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An Agent-Based Model to Address Coastal Management Issues in the Yucatan Peninsula, Mexico

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Abstract: The northernmost part of the Mesoamerican Barrier Reef (MBR) runs along the eastern Yucatan peninsula (Mexico). Over two decades, sprawling coastal tourism development and over-exploitation of marine resources have considerably reduced fringing reef's ecological functions. *SimReef* is an interactive model designed to better understand the interactions between regional and local drivers strongly influencing the health of coral reefs. *SimReef*'s development follows a collective design approach and an inductive process whereby dynamics are represented by data-driven relationships. Experts and stakeholders participate to the designing phase in order to help calibrating the model and to support a consensual validation of the results.

Keywords*: coral reef, coastal management, participatory modelling, SimReef, toy model, Yucatan*

1. INTRODUCTION

Over the last two decades, a growing number of marine resource managers and researchers from diverse disciplines have embraced the complex systems approach linking ecological resilience to governance structures, economics and society (Hughes et al., 2006). In their book 'Exploring Resilience in Socio-Ecological Systems', Walker and colleagues (Walker et al., 2006) lay the theoretical fundation for an integrative analytical framework. Lachica-Alino and colleagues (Lachica-Alino et al., 2006) provide a remarkable account of the influence of these innovative ideas onto successive modelling attempts of fisheries in the Philippines. But the quest for always more integrated socio-ecological models creates its own impediments as established earlier by Villa and Constanza (2000). Unlike ecological processes that can be described by a set of generic equations for very different reefs around the world, socio-economic processes often elude such approach: fishermen in Mexico and in the Philippines might be very different social entities, with unrelated decision-making processes and contrasted sets of values and beliefs. Dambacher and colleagues (Dambacher et al., 2007) provide a compelling example of such contextual intricacies with their modelling of coastal communities on Lihir island (PNG).

A recent report from the World Bank (2006) on coral reef ecosystem health states that useful environmental indicators must pass the test of: (i) relevance, (ii) data availability, (iii) scientific soundness, (iv) management responsiveness and (v) communicability (transparency). Likewise, useful integrated models should verify the above conditions, especially when these models aim to simulate socio-economic aspects influencing coral reef health. As a matter of fact, while researchers have developed ecological models for the Mesoamerican Barrier Reef (MBR) using, for example, the Ecopath platform (Arias-González et al., 2004), local and regional socio-economic drivers are yet much less documented. Beyond fishing, several other industries and activities often dramatically influence coral reef health. For example, according to Cesar (2000), direct threats of tourism on coral reefs include exploitation (building material), pollution (waste treatment) and degradation (carrying capacity), while indirect threats include: increasing demand on reef products (seafood, jewels) and pollution associated to urban sprawl around resort areas.

Our approach acknowledges the necessity for a greater transparency in the designing process. It involves a trans-disciplinary team of experts who contribute to the model by providing key drivers of the system, their operational scales, and related data sets if they exist. This information is then compiled and transformed into a simplified prototype-model in order to structure and enhance further development. Altogether, the model aims to support a common semantic, to develop a collective metaphor, and to outline actual data limitations. Agent-based modelling (ABM) is particularly suitable for such an incremental process whereby new entities (agents) can be added to the model or specific entities can have their dynamics modified without necessarily impacting on other components of the model. Hence we have used an ABM platform, called Cormas (Bousquet et al., 1998), to design our *SimReef* model.

2. METHODS

2.1 Case study

The study focuses on the state of Quintana Roo (Mexico), located on the eastern part of the Yucatan Peninsula, a large karstic limestone tableland protruding into the Gulf of Mexico. The fringing reefs lying 0.5 to 1.5 km offshore along the coastline constitute the northernmost part of the MBR. The state covers an area of 50,350 km², with a population of approximately one million residents in 2005 (SEIGE, 2006). The development of the tourism industry over the last 30 years has fuelled an unprecedented demographic growth, mainly through migration from the neighbouring states (Daltabuit et al., 2006). The ecological productivity of the reefs support local fishing industries, whilst their beauty attracts ever-increasing numbers of visitors and generates new sources of revenue for local communities.

