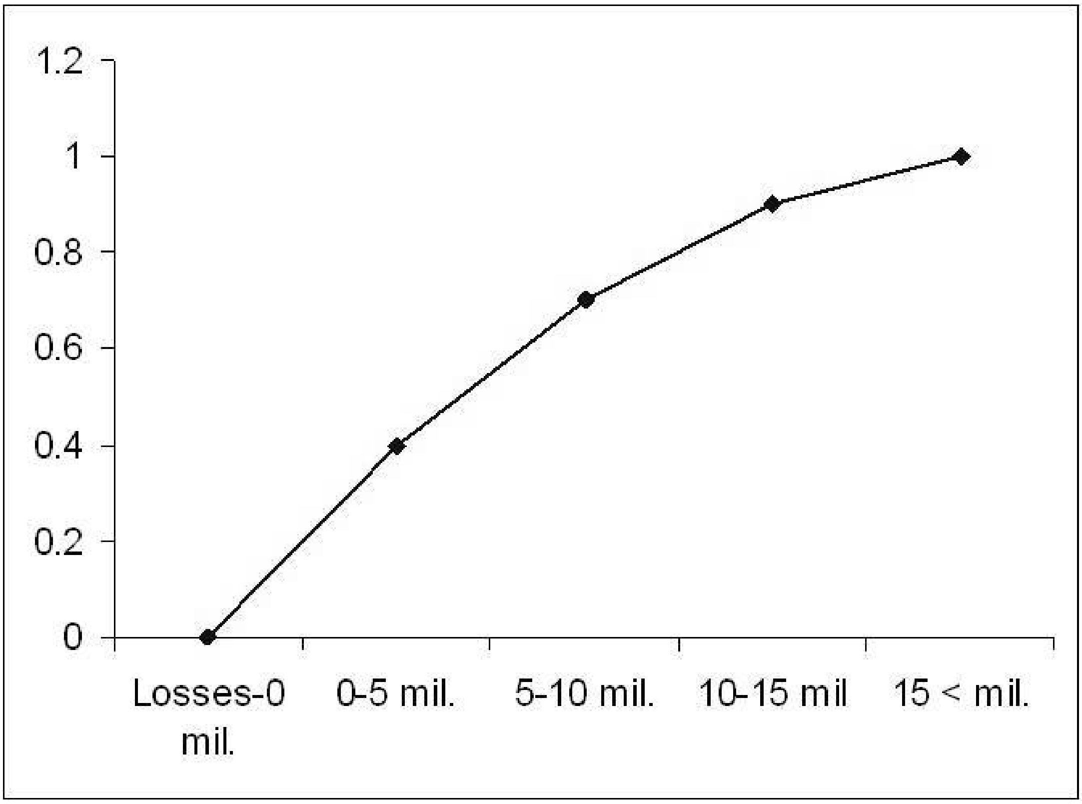

Figure 2. Unitless commercial utility function conditioned upon “Total_Profits” node which has five states each referring to a range of NPVs from the simulations (profits in millions of Euros discounted at 5% over the period 2009.

Our model assumes that fishers’ commitment enhances social capital and thus produces social utility. Social capital has been defined as a resource that facilitates individual or collective action, and emerges from social networks, reciprocity, trust and norms (Coleman, 1988). Commitment requires fishers to trust their fellow fishers to accept short-term sacrifices in the expectation of collective long-term benefits. Thus it contributes in creating or maintaining reciprocal social networks, and enhances the respecting of common norms (Coleman, 1988; Haapasaari *et al*., 2007).
Biological utility accounts for different types of salmon stocks and their probability to reach the management objectives. Management objectives in terms of the probability to reach carrying capacity threshold can either be set uniformly for all rivers, or alternatively because rivers in the Baltic vary greatly in terms of the resilience of their salmon stocks, more targets can be set on a river-by-river basis. We chose two stocks that are representative of weak (slow to recover, depleted stock) and strong (larger

and healthier stock which also has a potential to recover faster from depletion) salmon rivers in the Baltic, Simojoki and Tornionjoki, respectively.

