A Fuzzy Logic Model to Predict Coral Reef Development under Nutrient and Sediment Stress

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Abstract: *Coral reefs are highly complex systems characterized by mostly nonlinear relationships between biotic and abiotic components. Traditional models of reef dynamics often require unavailable data and precision, which limits their success and usefulness. We tested a new approach in coral reef modeling with fuzzy logic. Fuzzy logic has been applied successfully in modeling highly nonlinear systems in engineering, decision support systems, and ecology. As part of an integrated coastal zone management model, we constructed a coral reef model that predicts changes in coral cover and diversity under anthropogenic stress, namely nutrient enrichment and increased sedimentation. The model reflects our current knowledge of the fringing reefs of Curaçao, Netherlands Antilles. The seven input variables used were dissolved inorganic nitrogen and phosphate, suspended particulate matter, maximum colony size, substratum available for colonization, coral cover, and coral diversity. Each variable was divided into three triangular fuzzy sets reflecting low, medium, and high values. For each of the 2187 possible input combinations we estimated cover and diversity after 10 years. We consulted experts with a thorough knowledge of the local reef system and have automatically accounted for interactions between the variables described above. The model clearly shows how increases in nutrient and sediment inputs affect coral cover and diversity. Although the model can be refined continuously, it appears to reflect accurately the current knowledge of reef dynamics, making a beneficial contribution to education, management, and science.*

Modelo Lógico Indistinto para Predecir el Desarrollo de Arrecifes de Coral Bajo Estreees de Nutrientes y Sedimentos

Resumen: *Los arrecifes de coral son sistemas altamente complejos caracterizados por relaciones mayormente no lineales entre sus componentes bióticos y abióticos. Tradicionalmente los modelos de arrecifes de coral requieren de datos que no están a la mano, así como de precisión, limitando su éxito y su utilidad. Probamos una aproximación nueva en modelado de arrecifes conocida como modelo lógico indistinto (*fuzzy logic model*). Este sistema ha sido aplicado satisfactoriamente en modelado de sistemas no lineales en ingeniería, en sistemas de soporte de decisiones y en ecología. Construímos un modelo de arrecife coralino como parte de un modelo de manejo integral de zonas costeras que predice cambios en la cobertura coralina y la diversidad bajo estrés antropogénico (enriquecimiento de nutrientes e incremento en sedimentación). El modelo refleja nuestro actual conocimiento de la franja de arrecifes de Curazao, Antillas de los Paises Bajos. Las variables utilizadas fueron nitrógeno y fosfato inorgánico disuelto, partículas en suspensión, tamaño máximo de la colonia, disponibilidad de substrato para colonización, cobertura coralina y diversidad coralina. Cada variable fue dividida en tres juegos triagulares indistintos reflejando valores bajos, medios y altos. Estimamos la cobertura y diversidad después de 10 años para cada una de las 2187 combinaciones posi-*

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bles de datos. Las interacciones entre las variables descritas anteriormente fueron automáticamente tomadas en consideración utilizando expertos con un conocimiento meticuloso del sistema coralino local. El modelo muestra claramente como los incrementos en la entrada de nutrientes y sedimentos al sistema afectan la cobertura y diversidad coralina. Aunque el modelo puede ser refinado continuamente, aparentemente refleja con precisión el conocimiento actual de las dinámicas de arrecifes aportando una contribución benéfica para la educación, el manejo y la ciencia.

Introduction

Coral Reefs

Coral reefs are among the most diverse ecosystems on Earth. Relationships between the living and nonliving components are complex and often poorly understood. Coral colonies play a primary role in the construction and maintenance of reefs and provide support and shelter for the many other organisms that inhabit coral reefs. Because numerous reefs are experiencing unprecedented anthropogenic impacts including sedimentation (Bak 1978; Cortes & Risk 1985; Rogers 1990), eutrophication (Fishelson 1973; Tomascik & Sander 1985), and resource exploitation such as fishing (Munro 1983; McClanahan 1987; Hughes 1994), there exists an urgent need to understand the complex relationships between variables and processes that affect the long-term survival chances of coral reefs. Simulation of reef dynamics may provide a better understanding in the functioning of coral reefs.

