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ANALYSIS

An ecological–economic model for catchment management: The case of Tonameca, Oaxaca, México

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ABSTRACT

Coastal environmental impacts are generally due to both local and remote land uses. Eutrophication of coastal waters, for example, may be due to local urbanization and tourist development, but typically also stems from nutrient flows from agriculture away from coastal areas. To deal with this problem, catchment and coastal management need to be integrated. Management recommendations need to be supported by integrated analysis linking the geographically dispersed drivers of change from an appropriately interdisciplinary perspective. This paper presents an ecological–economic model that embeds existing food web models within fishery and tourism production functions. The aim is to identify optimal management strategies for catchments in which changes in nutrient loads have consequences for the relative abundance of economically important species. The model is calibrated on data for the Tonameca catchment, located on the coast of Oaxaca in Mexico.

1. Introduction

Coastal environmental impacts are frequently caused by both local and remote human activities (GESAMP et al., 2001). In addition to local fisheries, urbanization and industrialization, upstream agriculture can have a range of physical, chemical and biological impacts on coastal areas. These include the alteration and destruction of habitats, land and water pollution, declining fish stocks and altered hydrological flows. Since the remote effects of agricultural activities are seldom taken into account by farmers, there has been increased interest in linking catchment and coastal management (FreshCo Partnership, 2003). From an economic perspective, the development of coupled models of coastal and inland activity makes it possible to identify and evaluate the environmental externalities caused by the lack of markets for the physical impacts of agriculture on tourism and fisheries. The catchment is a natural ecological unit, where everything is self-contained and connected by water flows. Thus, environmental pressures from upstream to downstream can be estimated with reasonable precision on a catchment scale. Integrated catchment assessment methods have been widely used, and include both quantitative and qualitative approaches (Sada, 1991; Jakeman and Letcher, 2003).

There are relatively few examples of ecological–economic catchment models, but the ecological–economic approach has been used both to analyse spatial externalities in catchments and to generate specific management proposals (Goetz and Zilberman, 2000; Moreaux and Reynaud, 2006; Parker and Munroe, 2006). In this paper, we analyse the linkages between catchment and coastal activities through a set of production functions. Scientific knowledge of the ecosystem is used to describe cause–effect relationships between ecosystem services and the output of marketed commodities (Chee, 2004). Similar approaches have been used, for example, to investigate the role of tropical wetlands in support of shrimp fisheries (Barbier, 2000), and groundwater recharge functions in agriculture (Acharaya, 2000). This paper focuses on the Tonameca basin in Mexico, where semi-subsistence agriculture is the primary occupation inland and represents one of the main sources of water consumption and pollution, and where fisheries and tourism are the primary coastal activities. Artisanal fisheries are especially important in two coastal lagoons, and ecotourism is developing as a coastal activity.

The paper is organized as follows. The next section provides a description of the Tonameca catchment. This is followed by the specification of the model, and a description of the way it captures the interdependency of the main economic activities in the area through changes in the hydrological system and the food web. A fourth section reports our estimates of the external effects of agriculture on fisheries and tourism in Tonameca, and a final section offers a discussion of the results.

2. Tonameca catchment

The Tonameca catchment is located in the south Pacific coast of Mexico, in Oaxaca, the most diverse state in Mexico in terms of both

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biological and ethnic diversity (Neyra and Durand, 2000). The catchment covers around 50,000 ha and encompasses a population of 28,000, implying a population density of approximately 52 habitants/km^2 (INEGI, 2000). The hydrological characteristics of the catchment include 1200 mm average rainfall a year, large drainage volumes but high evaporation, corresponding to a tropical sub-humid climate with a rainy season (from June to November) and a dry season (Arriaga et al., 1998). The annual average temperature is 28 °C. Vegetation is composed of pine and, tropical forest in the upper part of the catchment (above 1200 m in altitude), and dry forest and mangrove close to the coast. Within the catchment, 99% of land is held communally, although villagers privately appropriate the gains from exploiting communal land. Oaxaca rural villages are generally poor. In Tonameca only 35% of households have electricity, 30% have water supply and 16.5% have sewage infrastructure (INEGI, 2000). Agriculture is the main source of revenue for 54% of the active population (INEGI, 2000) and is called "temporal" agriculture, meaning that production is rain fed and irrigation is minimal or non-existent (Marini, 1998). Most production is for own consumption or for sale on local markets (Marini, 1998). Products include coffee in the tropical forest, and maize, sesame, melon, beans, banana and mango in the dry forest (INEGI, 1998; SAGARPA, 2002). Livestock production accounts for 23% of the productive area, whilst arable production accounts for 72% (INEGI, 1998).

