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Research paper

Modelling the Impacts of Aquaculture in Wetland Ecosystems for Sustainable Aquaculture Management: An Integrated Ecosystem Approach

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Abstract

This research integrates information from both environmental and social sciences to inform effective management of the wetlands. A three-stage research framework was developed for modelling the drivers and pressures imposed on the wetlands and their impacts to the ecosystem and the local communities. Firstly, a Bayesian Belief Network (BBN) was used to predict the probability of anthropogenic activities affecting the delivery of different key wetland ecosystem services under different management scenarios. Secondly, Choice Experiment (CE) was used to quantify the relative preferences which key wetland stakeholder group (aquaculturists) held for delivery of different levels of these key ecosystem services. Thirdly, a Multi-Criteria Decision Analysis (MCDA) was applied to produce an ordinal ranking of the alternative management scenarios accounting for their impacts upon ecosystem service delivery as perceived through the preferences of the aquaculturists. This integrated ecosystem management approach was applied to a wetland ecosystem in Setiu, Terengganu, Malaysia which currently supports a significant level of aquaculture activities. This research has produced clear guidelines to inform policy makers considering alternative wetland management scenarios: Intensive Aquaculture, Conservation or Ecotourism, in addition to the Status Quo. The findings of this research are as follows. The BBN revealed that current aquaculture activity is likely to have significant impacts on water column nutrient enrichment, but trivial impacts on caged fish biomass, especially under the Intensive Aquaculture scenario. Secondly, the best fitting CE models identified several stakeholder sub-groups for aquaculturists, each with distinct sets of preferences for the delivery of key ecosystem services. Thirdly the MCDA identified Conservation as the most desirable scenario overall based on ordinal ranking in the eyes of most of the stakeholder sub-groups. Ecotourism and Status Quo scenarios were the next most preferred and Intensive Aquaculture was the least desirable scenario. The methodologies developed through this research provide an opportunity for improving planning and decision making processes that aim to deliver sustainable management of wetland ecosystems in Malaysia.

Keywords*: Ecosystem Services; Bayesian Belief Network (BBN); Choice Experiments (CE); Multi-Criteria Decision Analysis (MCDA).*

1. Introduction

An integrated multidisciplinary approach is widely recognized to capture the complex interrelationships between the ecological and economic components of the wetland ecosystem. From an ecological perspective, wetland ecosystem functions are difficult to model because of the many interactions between wetland ecosystems' characteristics, structures and processes. These interactions are likely to be non-linear, dynamic, stochastic and highly interconnected. Probabilistic or stochastic methods (e.g. Bayesian Networks, Influence Diagram and Markov Models) are therefore likely to be required to predict how a particular wetland will respond to different forms of management.

Ideally, socio-economic aspects should also be integrated in these probabilistic models so that socio-economic impacts can be assessed under different potential management scenarios. Socio-economic impacts can be assessed using a number of different economic valuation methods [1]. However, where valuation approaches are likely to be combined with scenario analysis in which the alternative management scenarios deliver varying combinations of desirable or undesirable outputs, Choice Experiment (CE) is likely to be more appropriate [2].

Managing wetlands sustainably and innovatively requires that ecological, economic and social outcomes of potential management scenarios are considered. A range of decision support tools have been used to inform management decision making: Multi-Criteria Decision Analysis, Citizen's Jury, Delphi Methods, Simulation Modelling, Q Methodology, Scenario Analysis, Cost Benefit Analysis, Cost Effectiveness Analysis, and Cost Utility Analysis. These tools differ in their ability to integrate and assess the ecological, economic and social impacts of wetland management. For this research, Multi-criteria Decision Analysis (MCDA) appears to be superior in its ability to synthesize results from the different assessment paradigms. MCDA could therefore be a useful tool for elucidating the management trade-offs which stakeholder groups must confront when alternative management scenarios are being considered.

