A Fuzzy Expert System for Effects of Climate Change on the Wadden Sea Ecosystem

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ABSTRACT: In order to evaluate the effects of climate change, an expert system was developed. In this expert system, experimental observations, model results and expert knowledge can be integrated and the results can be presented in both a qualitative and a quantitative way. Furthermore, the model offers the user the possibility to define and evaluate cases. In order to develop a model for the whole ecosystem of the Wadden Sea a modular, incremental approach was chosen. In this way, a variety of modules for different parameters can be prepared and subsequently integrated into a model of the complete ecosystem. For the underlying reasoning used for the implementation of knowledge rules, fuzzy set theory is used. The concept of fuzzy set theory provides a suitable means for the incorporation of ambiguities and lack of quantitative data into a classification scheme. For this study, dedicated software for a fuzzy expert system has been developed, called EcoFuzz. Its functionality includes the definition of fuzzy membership functions for all relevant aspects, the definition of fuzzy inference rules, and the evaluation of scenarios in a graphical form. The input of this expert system consists of observations from mesocosm experiments, results of model computations, and expert knowledge. Mesocosm experiments were carried out to verify the response of benthic organisms to climate changes. Model computations were made to predict changes in primary production. Experts were interviewed on their field of expertise and their knowledge was incorporated into the expert system. Subsequently the ecosystem components were coupled into an integrated description of the behaviour of the ecosystem under IPCC climate change scenarios.

1. INTRODUCTION

Climate change is rather slow: it acts in the time-domain of decades. As a consequence the analysis of the effects of climatic change addresses the change in the dominant processes, governing the large-scale behaviour of the morphological and ecological system. Given the present state of knowledge it is impossible to produce a quantitative model of all the processes and interactions fully describing the system. But the present knowledge can be organised in such a way that a qualitative / semi-quantitative evaluation of the functioning of the system can be achieved. One way to achieve this is to make use of an expert system. Expert systems in environmental assessments have been in use since many years (Waterman, 1986; Geraghty, 1993). One of the most promising techniques in expert systems for ecological assessments is fuzzy logic (Ecological Modelling, 1996).

This paper describes the results of the development and implementation of an expert system for the effects of climate change on the Wadden Sea ecosystem. This study was part of the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP-II project). Within the NRP-II project WL | Delft Hydraulics, in co-operation with the Dutch National Institute for Coastal and Marine Management, developed an expert system for assessing the effects of climate change on the Wadden Sea ecosystem. Specific objectives of this study were: (1) Develop an expert system for the effects of climate change on a large number of ecological parameters, (2) Present these results both in a qualitative as well as in a quantitative way and (3) Give the user the possibility to define and evaluate scenarios.

In order to develop a model for the whole ecosystem of the Wadden Sea, a modular, incremental approach was chosen. In this way, a variety of modules for different parameters could be prepared and subsequently integrated into a model of the complete ecosystem. The fuzzy expert system EcoFuzz contains knowledge rules on various ecosystem components and their behaviour under climate change for Mudflats, Phytoplankton, Microphytobenthos, Macrozoobenthos, Salt Marshes and Oystercatchers. For the underlying reasoning used for the implementation of knowledge rules, fuzzy logic was used.

2. CONCEPT OF FUZZY LOGIC

Fuzzy logic is an extension of conventional (Boolean) logic, that has been proposed by Zadeh in the 1960s (Zadeh, 1965) as a means to model uncertainty. Fuzzy logic introduces a concept of partial truth-values, that lie in between "completely true" and "completely false". The central concept of fuzzy logic is the *membership function*, which represents numerically the degree to which an element belongs to a set. In a classical set, a sharp or unambiguous distinction exists between the members and non-members of a set, while in a fuzzy set, the distinction between members and non-members is gradual. An element can be a member of a set to a certain degree and be at the same time member of a different set to a certain degree. The degree to which a member is element of a set is called the membership degree. Similar to traditional logic, in fuzzy logic membership values can be combined through operations on fuzzy sets, such as union, intersection and complement.

