Using Bayesian Network modeling to cope with the marine protected area governance issue

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Keywords: Marine Protected Areas, governance, Bayesian Networks, expert knowledge, probability, risk management, indicators, integrated approach, simulation, scenarios, fisheries,, tourism, social acceptability.

Abstract: Bayesian Networks are useful tools for modeling interactions and predictions in social-ecological systems since they offer a robust theoretical framework towards risk and uncertainty management problems through the use of probabilities. Furthermore, this theory gives the possibility to combine expert knowledge and data. That’s why they have been successfully used for helping resource-management decision-making process in numerous case studies. We propose to apply this approach in order to deal with the marine protected areas governance issue. A first model of Bayesian Network has already been developed from the French Polynesia case study concerning fisheries response to regulations in Moorea Island. This step allowed us to think about a more comprehensive model, which would encompass the ecological, economical and institutional components that underlie the understanding of the marine protected areas governance issue. Therefore we derived a second model from six case studies: three Mediterranean and three in French overseas. The first objective was to draw through the structure of the Bayesian Network a synthetic and comparative framework that represents the expert knowledge relative to the marine protected areas implementations and their consequences on the different components of the social-ecological system. The second objective is to simulate governance scenario for a particular case study – as the impacts of different regulation measures on the resources and biodiversity conservation of the ecosystem or on the satisfaction of users like fishermen or tourists – once the parameters of the model have been set up by using both database and expert judgment.

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INTRODUCTION

Marine protected areas (MPAs), whose implementation mainly results from conservation goals, are complex social ecological systems, which encompass a wide range of uses, original institutional forms, socio-economical and environmental contexts. That is why dealing with MPAs' governance issue from a comprehensive perspective is a strenuous task which implies a multidisciplinary work.

Tools must be developed in order to help MPAs' managers and public decision makers, who are both interested in two types of information. First of all, they need descriptions of the current system state in order to assess the MPA effectiveness regarding its goals. Secondly, they would need satisfying predictions concerning the impact of the different competitive measures they could establish, and this means dealing with risk or uncertainty.

This paper present an original model based on the Bayesian Network framework that can be helpful for both the needs of decision makers we were discussing above. It was developed during the "GAIUS" research program in order to sum up knowledge about MPA governance in six different case studies. Bayesian Networks are powerful probabilistic and graphical modeling tools using causal graphs and conditional probabilities diffusion in this graph. They are able to handle quantitative and accurate knowledge as well as qualitative knowledge, provided by experts. They are adapted to represent and model complex systems and to explicitly take into account the uncertainty and non-exhaustiveness of available knowledge.

On a first part, we will introduce the context of the research program in which this model is developed, and the main objectives that underlies its construction. Then we will present briefly the Bayesian Network modeling framework and discuss the usefulness of such an approach according to our problematic. On a second part, we will introduce and explain the structure of our model. In a third part, we will discuss the parameters learning process in order to deal with governance scenario simulation. A simple example of simulation derived from the Moorea case study will be displayed.

CONTEXT: MPA GOVERNANCE AND THE GAIUS RESEARCH PROGRAM

Many definitions of MPA exist in the literature; we choose the classical one given by UICN (*Kelleher G., 1999*): "An MPA is defined as « an area (…) which has been reserved by law or other effective means to protect part or all the enclosed environment ». MPAs can then be very different in terms of rules, management, geography, and have very various goals, but globally they aim at protecting marine ecosystems because of their value (cultural, economic, historical, ecological, social…).

The concept of governance is used in numerous contexts, from biological to social sciences. Thus, many meanings can be imputed to the term. However, in this study, we will use this term to refer to the changes in MPAs user's behaviors and activities imputed to the MPA creation and implementation of specific measures linked to the MPA management plan. Looking for "good" governance is setting up a way people are interacting to achieve MPA's objectives.