The dominant coastal activities are fishing and tourism. The fishery is based in the lagoon and river mouth. At normal water levels, the lagoon is divided, the fishery being located in the larger part. It is carried out with both lines and nets and is largely for own-consumption, the main genera caught being *Centropomus*, *Lutjanus*, *Mugil* and *Gerrrides.* The smaller part of the lagoon is the main tourist destination. The area is located between the tourist resorts of Puerto Escondido and Huatulco. After Cancun, Huatulco is the most important coastal resort in Mexico receiving 170,000 tourists a year, who generate a state income of 530 million pesos a year (SECTUR et al., 2001). Day visitors from Huatulco are the main source of tourist revenue in Tonameca and particularly in Ventanilla, which relies on ecotourism as the main source of revenue. Indeed, 90% of families in that community are engaged in tourism (Avila-Foucat, 2002). Visitors to Ventanilla typically spend a day in the small part of the lagoon seeing wildlife (mangrove forest, birds, crocodiles, and iguanas) during a lagoon boat trip, and sometimes eating traditional food in the women-run community restaurant.

3. Ecological economic model

The ecological–economic model is constructed in two stages. The first stage describes the linkages between the ecological and economic components of the model. The second stage describes the non-market interactions between economic activities: i.e. the environmental external effects of one activity on the others. A general conceptual schema is presented in Fig. 1. The main feature of the model is that it integrates an equilibrium food-web model of species interactions (Ecopath) with an economic model of production in each of three sectors: agriculture, fisheries and ecotourism. Since Ecopath is an equilibrium model it describes food web interactions in the steady state. Consistency requires that the economic component of the model similarly describes production in the steady state. Hence the integrated model provides insights into the properties of the general system only at equilibrium. This means that although it is possible to evaluate the impact of perturbations on the system equilibrium through the comparative statics of the model, it is not possible to evaluate the transition between equilibria — the convergence path. We believe that the loss of information involved by a focusing on the steady-state in this case is relatively small.

The main agricultural inputs are water, land, labour and fertilizer. We focus on the effects of fertilizer use rather than herbicides or pesticides, since it has been shown that fertilizers are the main source of downstream environmental effects in this area (GESAMP et al., 2001). Herbicide and pesticide use is restricted. Coffee production, for example, relies on specific pesticides for each types of pest (Regalado, 1996). In contrast, common fertilizers are applied to all crops in every season. Nutrient run-off, due to fertilizer use in agriculture, generates downstream changes in the estuary (Comisión Permanente del Pacífico Sur, 2000): specifically an increase in concentrations of nitrogen (nitrate) causing an increase in phytoplankton biomass (Chee, 2004). This has impacts on economic activities that depend on water quality, such as fisheries and ecotourism. Water quality influences mangrove (Clough et al., 1983; Twilley et al., 1998) and phytoplankton biomass in lagoons

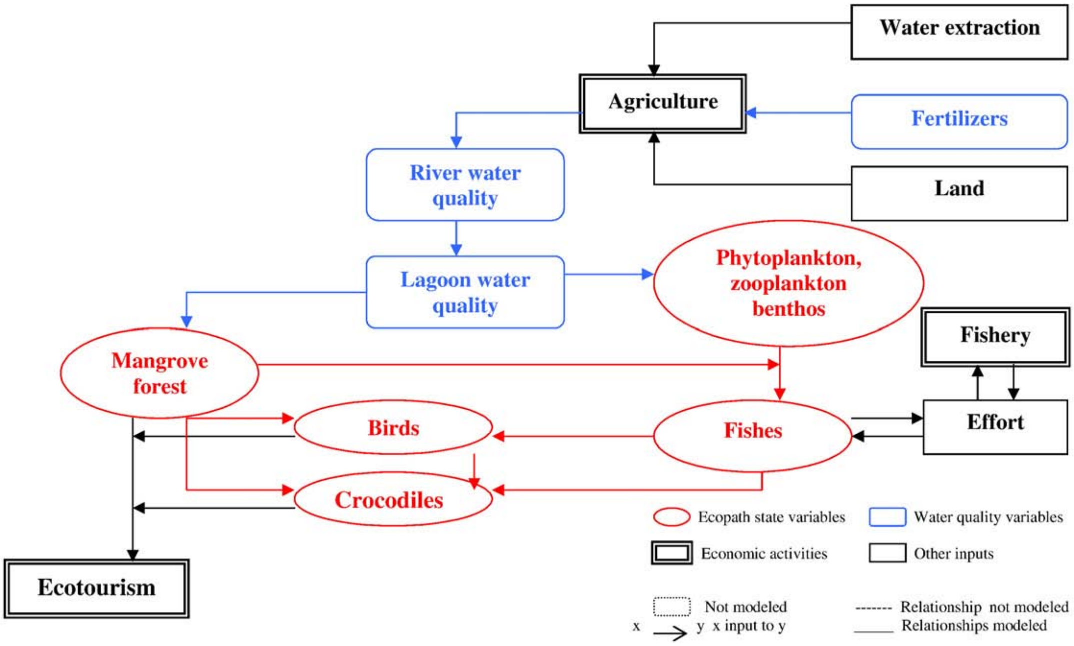

Fig. 1. Ecological economic model schema. The schema shows the relationship between upland agriculture and coastal lagoon fisheries and ecotourism, through water quality and food web components.

and coastal areas (Graham, 1986). At relatively low levels of enrichment, phytoplankton abundance increases, boosting zooplankton and hence fish biomass, and eventually the biomass of fish predators, such as birds and crocodiles. So at low levels of enrichment, fisheries and ecotourism may benefit from upstream fertilizer applications. However, at high levels of nutrient inputs phytoplankton may increase to a level where oxygen is not sufficient for the system, causing eutrophication and the death of organisms.