This paper aims to develop a more sustainable, efficient and equitable way of wetland management so that the services which are delivered by the ecosystems can generate the greatest net benefit for the stakeholders. By focusing on a unique wetland ecosystem, that is the Setiu Wetlands, this paper attempts to formulate a new procedure for natural resource management by constructing an integrated, multidisciplinary framework via the following steps:

- Firstly, an ecologically-based model of the impact of human activities on wetland ecosystem under different management scenarios will be developed using an ecological modelling tool, the Bayesian Belief Networks to capture some of the uncertainties in the complex linkages between wetland ecosystem structures, processes and functions.
- Secondly, this research quantifies the preferences of wetland stakeholders with regard to the ecosystem impacts under the various management scenarios. A choice experiment approach is used to quantify these preferences.
- Thirdly, the research integrates the findings from the ecological and socio-economic modelling by using a Multi-Criteria Decision Analysis. The general utility of these linked approaches will be discussed.

2. Methodology

Setiu Wetlands is located in the east coast of Peninsular Malaysia, specifically in the northern part of Terengganu state. Setiu Wetlands is classified as a natural coastal wetland ecosystem and consists of nine inter-connected major habitats that are sea, beach, mudflat, lagoon, estuary, river, islands, coastal forest and mangrove forest [3]. The wealthy Setiu Wetland ecosystems provide a range of economic opportunities for local people including aquaculture, wild fishing, small-scale industries (utilizing wetland resources for food product, handicraft and boat building industries) and ecotourism. Thus far, aquaculture, especially fish cage culture is a key activity in Setiu Wetlands as it contributes significantly to the local economy by generating income, creating job opportunities, reducing poverty, providing a source of food and protein and supplying input for local food-based industries.
The management policies for Setiu Wetlands are currently focused on aquaculture development, particularly fish cage culture. Rapid and intensive expansion of cage aquaculture is likely to pose a major threat to the ecosystem functions and processes which underpin delivery of many of Setiu's other ecosystem service outputs. Sustainable management of Setiu Wetland will require trade-offs to be made between expanding these economic opportunities and preserving key elements of the wetland's natural capital stock. In exploring such tradeoffs, Bayesian Belief Networks (BBNs) is utilised as an ecological impact model to investigate the complex linkages and interactions between anthropogenic interventions, wetland ecosystem functions and ecosystem service outputs relevant to wetland stakeholder groups.