Attempts to model the dynamic processes that take place on coral reefs have been conducted at various levels, ranging from modeling the effects on size distributions of single populations (Hughes 1984; Done 1987; Andres & Rodenhouse 1993) to modeling the productivity of whole reefs (Polovina 1984). According to systems theory, the precision with which a set of variables is measured decreases as the size of the system increases (Bosserman & Ragade 1982). Consequenctly, because coral reef ecosystems are large and complexly organized systems, many concepts and definitions are bound to be imprecise and exact data are often not available. Therefore the use of a modeling approach, such as fuzzy logic, that is by definition able to cope with this imprecision, seems attractive.

Using the case study of Curaçao fringing reefs, we constructed a model based on fuzzy logic which predicts reef development in response to anthropogenic perturbations.

Fuzzy Logic

In 1965 Lotfi A. Zadeh introduced fuzzy set theory, drawing on earlier work by Max Black and Jan Luckasiewicz (Zadeh 1965). Based on his experiences as an engineer and systems scientist, he concluded that traditional methods of systems analysis were unsuited to deal with systems in which relations between variables do not lend themselves to representation in terms of differential or difference equations or for which limitations of knowledge and/or data prevent precise definition of parameters. Such systems are the norm in biology, sociology, and economics.

Fuzziness, described by fuzzy mathematics or fuzzy logic, represents a type of deterministic uncertainty. Although it has some similarities to randomness, fuzziness is conceptually and theoretically distinct from randomness (Kosko 1990). Fuzziness results from the absence of precisely defined class membership and not from uncertainty concerning membership of an object in a set. A fuzzy set is a class with inexact boundaries. The transition from membership to nonmembership is gradual rather than abrupt. In this sense, the class of high mountains is a fuzzy set, as is the class of healthy reefs. The linguistic variable plays a key role in the application of fuzzy logic. Through its use the focus of attention is not on difference and differential equations but on fuzzy if-then rules in the following form: ***if x is a then y is b***, where x and y are linguistic variables and a and b are their qualitative values (e.g., if pressure is high then volume is low). Such rules serve to characterize complex dependencies, enabling only imprecise descriptions, particularly abundant in biological systems.

The qualitative value of a linguistic variable is approximated by fuzzy sets. In a fuzzy set an exact value belongs by a certain degree to the given fuzzy set. This is measured by the membership function that maps exact values onto the interval [0,1] (Fig. 1). These membership functions have a predefined geometric shape. For example, the variable "coral cover" can be divided into three fuzzy triangular sets representing low, medium, and high cover (Fig. 1). Coral cover of 15% is a member of the fuzzy set medium (membership value 1). A value is often part of more than one set at a time; 7% cover is in both the fuzzy sets low and medium (membership values both 0.38).

Fuzzy rules are evaluated for their degree of truth; those that have some truth contribute to the final output state of the solution variable set (method of implica-

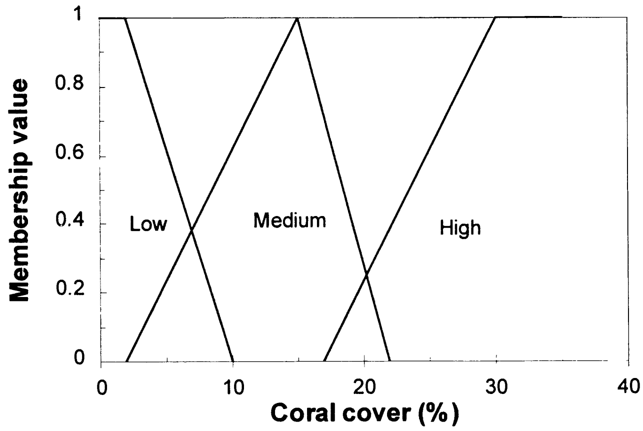

Figure 1. The variable coral cover divided into three overlapping fuzzy sets described as low, medium, and high and defined by the triangular membership function ranging from 0–1 as in Table 1.

tion). This set is then converted into an exact value. This is an important characteristic: the model uses fuzzy sets, but actual input and output values are exact. Methods of implication and "defuzzification" vary (for examples see Cox 1994).

An implicit assumption in fuzzy set theory is that the members of a fuzzy set are context dependent. For example, high nutrient concentrations for coral reefs are not equal to what specialists perceive as high concentrations in the North Sea. For practical reasons, most of the applications and successes of using fuzzy logic have been in the area of process and control engineering. Through fuzzy logic, manufacturers have reduced development time, modeled highly complex nonlinear systems, deployed advanced systems using control engineers rather than control scientists, and implemented controls using less expensive computer chips and sensors. But, fuzzy logic has also been introduced to environmental planning (Baas & Kwakernaak 1977; Yager 1977; Buckley 1985; Smith 1994) and the analysis of ecological data (Equihua 1990). We report the first results of an attempt to model reef dynamics through the use of fuzzy logic and fuzzy set theory. The study was undertaken in the framework of a larger project aimed at developing a methodology and model to carry out cost-effectiveness analyses for coral reef systems with case study sites in Jamaica (Montego Bay), the Netherlands Antilles (Curaçao), and the Republic of the Maldives.