A relationship between mangrove productivity and fisheries production has been demonstrated for coastal lagoons (Barbier and Strand, 1998). The effect of nitrogen concentration on mangrove biomass has not been explored fully, with most studies focussing on the nitrogen budget within the mangrove tree (Alongi et al., 1992; Twilley and Day, 1999; Rabalais, 2002). The nutrient concentration in mangrove soils has, however, been related to seedling success, salinity and species composition (Clough et al., 1983; Boto and Wellington, 1983; McKee, 1993; Twilley et al., 1998). Biomass changes have been measured through different variables such as, productivity, as well as leaf, root and branch growth (Clough et al., 1983; Boto and Wellington, 1984; McKee, 1995). Boto and Wellington (1983) observed that fertilization with up to 400 kg/ha of nitrogen resulted in significant increase in growth rate and foliar nitrogen in mangrove plants. There is evidence, therefore, that mangrove biomass production is higher when nutrients increase. However, the specific effect of nitrogen on mangrove biomass has not been explored, with the exception of Onuf et al. (1977) who find an increase in mangrove biomass when water nitrogen concentration is high. In this paper we do not model the impact of water nitrogen on fisheries via mangrove biomass, but concentrate on its impact via phytoplankton, using what is known about trophic relations, and the energy flows between the key species: crocodiles, fish and phytoplankton.

The economic component of the model is centred on the production functions for ecotourism, agriculture and fisheries, each of which is linked to changes in the ecological variables on which production depends. For instance, fish biomass depends on lagoon water quality, which is in turn driven by fertilizer run-off from agriculture. Hence fishery production is a function of fertilizer run-off, and this constitutes an external effect of agriculture. The model accordingly makes it possible to estimate the externalities between activities agriculture, ecotourism and fisheries, and to find the difference between private and social optima.

3.1. Fertilizer run-off and its effects on the mangrove food web

There are two significant sources of nitrogen in the system. The first is urea. Urea is the dominant fertilizer used in Tonameca, and is mainly composed of nitrogen. The second is

Total nitrogen run-off in the catchment is the sum of fertilizer (urea) and coffee pulp wash run-off:

$$R_t = \sum_{i}^{m} aU_{i_t}T_{i_t} + bW_{c_t} \tag{1}$$

where R_t = total nitrogen run-off at time t in t/year, U_{i_t} = urea recommended per crop i in kg at time t as a proxy for the fertilizer used in the system, T_{i_t} = hectares of crop i and W_{c_t} = the total amount of water used for coffee production in litres, a is the proportion of urea that leaches into watercourses, b is the nitrogen concentration of water used in pulp washing. Even when conditions are considered ideal for urea application, run-off is estimated to be around 20% of the applied urea, which is similar to estimates for temperate countries and for other kinds of fertilizers (Vinten and Smith, 1993). Riley et al. (2001) found that leaching loss from fertilizer application in Northern Mexico is between 14 to 26% of the applied nitrogen (Riley et al., 2001). Moreover, Matson et al. (1998) found a recovery of nitrogen in soil of 16 to 26% (Matson et al., 1998). Accordingly, our proxy for fertilizer run-off is 20% of the urea recommended per crop: $a = 0.2$. Recommended applications are used in the absence of detailed information of actual applications.

Our estimate of nitrogen flows from coffee pulp wash derives from the Environmental Agency of Cuba, which reports that around 15 mg/l (Agencia de Medio Ambiente, 2001) of nitrogen-rich effluent is generated by pulp washing, and this is usually emitted directly to rivers without any prior treatment. In the model adopted here, 15 mg/l is taken as an estimate of coffee nitrogen run-off, and the total nitrogen input from this source is simply this concentration multiplied by the volume of water used: $b = 0.15$. Since the volume of water used per kg of coffee beans produced is relatively constant at 20 l (Agencia de Medio Ambiente, 2001), we calculate nitrogen from this source directly from average annual coffee production.

Total nitrogen run-off has an impact on water quality in the lagoon through its effect on nitrogen concentrations in downstream flows. This also depends on the volume of water within the river system. In dry years the concentration would be expected to be higher than in wet years due to lower river flows (less dilution). Water volume in the river system also reflects the volume of surface water extraction, agriculture being the primary source of water demand (COLMEX and CNA, 2003). Water extraction is therefore also included as an explanatory variable in the nitrogen concentration model.

Water quality in the lagoon (here taken as nitrogen concentration in water) is related to nitrogen run-off and agriculture water extraction via the function H. Time is included as a variable to reflect the cumulative impact of nitrogen in the lagoon

$$N_t = \beta_{R_t}R_t - \beta_{W_t}W_t + \beta_t t \tag{2}$$

where N_t = Nitrogen concentration in water in the lagoon at time t in mg/l and β_{R_t}, β_{W_t}, β_t are estimated coefficients.