Fringing reefs are experiencing the consequences of rapid urban development and population growth along the Yucatan peninsula. According to recent statistics, nearly 6 million tourists visit the state annually (SEIGE, 2006). In order to accommodate such large crowds, littoral areas are increasingly turned into hotel grounds, deeply affecting local ecological dynamics (Arrivillaga and García 2004). Seafood demand from local restaurants has contributed to the decrease of catches across all commercial species over the past decade (Sosa Cordero et al., 2006). Sprawling urban neighbourhoods, home to those who service the tourism industry, also contribute to the increasing demand on local resources and to the alarming amount of accumulated waste products (Harborne et al., 2001). An unknown amount of this nutrient-rich waste filters into the karstic underground and flows out to the sea, adversely affecting reef ecosystems (Arrivillaga and

García 2004). The daily traffic of cruise ships also contributes to this widespread pollution. Finally, natural disturbances, such as hurricanes and coral bleaching, weaken even more the capacity of coral reefs to maintain their ecosystem functions (Harborne et al., 2001). In this regional context of marine ecosystems degradation and irreversible socio-economic changes, better understanding the human dimension of coral reef health has become a necessity.

2.2 Conceptual model

A trans-disciplinary group composed of Mexican and international marine biologists, economists, modellers and ethnographers was set up with the support of the Coral Reef Targeted Research (CRTR) project, funded by the World Bank. The experts individually and iteratively inform the collective design process. Alongside these consultations, a comprehensive literature review aims to confront heterogeneous information as well as to provide 'proxies' to quantify some relationships. This process helps to classify areas of broad consensus as well as to reveal knowledge gaps or contentious areas.

At the regional level, four social and economic actors are identified as key drivers of the ecological dynamics: the tourism industry, the fishing industry, conservation agencies, and the State related drivers (like migration flows, legal frameworks, or taxation systems). The latter being broadly called 'Government' driver. Successive causal loop diagrams are used to collectively and iteratively build a holistic model among experts. Figure 1 illustrates major mechanisms through which regional drivers (tourism development, taxation and subsidies) influence local social-economic dynamics (immigration, fishing efforts and pollution) and finally trophic interactions at the level of the coral reefs. However, several key relationships in this diagram are not supported by robust and quantitative evidence. For example, little is known yet about direct impact of coastal urbanization onto reef's health, due to the complex hydro-geological processes in karstic underground. Likewise, the relationship between regional growth of tourism and its local economic benefits is highly ambiguous.

The following sections describe four major components of *SimReef*, namely: (i) the reef ecology component, (ii) the fisheries component, (iii) the tourism component and (iv) the urbanisation component. Then, the overall structure of the agent-based model is presented, using an UML-based ontology. Socio-economic information is aggregated according to economic development areas (*eda*) including several administrative local areas.

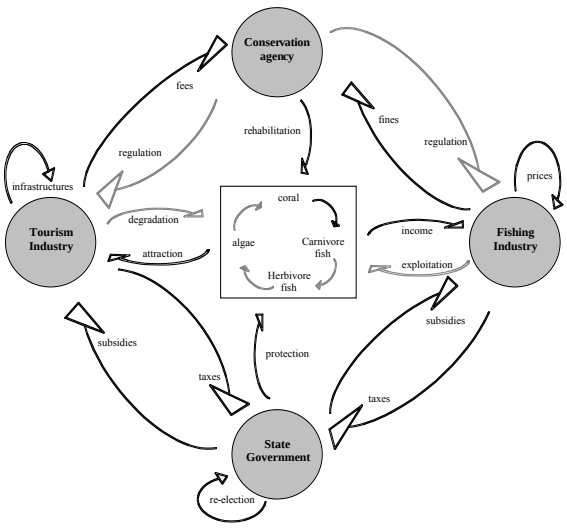

Figure 1: causal network of the coral reef-human ecosystem in Quintana Roo (Mexico). Arrows indicate directional relationships. Grey circles represent major social-economic drivers.

