Ecological-economic model for integrated watershed management in Tonameca, Oaxaca, Mexico

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Abstract

Coastal environmental impacts are due to land-based and coastal human activities. Urbanization, agriculture and tourism expansion, for example, can cause environmental impacts such as eutrophication. To deal with this problem watershed and coastal management need to be integrated. Management recommendations need to be supported by integrated diagnosis linking not only land and coastal aspects but also different disciplines, such as economics and ecology. Thus, an ecological-economic model is presented for linking the production function approach to existing food web models, such as ECOPATH, in order to identify optimal management strategies for watersheds. The model is applied to the Tonameca watershed, located on the coast of Oaxaca in Mexico. The model is an ecological diagnosis linked to agriculture, fisheries and ecotourism production functions and profits. Social optimization and externalities are also analyzed. The ecological results show that the Tonameca river and lagoon are not extremely polluted and only one scenario of nitrogen run-off estimation indicates high levels of nutrient loading. The mangrove food web analysis results show that the ecosystem is healthy and can support large amounts of nitrogen in water. The agriculture production function and profits depend mainly on water extraction and fertilizer use. Fisheries production function and profits depend on fish biomass and nitrogen concentration in water, which in turn is a measure of fertilizer used in agriculture. Ecotourism production and profits are a function of labor and crocodile biomass related to fish biomass and nitrogen concentration in water. The increase of fertilizer use influences positively in a short term the economic activities but not in a long term. The optimum levels of each activity are evaluated as well as the optimum point of nitrogen run-off for avoiding a negative externality from agriculture to fisheries and ecotourism. Finally, management recommendations for the Tonameca watershed are proposed based on the Mexican framework for coastal and watershed management.

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Acknowledgments

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Chapter 1.

Coastal environmental pressures: ecological-economic modelling for integrated management

Population growth and economic development depend on natural resources and the ecosystem services that they provide. Mangrove forests, coral reefs and up-welling areas have been considered as very productive and diverse systems generating such ecological services. By one estimate "the global value of goods and services provided by marine and coastal ecosystems is roughly double of value of those provided by terrestrial ecosystems, and is comparable with the level of global GDP" [1]. Coastal areas are therefore crucial for supporting life and economy on our planet. Coastal systems provide 90% of global fisheries and produce about 25% of global biological productivity. Marine transport is also significant, 90% of the world tonnage is transported by ships [2]. Marine fisheries and aquaculture produce close to 100 million tonnes of fish providing direct and indirect livelihood to about 140 million people [3]. Finally, tourism has a vital role in the economy of coastal regions. The World Travel and Tourism Council (WTC) estimated that 10.9 % of the world GDP is generated by tourism [4].

Coasts comprise 20% of earth's surface with 50% of human population located within 200 km of the coast (70 % of the world's cities) with an average human population of 80 individuals per square km [2] [5]. In Latin America, rural populations are predominantly in coastal regions, and the majority of the world's cities are located on the coast. Sixty-one percent of the world's population is classed as poor, with 60 million people suffering from food insecurity, the majority of which live in coastal rural regions [6].

Given the high economic activity and population pressure, coastal regions experience significant environmental impacts. For instance, activities such as agriculture, fisheries, urbanization and industrialization, can generate geomorphologic, physical, biological and social impacts.

The alteration and destruction of habitats, sewage effects on human health, eutrophication, declines of fish stocks and hydrological changes are amongst the major impacts.

Coastal resources are also prime examples of common pool resources, making environmental management and regulation difficult to achieve. Coastal lagoons and wetlands, for example, provide goods and services for many people, but property rights and land tenure definitions are difficult to establish. Adger (2000) defines the common property as " property whose individual users tend to have higher incentives to co-operate with each other than to pursue individualist strategies".

In addition, Adger (2000) states that common property is viable when "groups are small with shared needs and norms, clear boundaries for resource management; and relatively low costs of enforcement".

Establishing management recommendations for sustainable natural resources use in a rural watershed with a common property regime, can be addressed with an integrated ecological-economic approach. This enables both internalization of externalities and an understanding of local norms and culture. In order to build an integrated approach I review, in the next section coastal environmental pressures in more detail. The review is not intended to be exhaustive but to introduce those aspects of immediate relevance to the thesis.

1.1 Coastal environmental pressures

1.1.1 Agricultural impacts

Latin America has 23 % of the world's land potential for agriculture, of which 12% is cultivated land and 46 % is tropical forest that could be transformed [6]. In tropical ecosystems, deforestation is mainly due to agriculture. In Southern Mexico, crop cultivation is dominant compared to livestock production [7], and agriculture growth is the main source of pressure on the environment.

Agricultural impacts are strong, causing alteration in vegetation coverage and damage to water quality by fertilizer and soil run-off. The global use of fertilizers would increase from 50 million nutrient tonnes in 1960 to more than 200 million tonnes by 2020 [1]. The permanent Commission of South Pacific Action Plan for the Protection of Marine Environment and Coastal Areas, identified agriculture as an important source of pollution in that region [8].