Eq. (2) is used to estimate the changes in nitrogen concentration in water as a result of changes in upstream urea application, nitrogen run-off and water extraction. The estimated change in nitrogen concentration is then used to project changes in phytoplankton and mangrove biomass, as explained below. The method derives from Onuf et al. (1977) who compared nutrients and growth for 2 islands near Fort Pierce in Florida, a control island and another receiving 1 g/m^2 a day of ammonium from bird's guano. Onuf et al. (1977) argue that this concentration is greater than that in sewage or in other pollution case studies such as the classic studies on the east coast of the US by Valiela et al. (1975). Higher concentrations of ammonium in water were found alongside increased levels of biomass at the enriched site. The difference in biomass production between the low and high ammonium sites is of the order of 30%. Based on Onuf et al. (1977), and assuming that nitrogen within sediments derives from river water entering the system, mangrove biomass change $B_{m_{t+1}}$ is estimated increasing a percent of change such as 30% from the initial biomass B_{m_t}.

Phytoplankton biomass change is estimated using the Monod (1942) equation describing the logistic growth of phytoplankton in relation to nutrient availability in water (Graham, 1986). That is, the growth rate μ_t is a function of the nutrient concentration in water. Flynn showed that the Monod equation is appropriate for analysing phytoplankton growth with respect to one limiting nutrient (Flynn, 2003). In this case, N_t is considered the limiting nutrient in the coastal lagoon, in common with the majority of estuarine and coastal studies (Boto and Wellington, 1983). The Monod equation is:

$$\mu_t = \mu_{\max}\left(\frac{N_t}{K_s + N_t}\right) \tag{3}$$

where, K_s is half of the saturation constant growth of phytoplankton, $\mu_{\max}$ is the maximum specific growth rate of phytoplankton and N_t is the nutrient concentration in water in mg/l.

Phytoplankton growth can be also expressed in the following form:

$$\mu_t = \left(\frac{B_{p_{t+1}} - B_{p_t}}{B_{p_t}}\right)$$

where B_{p_t} is the initial phytoplankton biomass in t/km^2 and $B_{p_{t+1}}$ is the change in population growth in t/km^2. Hence we can re-write the relationship as:

$$B_{p_{t+1}} = B_{p_t} + \mu_t B_{p_t}$$

Substituting for μ_t from Eq. (3) we obtain:

$$B_{p_{t+1}} = B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{K_s + N_t}\right) \tag{4}$$

Eq. (4) describes phytoplankton biomass change.

The effects of phytoplankton on the structural and functional aspects of the system are then analysed using the mass-balance trophic model, Ecopath (Zetina-Rejón et al., 2004; Cury et al., 2005). Ecopath balances production and consumption in the steady state, meaning that production is equal to the sum of all losses. It has been used in Mexico to analyse food-web interactions in the Yucatan Peninsula by Christensen and Pauly (1998), Pérez-España and Arreguín (1999), Vega-Cendejas and Arreguín (2001) and in Huizache Caimanero lagoon, in Sinaloa, by Zetina-Rejón et al. (2003). The general Ecopath equations for each group are presented in Appendix A.

The inputs for each group needed to run the program are biomass, total mortality, and the consumption biomass ratio (Appendix A). The outputs describe the trophic structure and energy flows through parameters such as trophic levels, respiration, energy flows, connectance and transfer efficiency. The effect of perturbations to biomass are calculated using Ecosim, which allows us to test the impacts of nitrogen-induced phytoplankton change on the biomass of other trophic groups, such as crocodiles and fish.

This then enables us to estimate the production functions for agriculture, fisheries and tourism. In this paper we do not estimate emigration or immigration rates, since the populations concerned are relatively stable. Phytoplankton biomass is determined from Eq. (4) from the amount of nitrogen in water. The values obtained are then used in Ecopath to estimate the effects on the food web groups, the resulting values for fish and crocodile biomass being applied to the production functions. As in other studies where it has been applied (Christensen and Walters 2004, Zetina-Rejón et al., 2004) Ecopath and Ecosim have been shown to provide useful information for fisheries management.

3.2. Fisheries, agriculture and ecotourism production functions

3.2.1. Fisheries

The fisheries sector is modeled using a Gordon–Schaefer model. Total output, Q_{h_t}, is given by the sum of the harvest of each species and is assumed to be a function of fishing effort, fish biomass and catchability.

$$Q_{h_t} = \sum_{x}^{n} Q_{x_t} = \sum_{x}^{n} qE_tB_{x_t} \tag{5}$$

where q = catchability constant, E_t = fishing effort at time t in hours, B_{x_t} = biomass of fish specie x in t/km^2.

The catchability constant is assumed to be the same for all fish species, since the artisanal fishery focuses on species of similar size and feeding characteristics. Phytoplankton biomass enters directly into the equation for fish biomass (Barbier, 2000; Sánchez, 2002), and is related to changes in nitrogen concentrations in water (Onuf et al., 1977; Flynn, 2003). Fish mortality reflects both natural mortality and predation by crocodiles, fishes or piscivorous birds. $\sum_j O_{js_t}$ represents total predation (by all predators) in group j at time t.