2.3 Reef ecology component

Marine ecosystems are separated according to the main fisheries along the Yucatan coastline: (1) reef fish, (2) lobster, (3) pelagic fish, and (4) prawn. Only the first category is described through a comprehensive but simplified dynamical model of interactions between coral, turf, herbivore fishes, and carnivore fishes. The following dynamical equations describe the evolution of coral cover (coral in %), turf cover (turf in %), herbivore fish stocks (fishH in $t.km^{-2}$), and carnivore fish stocks (fishC in $t.km^{-2}$) on reef and lagoon cells only:

$$\Delta coral = \alpha_{cor}*(coral+\varepsilon_{cor}) + \beta_{cor}*(coral^2/(coral+turf)) - \gamma_{cor}*coral \quad [1]$$
$$\Delta turf = \beta_{tur}*turf - \theta_{tur}*(turf*fishH) \quad [2]$$
$$\Delta fishH = \alpha_{fh}*(fishH+\varepsilon_{fh}) + \beta_{fh}*(fishH*turf) - \gamma_{fh}*fishH - \theta_{fh}*(fishH*fishC) \quad [3]$$
$$\Delta fishC = \alpha_{fc}*(fishC+\varepsilon_{fc}) + \theta_{fc}*(fishH*fishC) - \gamma_{fc}*fishC - \eta_{fc}*fishC^2 \quad [4]$$

where:

α reproduction parameter ($month^{-1}$)
β growth parameter ($month^{-1}$)
γ death parameter ($month^{-1}$)
θ predation parameter ($t^{-1}.month^{-1}.km^2$)
η competition parameter ($t^{-1}.month^{-1}.km^2$)
ε recruitment parameter (% or $t.month^{-1}.km^{-2}$)

Fishing activities influence the fish stocks according to equations [5] and [6] below. We assume that fishermen preferentially target carnivore fishes and "fish down" the food chain when the resource is depleted. This model doesn't support 'phase shift' transitions but it is robust enough to describe coastal fisheries depletion and further collapse within realistic ranges of initial total fish biomass (100 to 250 $t.km^{-2}$) and monthly fishing pressures (0.1 to 0.5 $t.fisher^{-1}.month^{-1}$). Despite few noticeable studies (Sosa Cordero et al., 2001), lobster, prawn and pelagic fisheries are much less documented. Thus, passive stocks of biomass represent them. These stocks have a simple probability of regeneration calibrated against statistics of catches by fishery (SEIGE, 2006): 0.8% for lobster, 0.08% for prawn and 10% for pelagic fish. Stocks are influenced by fishing activities only. Pelagic fishes and prawns move according to directional vectors based on static maps of the Yucatan current's general circulation (Cetina, 2006).

2.4 Fisheries component

In order to implement the fisheries model we need to estimate: (i) the proportion of different vessel types in each municipality, and (ii) nominal fishing pressures (per unit of effort, CPUE). By way of simplification, we distinguish three different types of vessels only: coastal vessels (1 to 2 fishers on board), high sea trawlers (5 to 10 fishers on board) and prawn trawlers (5 to 10 fishers on board) and we extrapolate the proportions available in 1994 over the entire period (SEIGE, 2006). Taking into account the seasonality of some fisheries, we assume the following fishing periods: 100 days for lobster, 200 days for prawn and fish. Based on these assumptions, nominal fishing pressures range from 3 to 4 $kg.vessel^{-1}.day^{-1}$ for lobsters, 15 to 17 $kg.vessel^{-1}.day^{-1}$ for fishes and 12 to 89 $kg.vessel^{-1}.day^{-1}$ for prawns. Based on this information, a simple micro-economic model calculates individual incomes on a monthly basis, depending on the fishing season (lobster or reef fish) and market prices (P_{fishC}, P_{fishH} and $P_{lobster}$ in US$ per tonne). Equations [5] and [6] are constrained in order to respect the mass balance of the ecological model (*fp*: fishing pressure):