With respect to recreational utility, a review of the valuation literature also undertaken as a part of the SAP impact assessment (Anon, 2009) has shown that anglers' willingness to pay increases with increasing catch possibilities. Therefore, we define recreational utility as a function of adult fish abundance in the rivers, e.g. population reduced by commercial exploitation (at sea and along the coasts) and consisting of salmon returning from the sea to their natal rivers to spawn. Because the study of recreational benefits covered only Tornionjoki, the utility function in the model is based on the spawner abundance in that river.

The tables specifying each utility function are presented in the Appendix, Tables 2A-4A.

The management options can now be ranked and compared based on the sum of the separately defined utility functions for each performance criteria according to each stakeholder's preferences. Because utilities are defined on a normalised unitless scale, combined expected individual utilities can be simply added. This is equivalent to a situation where decision maker chooses not to give different weights to different objectives. Additionally, the options can be ranked separately under different utility functions. The results can be analysed by comparing the ranking of options under different objectives.

Sensitivity of ranking the management options can be examined by considering different utility functions. Further, BBN is useful in demonstrating robustness with which management options are ranked, for example, to the different ways in which conflicting interests are weighted in the decision making process. We examine both of these issues in the next section.

3. Results

Using the BBN model we describe above we can rank the combinations of four management options (in terms of effort reduction) and biological objectives (in terms of target proportions of smolt productions relative to a maximum each river can support) according to different stakeholder perspectives represented by different utility functions; and we can also calculate overall utility by combining utility values. Rather than weighting each interest the same, managers might decide on priorities. To investigate robustness of ranking of management options to the differential weighting of interests we calculate the overall utility under this plausible scenario: the conservation interest is given a weight of 0.5, commercial - the weight of 0.3, recreational fisheries = 0.15 and social utility = 0.05. These results are presented in the tables 3, 4 and 5 along with the scenario where each interest receives exactly the same weight (0.25) whenever utility scores are combined.

Table 3. Ranking of management options (in terms of effort reduction) and biological objectives (in terms of target proportions of carrying capacity) according to recreational, commercial and biological utilities and the three utilities combined with equal and unequal weights.

Management objective in terms of carrying capacity target to be achieved by 2015	*Management option in terms of effort reduction in commercial fisheries*	*Rank according to all utility functions combined with unequal weights*	*Rank according to all utility functions combined with equal weights*	*Rank according to recreational utility only*	*Rank according to commercial utility only*	*Rank according to biological utility only*
75% of CC	*No change in effort*	3	2	4	1	4
75% of CC	*-25%*	2	1	3	2	3
75% of CC	*-50%*	1	1	2	3	2
75% of CC	*-75%*	2	1	1	4	1
50% of CC	*No change in effort*	3	3	4	1	4
50% of CC	*-25%*	2	2	3	2	3
50% of CC	*-50%*	1	1	2	3	2
50% of CC	*-75%*	1	1	1	4	1
A combination of targets	*No change in effort*	3	3	4	1	4
A combination of targets	*-25%*	2	2	3	2	3
A combination of targets	*-50%*	1	1	2	3	2

A combination of targets	*-75%*	1	1	1	4	1

Results show that taking only commercial fishery interests into account would result in "no reduction in effort" policy, whereas, predictably, both conservation and recreational fishery's concerns are addressed by a reduction in commercial fishing effort. The greater the reduction in effort the easier it is to meet conservation and recreation fishery objectives. So clearly there are trade-offs to be considered in making management decisions. The combined utility function represents the sought after compromise.

Higher effort reduction options are preferred under any choice of management objectives, in both scenarios for combining utilities, Table 4.