Fuzzy logic is often used for reasoning in knowledge-based systems, such as fuzzy expert systems. The knowledge is typically represented in terms of IF-THEN rules. An example is: IF A AND B THEN C. The IF-part of the rule is called the *premise* and the THEN-part the *consequent*. The truth value of the rule's premise describes to what degree the rule applies in a given situation. The so-called *fuzzy inference mechanism* is used to determine the consequent fuzzy set based on the truth value of the premise (this is often called the *degree of fulfillment*). Consequent fuzzy sets of individual rules are then combined (*aggregated*) into a single fuzzy set. In most practical applications, the resulting fuzzy set is converted (*defuzzified*) in to a real (*crisp*) value. The complete inference mechanism has five steps:

1. In the *fuzzification* step the membership degrees of the actual values of the premise variables are calculated.
2. Then the *degree of fulfilment* for the premise of each rule is computed, using fuzzy logic operators.
3. In the *inference* step, the degree of fulfilment of the premise of each rule is used to modify the consequent of that rule accordingly. This operation represents the If-Then implication, i.e. an intersection operator. Usually the minimum operator is used.
4. Then, the consequent fuzzy sets of all the rules are *aggregated* into a single fuzzy set, using an operator that represents the fact that the rules are valid simultaneously.
5. Finally, the resulting fuzzy set can be *defuzzified* to yield a crisp value. Defuzzification can be seen as an operator that replaces a fuzzy set by a representative value.

3. KNOWLEDGE SOURCES

The Wadden Sea expert system was mainly constructed using information of human experts. The expert system was developed to formalise the (linguistic) knowledge of various experts and to combine this with the knowledge of (numeric) models. Literature and maps were supplementary collected on climate change, the morphology of the Wadden Sea, the different species and functional groups of the ecosystem of the Wadden Sea, their life history, ecotopes etc. The available literature formed the base knowledge in the interview sessions with experts. Existing models of (parts of) the hydro- and morphodynamic system and ecosystem of the Wadden Sea also contain a lot of knowledge that was translated into IF-THEN rules and integrated in the knowledge system. Additional knowledge on the effects of climate change on macrozoobenthos was gathered in mesocosm experiments carried out in the NRP-II project.

The implementation of expert knowledge from interviews was carried out in an iterative way. The assumptions on the systems behaviour were discussed with the experts and the expert knowledge was incorporated into EcoFuzz. Feedback from the experts resulted in the final implementation of the expert rules.

4. GENERAL STRUCTURE OF THE EXPERT SYSTEM

For this study a fuzzy logic expert system was developed, called EcoFuzz. Many parts of the ecosystem are linked to each other and act upon each other. Therefore a modular structure for the expert system was chosen. The general structure of EcoFuzz consists of different modules for specific parts of the ecosystem, that together form a model of the complete ecosystem. The application of EcoFuzz made for the NRP II project contains ecosystem modules for the Wadden Sea with dedicated rules for the possible effects of climate change. The EcoFuzz expert system does not describe a dynamic development of the ecosystem over a period of 100 years, but gives a static presentation of expected changes in model variables that are valid after 100 years of climate change, i.e. in the year 2100.

To establish the knowledge on climate change, the expert system EcoFuzz contains the following elements (Figure 1):

- *aspects;*
- *relational systems;*
- *relational schemes*.

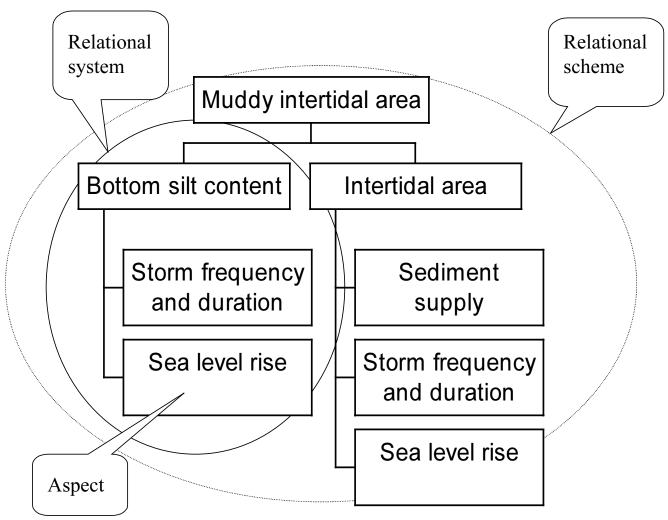

Figure 1 Elements in EcoFuzz.