How to configure marine protected areas and their regulations in order to reach the goals that have been set, namely biodiversity conservation, sustainable management of fisheries, local heritage and capital conservation, sustainable development of recreational activities and tourism?

This question sparks off the problematic of the “GAIUS” research program, which aims to provide some answers through a multidisciplinary analysis of six case studies sites (three Mediterranean and three in French overseas) with different ecological, economical, institutional and political contexts. Alongside data analysis, synthesis and indicators development, several modelling approaches have been explored within the program.

Our study aims at introducing through the structure of a Bayesian Network a synthetic and comparative framework that represents the GAIUS expert knowledge relative to the marine protected areas implementations and their consequences on the different components of the social-ecological system. A second objective will be to simulate governance scenario for a particular case study – as the impacts of different regulation measures on the resources and biodiversity conservation of the ecosystem or on the satisfaction of users like fishermen or tourists – once the parameters of the model have been set up by using both database and expert judgment.

BAYESIAN NETWORKS MODELING

Brief presentation of Bayesian Network

A Bayesian Network consists in probability distribution and directed acyclic graph (F. V. Jensen, 2001), whose nodes are variables (states, events…) linked between them by causal relationships represented by directional arcs (i.e. arrows). It gives the possibility to use the information relative to the state of one variable in order to know the state of another one, by using conditional probabilities, whatever is the link between those two variables. Both the graph and the probabilities of a Bayesian Network can be obtained automatically, from data bases, or manually, from human experts’ knowledge and the literature of the domain to be modeled. For a detailed presentation concerning Bayesian Networks, the reader can refer to *P. Naïm & al.* (2007).

To our knowledge, this study, which follows the work of (*Badie et al., 2009*), is the first attempt to use the Bayesian Networks framework in order to cope with the marine protected area governance issue from a global perspective.

Advantages and weaknesses of Bayesian Networks regarding our objectives

The structure of our network is based on numerous variables, whose states can be determined through the use of expert judgment, indicators and other data, or both. Our main objective is to describe and analyze behaviors and impacts of MPA’s users such as fishermen, individual recreational users (divers, amateur sailors…) or service providers given the set of regulations introduced by the MPA. Using Bayesian Networks theoretical framework provides several benefits compared to other models (*Marcot & al., 2001*):

- A rigorous handling of uncertainty in probabilistic terms: they are therefore suitable for risks analysis and management contexts, and this is especially relevant in poor data contexts.
- The possibility to combine prior knowledge with new information as well as empirical data and expert judgment. In MPA’s context, expert knowledge could be crucial to overcome the lack of data concerning global ecological situation and ecosystem vulnerabilities, informal fishing, MPA user’s impacts or adherence to regulating measures.

- A capacity to evolve and change: Bayesian Networks modeling offers a significant flexibility since updating or refinement of knowledge is easily incorporated, either through new nodes, either through new probabilities.
- The use of the causal graphical representation as a communication tool: decision makers can rapidly understand the global operating system of the network, namely chain of cause and effect and conditional independence between the different nodes. This allows bridging the understanding gap between scientific and decision makers which take place with too complex model often perceived as black box.

Nevertheless, it is also worth noticing some weaknesses concerning this approach. The main one is due to the limited number of direct parents that can have a given variable in practice, since each parameter of the Bayesian Networks is a joint probability distribution whose size grows exponentially depending on the number of parents of a given variable. In complex systems like MPA, which cannot be described without the use of numerous variables and interactions, it will be a major problem to deal with. However, several methods exist in order to simplify a conditional probability distribution: here again, for further details, the reader can refer to *P. Naïm & al.* (2007).

Furthermore, the Bayesian Network approach does not lend itself easily to dynamic system modeling, since no feedbacks are allowed (due to the acyclic property). Yet it is possible to model dynamics of a system using time slices, inside the model or by developing several models, each one peculiar to a specific period. For example, dynamics of MPA's governance could be modeled by developing different networks representing different MPA's development stages. Similarly, inside one given network, it is possible to introduce initial and final states for the same variable, and thereby distinguishing two nodes for each of these states.