The sociological study showed that choosing river-specific targets (75% of CC for strong stocks and a less ambitious 50% of CC target for weaker stocks) would result in the highest commitment of fishermen to the management decision. In contrast, the conservation utility is higher when lower targets are adopted since lower targets are more likely to be exceeded. This explains the fact that under equal weighting scenario the combined utility is maximised under "both" targets regime, but when conservation utility is valued higher than social one the combined utility is maximised under less ambitions targets (50% of carrying capacity for all rivers), Table 4.

The ranking of management options is robust to preferential treatment of stakeholder interests in the tested scenario, but one of the consequences of unequal weighting is the increase in the range of values of a combined utility function - that is, different management options become more distinguishable, Table 4.

Table 4. Utility scores of management options (in terms of effort reduction in the commercial fisheries) and biological objectives (in terms of target proportions of carrying capacity) according to recreational, commercial and biological utilities and the three utilities combined.

Management objective in terms of carrying capacity target to be achieved by 2015	*Management option, effort reduced by*	*All utility functions combined With unequal weights*	*All utility functions combined With equal weights*	*Recreational utility only*	*Commercial Utility only*	*Biological Utility only*
75%	*none*	0.47	0.53	0.45	<u>0.93</u>	0.19
75%	*-25%*	0.48	0.54	0.48	0.92	0.21
75%	*-50%*	0.49	0.54	0.51	0.87	0.24
75%	*-75%*	0.48	0.54	<u>0.55</u>	0.81	<u>0.26</u>
50%	*none*	0.60	0.59	0.45	<u>0.94</u>	0.44
50%	*-25%*	0.61	0.60	0.47	0.92	0.47
50%	*-50%*	**<u>0.62</u>**	0.61	0.51	0.89	0.51
50%	*-75%*	**<u>0.62</u>**	0.61	<u>0.55</u>	0.82	<u>0.54</u>
Both	*none*	0.57	0.60	0.45	<u>0.93</u>	0.39
Both	*-25%*	0.59	0.61	0.48	0.92	0.42
Both	*-50%*	0.60	**<u>0.62</u>**	0.52	0.88	0.45
Both	*-75%*	0.60	**<u>0.62</u>**	<u>0.56</u>	0.79	<u>0.49</u>

In general, it is interesting to notice how relatively flat the utilities of different management plans are: from each of the stakeholder perspective the utilities of the worst and the best management plan are not that different. Conservation utility is the most sensitive to management decisions, whereas the combined utility function is the least sensitive because its component utilities are affected by effort reduction in opposite ways. One of the reasons for this insensitivity to management decisions is the implementation uncertainty, which in our model is a consequence of uncertainty in commitment of fishermen. By looking at a modified version of BBN which assumes

100% commitment (no implementation error) we can demonstrate quantitatively the effect of commitment on utility functions.

Table 5. Assuming 100% commitment. Utility scores of management options (in terms of effort reduction) and biological objectives (in terms of target proportions of carrying capacity) according to recreational, commercial and biological utilities and the three utilities combined.

Management objective in terms of carrying capacity target to be achieved by 2015	*Management option, effort reduced by*	*All utility functions combined With unequal weights*	*All utility functions combined With equal weights*	*Recreational utility only*	*Commercial Utility only*	*Biological Utility only*
75%	*none*	0.49	0.64	0.44	0.94	0.19
75%	*-25%*	0.51	0.66	0.51	0.91	0.23
75%	*-50%*	0.53	0.68	0.58	0.84	0.28
75%	*-75%*	0.51	0.66	0.64	0.66	0.33
50%	*none*	0.62	0.71	0.44	0.94	0.44
50%	*-25%*	0.65	0.73	0.51	0.91	0.51
50%	*-50%*	**0.67**	**0.75**	0.58	0.84	0.57
50%	*-75%*	0.66	0.73	0.64	0.66	0.63
Both	*none*	0.59	0.69	0.44	0.94	0.39
Both	*-25%*	0.62	0.72	0.51	0.91	0.45
Both	*-50%*	0.64	0.73	0.58	0.84	0.5
Both	*-75%*	0.62	0.71	0.64	0.66	0.55