2.1. Ecological Modelling

This ecological impact model uses BBN cause-effect framework to explore the interactions and relationships that occur between natural and human elements within the Setiu Lagoon ecosystem. BBN is a probabilistic graphical model which represents correlative and causal relationships among variables [4, 5]. BBNs are directed acyclic graphs (DAG) represented by nodes which are linked by arrows to represent the direct correlations or causal influences [4]. Underlying each node is a modeller-defined table called a Conditional Probability Table (CPT). This table specifies the probability for each state for child nodes for all possible combinations of states in the parent nodes of that child. The final "posterior probabilities" of states or values of the output nodes are calculated in the network using standard Bayesian learning statistics [6]. The conditional probability table could be populated using the "beliefs" or experience and expertise of experts, as well as known quantified scientific relationships.
The information available for delimiting the model structure and for parameterising the probability tables is gained by a combination of limited field measurements and data specific to Setiu provided by Department of Fisheries, Setiu and Universiti Malaysia Terengganu, the literature dealing with aquaculture activity effects on water and sediment quality and also expert opinion from those with experience and expertise in aquaculture effects on marine environments.
Initially, the selection of the variables (boxes in the box-and-flow model) was established through consideration of the Driving Forces-Pressures-States-Impacts-Responses (DPSIR) framework, based on previous studies of aquaculture effects on sheltered marine systems. This ecological impact model use this DPSIR framework to explore the interactions and relationships that occur between natural and human elements within the Setiu Lagoon ecosystem using five elements as follows: 1) *drivers* are defined as the fundamental sources of the ecological impacts and are assumed to be caused by aquaculture activity in the Setiu Lagoon, 2) *pressures* represent the variables that respond directly to the drivers, 3) *states* report the ecological conditions in the lagoon (water column and sediments), 4) the resulting *impacts* describe the consequent effects on ecosystem services of relevance to key stakeholder groups, 5) the different management scenarios could then be envisaged as policy *responses* which the various stakeholders might consider in order to manage aquaculture's impacts and, ideally, deliver sustainable wetland management. This framework provides a conceptual starting point for the implementation of a BBN cause-effect model of the Setiu aquaculture system.
The elements of this framework were then represented as the boxes within the BBN and the links between them added. The identity of the box variables and the linkages between them are not contentious, since the effects of particulate and dissolved nutrients on water quality and the sediment environment, and the feedbacks to aquaculture and wild fisheries production and to human health are well documented in a qualitative sense.
The main driver aquaculture variables affected by policy are the area of water under fish cages and what type of food is supplied to the fish: a smaller area of cages will be expected to have less of an impact than a larger area, whilst fish pellets have far less environmental impact than waste or trash fish. All other variables were given states representing the present situation (normal), a moderate change or a large change in the state. The probability of each state occurring in a child node following changes in the condition of the parent mode are given as conditional probability tables which must be parameterised by the BBN user. The contentious nature of a BBN lies in the probability values actually given in the conditional tables, and specifically how these are derived.
The BBN was compiled using Netica Software. At this stage, the behaviour of the CPTs were tested by introducing different combinations of input values and observing the resulting probabilities in each intermediate node or the final output node(s). If the model exhibited unrealistic behaviour, CPT values were adjusted, nodes combined, split, or redefined, and so were the variable states and their interconnections until the responded reasonably. Using the model, four policy scenarios were explored for Setiu Wetlands: the status quo, intensive aquaculture, conservation and ecotourism. These scenarios are driven by changes in the states of two parent nodes representing the kind of food supplied to caged fish (trash fish or pellets) and the area under cages (small scale, medium scale and large scale). Each of these scenarios will be explored in turn.

2.2. Economic Modelling

This study implements CE for eliciting relative preferences for the delivery of different wetland ecosystem services. The following data were used to construct the basic choice set for this research;

- The Setiu Wetland stakeholders.
- The existing management practices potential alternative practices.
- The list of attributes and attribute levels by which those management practices could be portrayed in terms of outcomes relevant to the interests of the different stakeholders.

Aquaculturists were identified as a focal stakeholder group in the present study because of the considerable impacts which aquaculture imposes on the wetland ecosystem. The management practices of aquaculturists influence the condition the lagoon ecosystem and thus affect its ability to deliver ecosystem service outcomes to other stakeholder groups. If restrictions were to be placed on aquaculture practices, then these would undoubtedly affect aquaculturists' management.

Based on the decision nodes in the BBN, up to six hypothetical scenarios could have been visualised; however, the selection of alternative management scenarios for use in the CE should be consistent with potential future management scenarios for Setiu. The three selected future scenarios were intensive aquaculture, tourism and environment. Exploring the same management scenarios in the ecosystem impacts modelling work and in the CE also ensured that results from the BBN approach could be linked to the socio-economic results from CE models in a subsequent inter-disciplinary exploration of potential management alternatives.

A list of attributes and attribute levels for the CEs was produced by using the BBN cause-effect model to predict likely levels of ecosystem service delivery under the four chosen management scenarios. It was not practical to depict all the variables and states in the BBN diagram as attributes and levels in the CEs for a number of reasons. As the number of attributes and attribute levels increases, the number of cards in the choice sets will also have to increase. The main concern here is complexity since respondents with lower educational levels, particularly amongst the aquaculturists might lack the cognitive capability to cope with the multiple comparison and selection tasks presented in complicated and lengthy choice sets. Also, the BBN cause-effect diagram implies that some attributes are 'causally prior' to other attributes and these attributes should not be included independently in the CE to avoid presenting respondents with apparently incompatible sets of attributes in any particular choice option on a choice card. The selection of attributes and attribute levels for the choice cards in the CEs through the elimination of irrelevant and inter-related variables from the BBNs was based on expert opinion, consultation with administrators and policy makers, interviews and discussions with the stakeholders, and literature reviews.