$$Catch_{fishC} = Min[Max[(fp_{fish} - (fp_{fish}^2/fishC); 0]; fishC] \quad [5]$$
$$Catch_{fishH} = Min[(fp_{fish}^2/fishC); fishH] \quad [6]$$
$$Catch_{lobster} = fp_{lob}.(stock_{lob}/stock_{max}) \quad [7]$$
$$Income = P_{fishC}.\ Catch_{fishC} + P_{fishH}.\ Catch_{fishC} + P_{lobster}.\ Catch_{lobster} \quad [8]$$

SimReef doesn't include yet an algorithm describing decisions from private shipowners or cooperatives to change the number of vessels according to environmental incentives or constraints. But fishing fleets are able to assess the seasonal profitability of their fishing grounds and to eventually select another area based on recorded catches. A fishing fleet is declared bankrupt when unable to meet salary costs over a one year period.

2.5 Tourism component

The flow of tourists entering Quintana Roo is considered as a forcing variable. Hence, an external file reproduces tourist trends between 1994 and 2004, on a monthly time step. Seasonal variations observed between 2000 and 2004 are extrapolated to the whole time series (SECTUR, 2006). Three categories of tourist accommodation are created: low (*1 star*), medium (*3 star*) and high (*5 star*) capacity resorts, offering 15, 35 and 245 rooms respectively (lodging capacity, Cap_{cat}), based on average annual figures extracted from SEIGE (2006). The same database provides reliable monitoring of the number of establishments per category and municipality over time (1994-2004). In order to link monthly flows of tourists to the lodging capacity, we assume an average 5-night stay per tourist and 2 tourists per room, these estimates being consistent with regional and national figures (SEIGE, 2006).

We assume the following values for the overall employment capacity (μ_{cat}): 0.4, 0.7 or 2.2 job.room^{-1}.month^{-1} for a *1 star*, *3 star* or *5 star* establishment, respectively. In order to artificially represent the seasonal nature of tourism, we also assume that μ_{cat} is based on actually occupied rooms, not on the overall capacity per establishment. Finally, we create a simple environmental impact index based on the number of establishments in a given area and an impact parameter (ω_{cat}), taking the following values: 1, 2 or 3 for a *1 star*, *3 star* or *5 star* establishment, respectively. For each economic development area (*eda*) the following equations are solved on a monthly time step:

$$room_{QR} = \sum_{eda}\sum_{cat}(N_{cat}.Cap_{cat}) \quad [9]$$

$$occup_{eda} = (tourist/12).(\sum_{cat}(N_{cat}.Cap_{cat})/room_{QR}) \quad [10]$$

$$occup_{cat} = (N_{cat}.Cap_{cat}).(occup_{eda}/(\sum_{cat}(N_{cat}.Cap_{cat})) \quad [11]$$

$$job_{eda} = \sum_{cat}(occup_{cat}.\mu_{cat}) \quad [12]$$

$$impact_{eda} = \sum_{cat}(N_{cat}.\omega_{cat}) \quad [13]$$

with:

N_{cat}	number of hotels of category '*cat*' in a given economic development area (*eda*)
$room_{QR}$	total number of rooms available in Quintana Roo (*QR*)
$occup_{eda}$	number of rooms occupied in a given economic development area (*eda*)
$occup_{cat}$	number of rooms occupied in a given category (*cat*)
job_{eda}	number of jobs needed in a given economic development area (*eda*)
$impact_{eda}$	environmental impact of tourism in a given economic development area (*eda*)