4.1. *Aspects*

Aspects are the building blocks of the reasoning system. Each aspect is defined as a set of classes with fuzzy boundaries, so called fuzzy sets. Each value of an aspect has a membership degree for one or more of the fuzzy sets. As an example, the aspect 'Accelerated Sea Level Rise (SLR)' is presented in Figure 2. This aspect is classified into four classes: autonomous SLR, low accelerated SLR, intermediate accelerated SLR, and high accelerated SLR.

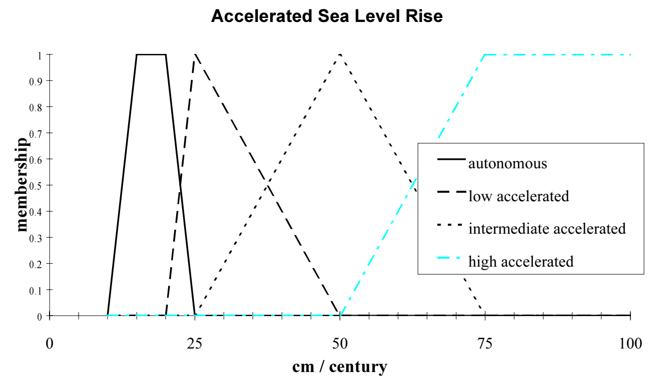

Figure 2 Membership functions for the aspect Accelerated Sea Level Rise.

4.2. *Relational systems*

The relationships between the aspects define the knowledge in the expert system. The way aspects relate to each other is defined in *relational systems*. A relational system contains the inference rules for the combination of the fuzzy sets, such as: IF A decreases AND B decreases THEN C decreases. A relational system can have one or more *affecting* aspects and always has one *affected* aspect.

As an example, the relational system for the Bottom Silt Content is presented. The aspect Bottom Silt Content has five fuzzy sets that denote the relative change in silt content compared to the present situation. The Bottom Silt Content in the Wadden Sea is affected by the Sea Level Rise and the Storm Frequency and Duration.
The latter aspect has four fuzzy sets that denote the relative change in storms compared to the present situation. The inference rules for the relational system are presented in Table 1.

4.3. *Relational schemes*

A combination of systems is implemented into EcoFuzz as a *relational scheme*. As an example, the relational scheme for Mudflats is presented in Figure 1.

Table 1 Relational system for Bottom Silt Content.

Bottom Silt Content (%change)	Storm Frequency and Duration (%change)			
Sea Level Rise (cm/century)	decrease	present	increase	strong increase
present	present	present	present	decrease
low	present	present	present	decrease
intermediate	present	present	decrease	strong decrease
high	decrease	decrease	strong decrease	strong decrease

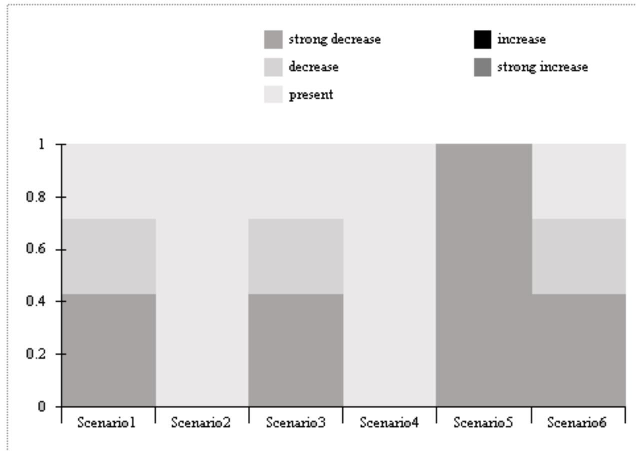

Figure 3 Fuzzy output for six scenarios of effects of climate change on relative change in the Muddy Intertidal Area.