DEVELOPMENT OF THE NETWORK STRUCTURE

The development of a "Bayes net" begins with eliciting mental models about the cause-and-effect relationships among system variables from subject matter experts. Represented as a graphical network, these models imply a set of assumptions about the conditional dependencies among the variables, which simplifies the problem of working with imprecise knowledge (*Borsuk, 2004*).

A multidisciplinary questionnaire survey was submitted to the GAIUS researcher, in order to select and prioritize the different variables and their interactions that describe social and institutional context, extractive and non-extractive activities and their impacts on the ecosystems. The selection was made to design the most parsimonious yet realistic model so that each possible node for the network was reviewed to determine if the variable it represented was either: (1) controllable, (2) predictable, or (3) observable at the scale of the management problem (*Borsuk & al., 2004*). If not, then the node was removed from the network. Our strategy to build the structure was also linked to the fact that parameters learning will be based mainly on expert knowledge, which means another expert survey or interviews. The two main consequences were the following:

- Restriction of the number of direct parents (up to a maximum of four).
- Restriction of the number of variable states. We always tried whenever it was possible to select only binary variables (up to a maximum of three possible states for some variables).

In total, ten researchers from different domains answer to the entire questionnaire. We developed several possible structures from all these answers, and after several peer reviews, we arrived to the result presented below, which may not be the definitive structure since other reviews will come.

Our final network can be divided into four different interacting parts:

- A “context” part in which we explain the probability of adherence of fishermen, non-extractive users and service providers to the regulations introduced by the MPA. It amounts to identifying the links between the MPA functioning (regulations, control and communication measures, contribution of users in the decision making process, available logistical, financial and human capital…) and the users’ adherence process to regulations.
- An “Extractive and non-extractive uses” part in which we try to describe the evolution of uses depending on the institutional, socio-economical and environmental context of the MPA. Once probabilities of adherence to regulations have been assessed, consequences of the MPA’s measures on fisheries (fishing effort and catches) and non-extractive uses (frequentation) should be specified, and the probabilities of their evolutions identified.
- An “Environmental” part, fully linked to the previous one, in which we will describe the conditional links between availability of natural resources and the evolution of extractive use as well as the main impacts of the different activities on ecosystems depending on their intensity.
- An “Output” part, which gives the probability of the users satisfaction level evolution relative to the evolution of their activities (catches for fishermen, ecosystems quality for recreational users) and to the overall frequentation (space competition).

The figure 1 presents a simplified structure of our network. Actually, each node represents a network that contains numerous other nodes which make the overall structure a lot more complex and precise. Before going further, it seems important to introduce our modeling framework and main hypothesis.