The general expression for biomass of the x^{th} of n fish species is:

$$B_{x_t} = F\left(B_{p_t}(R_t), \sum_j O_{xj_t}\right) \tag{6}$$

and the general expression for harvest of the n species fished is:

$$Q_{ht} = \sum_{x}^{n} q\,E_tF_x\left(B_{p_t}(R_t), \sum_j O_{xj_t}\right) \tag{7}$$

where B_{P_t} is phytoplankton biomass and $\sum_j O_{xj_t}$ is predation by all predators of x at time t. The cost of fishing effort $P_{E_t}E_t$. Since the price of harvest is denoted P_{h_t}, and total harvest is Q_{h_t}, fishing profits are:

$$\Pi_{h_t} = P_{h_t}Q_{h_t} - P_{E_t}E_t \tag{8}$$

3.2.2. Agriculture

The main agricultural inputs are labour, water, fertilizer and land. In a system of the Tonameca type, these inputs tend to be used in virtually fixed proportions, and we exploit this fact in what follows. We have already observed that nitrogen run-off is directly related to fertilizer use, and once again is close to being a fixed proportion of the fertilizer used. Agriculture production Q_{a_t} is described by the general function:

$$Q_{a_t} = \sum_{i}^{m} I(T_{i_t}, L_{i_t}, W_{i_t}, U_{i_t}) \tag{9}$$

where T_{i_t} denotes land committed to the i^{th} crop at time t, and L_{i_t}, W_{i_t}, U_{i_t} are labor, water and fertilizer similarly committed. In the empirical application, the assumption of close-to-fixed proportions implies that the choice of U_i simultaneously implies a choice of the other farming inputs. The profits from agriculture, Π_{a_t}, are obtained by multiplying agricultural output, Q_{a_t} by the average price P_{a_t} of different crops and subtracting costs of production, comprising the cost of labor (P_{L_t} L_{a_t}) and the cost of fertilizer (P_{R_t} R_t), where P_{R_t} adjusts the fertilizer price to reflect our use of run-off as the measure of fertilizer use.

$$\Pi_{a_t} = P_{a_t}Q_{a_t} - P_{L_t}L_{a_t} - P_{R_t}R_t. \tag{10}$$

While agricultural output that is directly consumed by farming households is excluded from the profit function we note that farmers have a choice as to whether to consume or market their output and will only choose to consume it when the net benefits of direct consumption are no less than the net benefits of sale.

3.2.3. Ecotourism

The production function for this sector reflects the fact that a number of studies have shown that environmental attributes are among the most important ‘inputs’ in ecotourism production functions (Guyer and Pollard, 1997; Deng et al. 2002; Huybers and Bennett, 2003). These accordingly take the general form:

$$Q_{v_t} = G(A_t, X_t)$$

where A_t is the set of ecological attributes being sold and X_t is the set of other factors of production. The function $G(A_t)$ describes which ecological attributes are most relevant for tourism. In the Tonameca case the most significant attribute is the abundance of crocodiles, B_{c_t}. This in turn depends on other components of the food web, and so ultimately on phytoplankton biomass. The other inputs comprise labor used both directly, and indirectly via the construction and maintenance of tour boats built by the operators. Hence, production of Q_{v_t} is assumed to depend on crocodile biomass and labor, L_{v_t}

$$Q_{v_t} = G(B_{c_t}, L_{v_t})$$

where $B_{c_t} = V\,(B_{x_t})\,B_{x_t}$ being fish biomass in t/km^2. Using Eq. (6) for fish biomass, we obtain:

$$B_{c_t} = V\left(F_x\left(B_{p_t}(R_t), \sum_j O_{xj_t}\right)\right)$$

which, on substitution into the ecotourism production function yields:

$$Q_{v_t} = G\left[L_{v_t}, V\left(F_x\left(B_{p_t}(R_t), \sum_j O_{xj_t}\right)\right)\right] \tag{11}$$

Ecotourism profits are then determined by the output of ecotourism services, Q_{v_t}, the ecotourism 'price', P_{v_t}, and the cost of ecotourism services, $P_{Lv_t}L_{v_t}$.

$$\Pi_{v_t} = P_{v_t}Q_{v_t} - P_{L_t}L_{v_t} \tag{12}$$

As in other tourism studies we assume that the lower bound on the ecotourism 'price' is the fee that visitors pay to access the place, plus the cost of travel to the site. Since Tonameca is typically one of several destinations in a day trip from the primary tourist destination, travel cost is limited to the marginal cost of accessing the site. The primary element in the 'price' of ecotourism services is thus the cost of adding a boat tour of the lagoon to a day trip from one of the two major tourist centres. The cost of ecotourism services are comprised of labour costs, and for the most part these are dominated by the cost of tour guides.

Decision-makers in each sector are assumed to maximize some measure of net benefit. In the fishery, net benefits are maximised by choice of effort. In the agricultural sector, where there are no direct data on the labour time committed by members of the family farm, and where coefficients are largely fixed, we assume that net benefits are maximised by choice of fertilizer input. In the ecotourism sector, profits are maximised by choice of labour committed to tourist activities.