The fuzzy expert system EcoFuzz contains knowledge rules on various ecosystem components and their behaviour under climate change. In total six different schemes were implemented for Mudflats, Phytoplankton, Microphytobenthos, Macrozoobenthos, Salt Marshes and Oystercatchers. Due to the modular structure of EcoFuzz (parts of) these schemes can be connected to each other. This is typically the case for the description of higher organisms. The relational scheme for the Oystercatcher carrying capacity in the Wadden Sea for example contains (elements) of the schemes for macrozoobenthos, morphology and salt marshes. The macrozoobenthos scheme itself is connected to the primary production scheme. In this way the know-how of experts in their own fields of expertise can be coupled into an ecosystem model.

4.4. *Example of EcoFuzz output*

As an example, the resulting fuzzy output for the aspect Muddy Intertidal Area is presented in Figure 3. EcoFuzz presents the results of the computation as fuzzy memberships for the sets, or as defuzzified values.

Figure 3 shows that scenarios 2 and 4 have a membership degree of 1 for the *present* class. Scenario 5 is the result of a decrease in Intertidal Area and a decrease in Bottom Silt Content and results in a membership of 1 for the *strong decrease* class. Scenarios 1, 3 and 6 have membership degrees in three classes; 0.43 for *strong decrease*, 0.29 for *decrease* and 0.29 for *present*.

Fuzzy inference

As an example of the fuzzy inference in this expert system, the outcome for scenarios 1, 3 and 6 is analysed. The combinations shown in Table 3 are relevant for the computation of the memberships for these scenarios. The relative changes of the Intertidal Area and the Bottom Silt Content, as a result of climate change, have membership degrees of 0.6 in the *decrease* class and 0.4 in the *present* class. The combination of the changes in these parameters defines the change in Muddy Intertidal Area.

Table 2 Relevant inference rules of the relational system for Muddy Intertidal Area.

Muddy Intertidal Area (%change)	Bottom Silt Content (%change)	
Intertidal Area (%change)	decrease: **0.6**	present: **0.4**
decrease: **0.6**	strong decrease	decrease
present: **0.4**	decrease	present

For both aspects the membership degree for the *decrease* class is 0.6 and for the *present* class is 0.4. The resulting membership degrees for Muddy Intertidal Area for the four combination rules of Table 3, using the MIN operator are:

1. *strong decrease* = MIN (0.6,0.6) = 0.6
2. *decrease* = MIN (0.4, 0.6) = 0.4
3. *decrease* = MIN (0.6, 0.4) = 0.4
4. *present* = MIN (0.4,0.4) = 0.4

The aggregation of the membership degrees for these rules, using the MAX operator yield: *strong decrease* 0.6, *decrease* 0.4, *present* 0.4. These outcomes are subsequently scaled between 0 and 1, using the sum of scores, which is 1.4:
strong decrease = 0.6/1.4 = 0.4286;
decrease = 0.4/1.4 = 0.2857;
present = 0.4/1.4 = 0.2857.

Table 3 Climate change scenarios based on IPCC predictions.

	(1) baseline A	(2) stab 450	(3) baseline A rad	(4) stab 450 rad	(5) sea level extreme	(6) changing circulations
acc. sea level rise (cm/century)	65	50	65	50	110	65
mean winter temperature (°C)	+ 8	+ 4	+ 8	+ 4	+ 8	-1
mean summer temperature (°C)	+ 5	+3	+ 5	+3	+ 5	+ 6
summer irradiation (%change)	0	0	-4	-4	-4	-4
storm freq. and duration (%change)	0	0	0	0	0	0
sediment supply (insuff.-suff.=0-1)	1	1	1	1	1	1

Defuzzification
Using the membership functions of the individual aspects, the fuzzy results can be defuzzified into crisp values. Table 4 presents the defuzzified output for the Morphology scheme.

Table 4 Defuzzified output for the Morphology scheme.