Methods

Definition of Variables and Fuzzy Sets

Living cover of hard corals and species number were selected as the output variables because of their general ability to describe the condition of any particular reef as well as the availability of data. Increasing the number of variables increases at an exponential rate the number of rules to be defined. As a result, we restricted the number of input variables as much as possible while maintaining a reasonably accurate description of reef development over 10 years. This meant that other factors also of influence to the development of the reef (e.g., recruitment, fish stocks, grazing intensity) were not included in this version. It may become apparent through testing that these need to be included in more refined versions of the model. The final model structure was based on seven input and two output variables. The input variables can be separated into the impact variables of suspended particulate matter (SPM), dissolved inorganic nitrogen (DIN), and soluble reactive phosphorous (P) and the regulatory variables of diversity of hard corals (DIV), coral cover (COV), available substratum (SUBS), and maximum colony size (SIZE). For each output, we defined 2187 rules based on our knowledge of the fringing reefs of Curaçao, creating a fully saturated rule base. Through the definition of the rule base the interactions between the variables are implicitly taken into account. This means that the complex relationships between the variables do not have to be explicitly defined.

Although the model has been set up for the Curaçao application, the variables used are also applicable to other parts of the world. Consequently, the model may serve as a basis for describing other reefs as well.

Suspended Particulate Matter

Sedimentation is one of the most important factors threatening reefs globally (Ginsburg 1993). Traditionally, sediment traps have been used to quantify sedimentation, but high spatial and temporal variation of trap data (Pastorok & Bilyard 1985), as well as additional variation introduced through the use of different trap designs (Bloesch & Burns 1980), makes this variable unreliable. Trap height above the bottom is also critical because bottom sediment is resuspended in different concentrations to different heights at a fixed wave regime (Meesters 1995). This necessitated the use of a different variable to describe the sediment regime. Based on data from Curaçao (Meesters 1995) and Barbados (Tomascik & Sander 1985; Wittenberg & Hunte 1992), we decided to use suspended particulate matter (SPM). The SPM concentrations represent an instantaneous measure of the concentration of particles suspended in the water column, whereas sediment trap data measure the total downward flux of suspended particles. Because short-term increases, having a greater influence on trap data, are less deleterious to corals than chronic increases (Dodge & Vaisnys 1977; Bak 1978; Tomascik & Sander 1985), SPM is probably a better descriptor of long-term sediment effects on coral reefs.

Nitrogen and Phosphorus

In many coastal regions (e.g., parts of the North Sea, northern Adriatic Sea, Baltic Sea, Great Barrier Reef Lagoon, wider Caribbean, coastal areas of the U.S.) there is large-scale and in some cases chronic nutrient enrichment by nitrogen and phosphorus. In some regions the link between eutrophication and the destruction of an ecosystem is obvious, with excessive algae growth and water-column anoxia. In other cases, particularly in more fragile ecosystems, such as coral-reef and seagrass areas, the links are less obvious, yet the long-term effects of eutrophication in such regions can be devastating (Gabric & Bell 1993). The majority of the world's coral reefs thrive in relatively nutrient-poor waters, although corals in aquaria can survive under high nutrient concentrations (Atkinson et al. 1995). Many studies have demonstrated the detrimental effects of anthropogenic input of excess nutrients (Smith et al. 1981; Tomascik & Sander 1985; Cuet et al. 1988; Bell & Tomascik 1993), and alterations in reefs from coral dominance to algae dominance have been attributed to eutrophication (Littler & Littler 1984).

Maximum Colony Size and Available Substratum

Maximum colony size, measured as living surface area, is used here as an integrated measurement for disturbance intensity and frequency (Connell 1978; Done 1992). Small sizes reflect high-energy regimes in which colonies are frequently disturbed and do not attain large sizes (Done & Potts 1992). Large maximum sizes are interpreted as characteristic of more stable environments.