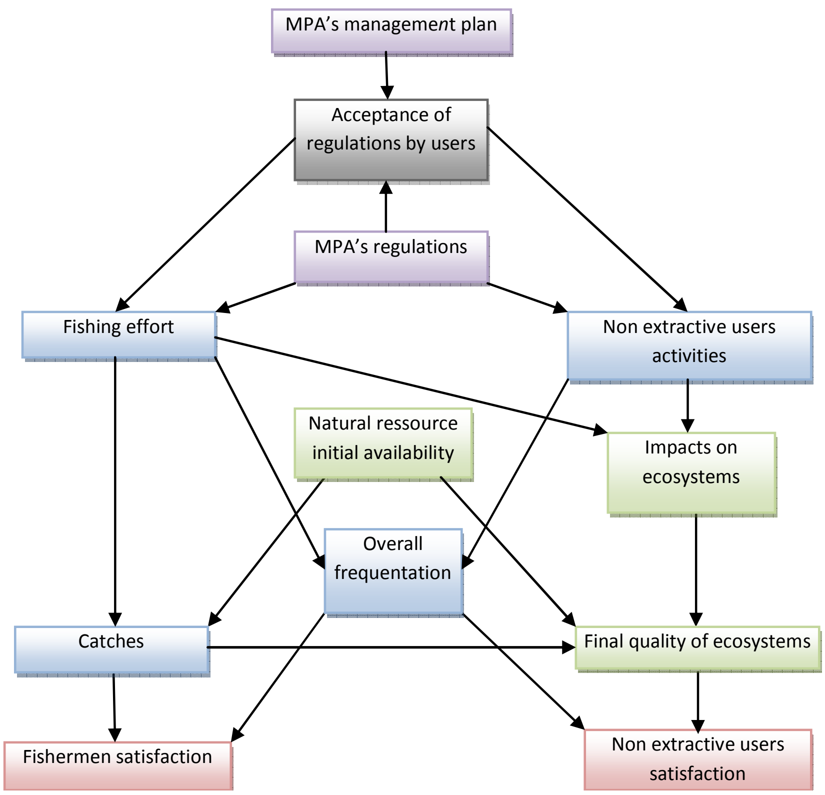

Figure 1 Basic structure of the network

Modeling framework and hypothesis

- *A global network structure covering six case studies*

Our model was originally designed to be build and inferred through expert knowledge, so that we tried to make the best compromise between handiness (through a simplistic structure) and precision. Thus, the consequences of the MPA's implementation are supposed to be expressed and described in qualitative terms associated with probabilities. Indeed, we decided to work on trends for the different states of all the "extractive and non extractive uses" nodes (fishing effort, catches, users' frequentation…) and "output" nodes (satisfaction of users, final quality of ecosystem). To put it in a nutshell, we will use the probabilities of all these variable states evolutions due to MPA's governance measure between a time of reference and a final one. This approach seems to be more relevant in a poor data context and well-adapted to the fact that our network is meant to adapt to several case studies.

Furthermore, one has to be careful when looking at the model structure. All the nodes of the "extractive/non-extractive uses" and "output" parts represent the consequences of the MPA's measures and regulations on a specific variable, which means that we are explaining and describing only its variation attributable to the presence of the MPA.

- *Geographical zoning in the network*

We considered two geographical areas for our network:

- A zone where all the MPA's regulations we considered in order to analyze their consequences on ecosystems and human activities are applying: we will call it "zone 1".
- A "zone 2", which is adjacent to the "zone 1", in order to assess possible human activities transfers towards non regulated areas and ecological spillover. In our model, we will only introduce a "zone 2" for the nodes relative to the fishing activity, that is to say fishing effort, catches, natural resource initial availability.

- *Categories of users*

We distinguished different types of users, in order to specify the adherence processes to regulations, the evolution of the different activities and their different impacts on ecosystems. We chose them in a way they can fit in the MPA's official categories of users: it guarantees compatibility between the model and existing data from the MPA, and it gives a more understandable and easier readable model to the MPA's manager.

We will now explain briefly all the different nodes presented in figure 1.

MPA's management plan

The MPA's management plan represents the main measures of the MPA we considered for our network: control and communications. These measures are linked to the MPA's financial capacity. Control and communication nodes can be specific to user's category.

MPA's regulations

There are two different effects to consider here. On the one hand, it is a parent node of the fishing effort and non extractive users' activities, since the regulations introduced by the MPA will have consequences on the different uses; in the case they are respected. If users disregard regulations (which means no acceptance), then there will be no change in their fishing effort or frequentation. On the other hand, it is a parent node of the “Acceptance of regulations by users”, which represents the impact of the regulations level on the adherence process towards the MPA: indeed, the more restrictive the regulations are, the less the users tend to accept them.

Natural resource availability

Fishing catches are linked to the fishing effort and to the availability of the resource, which we considered to be given by the abundance of biomass. Distinction between zone 1 and zone 2 is made. Only two possible states for the initial abundance variable are considered: high or low level of total biomass.