	Bottom silt	Intertidal	Muddy intertidal
Scenario 1	-1.2	-1.2	-2.714286
Scenario 2	0	0	0
Scenario 3	-1.2	-1.2	-2.714286
Scenario 4	0	0	0
Scenario 5	-2	-2	<= -5
Scenario 6	-1.2	-1.2	-2.714286

All results are expressed as %change relative to present situation.

An example will clarify the process of defuzzification. For scenario 1 the membership degrees for the Muddy Intertidal Area classes are given by:
strong decrease = 0.4286;
decrease = 0.2857;
present = 0.2857.

The membership functions for Muddy Intertidal Area are presented in Figure 4.

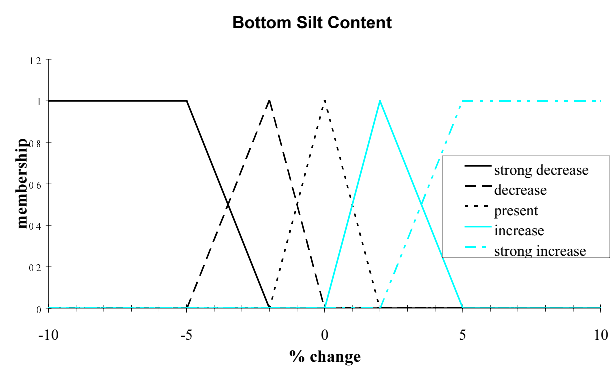

Figure 4 Membership functions for the aspect Muddy Intertidal Area.

In the defuzzification step, the centre of each membership class is used for functions that do not go to infinitely, and the right or left boundary values of membership values are used for functions that do go to infinitely. The crisp values of the membership classes are therefore:
strong decrease: -5%
decrease: -2%
present: 0%
increase: +2%
strong increase: +5%
The membership degrees for each class are then multiplied with the crisp class value. For the membership degrees of scenario 1 this yields:
0.4286*-5 + 0.2857 * -2 + 0.2857 * 0 = -2.71%.

5. SCENARIO COMPUTATIONS

The completed expert system EcoFuzz was used to compute the effects of climate change on the functioning of the Wadden Sea Ecosystem. Six climate change scenarios were defined using assumptions on changes in accelerated sea level rise, mean winter and mean summer temperature, summer irradiation and storm frequency and duration (Table 2). The scenario definitions for these parameters are based on IPCC predictions. In all scenarios it was assumed that there is 'sufficient' sediment supply to the Wadden Sea. In these scenarios the sea level rise has a range between 50 cm/century and an extreme 110 cm/century, the mean winter temperatures rises considerably in most scenarios (4 or 8 degrees), the mean summer temperature rises in all scenarios, and the summer irradiation decreases in four scenarios. Although the storm frequency and duration and the sediment supply stay unchanged, knowledge on the effects of changes of these parameters is included.

6. RESULTS

The results of the scenario computations denote the expected changes in the Wadden Sea ecosystem. These computations were carried out for the six relational schemes that were implemented in the EcoFuzz application, i.e. Mudflats, Phytoplankton, Microphytobenthos, Macrozoobenthos, Salt Marshes and Oystercatchers. A comprehensive analysis of the knowledge schemes and results are not subject of this paper, but a summary of expected changes is given below.

6.1. Mudflats

The Mudflats relational scheme is already discussed in this paper. The results of the scenario computations show that the area of intertidal mudflats will not be affected as long as the accelerated sea level rise velocity is less than 50 cm/century, the storm frequency and duration do not increase and as long as there is a sufficient sediment supply to the Wadden Sea basin. When these conditions are exceeded the relative decrease in the area of mudflats is limited to a couple of percents, unless there is an extreme sea level rise, than the relative decrease will be more than five percent.

6.2. Phytoplankton

The relational scheme for phytoplankton is simple, changes in summer temperature and summer irradiation affect the phytoplankton. Results of the scenario computations show that the phytoplankton biomass in the Wadden Sea will not be affected by the estimated rise in summer temperature and summer irradiation. The assumption that is made here is that the nutrient levels and salinity remain constant.