The experimental design developed for this study used an optimal orthogonal in differences (OOD) approach, as developed by [7]. This approach makes data collection highly efficient and produces very compact card sets because it forces respondents to trade off their preferences across all attributes on each of the choice cards and thus maximises the amount of information on relative preferences obtained from each choice the respondent makes [7-8]. The OOD experimental design requires each respondent to complete the same set of choice cards.

The questionnaire was structured into three main sections; problem statements, choice cards, and questions to quantify respondents' background and attitudes. For this study, the problem statements were presented initially as a poster which presented key information such as the background to the study, problem statements, potential management plans with their associated attributes, and maps of Setiu Lagoon. For the choice card section, each respondent was presented with six choice sets consisting of four alternative options each featuring four attributes, where each attribute could be present at three levels of delivery – except for the aquaculture fee attribute which was presented at three levels in the future options and at a fourth, lower, level in the status quo.

The CE section concluded with a series of follow-up questions intended to identify any protest responses, lexicographic preferences, biases and inability to handle the complexity of the choice cards or to understand the questionnaire. The final section obtained information on respondents' backgrounds and attitudes which could be used as inputs for economic and discrete choice modelling component as well as for verifying the representativeness of the sample. The questions collected data on socio-demographic and economic characteristics, and respondents' attitude towards socio-economic activities, the perceived potential for further expansion of aquaculture in Setiu, and the perceived level of threat which these socio-economic activities might pose to the Setiu Lagoon ecosystem. The questionnaire survey was conducted by personal face-to-face interview using enumerators.

The results on individual preference variations were analysed based on the following discrete choice models. The most basic form of discrete choice model specification has been the Multinomial Logit (MNL) specification (also known as Conditional Logit (CL) Model) and more advanced models such as the Random Parameters Logit (RPL) model and the Latent Class (LC) model. The basic CE models estimated for aquaculturists contained four representations of deterministic utility, one for each of the choice options on each card, expressed in terms of the levels of each of the four attributes present in each option on the cards. A numbers of CE model estimations.

The Conditional Logit (CL) model can be interpreted as the conditional indirect utility derived from the various choice options on the cards which contain combinations of attributes and levels which could be derived from the different management scenarios. A multinomial logit (MNL) model examines choice probabilities knowing individual characteristics of respondents as well as the attributes of the available choice options. Allowing for variation in the characteristics of individual respondents could provide a better explanation of the observed choices and increase the explanatory power of the estimated discrete choice model.

The latent class (LC) model is one of a number of alternative approaches in choice experiments which can accommodate preference heterogeneity among the respondents. The estimated LC models were derived from the same choice card set in which each card presents four different options comprising four attributes present in three levels. The LC estimation equations can be interpreted as the estimated conditional indirect utilities derived from the different choice options present on the cards (V_Q, V_A, V_B and V_C).

3. Results and Discussion

3.1. BBN Results: Probabilities under the Different Management Scenarios

The BBN approach revealed that, for the model as parameterised, the impacts of fish cage culture are likely to be quite different under the different management scenarios. The results suggest that currently fish cage culture activity in Setiu Wetlands has only limited impacts to the lagoon ecosystem, except for water column nutrients. In this scenario, by operating at medium scale of cage area and equal rate of trash fish and pellet food feeding, the sediment and water column nutrients are most likely to be moderately high (enriched/polluted) and dissolved oxygen is most likely to be at a normal level, consequently sediment invertebrates and wild fish stock are only moderately affected and are still most likely to be at normal levels. The caged fish have a low probability of being stressed or killed (12 %) and there is a high probability of normal phytoplankton growth. Consequently, cage fish and wild fish production are relatively high, and there is little risk to human health or to incomes.

The worst environmental scenario would be expected to occur if the government allowed fish cage culture activity to operate at its maximum capacity (up to 2000 fish cages) with the majority of culturists using trash fish as the food source. Under this scenario there are much high probabilities of the sediment and the water column being polluted and a significant (46 %) risk of a low level of dissolved oxygen. Sediment invertebrates are likely to be reduced, phytoplankton abundance is most likely to be elevated, imposing increased stress on both caged and wild fish stocks and posing a risk to human health. Culturists and fisheries incomes would also be expected to decline.

