System Dynamics as a methodology for sustainable coastal-zone management

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1 Introduction

The central aim of the multidisciplinary WOTRO[1] research program is to develop the scientific knowledge required for the sustainable utilization of the coastal resources in tropical countries. The study area consists of the coastal zone of South-West Sulawesi, Indonesia. Most coastal-zone policies are implicitly based on the expected interaction between natural and social processes, many of which have been the subject of detailed scientific research in the past. However, a methodology suitable to apply this knowledge to support the integrated management of coastal resources is still lacking. A quantitative system approach is followed for the management component of the project to deal with the dynamic nature of the coastal-zone processes and cross-sectoral linkages. The integration of the theoretical concepts developed by the social scientists of the project in a quantitative system network is less obvious than for the natural sciences. The fisheries sector is one of the key elements of the coastal-zone system in which human behavior plays a role. The increasing fishing effort and introduction of destructive fishing practices have lead to severe overfishing of near coast fish resources. A number of policy options are available to deal with the problem including mesh size and effort restrictions, catch quotas and the installation of marine parks. The effectiveness of these regulations depends largely on the cooperation of local fishermen. Fishermen may decide to increase the number of fishing trips above the sustainable level unless the imposed sanctions exceed the surplus profit and are effectively enforced. The perception and fishing effort of individual fishermen can be considered as the net result of the expected social and economic costs and benefits [1]. A simple bioeconomic model for the exploitation of a fish stock will be used to show how human behavior can be included in a quantitative system model in order to analyze an effort restriction policy.

2 The Model

The basic bioeconomic model [2]used consists of a logistic growth equation for the biomass B of the fish stock and a profit-driven model for the fishing effort E:

$$\frac{\partial B}{\partial t} = gB\left(1-\frac{B}{B_{max}}\right) - qEB \tag{1}$$

$$\frac{\partial E}{\partial t} = r\left(pqB - c\right)E, \tag{2}$$

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[1] Netherlands Foundation for the Advancement of Tropical Research

where B_{max} denotes the maximum biomass, g is the logistic growth constant, q is the catchability per unit effort, and the parameters p and c represent the price per unit catch and costs per unit fishing effort. The parameter r reflects the flexibility of fishermen to respond to changes in profit as a result of declining catches. The biomass, fishing effort, and catch C are expressed per unit surface area. A key variable in fisheries management is the catch per unit effort ($CPUE$) given by $C/E = qB$. To describe the influence of differences in fishing behavior on the total fishing effort the community of fishermen is divided into two groups. The effort of the first group, denoted by E_1, corresponds to a constant sustainable level of exploitation in accordance with the existing fishing regulations. The second group of fishermen consists of rule breakers fishing at profit-driven effort E_2 as in Eq. [2]. The total fishing effort is given by

$$E_{tot} = (1-\alpha)\,E_1 + \alpha E_2, \tag{3}$$

where α is the fraction of fishermen belonging to group of rule breakers. The effort of the individual fishermen within each group is assumed to be identical. A probable situation is that more members of the first group will decide to break the regulations if the proportion of fishermen belonging to the second group increases [1]. Furthermore, the fraction of rule breakers can be expected to increase with the gain expected from the surplus effort. Mathematically this can be expressed by

$$\frac{\partial\alpha}{\partial t} = \begin{cases} k\alpha\pi & \alpha \le 1 - k\alpha\pi \\ 1-\alpha & \alpha > 1 - k\alpha\pi \end{cases}, \tag{4}$$

where the coefficient k represents the rate of group conformation, and π is the profit surplus as a result of the rule breaking:

$$\pi = (p\,q\,B - c\,)\,(E_2 - E_1)\,. \tag{5}$$

If the proportion of rule breakers increases the total fishing effort may exceed the sustainable level of exploitation. A policy of graduated sanctions [3] may be introduced to reduce the fishing effort to the sustainable level. This can be described by rewriting Eqs. [2] and [5]:

$$\begin{aligned} \frac{\partial E_2}{\partial t} &= r\,(\,(p\,q\,B - c)\;E_2 - <s>) \\ \pi &= (p\,q\,B - c)\;(E_2 - E_1)\; - \;<s> \end{aligned} \tag{6}$$

The expectation value $<s>$ of the sanction has now been subtracted from the profit and is obtained from:

$$<s> = \begin{cases} f\beta\,(E_2 - E_1) & E_2 > E_1 \\ 0 & E_2 \le E_1 \end{cases}, \tag{7}$$

where f is the fine imposed per unit effort surplus and β represents the fraction of rule breaking fishermen getting caught. The model parameters and corresponding dimensional units are shown in Table 1.

3 Results

The model results are particularly sensitive for changes in the value of the parameters r [4] and k. Therefore, the influence of these parameters on the time-dependent behavior of the

initial biomass B_0	[mton/ha/yr]	0.2	growth rate g	[1/yr]	0.50
maximum biomass B_{max}	[mton/ha/yr]	1.0	catchability	[1/(trip/ha)]	0.05
sustainable effort E_1	[trips/ha/yr]	5	price p	[US$ /kg]	2.0
initial free effort E_2	[trips/ha/yr]	5	costs c	[US$/trip]	25.0
fine f	[1000 US$]	10.0	β		0.10
adaptability k	[1/(US$/ha)]		flexibility r	[trips/yr/US $]	

Table 1: Parameters and dimensions used for the bioeconomic model. Numerical values are given for fixed parameters only.