Fishing network structure

Nodes of the fishing network are differentiated following fishermen category and fishing gears. We distinguished three main fishermen categories: commercial fishermen (whose activity is mainly commercial), subsistence fishermen (whose activity is mainly for home or family consumption), and recreational fishermen. Adherence to the regulations is specific to each category.

We considered different fishing gears for each category: on the one hand, most of the fishing regulations apply to specific fishing gears; on the other hand, each gear has its own impact on the ecosystem in terms of catches and degradations.

Fishing effort and catches states are described through three possible trends: increase, stable or decrease, compared to a given time of reference. Moreover, as we said before, we introduced in the network the distinction between zone 1 and zone 2.

Non extractive user’s categories and detailed network structure

We also considered several non extractive users categories. Three main categories have been identified: individual non-resident non-extractive users, individual resident non-extractive users and service providers. Within this last category, it could be relevant to distinguish between hotels and other activities centers, in order to deal specifically with coastal management issues.

Adherence of the different users to the regulations explains the evolution of frequentation (increase, stable, decrease compared to a given time of reference) for the different activities. These trends of frequentation explain the evolution of impacts on the ecosystems. Frequentation and impacts on ecosystems nodes concern only the zone 1.

In terms of impact, frequentation and regulations, we only considered two main types of activities for our global network: underwater activities (snorkeling, diving…), and activities on the surface of water (boating, board sports…). Regulations and impacts nodes for hotel could be added if necessary.

Acceptance of regulations by users: the adherence process

What we are trying to identify here is a general mechanics behind each representative user of a category that could define the process of supporting or not the MPA’s existence and regulations. As we already pointed out before, if the acceptance of regulations is specific to each user’s category, the adherence process remains the same (excluding the one for nonresident users where adherence is only due to communication and control).

Four main factors explaining why an individual would accept or refuse to respect the MPA's regulations are considered: restriction or benefits from the regulations, presence and efficiency of the control, level of communication and consultation/participation of users. Distinctions have also been made between legitimacy of the MPA institution, which is defined as the raison d'être of the MPA institution for the users, and their beliefs into the MPA's performance.

Degradation and final quality of the ecosystem

As we said before, impacts on ecosystems are differentiated according to the cause of the degradations: fishing activities (each gear type has its own impact), non extractive activities, and hotels. Three possible states for the impacts on ecosystems variables are considered: increasing, stable or decreasing level of degradation.

All these specific impacts, as well as the fishing pressures, have consequences on the final quality of the habitat and biodiversity of the MPA. Here again, this final quality of the overall ecosystem can be described through three possible states: better, same or lower quality than before.

Satisfaction of users

Satisfaction nodes are also derived for each category of users. They represent the variation of the satisfaction level due to the MPA's measures impacts on their activities. Fishermen satisfaction level is mainly economic and due to their catches. We also considered that spatial competition with other users (both fishermen and non extractive users) has an impact on their satisfaction. For individual non-extractive users, what matters the most is the pleasure they are taking in doing their activities, which is mainly due to the overall quality of the ecosystems (habitat, biodiversity, and emblematic species) and to the availability of practicing areas (spatial competition). Finally, for service providers and hotels, their satisfaction level is mainly due to economic considerations, and more precisely to the number of customers.

Validation of the global structure and construction of the final six specifics networks

Our structure was derived from a questionnaire and experts interviews. The only way of validating it is through peer reviews. Then, once our global structure is definitely validated, it has to be adapted to the different case studies in order to begin parameters learning and simulation. Therefore, for each MPA, a specific network is derived from the one presented above, with appropriate zoning, regulations, fishermen categories and fishing gears, non-extractive users and ecosystems impacts. If enough data are available, it could be interesting to validate these models by carrying out statistical tests on the different conditional probability distributions involved in the causal relationships between nodes.