The amount of substratum available for settlement of coral larvae is defined as that part of the bottom not covered by sand, macro-algae, or dense stands of algae turfs. Space for recruitment and growth is generally limited in coral reef communities (Connell & Keough 1985). New settlement of recruits and growth of established colonies are necessary to offset natural losses in coral cover and diversity.

Coral Cover and Species Number

Coral cover is given as the percentage of the bottom covered by living scleractinian corals, including *Millepora* spp. because *Millepora* spp. constitute an important part of the reef fauna and contribute to reef formation through calcification. Boundary values of the fuzzy sets were set after we analyzed chain transect data collected for this purpose and compared it with published data (Tomascik & Sander 1987).

The number of species that will be encountered in line transects is an underestimate of total species richness. Species that are largely restricted to cryptic habitats and those characterized by small adult sizes will have less chance of detection. There are also large differences in coral diversity between Atlantic and Indo-pacific regions. For these reasons, we decided to use the variable species number (DIV) as a percentage of the maximum number that can be found in the geographical region under consideration (i.e., the maximum number at a number of pristine sites measured with the same technique).

Fuzzy Sets and Data Collection

Each variable was divided into three triangular fuzzy sets reflecting low, medium, and high values (Fig. 1). Boundaries for the fuzzy sets were determined by analyzing data collected specifically for this purpose and comparing it with data in the literature (Meesters 1995).

During a field survey of Curaçao reefs in August 1995 we sampled three control and two nutrient-enriched sites. The controls were situated in the area between Cornelis Bay and Lijhoek, the impact sites approximately at Hala Canoa and adjacent to the Avila Beach Hotel. At each site, 18 samples (chain transects) of the benthic community were recorded. A site consisted of a stretch of shore 150–200 m long. Perpendicular from the shore we laid out three long lines (50–70 m, depending on terrace width) at evenly spaced distances from 1 m depth to the drop-off. On each line, six perpendicular 10-m line transects were stretched out at randomly chosen points. Under each line transect a chain was rolled out; bottom characteristics and species under the chain were noted in terms of the number of links. From these we estimated species cover, number of species, available substratum, and maximum colony size.

Construction of the Rulebase

The rules that determine the behavior of the model are stored in a so-called rule base. With seven variables, each divided into three fuzzy sets, there are 2187 possible combinations for each output variable. Each combination forms, together with the expected output, one rule. We assessed every combination and estimated the development of the two output variables (coral cover and diversity) after 10 years. A period of 10 years was chosen as a compromise between the need for answers to pressing management problems and the normal time frame of coral reef processes, which can be substantially longer (Stoddart 1963; Pearson 1981; Rogers 1990). One such rule might be as follows: if SPM P, N, SIZE, SUBS, COV and DIV are low, then COV (in 10 years) will be low. We used the software program Fuzzy Systems Engineering (1994).

Table 1. The variables and boundary values of the membership function values of 1 and 0 used in the development of the fuzzy logic model of coral reef development in Curaçao.

	Low			*Medium*			*High*		
*Variable**	*1*	*1*	*0*	*0*	*1*	*0*	*0*	*1*	*1*
SPM (mg/L)	0	1.0	2.5	1.5	4.0	6.5	4.0	7.0	7.0
P (μmol/L)	0	0.04	0.07	0.05	0.09	0.12	0.09	0.15	0.20
DIN (μmol/L)	0	0.3	1.0	0.6	1.3	2.0	1.5	3.0	3.0
SIZE (m^2)	0	0.1	0.5	0.3	0.5	0.7	0.5	0.9	1.0
SUBS (%)	0	0	25	10	30	50	40	50	70
COV (%)	0	2	10	2	15	22	17	30	35
DIV (%)	0	25	50	25	50	75	50	75	100

**SPM, suspended particulate matter; P, soluble reactive phosphorous; DIN, dissolved inorganic nitrogen; SIZE, maximum colony size; SUBS, available substratum; COV, coral cover; DIV, diversity of hard corals.*

Results and Discussion

Fuzzy Set Boundaries and Rules

The boundary values of each fuzzy set (Table 1) were based on the collected data and literature. Variable ranges can easily be extended to incorporate the whole range found in the field, but this would greatly decrease the relative area in which most of the effects would be taking place. For example, nitrogen values above 3 μmol/L can be found in the field, but any concentration above this value is definitely high; in fuzzy terminology, the value would have the maximum membership value of 1 in the fuzzy set high. Consequently, the effects would not become stronger beyond 3 μmol/L, at least in the output of the model. The same reasoning applied to phosphorus and suspended particulate matter.