CPUE was determined first using the Powersim simulation program [5]. The behavior of the catch per unit effort for different values of r and k is shown in Figure 1 for a time horizon of fifty years, using a Runge-Kutta integration routine and an integration step of one month. The CPUE corresponding to the sustainable level of exploitation $\frac{1}{2}qB_{max}$ is 25 kg/trip. The values $r = 0.001$ and $k = 0.001$ are selected in order to avoid undesirable oscillations of the effort while still allowing for the situation of non-sustainable exploitation. To illustrate how a policy of graduated sanctioning restores the sustainability of the exploitation the CPUE and fraction of rule breaking fishermen in the absence and presence of graduated sanctions are shown in Figure 2.

4 Discussion

The method discussed here shows how the behavior of fishermen can be incorporated in a quantitative system model. Other types of fisheries management can be analyzed as well by changing the model parameters. For example, an open-access policy is simulated by omitting the sanction and setting the rule-breaking fraction equal to one. The next step is to include the socio-cultural factors in the model which may be relevant in a policy analysis context, such as local leadership and traditional resource-management institutions. This requires the translation into mathematical terms of the corresponding anthropologic concepts. If necessary, a game-theoretic approach could be followed to predict the consequences of social organization and the choices made at the individual level for the effectiveness of fishing regulations.

References

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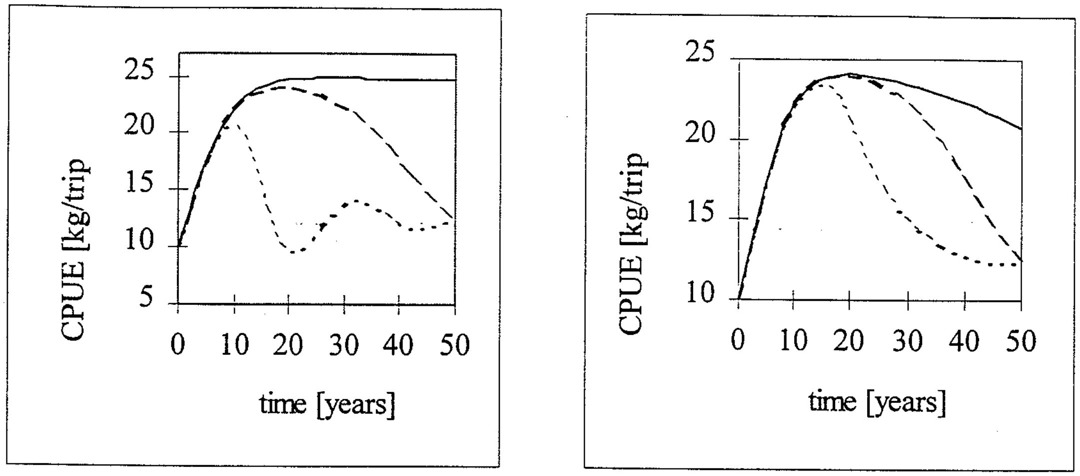

Figure 1. Left-hand side: catch per unit effort for $k = 0.001$ and $r =$ 0.0001 (solid line), 0.001 (dashed line), and 0.01 (dotted line); right-hand-side: catch per unit effort for r = 0.001 and $k = 0.0001$ (solid line), 0.001 (dashed line), and 0.01 (dotted line). No sanctions are imposed.

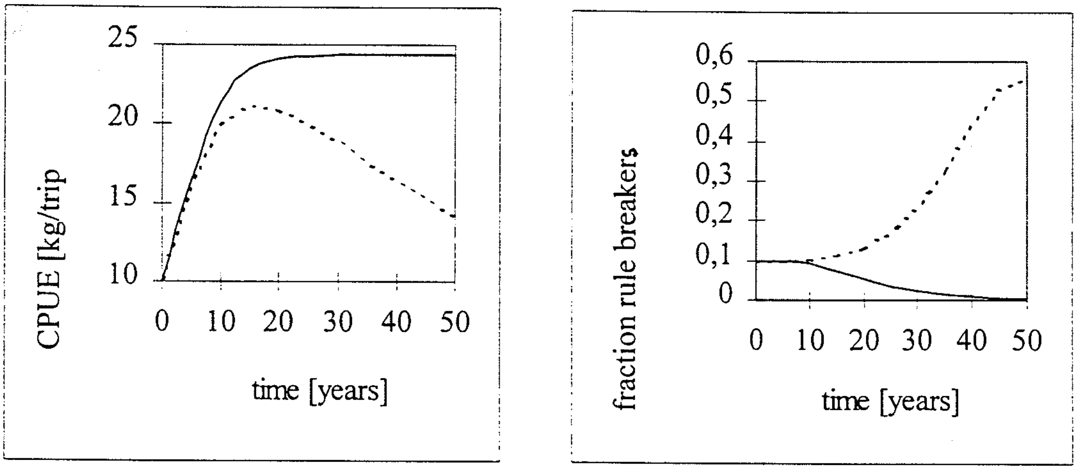

Figure 2. Catch per unit effort and fraction of rule breakers in the presence (solid line) and absence (dashed line) of a sanction with fine $f =$ US$ 1,000 and caught fraction $\beta = 0.10$. The initial fraction of rule breakers is set at $\alpha = 0.10$.