2.6 Urbanisation component

Unfortunately, without detailed ethnographic information on migration it is impossible to disentangle tourism-driven flows from the influence of other drivers (variations in natality rate, for example). Hence, our urbanisation model assumes that: (i) there is a direct link between tourism development and population growth, (ii) this empirical relationship is best fitted by a polynomial function, and (iii) there is no hysteresis effect when employment levels drop down. We use equation [12] to calculate annual employment levels in the following economic development areas (*eda*): Cancun, Riviera Maya and Cozumel. Then, these figures are fitted to a 3rd order polynomial function against population census in 1985, 1990, 1995, 2000 and 2005:

$$pop_{eda} = 2.10^{-8}\, job^3_{eda} + 9.10^{-4}\, job^2_{eda} + 17.821\, job_{eda} + \Omega_{eda} \qquad r^2 = 0.949 \quad [14]$$

with:

pop_{eda}	simulated annual population in a given economic development area (*eda*)
Ω_{eda}	level of population when $job_{eda} = 0$ in a given economic development area *eda*

Values of Ω_{eda} correspond to observed or estimated levels of population when tourism started to develop in a given economic development area. This approach aims to take into account significant levels of population in Riviera Maya and Costa Maya (including Chetumal) before the onset. So far, the following values are used: 40,000 for Ω_{RM} and 190,000 for Ω_{CM} (Ω_{CA} and Ω_{CO} are nil). Finally, in order to avoid unrealistic variations due to sudden changes in employment levels, equation [14] is used with 3-year moving averages of employment figures when predicting annual population levels.

3. RESULTS

In order to keep the clarity of this paper, and despite the integrated nature of *SimReef*, we are presenting results according to the different components described above. We first present results corresponding to stand-alone simulations (without human interventions). Each series of results include a validation period (1990-2005), followed by a 10-year prospective period (2004-2014) based on assumptions developed in the following sections.

3.1 Fisheries component

Figure 2 illustrates two contrasted scenarios: on the left side, actual levels of fishing pressure (0.3 t.month^{-1}.vessel^{-1} for fish and 0.08 t.month^{-1}.vessel^{-1} for lobster) drive coastal fisheries into the extinction of the most valuable fishes (FishC) and a slow degradation of fisher's income over 50 years. On the right side, nearly doubling both fishing pressures leads to a collapse of both fish populations (fishC and fishH) while the population of lobsters decreases dangerously. After enjoying initial and substantial profits, fishers face an unsustainable situation after 50 years.

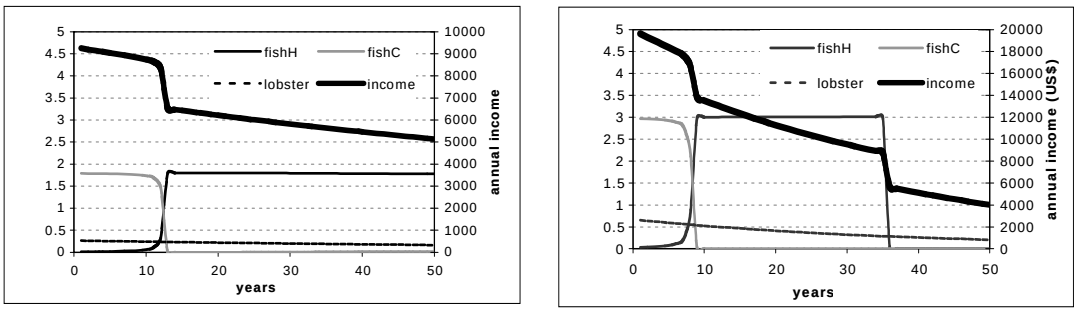

Figure 2: Simulated evolution of catches and income over 50 years. Left: fp_{fish} = 0.3 t.month^{-1}.vessel^{-1} and fp_{lob} = 0.08 t.month^{-1}.vessel^{-1}. Right: fp_{fish} = 0.5 t.month^{-1}.vessel^{-1} and fp_{lob} = 0.2 t.month^{-1}.vessel^{-1}. In both cases, nominal prices per tonne are kept constant: P_{fishH} = US$1,000; P_{fishC} = US$2,200; $P_{lobster}$ = US$20,000.