After surveying data of nutrient concentrations on the reefs (Gast et al. 1998) and in the literature (Tomascik & Sander 1985; Wittenberg & Hunte 1992), we set the boundaries of the fuzzy sets according to observed concentrations in the field. But the reported degrees of change in coral communities as a result of nutrient enrichment vary enormously, indicating that local community composition and abiotic factors are possibly of considerable influence. Also, data are lacking that would

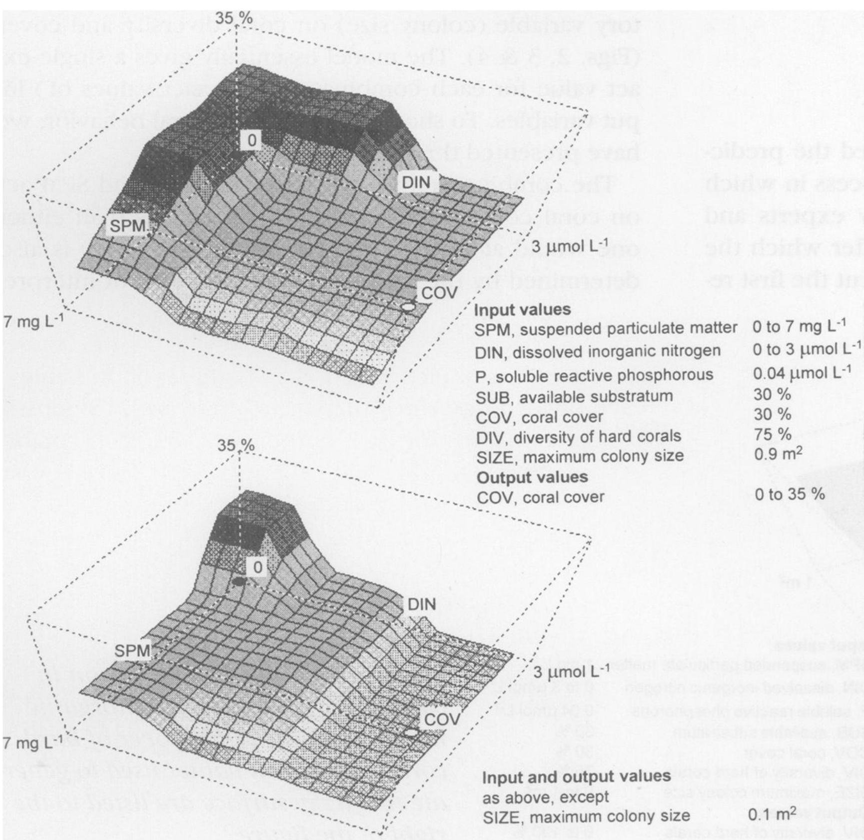

Figure 2. The effects of variations in suspended particulate matter (left axis) and dissolved inorganic nitrogen (right axis) on the living cover of hard corals (vertical axis) for two values of colony size. The input values used to generate the fuzzy surface are listed to the right of the figure.