First, notice that overall utility scores are higher – this is because assumed absolute commitment increases social utility. Further, under no implementation error scenario, management decisions have a greater impact on each of the commercial, recreational and biological utilities. Reducing effort by 75% increases the biological utility by 74% in the case of perfect commitment compared to 37% when commitment is uncertain. This approach quantifies how uncertainty due to the lack of commitment of fishermen to a management regime reduces ability of management to secure conservation and recreational fisheries goals. That is, no matter what management plan is adopted the uncertainty due to the lack of commitment makes expected actual outcomes under different decisions more similar than they would have appeared based on simulation study alone. This demonstrates the crucial role that sociological research can play when it is taken into account. When simulation model results were considered independently of the sociological study, the bio-economic modelling results suggested that policy decisions had greater biological and economic impacts because implementation uncertainty was underestimated (Anon, 2009).

Utility scores depend on the specification of utility function and also on a way the probability distribution of the stochastic variable upon which the utility function depends was discretised. A sensitivity analysis to changes in both of these factors should be carried out; in our case, the ranking of management options seemed to be robust.

Finally, the effect of environmental uncertainty on the utility and ranking of different management options can be examined with the BBN. The main result here is that assuming different environmental scenarios (level of post-smolt survival) does not change the ranking of management plans. However, the relative utility of reducing effort by 50% is greater compared to other options if the survival is low compared to the scenario when the survival is high, confirming a belief that management matters more when environmental conditions are unfavourable.

4. Discussion

The purpose of constructing a simulation model and performing evaluations with different management options is to explore the relationships between uncertainties in the modelled system and the ability to control the system in a satisfactory manner. The complexity of analysis arises not only through the many combinations of parameter and structural uncertainties, options for economic and environmental scenarios, and the management choices modelled, but also from existence of diverse perspectives of what would be a satisfactory outcome of management. Decision makers need to know how various uncertainties can influence their choice of action and how different stakeholders can be affected by the decisions (Burgman, 2005; Marcot *et al*., 2001; Pollino, 2007, Raphael, 2001). In this paper we demonstrate how Bayesian Belief Networks methodology can be used as a decision support tool to help discern the interactions between uncertainties, scenarios and diverse stakeholder interests.

The implementation of management measures depend on commitment of fishermen to the management regime which itself depends on objectives that managers chose to achieve. Further, commitment of fishermen towards management measures is highly variable and uncertain and the sociological study undertaken here suggests that implementation error will play greater role as more drastic management actions are chosen: it is quite certain that if management chooses not to reduce effort then the fishing effort will stay the same, while it is much less certain that management will be able to secure commitment with a 75% effort reduction. The significance of implementation uncertainty and the value of reducing it can be quantified using BBN (Varis and Kuikka, 1997; Varis and Kuikka, 1999).

In this paper we combined results from several studies that were commissioned to address a single management problem, and even though those studies were not conducted with the view of combining the results later within one methodological framework we could still use BBN to synthesize them. This methodology would have been easier to apply if disparate studies were harmonised from their conception, but, as we have showed, BBN is a viable approach even in the absence of consistent coordination between studies from multiple disciplines.

Further, BBN is an appropriate tool for exploring the sensitivity of management decisions to different representations (utility functions) of stakeholder interests, and for exploring robustness of management decisions to a variety of ways in which different interests can be prioritised. Currently the European legislation lacks specific guidance on how different interests need to be weighted in the decision-making process. The management plans could be more specific on how conflicting interests should be treated, on what principles should guide the balancing of trade-offs between conservation, recreational and commercial interests. BBN methodology not only can be used to implement such guidance for combining conflicting interests in the decision-making in a transparent quantitative way, but it can also be effective in alleviating the perception of a conflict by demonstrating that management decisions are actually robust to a certain amount of uncertainty over management priorities.