3.2 Tourism component

We used our model not only to reproduce the regional development of tourism observed between 1994 and 2004, but also to assess plausible scenarios up until 2014. As a matter of fact, the Government has already decided on developing the Costa Maya in a similar way Riviera Maya was developed in the 90's (Daltabuit et al., 2006). Figure 3 shows the evolution of room capacities, occupancy rates, levels of employment and environmental impact indexes for each economic development area between 1994 and 2014. Unlike Lutz and colleagues (2000), in this scenario we assume that the annual number of tourists reaches a plateau in 2004 (6.7 million visitors) and remains constant ever after. The projections beyond 2004 are based on: (i) Cancun and Cozumel maintaining their lodging capacities, (ii) Riviera Maya increasing its capacity at a rate equivalent to Cancun's one during the previous decade and (iii) Costa Maya increasing its capacity at a rate equivalent to Riviera Maya's one during the previous decade.

Under this scenario - full development of Costa Maya while the number of tourists remains constant - capacities of employment would start plummeting and the overall environmental impact would reach alarming levels by 2014. According to SECTUR (2006), average wages in the hospitality industry range from $350 to $600 per month. These figures are equivalent to fisher's earnings when stocks aren't depleted, like in Costa Maya (including Chinchorro bank). This comparison suggests that a future slump in tourism employment would probably result in a dramatic increase in (illegal) fishing activities.

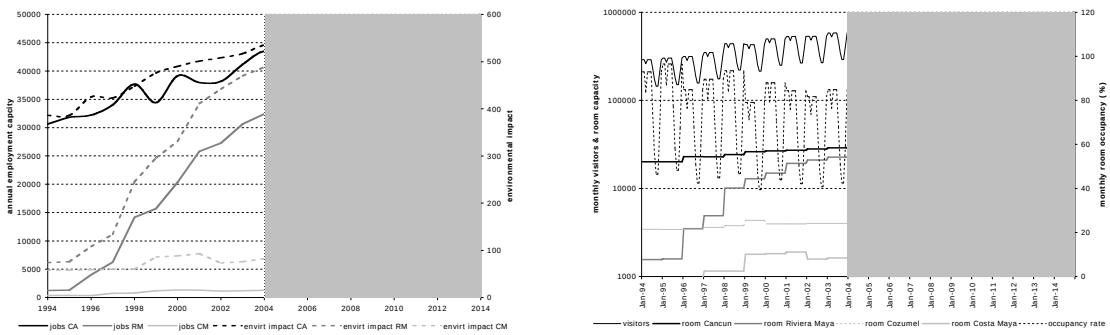

Figure 3: Monthly evolution of tourism and its simulated environmental impact. Left: number of visitors, lodging capacity and occupancy rate. Right: level of employment and environmental impact index. Figures are plotted for each economic development area. Shaded parts on each graph correspond to hypothetical projections beyond 2004

3.3 Urbanisation component

Due to the empirical nature of its algorithm (equation [14]) and the complex demographics at stake, this component doesn't pretend to be a reliable proxy for future scenarii. But, despite its limitations, the model simulates reasonably well the evolution of population in the different *eda*s between 1980 and 2004. Beyond 2004, as population fluctuations follows employment patterns (3-year moving averages), stagnation of tourist intakes translates into a sharp decline of residents in the Cancun *eda*, partly compensated by new settlements in Costa Maya (Figure 4, left).

The overall (tourism + urbanisation) environmental impact index shows a dramatic increase of the threat in the Costa Maya *eda* while the relative decline in Cancun needs to be taken cautiously (Figure 4, right). As a matter of fact, common sense would suggest that environmental impact might remain the same despite population decrease due to a strong hysteresis in the relationship. Nevertheless, in 2014, according to our modelling assumptions, the environmental impact index in the Costa Maya *eda* reaches the same level of threat as Cancun *eda* in 2000.