The best environmental scenario would be expected to occur if the government implemented a conservation strategy where cage culture activity operated at the minimum fish cage area (approximately 800 cages) and most of the culturists used only pellets as the food source. This conservation scenario is most likely to produce normal levels for sediment enrichment, water column nutrients and dissolved oxygen, with correspondingly high probabilities of normal sediment, phytoplankton communities, caged fish and wild fish stocks. Risks to human health are most likely to be minimal, aquaculture production is likely to be high, as is in wild fish production, with correspondingly high incomes for fishermen and culturists.

Results for the ecotourism scenario in which aquaculturists feed only pellets to fish in a medium total fish cage area are almost identical to those which arise under the status quo, in term of qualitative changes to the pressure variables, states and impacts, although the actual probabilities produced are slightly different.

Based on the findings, the Conservation scenario was identified as the most attractive, followed by Ecotourism and the Status quo, whereas Intensive Aquaculture was seen as undesirable, with water column enrichment identified as the variable which is most vulnerable to the different aquaculture conditions. As such, the BBN has indicated that when making future recommendations for particular policies or management scenarios for these wetlands, it would be sensible to research further the key processes surrounding water column enrichment, since these processes have the greatest effect on the model.

3.2. CE Results: Aquaculturists Preferences

Elicited preferences from the choice card were quantified using Conditional Logit (CL) model, Multinomial Logit (MNL) model and Latent Class (LC) Model. The overall fit of the estimated basic CL model was fairly poor, however, this model do provide results which are in general agreement with the opinions and views expressed during the focus group discussions and interviews. The MNL model also showed that the annual license fee attribute was insignificant for the culturists. This could be because many aquaculturists ignore the current flat rate fee for operating cage culture in the lagoon, and/or because they were unconvinced that government enforcement of the proposed per cage fee would be effective and so they simply disregarded the license fee attribute on the choice cards.

Results indicate that aquaculturists with low incomes, higher education levels, fewer fish cages and with more experience hold stronger innate preferences for the status quo. The interaction effect with experience here suggests that aquaculturists may display increasing innate conservatism with age, but this is by no means the only possible explanation for these status quo interaction effects. Results from the three-segment LC model classify the sample into three fairly evenly-sized segments; 41 % in Segment 1, 28 % in Segment 2, and 32 % in Segment 3. The three segments show relatively distinct sets of preferences.

3.3. The Multi-Criteria Decision Approach for Sustainable Wetland Management

The MCDA framework presented here combined the scientific predictions from the BBN-based ecosystem impact model with the outcomes from discrete choice models derived from CE data to estimate the relative utility associated with each level of delivery of relevant ecosystem services for Setiu Wetland stakeholders under four different management scenarios. Overall, the ordinal rankings produced suggest that Conservation and Ecotourism are regarded as the best or second best management scenarios. Overall rankings also indicate that the Intensive Aquaculture and Status Quo scenarios are regarded to be less attractive. These results will help decision makers to rank management alternatives and should facilitate decision making for management of Setiu Wetlands in the future.

4. Conclusion

Overall, this framework has succeeded in achieving its main objectives. Firstly, it provides important scientific knowledge and helps decision makers to understand and appreciate the complexity, uncertainty and variability which surround management action within the wetland ecosystem. An awareness of these issues is vital for informing management decisions. Secondly, it provides quantified estimates of the main stakeholders’ relative preferences for important ecosystem services and reveals that there are several stakeholder sub-groups, each holding distinct and diverse preferences. Such analyses are very useful for identifying the relative value of different categories of ecosystem service from the viewpoint of the different stakeholder groups. Thirdly, the MCDA analysis suggests which management strategy is capable of delivering the highest utility values for each stakeholder sub-group and, by extension, across all stakeholders.

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