Social net benefits are assumed to be the sum of the net benefits realised in each sector. Joint profit maximization in the steady state then allows us to account for the steady state externalities from one activity on the others. Using Eqs. (8) for fisheries, (11), for agriculture and (12), for ecotourism; social net benefits at time t can be expressed as follows:

$$\Pi t = P_{h_t}Q_{h_t} + P_{a_t}Q_{a_t} + P_{v_t}Q_{v_t} - P_{E_t}E_t - P_{L_t}L_{a_t} - P_{R_t}R_t - P_{L_t}L_{v_t} \tag{13}$$

Maximization of this measure of social net benefit using the choice variables available to private decision-makers in each sector enables us to identify the costs/benefits not taken into account by those decision-makers, i.e. the intersectoral externalities. Taking ecotourism first, the first order necessary conditions for optimising social net benefit in that sector require that, in the steady state:

$$\frac{d\Pi t}{dL_{v_t}} = P_{v_t}\left(\frac{dQ_{v_t}}{dL_{v_t}}\right) - P_{L_t} = 0. \tag{14}$$

This is the usual condition that marginal revenue be equated to marginal cost, and reflects the fact that the level of tourism activity has no impact on output in either the fishing or agricultural sectors. The only relevant data are marginal tourism costs and revenues.

The position is different in the other two sectors. In the fishery, for example, the first order necessary conditions for optimising social net benefit through choice of effort require that

$$\frac{d\Pi t}{dE_t} = P_{h_t}\left(\frac{dQ_{h_t}}{dE_t}\right) + P_{v_t}\left(\frac{dQ_{v_t}}{dB_{c_t}}\frac{dB_{c_t}}{dB_{x_t}}\frac{dB_{x_t}}{dE_t}\right) - P_{E_t} = 0 \tag{15}$$

where

$$\left(\frac{dQ_{v_t}}{dB_{c_t}}\frac{dB_{c_t}}{dB_{x_t}}\frac{dB_{x_t}}{dE_t}\right) < 0$$

The external effect of fishing on tourism is negative by virtue of the fact that $\frac{dB_{x_t}}{dE_t} < 0$ while fish are the primary food for the charismatic species on which tourism depends.

Lastly, the first order necessary conditions for optimising social net benefit through choice of fertilizer applications in dry and wet tropical agriculture (measured through run-off) require that:

$$\frac{d\Pi t}{dR_t} = P_{a_t}\left(\frac{dQ_{a_t}}{dR_t}\right) + P_{v_t}\left(\frac{dQ_{v_t}}{dB_{c_t}}\frac{dB_{c_t}}{dR_t}\right) + P_{h_t}\left(\frac{dQ_{h_t}}{dB_{x_t}}\frac{dB_{x_t}}{dR_t}\right) - P_{R_t} = 0 \tag{16}$$

where

$$\frac{dB_{c_t}}{dR_t} = \frac{dB_{c_t}}{dB_{p_t}}\frac{dB_{p_t}}{dN_t}\frac{dN_t}{dR_t} \gtreqless 0$$

and

$$\frac{dB_{x_t}}{dR_t} = \frac{dB_{x_t}}{dB_{p_t}}\frac{dB_{p_t}}{dN_t}\frac{dN_t}{dR_t} \gtreqless 0$$

The ambiguity in the sign of the externality of agriculture in both ecotourism and fishing stems from the non-linear relation between nitrogen run-off and the growth of phytoplankton and fish biomass. Up to some threshold, an increase in nitrogen run-off has positive effects on both phytoplankton and fish biomass, and hence on the biomass of fish predators. Beyond that threshold, however, fish, crocodile and bird biomass may be depleted as a result of eutrophication.

4. Estimating agricultural externalities on fisheries and tourism in Tonameca

In Tonameca, fishing and ecotourism take place in different parts of the mangrove system. Ecotourism takes place in the smaller lagoon, fishing takes place in the main lagoon. The lagoons are connected via the mangrove area when flooding is high. Therefore, the effects of fishing effort on tourism might be expected to be only intermittent at best, and generally appear to be negligible. However, the same is not true for agriculture. Whether it is important to introduce measures that will induce decision-makers in agriculture to internalise the external effects of fertilizer depends on the strength of these effects. Given the data available on each of these sectors in the Tonameca catchment, we can now identify the impact of fertilizer applications in agriculture on both fisheries and tourism.

Profits in both tourism and fisheries depend on fish biomass, and hence on phytoplankton. In tourism, increasing fish abundance implies increasing crocodile (and bird) abundance. In fisheries, the relation is more direct. Fish biomass is, however, quadratic with respect to phytoplankton, while phytoplankton is increasing in nitrogen concentrations. It follows that the external effects of agriculture on both fisheries and tourism is positive up to some level of fertilizer use and negative after that.