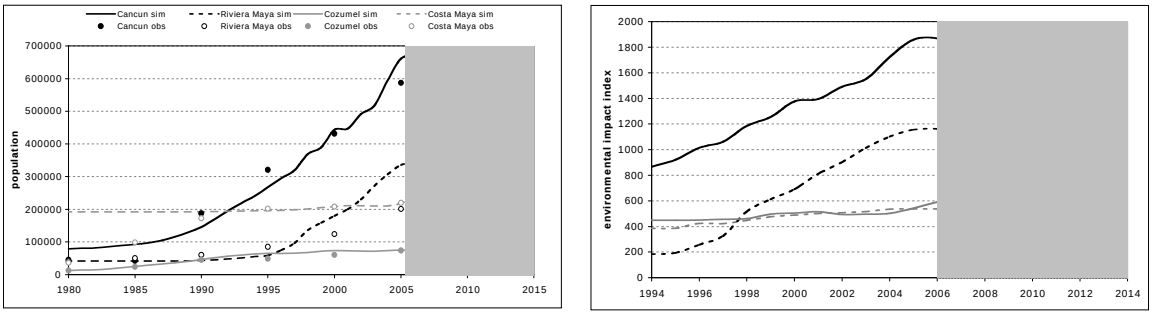

Figure 4: Simulated annual evolution of population and its overall environmental impact. Left: simulated (line) and observed (dot) level of population. Right: cumulative environmental impact index (tourism + urbanisation). Figures are plotted for each economic development area. Shaded parts on each graph correspond to hypothetical projections beyond 2004.

4. DISCUSSION AND CONCLUSION

SimReef is an interactive simulation model aiming to better our understanding of complex interactions influencing coral reef health along the Yucatan peninsula. As such, *SimReef* is an evolving model trying to resolve the current tension existing between conceptual limitations and managerial requirements. Conceptual limitations might stem from data scarcity or theoretical bottlenecks (Perez, 2008). Managerial requirements encompass acceptable levels of uncertainty and action-oriented information (World Bank, 2006).

Ill-defined predicates often characterize relationships insufficiently supported by observations or databases. Corresponding algorithms constitute acceptable proxies at the time and evolve according to new evidence. Simulated variations of population in *SimReef* belong clearly to this category. Likewise, in the absence of a locally calibrated model representing the effect of pollution on coral reefs, our *Environmental Impact Index* can be seen as the simplest proxy available. Sedimentation is another driver influencing coral reef health that is being left aside. As a matter of act, Burke and Sugg (2006), in their comprehensive study of the MAR, admit that the karstic and fractured nature of the Yucatan peninsula has deceived any modelling attempt so far. But the modular and iterative nature of *SimReef* supports the replacement of current proxies by more sophisticated ones or the addition of new drivers. The influence of fishing pressure (*fp*) on ecological dynamics as described by equations [1] to [6] clearly relies on non-linear interactions, especially when marine resources and fishing fleets are distributed across a spatial grid. As stated in the corresponding section, our ecological model is over-simplistic - discarding phase shift transitions, for example – compared with more challenging models proposed by Vidal and Basurto (2003) or Arias-González and colleagues (2004). But its level of sophistication matches the quality of observations used to calibrate its parameters.

In term of accuracy, outcomes simulated with the stand-alone version of *SimReef* reproduce faithfully ecological, economic and demographic trends from 1990 to 2005. This result might not come as a surprise as

some of the local dynamics have been calibrated against empirical evidence. The value of *SimReef* lies more in its capacity to integrate social, economic and ecological into a coherent framework. It is indeed a necessary condition in order to better understand multi-level governance issues and to better inform public policy. Current dynamics along the Yucatan peninsula epitomize such complex interactions between regional fast drivers (tourism development) and local slow ones (local fisheries) as described by Daltabuit and colleagues (Daltabuit et al., 2006).

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