6.3. Microphytobenthos

The relational scheme for microphytobenthos consists of two parts. One part is the scheme for mudflats and denotes the preferable habitat of microphytobenthos. The other part denotes the changes in microphytobenthos density affected by the changes in summer temperature and summer irradiation. When the summer irradiation decreases, the primary production and density will decrease. When the summer temperature increases, the density will decrease as a result of a higher mortality rate. For all scenarios it is expected that the microphytobenthos biomass will decrease with a relative change between the 0.8% and 4.4% for the scenarios, with the exception of scenario 5 (extreme sea level rise) when the decrease is more than five percent.

6.4. Macrozoobenthos

The relational scheme for macrozoobenthos is a more complicated one. The area of mudflats and the biomass of benthos per square metre depict the relative change in total amount of benthos. The biomass of benthos is divided into a summer biomass and a winter biomass. Growth and reproduction depict the summer biomass and the winter biomass is depicted by winter mortality that is affected by the mean winter temperature. The mean summer temperature and the phytoplankton biomass depict the growth of benthos. The weight of adults in spring and the predation pressure on benthos in spring are both affected by the mean winter temperature and depict the reproduction.

A decreased mortality rate of macrozoobenthos in warmer winters will result in a higher biomass in winter, but a decreased growth and reproduction rate will cause a lower biomass in warmer summers. As a result the biomass of benthos per square metre will show a more stable seasonal pattern and a net increase. The scenario computations show that the total amount of macrozoobenthos in the Wadden Sea will increase with 6 percent for scenarios with limited sea level rise (50 cm/century) and higher temperatures. It will decrease slightly with about 1.5 percent for scenarios with an intermediate sea level rise (65 cm/century) or even 10 percent for extreme sea level rise (110 cm/century), primarily caused by the effects on their preferable habitat, the area of intertidal mudflats. In case of a combination of intermediate sea level rise and colder winters the total amount of macrozoobenthos will decrease with 19 percent.

6.5. *Salt marshes*

The relational scheme of salt marshes predicts the relative changes in the pioneer zone of the marshes. The bottom shear stress imposed on this zone and the vegetative growth depict the changes in the pioneer zone. The bottom shear stress is affected by the storm frequency and duration and the sea level rise. These parameters also affect the bottom silt content. The bottom silt content and the bottom shear stress together depict the vegetative growth. The vegetative growth will decrease in coarser sediments and in places with more scour.

The scenario computations show that the bottom shear stress will increase, the vegetative growth will decrease and as a result the area of salt marsh pioneer zone will show a decrease of more than five percent.

6.6. *Oystercatchers*

There are two relational schemes for Oystercatchers. The annual cycle in Oystercatcher abundance in the Wadden Sea was divided into a winter population and a summer population. The winter scheme predicts the changes in maximum carrying capacity for wintering birds. The mean winter temperature has a direct effect, through migration and mortality, and the food availability plays a role. The biomass of benthos in winter and the intertidal area depict the food availability. The summer scheme predicts the maximum carrying capacity in summer. The food availability in summer and the area of salt marshes depict the carrying capacity. The food availability is affected by the biomass of benthos in summer and the intertidal area.

Results of the scenario computations show that the carrying capacity of Oystercatchers in summer will decrease with more than ten percent for the first five scenarios, due to a decreased food availability and salt marsh area. The exceptional sixth scenario with colder winters results in a stabilisation of summer benthos biomass and shows therefore a decrease of only eight percent. The carrying capacity of Oystercatchers in winter will show a net increase for the first four scenarios, due to the increased food availability in warmer winters. The fifth scenario with extreme sea level rise shows the highest decrease in intertidal area, but this is compensated for by the increase in food availability and shows a net stabilisation of carrying capacity. The sixth scenario with colder winters shows a decrease in food availability and therefore a decrease in Oystercatcher carrying capacity.

7. DISCUSSION AND RECOMMENDATIONS

7.1. *Discussion*

This project has integrated available knowledge on the functioning of the Wadden Sea ecosystem under climate change scenarios in an expert system. A new software tool was developed to aggregate this knowledge in a formalised way, using fuzzy set theory as a mathematical basis.