To see the impact of agriculture on fisheries and ecotourism profits, production in those sectors is expressed firstly in terms of phytoplankton biomass, and secondly in terms of nitrogen run-off. Eq. (17) expresses fisheries profits as a quadratic function of phytoplankton biomass:

$$\Pi_{h_t} = P_{h_t}\sum_i^n qE_t\left(a_{xi}(B_{p_t})^2 + b_{xi}(B_{p_t}) + c_{xi}\right) - P_{E_t}E_t. \tag{17}$$

Thus, the impact of fertilizer run-off on fisheries profits is:

$$\frac{d\Pi_{h_t}}{dR_t} = \frac{d\Pi_{h_t}}{dB_{p_t}}\frac{dB_{p_t}}{dR_t}$$
$$\frac{d\Pi_{h_t}}{dR_t} = P_{h_t}\sum_{i}^{n} q\,E_t\left(2a_{xi}\left(B_{p_t}\right) + b_{xi}\right)\frac{dB_{p_t}}{dR_t} \tag{18}$$

The relation between ecotourism profits and phytoplankton is even more strongly non-linear, reflecting both the relation between crocodile and fish biomass, and fish and phytoplankton biomass. Specifically, crocodile biomass is a cubic function of phytoplankton biomass (this was obtained in the Ecosim results):

$$\Pi_{v_t} = P_{v_t}\beta_{c_t}\left(a_c\left(B_{p_t}\right)^3 + b_c\left(B_{p_t}\right)^2 + c_c\left(B_{p_t}\right) + d_c\right) - P_{L_t}L_{v_t} \tag{19}$$

Since

$$\frac{d\Pi_{v_t}}{dR_t} = \frac{d\Pi_{v_t}}{dB_{p_t}}\frac{dB_{p_t}}{dR_t}$$

we have

$$\frac{d\Pi_{v_t}}{dR_t} = P_{v_t}\beta_{c_t}\left(3a_c\left(B_{p_t}\right)^2 + 2b_c\left(B_{p_t}\right) + c\right)\frac{dB_{p_t}}{dR_t} \tag{20}$$

Given that the marginal private net benefit of fertilizer use in agriculture is $\frac{d\Pi_{a_t}}{dR_t}$ the marginal social net benefit of fertilizer use is:

$$\frac{d\Pi_t}{dR_t} = \frac{d\Pi_{a_t}}{dR_t} - \left[P_{h_t}\sum_{x}^{4}\mathrm{qE_t}\left(2\mathrm{a_{xi}B_{p_t}} + \mathrm{b_{xi}}\right) + \mathrm{P_{v_t}}\beta_{\mathrm{c_t}}\left(3\mathrm{a_c}\left(\mathrm{B_{p_t}}\right)^2 + 2\mathrm{b_c B_{p_t}} + \mathrm{c_c}\right)\right]\frac{dB_{p_t}}{dR_t} \tag{21}$$

where

$$B_{p_t} = B_{p_{t-1}} + B_{p_{t-1}}\mu_{\max}\left(\frac{\beta_{R_{t-1}}R_{t-1} - \beta_{W_{t-1}}W_{t-1} + \beta_{t-1}t-1}{K_s + \left(\beta_{R_{t-1}}R_{t-1} - \beta_{W_{t-1}}W_{t-1} + \beta_{t-1}t\right)}\right) \tag{22}$$

From Eq. (16), the socially optimal level of fertilizer should be selected to satisfy:

$$P_{a_t}\left(\frac{dQ_{a_t}}{dR_t}\right) - P_{R_t} = -\left(P_{v_t}\left(\frac{dQ_{v_t}}{dB_{c_t}}\frac{dB_{c_t}}{dR_t}\right) + P_{h_t}\left(\frac{dQ_{h_t}}{dB_{x_t}}\frac{dB_{x_t}}{dR_t}\right)\right) \tag{23}$$

In other words, to maximise net benefits of fertilizer use to the whole of Tonameca society it is necessary to equate the private marginal net benefit of fertilizer use in agriculture with the social net cost of fertilizer use in the fishery and tourism sectors.

To test the strength of the fertilizer externality on these sectors, U^* is determined using Eq. (1) and the estimated values of the parameters and variables of the sectors production functions presented in Table 1. We find that $U^* = 80{,}950$ t, implying an optimal level of runoff, R^*, of 16,190 t which is significantly greater than the value of $R = 2100$ t observed during the study period. Therefore, the marginal external net benefit of pollution is positive – downstream productivity gains dominate any damage – and the current rate of nutrient loading in the river system is lower than the social optimum.

5. Discussion and conclusions

The ecological–economic model presented in this paper is designed to capture the impact of agriculture externalities in a coastal catchment. In particular the model captures the environmental consequences of land use in the upper catchment for activities on the coast through the effect of nutrient enrichment, as tracked by Ecopath (with Ecosim), on downstream populations. That is, the paper models the feedback effects of agriculture on fisheries and ecotourism. While there are a few studies of the links between fresh water quality changes, lagoon water quality and the corresponding economic impacts, the use of Ecopath makes it possible to evaluate at least the food web dynamics that underlie the environmental externalities identified in the paper. Although we would generally expect a negative impact from fishing effort on ecotourism, we have no evidence of this in the case of Tonameca. There is evidence for an externality of agriculture on fishing or ecotourism, but we find that, at current levels of fertilizer application, this externality is positive. We note that the optimal level of nitrogen should be such that the marginal external damage and marginal net private benefit from fertilizer application are equated, but that this implies significantly higher levels of fertilizer application than currently occur. The fact that there are currently positive downstream externalities to fertilizer applications in agriculture suggests that it should be encouraged, through either economic incentives or constructive use of the extension system, or some combination of the two. We also note that the sector in Tonameca is in fact facing declining productivity and considerable outward migration (Aragonés, 2004). This is partly as a result of the Mexican 'agricultural crisis' (Rubio, 2004). The fact that agriculture offers off-site benefits should be relevant to any strategy to address this fact.