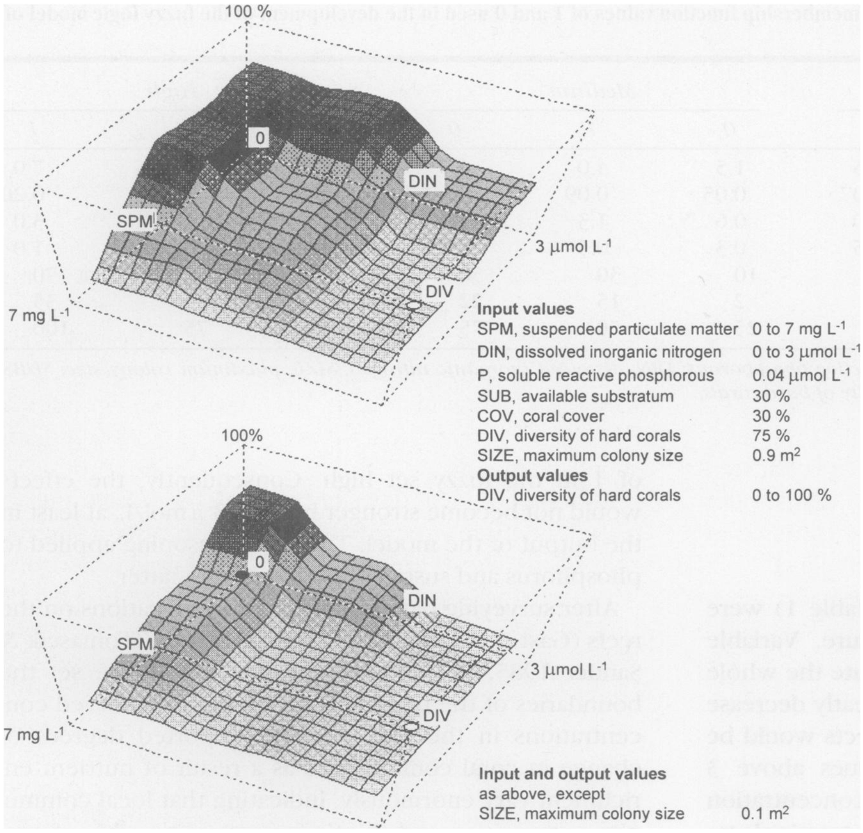

Figure 3. ***The effects of variations in suspended particulate matter (left axis) and dissolved inorganic nitrogen (right axis) on coral (vertical axis) for two values of colony size. The input values used to generate the fuzzy surface are listed to the right of the figure.***

allow a clear differentiation of the effects of combined changes in nitrogen and phosphorus. Clearly, more research is necessary in this area.

Model Scenarios

After we defined the rules, we investigated the predictions of the model. This is an iterative process in which the model's predictions are evaluated by experts and compared with available case histories, after which the necessary adjustments are made. We present the first results, showing the combined effects of the impact variables (sedimentation and nutrients) and of one regulatory variable (colony size) on coral diversity and cover (Figs. 2, 3 & 4). The model essentially gives a single exact value for each combination of (exact values of) input variables. To show the model's general behavior, we have presented three-dimensional pictures.

The combined effects of increasing DIN and SPM act on coral cover at substantially lower levels than either one would alone (Fig. 2). The response surface is also determined by the other variables. For ease of interpre-

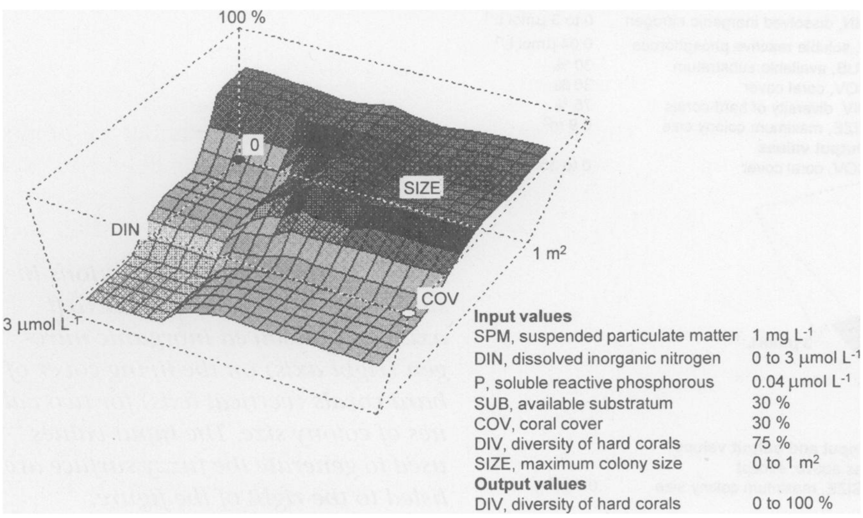

Figure 4. ***The effect of variation in colony size and dissolved inorganic nitrogen on the living cover of hard corals. The input values used to generate the fuzzy surface are listed to the right of the figure.***

tation, values of the other input variables were chosen at their maximum membership value. In this case, phosphate concentration was set to the value with the maximum membership in the fuzzy set low (0.04 μM), substrate availability to medium (30%), and initial coral cover, diversity, and maximum colony size set to high (30%, 75%, and 0.9 m^2, respectively). The effect of increasing either SPM or DIN only becomes apparent when the impact level reaches one of the high fuzzy sets. After this threshold, coral cover starts to decrease to medium values. The combined effect of SPM and DIN occurs at lower impact levels, about half of the threshold level stated above.

If we decrease colony size from 0.9 m^2 to 0.1 m^2, leaving the other variables the same, coral cover is affected sooner (Fig. 2). This reflects the assumption that smaller colonies are more susceptible than larger colonies to overgrowth by algae and smothering by sediment.