There are various knowledge sources used to feed the expert system with relevant information, of which interview sessions with experts were the most important. In these interview sessions experts were asked to give their opinion on the potential effects of climate change, each on their own field of expertise. The most difficult information to gather was a quantification of the magnitude of the effects. Most experts were able to present a probable direction into which the changes may take place, but the size of the effects was often difficult to estimate. Therefore, the quantification of the effects presented in this study must be interpreted with care.

The expert model that was developed in this project, EcoFuzz, is generally applicable for the implementation of other expert systems. This software has also been successfully used to model floating algae in the IJsselmeer (Vonk & Michielsen, 1998).

In this project a knowledge base of relevant parameters for the Wadden Sea ecosystem has been set up and filled with knowledge on systems behaviour under climate change scenarios. This expert system is able to handle knowledge from different domains on different time and spatial scales in a formalised way. The model can aggregate information to ecosystem level and is able to present a qualitative to semi-quantitative evaluation of the integrated effects of climate change on geomorphological and ecological processes.

The results of the climate change scenarios show the expected effects for different abiotic and biotic system components and the system as a whole, because the system components are linked to each other. A selection of species or functional groups was made, based either on relevance for the ecosystem or on available knowledge on the potential effects of climate change. Each system component was described in the most simple way, in order to minimise the amount of rules needed to describe the system and to keep the system behaviour understandable. When using expert systems, it is important for the experts to be able to follow the different steps in detail. Black-box systems are not appropriate.

7.2. *Recommendations*

Several recommendations can be made on the methodology of the Wadden Sea experts system and on the instrument itself.

The ecosystem of the Wadden Sea is described in a very simplified form. The mathematical methods used to describe the ecosystem of the Wadden Sea are linear functions on a limited number of parameters. The way these relations are implemented fits the way of thinking of experts. The problems of climate change are complex and in many cases knowledge is lacking to give a clear and complete overview of impacts. Experts must then rely on their gut-feelings and will provide an estimation of effects mainly in terms of general directions and magnitudes. Another reason for a simplified description is that it makes the expert system transparent, so that an expert is able to follow each step and its consequence.

The question is to what extent EcoFuzz may be an oversimplification of truth. Many relationships in nature are non-linear, show feedback coupling and there are many dynamic processes on different time and spatial scales. EcoFuzz does not describe a dynamic development of the ecosystem, but merely gives a static presentation of expected changes in model variables that are valid after 100 years of climate change, without feedback loops. The model does not take into account extreme events, such as the introduction of invader species, or parasites. Furthermore EcoFuzz assumes a constant gene-pool in the faunal communities and does not take into account possible adaptive responses to climate changes.

A validation of the results of EcoFuzz is only partly carried out. The knowledge that is incorporated into EcoFuzz mainly stems from interviews with experts that was presented to them once. Each consulted expert was given the possibility to review its own representation of expert knowledge on its own field of expertise. Afterwards, all available knowledge was related to each other and combined in the present version of EcoFuzz. Subsequently the effects of the climate change scenarios were computed and these results are presented in this study.
Regarding the way the Wadden Sea system is described in EcoFuzz it is recommended to:

- present the model results of the climate change scenarios to the consulted experts;
- validate the model results with expert knowledge of a different set of experts;
- execute a sensitivity analysis of EcoFuzz;
- improve the mathematical description of ecosystem behaviour.

In developing the software for the expert system a flexible user-interface is coupled to a modular build-up of ecosystem components and relationships. EcoFuzz makes use of external ascii-files that contain the fuzzy membership functions for the aspects, the inference rules for the systems, the selection of systems into schemes, the scenario input and the model output. For the stand-alone user this is not always very user-friendly, but an advantage is that EcoFuzz can be easily coupled to other ecosystem models or incorporated in other software such as Decision Support Systems.

Regarding the software-instrument EcoFuzz, it is recommended to improve the user interface with respect to the use of external files.

8. ACKNOWLEDGMENTS

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