Table 1
Tonameca ecological economic model variables and parameter values.

Variable	Value	Units	Reference
B_{p_t}	7.2	t/km^2	(Vega-Cendejas and Arreguin-Sanchez, 2001)
R_t	2402	t/yr	(Avila-Foucat, 2006)
U_{i_t}	300 to 600	kg/ha	(Avila-Foucat, 2006)
T_{i_t}	39933	ha	(INEGI, 1998)
L_{a_t}	1503	persons	(INEGI, 1998) (Includes hectares for coffee production)
B_{h_t}	4.4	t/km^2	(Avila-Foucat, 2006) B_{h_t} is the sum of the biomass of each of the four species B_{x_t}
E	13944	h/year	(Avila-Foucat, 2006)
P_{h_t}	24	Pesos	(Avila-Foucat, 2006)
q	0.00003		Constant
P_{E_t}	18 000	Pesos/year	(Avila-Foucat, 2006)
P_{R_t}	8836	Pesos/year	(Avila-Foucat, 2006)
L_{v_t}	20	persons	(Avila-Foucat, 2006)
B_{c_t}	0.58	t/km^2	(Avila-Foucat, 2006)
P_{v_t}	35	Pesos/trip	(Avila-Foucat, 2006)
P_{Lvt}	147 075	Pesos/year	
P_{a_t}	5061	Pesos/t	(Avila-Foucat, 2006)
P_{La_t}	12.5	Pesos/day	(Avila-Foucat, 2006)
P_{w_t}	30	Pesos	(Avila-Foucat, 2006)
W	261145	m^3	(COPEI Ingenieros SA de CV, 2000)
u_{max}	1	µg/l	Constant
K_s	10	µg/l	Constant
a_x	0.024		Estimated coefficients
a_x	−0.21		
a_c	0.0005		
b_c	−0.009		
c_c	0.06		
β_t	0.49		
$\beta_{B_{ct}}$	14611		
β_{wt}	0.062		
β_{R_t}	18.04		

We have assumed that, consistent with the literature, 20% of fertilizer applied to fields runs off and enters the river system, but we note that our conclusion – that at current levels of activity there is a positive external effect of agriculture in both fisheries and tourism – is not sensitive to this proportion. Doubling or halving the rate does not change that conclusion. This said, we have not explored the environmental consequences of changes in other agricultural inputs or other environmental variables such as sedimentation. Since we have assumed fixed coefficients, an increase in fertilizer use implies proportional increases in land, labor and other inputs — and these too have potential environmental impacts.

In more input-intensive agricultural systems nutrient runoff is a major source coastal pollution. The dead zone in the Gulf Mexico, for example, is a function of excess nitrogen application in farms in the Mississippi catchment. But the impact of nutrient loading in catchments is not monotonic, and if well-being depends on the productivity of aquatic systems some nutrient loading can be beneficial. We find that in the Tonameca catchment significant extensive growth of agriculture (at the current technology) would yield downstream benefits. It follows that some intensification of agriculture would be similarly beneficial for both the coastal fishery and ecotourism. As in other coastal systems, however, there is a limit to this, and at some point the effects of additional nutrient flows would become negative.

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Appendix A

The Ecopath equation is

$$B_{s_t}(P/B)_{st}EE_{s_t} - \sum_j B_{j_t}(O/B)_{js_t}DC_{js_t} - EX_{s_t} - BA_{s_t} = 0$$

where

B_{s_t} = biomass of group s in t/km^2, P_{s_t} = production t/km^2, $(P/B)_{s_t}$ = production/biomass ratio that is equal to the coefficient of total mortality in year t, EE_{s_t} = Ecotrophic efficiency or the fraction of production that is consumed within or caught from the system, B_{jt} = biomass of group j at time t in t/km^2 $(O/B)_{ji_t}$ = consumption/biomass ratio of group j,

DC_{js_t} = fraction of s in the average diet of j in biomass, EX_{s_t} = export of group s, in biomass, BA_{s_t} = biomass accumulation in t/km^2 per year. All variables are expressed at time t.

The Ecosim equation is:

$$\frac{B_{s_{t+1}} - B_{s_t}}{B_{s_t}} = g_{s_t}\sum_j O_{js_t} - \sum_j O_{sj_t} + I_{s_t} - (M_{s_t} + F_{s_t} + e_{s_t})B_{s_t}$$

where, $\frac{B_{s_{t+1}} - B_{s_t}}{B_{s_t}}$ = biomass growth during the interval t for group s, g_{s_t} = net growth efficiency, M_{st} = natural mortality rate at time t, F_{s_t} = fishing mortality rate at time t, e_{s_t} = emigration rate in t/km^2 at time t and I_{s_t} = immigration rate in t/km^2 at time t, $\sum_j O_{js_t}$ = total consumption by group s in t/km^2 at time t, $\sum_j O_{sj_t}$ = predation by all predators in group s in t/km^2 at time t.

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