Lower levels of SPM affect diversity sooner than the same levels of DIN (Fig. 3). As with cover, decreasing the maximum colony size to 0.1 m^2 (Fig. 3) shows the diversity to be more vulnerable to lower impact levels.

Next to the impacts of DIN and SPM, any other combination of variables can be chosen. The model was used to show the effects of DIN on coral cover for reefs with different maximum-size colonies (Fig. 4). Larger colonies will be less affected after 10 years than populations characterized by smaller colonies, except at very low concentrations of DIN, where there is no effect on coral cover regardless of the maximum colony size.

These results show that fuzzy logic is a useful approach to describing coral reef processes. The model visualizes and describes complex interactions between seven input variables and brings together expert knowledge from many sources. The accuracy of the model depends largely on the accuracy of the available data, but even in situations where data are scarce, this type of modeling could provide useful approximations. Once the rules are set, the boundaries of the various fuzzy sets can be changed and the performance of the model reviewed. Fuzzy sets can have more or less overlap, increasing or decreasing the smoothness of the response surface. Interactions between different variables can be visualized easily, resulting in a better understanding of the system. This may also lead to the definition of gaps in current knowledge and the formulation of new hypotheses. Such a model makes this type of knowledge readily available to nonbiologists, potentially allowing more informed decisions to be made in the management of coral reefs.

Limitations and Assumptions

The model has a number of limitations. Verification of the predicted changes in cover and diversity for the time period over which the model has been defined (10 years), as well as for any other time interval, is problematic because of a lack of data. Most studies are ad hoc, and information about the duration of increased nutrient or sediment values is almost always absent from reports on community change.

Information about interactions between variables is even less available. Available data strongly suggest that eutrophication has a negative effect on reefs, but in most cases reported, many confounding factors prevent identification of a clear cause-and-effect relationship. The effects of phosphorus and nitrogen, separately and combined, need to be studied in more detail with respect to their effects on whole reefs. Also, the effects on populations with different colony size-frequency distributions should be investigated.

Although the outcomes of the model are exact, the accuracy of these predictions need to be tested. The results of the model are, however, close enough to reality to indicate to managers and decision makers in what direction coral cover and diversity will change under certain development scenarios and, with a lesser degree of confidence, the size of this change. The model should find a place in coral reef management (after careful evaluation of local situations). Another important aspect is the educational value of the model. Processes can be visualized easily, variables changed, and their effects watched instantaneously.

The model was developed with the case study of Curaçao in mind. Curaçao reefs are under pressure from coastal development and overfishing, but, relative to other islands in the Caribbean such as Barbados (Tomascik 1991) and Jamaica (Hughes 1994; Andres & Witman 1995), the reefs are still in relatively good condition. Nutrient and sediment concentrations are not very high, and the island lies outside the hurricane belt. Also, overfishing of important grazers (Scaridae, Acanthuridae) is not yet a major problem, and the *Diadema antillarum* die-off (Lessios et al. 1983), which also decimated urchin populations in Curaçao (Bak et al. 1984), has not resulted in excessive coral death (Bak & Nieuwland 1995).

Refinement

The model can be improved on a number of points. More than three fuzzy sets can be used to define the variables. This would give more flexibility and detail in the output. Small changes in the input variables could then be addressed more precisely in the rules, the resulting output would be more accurate, and changes would occur gradually.

The amount of overlap between fuzzy sets can be increased. It depends on the underlying concept of the fuzzy set and the intrinsic degree of imprecision in the data associated with two neighboring states of the variable. More overlap in general results in smoother response surfaces. Fuzzy sets can also be represented by different shapes, such as a bell curve. This may give better results, especially because the object of the model is a living system, but in practice fuzzy models are not sensitive to these changes. Another possibility is the use of hedges. A hedge modifies the surface of a fuzzy set, causing a change in the membership function. A hedge thus transforms one fuzzy set into another. In linguistic terms, hedges are adverbs (with the fuzzy sets themselves being the adjectives) such as *very, extremely, about, near.*

More variables can be included, for example, time could also be a variable, as could grazing pressure or recruitment. A disadvantage is the exponential increase in the number of rules that need to be defined, but the model can be made "self-learning." Through the complementary use of neural network or cellular automata techniques, for example, it is sometimes possible to infer from empirical data rules not specified by the expert.

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