PARAMETERS LEARNING

Parameters learning based on expert knowledge

Probabilities elicitation issues have been discussed in numerous studies (see for example *S. Renooij, 2001*). Usually, the most difficult task is to find available experts accustomed to probability basic theory. Then, appropriate tools should be provided to the expert so that he can associate qualitative and quantitative notions in order to give a probability to each events or states of one variable. The most well-known one is the probability scale (*L. de Campos et J. Huete, 2000*), which allows the expert using numerical and textual information in order to set a realization degree of such or such assertion.

Then, coherence of the expert's estimations has to be assessed, especially if there are several estimations to combine. Possible biases have to be taken into account. In our case, the main difficulty is how to get and merge expert knowledge's from different research area.

A simple example: coral reef fisheries in the French Polynesia case study

Since we are just beginning to initialize our global model for specific case studies, we will present here another example, derived from the PGEM (Marine Management Plan) of Moorea case study. The PGEM, which covers a network of 8 MPAs, was launched in 2004. The main objectives are fishery viability and biodiversity conservation for tourism. This model (presented in figure 3) is a simplified part of the global fisheries Bayesian Network we presented above.

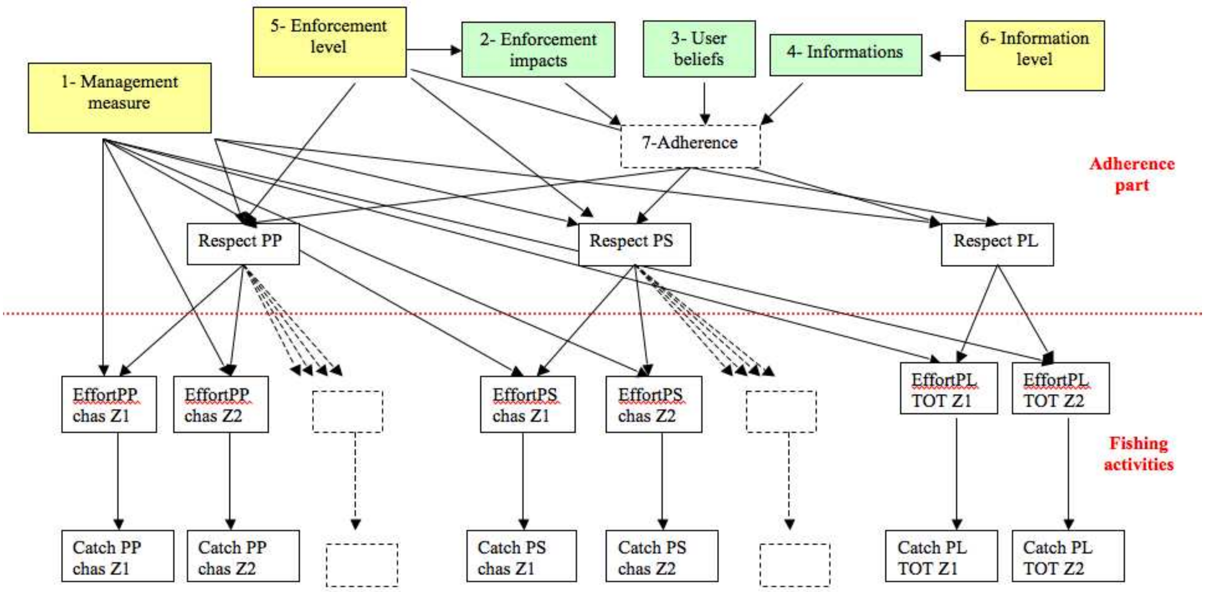

Figure 2 Bayesian Network developed for Moorea MPA's fisheries

Fishing activities in the Moorea coral reef lagoon are usually both performed by professional (PP), subsistence (PS) and recreational users (PL). Therefore, "Effort" and "Catch" nodes are described by the status of fisherman (PP, PS, PL), his fishing gear (spear fishing = "chas", gill net = "fil", line = "lig"), and his area (Z1, Z2). Catches are expressed in CPUE (catches per unit of effort).