5. Conclusions

Increasingly managers are asked to consider stakeholder views and to take account of scientist's knowledge from areas as diverse as ecology, sociology and economics. We have demonstrated how research from different disciplines can be combined to enable policy makers to take into account various stakeholder perspective formally using Bayesian Belief Network methodology. We conclude that BBN is a viable approach to analyze trade-offs in management based on multi-disciplinary assessments/evaluations of proposed measures. BBN is one methodology that can increase transparency and help facilitate broadly based policy decisions. This approach can quantify the impacts of a particular source of uncertainty and highlight the gaps in the understanding of the system that should be a priority for research. In this paper, we demonstrated how uncertainty highlighted by the sociological study of commitment of fishermen quantifiably reduced the effectiveness of possible new management plans. Although neither implementation uncertainty nor environmental uncertainty affected the ranking of management options, the BBN model showed that improving commitment would increase effectiveness of management, and knowing that environmental conditions are adverse would increase the relative utility of selecting the management strategy that best balances competing stakeholder interests.

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Appendix

Table 1A. Description of the model variables

Variable	***Description***	***Discretized levels***	***Derived from***	***Conditional on***
Management Decision	Change in the commercial fleet's fishing effort in relation to 2008 effort levels	no change, -25%, -50%, -75%	DG Mare	None
Management Biol. Objective	Management objective based on the stock specific carrying capacities (CC)	no objective, 50% of CC, 75% of CC, 50% or 75% of CC depending on the river	ICES	None
Post-Smolt Survival	Survival of juvenile salmon during its first year at sea	high, low	ICES	None
Implementation	Implementation of management decision	no change, -25%, -50%, -75%	Sociological study	Management Decision, Commitment
Commitment	Stakeholders' support to the management option	committed, somewhat committed, slightly not committed, not committed	Sociological study	Management Biol. Objective
Recruitment Strong River	Number of smolts with respect to the carrying capacity in river Tornionjoki	0-10% of CC, 10-25%, 25-50%, 50-75%, 75-up%	Simulation model	Post-Smolt Survival, Implementation
Recruitment Weak River	Number of smolts with respect to the carrying capacity in river Simojoki	0-10% of CC, 10-25%, 25-50%, 50-75%, 75-up%	Simulation model	Post-Smolt Survival, Implementation
Total Profits	Net present value of the commercial salmon fleet profits in years 2009-2015. The fleet	losses - 0 profit, 0-5 millions, 5-10 millions, 10-15 millions,	Simulation model	Post-Smolt Survival, Implementation

	accounts for Finland, Sweden, Denmark and Poland	above 15		
Index River Abundance	Number of salmon ascending river Tornionjoki	low, medium, reasonable, high	Simulation model	Post-Smolt Survival, Implementation
Biological	Utility in terms of the stock specific carrying capacity	Unitless, normalised	Expert opinion	Recruitment Strong River, Recruitment Weak River, Management Biol. Objective
Commercial	Utility in terms of the commercial fleet's profits	Unitless, normalised	Expert opinion	Total Profits
Recreational	Utility from recreational fishery in terms of salmon ascending to river Tornionjoki	Unitless, normalised	Expert opinion, recreational fisheries study	Index River Abundance
Social	Utility from good implementation	Unitless, normalised	Expert opinion, sociological study	Commitment

Table 2A. Social utility as a function of commitment.

Commitment	Committed	Somewhat Committed	Slightly Not Committed	Not Committed
Utility	1	0.75	0.5	0

Table 3A. Utility functions for commercial fisheries

Total Profits	Losses-0 mil.	0-5 mil.	5-10 mil.	10-15 mil	15 < mil.
Utility	0	0.4	0.7	0.9	1

Table 4A. Utility functions for recreational fisheries

Index River Abundance	Low	Medium	Reasonable	High
Utility	0.2	0.6	0.8	1