In this network, there is no consideration of fisheries impacts on ecosystems. In fact, there are no environmental considerations at all.

Fishing area is divided into two different zones. Zone 1 stands for MPA zone. Zone 2 is outside of MPA. It includes a zone that might benefit from a possible "spill over effect" (McClanahan and al, 2000). However, these zones were not delimited with those ecological considerations but with field considerations. In tropical reef fisheries fishers are used to describe their fishing zone taking for reference pass across the reef. The zone 2 was delimited from the border of zone 1 to the next pass across the reef. Efforts and catches are described by three possible trends: decreasing, stable and increasing.

We now detail briefly how to interpret each of the upper nodes of the network (identified by a specific number):

1- Three types of MPA regulations are possible: no-take zone, catch size limitation zone or gear restrictions zone. Types of management measures affect fishermen's respect in regulation zones: the stricter the measures are (cf. no take areas), the lower the respect is. It also affects fishers' effort on marine resources inside and outside of the MPAs. Basically the probability of high effort in a no take area should be smaller than in a gear restriction zone.

2- Does enforcement level have an impact on Fishers' adherence? Yes/No

3- Do fishermen have environmental consciousness? Yes/No

4- Are fishermen well informed about PGEM and management measures in their fishing areas? Yes/No

5- It shows if enforcement level matters on fishers' behavior. Enforcement level is currently low today, but what would happen if it was higher?

6- It shows if communication level matters on fishers' mind. Information level is currently low, but what would happen if it was higher?

Nodes 5 and 6 allow us to make assumptions about enforcement and information levels so that we could model hypothetic scenarios.

7- Decision rule: if (node 2=yes, node 3=yes, node 4=yes), then Adherence = yes. If not, then Adherence = no. Fisherman's respect of MPA regulations will then impact fisherman's behavior in his choice of fishing area.

Quantitative surveys in conjunction with qualitative interviews were used. A face-to-face multiple choice questionnaire was conducted with 96 fishers in three different areas where three different management measures were in place. Several experts were interviewed on how coral reef fishers are impacted by MPAs, the extent of their knowledge regarding regulations, their opinions on management. Expert knowledge from Fishery Service Administration permits to get information about fishermen not covered by field data.

Experts used the Verbal Elicitor software from *Hope and al.* (2002) in order to describe all conditional probabilities of fishing activities. This software allows entry of probability values in ordinary English. The domain expert makes qualitative assessments using a scale with numerical and verbal anchors, by selecting a verbal cue such as "unlikely" or "almost certain". The associated numerical probabilities are either set manually or optimised to minimise probabilistic incoherency (*Thomas and al, 2008*).

The data collected, and the questionnaire, were also used through statistics tests in order to validate the network structure: several models based on binomial distributions were compared using the Akaike criterion. Besides, Chi-square tests have been realized and confirmed that fishermen's respect of regulations has to be differentiate according its category.

The network was then build using the ELVIRA software (for a detailed explanation about the use of ELVIRA software, the reader can refer to *C. Lacave & al., 2002*). The major interest of this type of graphical representation is the possibility to simulate easily numerous management scenarios through inferences: the probability for one given state of a specific variable is substituted by any chosen value and the information is then echoed through the entire network, modifying other conditional probabilities. An example of possible outputs is presented below, describing professional underwater hunting fishermen's response to a total prohibition regulation. When looking at this model, any observer can directly know for instance the probabilities of the evolution of fishermen catches due to this regulation. This is why Bayesian Network modelling is such a powerful communication tool.

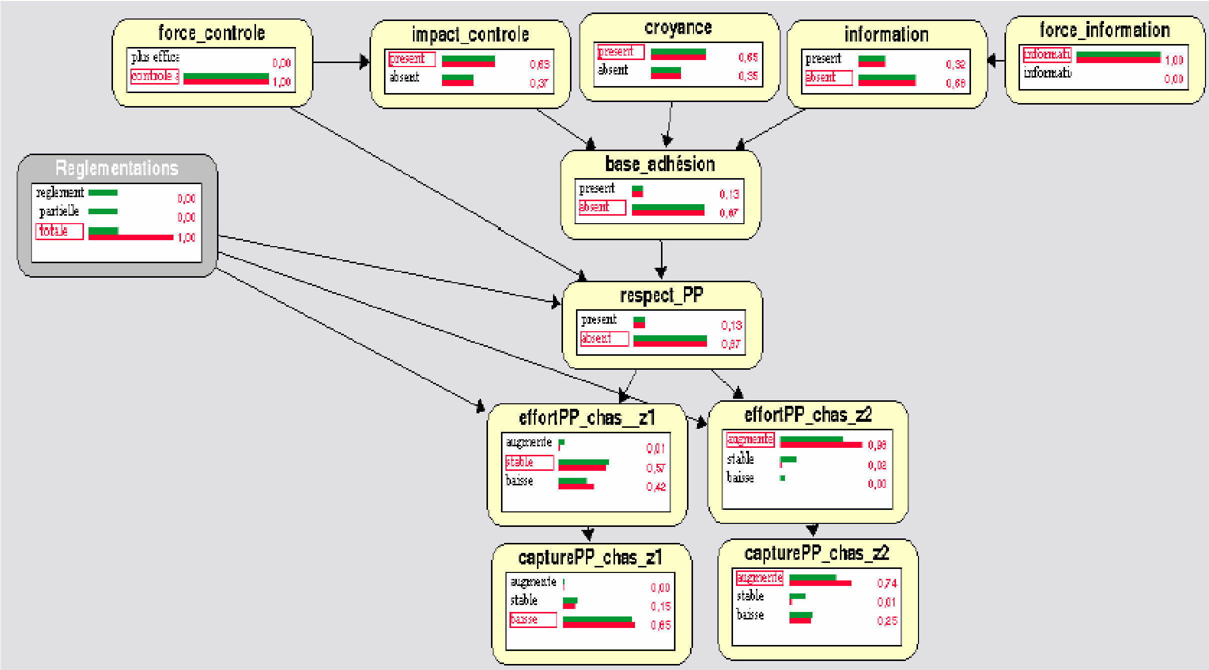

Figure 3 Models outputs for professional underwater hunting fishermen for total prohibition of fishing regulations. "Capture" = Catches, "Croyance" = User beliefs, "Controle"=enforcement, "Base adhesion"=Adherence, "Reglementations"=Regulations, "augmente"=increase, "baisse"=decrease.

Several scenarios were tested, for all the fishermen categories and fishing gears. Impacts of the different nodes were analyzed. Besides, several sensitivity analysis of the model to marginal probabilities have also been realized. However, we will not present the results here, our main goal was just to show a simplistic example of what can be achieved using Bayesian Networks for MPA's governance issues.

CONCLUSION

Simulation of MPAs governance scenarios requires a multidisciplinary model including ecological, socio-economical and institutional knowledge. Bayesian Networks are adapted to this constraint. They are powerful tools which can manage in the same model different types of knowledge, from many different sources, based on bibliography, statistical estimation or expertise. Uncertainty, imprecision and variability are explicitly represented by probabilities. Updating or refinement of knowledge is easily incorporated.

Simulations can provide many outputs, based on the different final states of some chosen variables used as indicators, which reflect the states of MPA and its sustainability. But criteria associated to each of them are often conflictual for one individual, and are not the same for all players. This implies that perfect scenario doesn't exist. A multi-criteria and multi-actor analysis based on outranking methods must then be developed to compare different scenarios. Dynamics of MPA's governance can also be modeled by linking different networks representing different MPA's development stages.

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