Colombia, for example, has used during 1994-1995, 9.6 kg/ha of fertilizer. As a consequence, the Tumaco Bay has high concentration of nutrients. Nitrate concentration is low and ammonium is high, representing a typical condition of eutrophication [8]. Agricultural productivity loss, due to fertilizers use as well as, by mono-cultivation is common. An example in the Amazon is illustrated by Weinhold (1999) where land productivity drops in the first 5 years after high amounts of fertilizer use [9]. High nutrient concentration in water such as nitrate, have been related to land use changes for agriculture and fertilizer use [10, 11] [12, 13]. On occasion the nutrient increase causes eutrophication [14] [11].

Pesticides are another source of pollution from agriculture. The Gulf of Fonseca in Honduras, for example, has severe problems of pollution due to pesticides [6]. Moreover, it has been estimated in the world that 20 000 human deaths are due to pesticides poisoning [6].

Overexploitation of water for agriculture is causing an increase in soil salinity and 10% of irrigated land suffers from severe problems in this respect. In Mexico, 50 000 ha have been abandoned due to extreme soil salinity [6]. Efforts have been focused on establishing global and regional agricultural carrying capacity, showing that soil fertility and water supply are problems for agriculture expansion [15].

1.1.2 Fisheries overexploitation

Fisheries represent for 120 million people a source of income world-wide and fish makes up about 19% of the total animal protein consumption in developing countries [16].

However, 47% of fish stocks are fully exploited and 28% are overexploited or depleted [3]. Overexploitation of marine resources increases the vulnerability of ecosystems and food webs when receiving additional environmental pressures such as, temperature and eutrophication. Environmental pressures cause a depletion of populations and disequilibria in food webs. Global and local fisheries are collapsing, due to the combined effects of sedimentation, pollution, over-fishing and introduction of exotic species [1].

Over-fishing is one of the primary reasons for fisheries collapse in many countries. In Guerrero state, in Mexico for example, capture has declined since 1990 due to overexploitation [17]. In Mexico, overexploitation and inefficient exploitation of sea products have been pointed as causes of fisheries depletion [17]. Inefficiency is mainly due to the lack of infrastructure in the coastal region for processing sea products leading to local and regional markets where products have low prices. The lack of adequate commercialisation is also due to the low level of education of fishermen as well as market failures.

For instance, the Mexican market for fish is almost non-existent. The national consumption of fish is 10 to 12 kg annually per person, from which a high percentage is used to feed chickens [18]. The industrial fishery is important in terms of the national economy and exports, but not necessarily in terms of local nutrition or welfare improvement.

Fishery technology has caused overexploitation, inefficiency and habitat destruction. Sheppard (2001) argues that fishing methods like mining in coral reefs and aquaculture are the main pressures for the Indian Ocean and the Western Pacific [19]. In Mexico, the shark fishery decreased enormously in 1985 in Michoacan and Colima due to the introduction of gill nets, until fishermen decided to stop fishing with this method [18].

Fisheries depletion occurs also due to sedimentation and pollution of coastal areas. Agriculture contributes to sedimentation coastal lagoon due to deforestation and erosion of soils causing lower volume of water and less sea water exchange. Moreover, the use of fertilizer and pesticides are one of the main sources of pollution. In the previous section the high rates of fertilizer in Latin America have been described, especially in Colombia [8]. The loss of fisheries and aquaculture is high due to eutrophication [20]. In Mexico, the National Fisheries Chart indicates that agriculture is one of the main pressures for Oaxaca's coastal lagoons [21].

Other sources of pollution such as, urban discharge, hydrocarbons, heavy metals, also have impacts on fisheries production [1].

In Havana Bay, there have been high concentrations of pollutants recorded, such as 1.27 μg/l of hydrocarbons in water and 994 μg/g in the sediments. Similarly, 10 000 million tonnes of hydrocarbons reach the coast in the Wider Caribbean [22].

Coastal geo-morphology changes are also a cause of fisheries depletion. For example, lagoon dynamics change due to port and power station construction. The impacts include temperature increase, lagoon sedimentation, erosion of the coastal line, as well as social impacts. For example, fishermen are removed from their lands, working in ports construction instead, in resorts or in power plants.

In Michoacan state, Mexico, fishermen were moved from their lands due to the construction of a power station; and compensation has not able to ameliorate welfare. Compensation became an instrument for political control and a form of corruption for local leaders [17]. A similar case exists in Manzanillo, where a power plant was created. The community was moved with low compensation and the major environmental impact was due to water temperature increase provoking fish death [18].

Construction of ports and tourism resorts are other pressures causing deforestation, resulting in sedimentation and nutrient concentration variations in water. For instance, in the Balsas region in Mexico, the destruction of mangrove habitat has reached 72% since the beginning of the century due to coastal construction [17].

Environmental pressures on fisheries have been explored but little is known about social pressures and impacts. Fisheries analyses have been focused on understanding fish populations and human exploitation in terms of capture and market (where artisanal fishery data are not included), but few studies have examined social aspects.

Alcalá (1999) argues that "it is equally important to know the volume of capture as well as, the number of fishermen", it is central to understand the history of fishermen (from migration to the actual situation), cultural diversity in attitudes, the social evolution of ports and more precisely to understand what welfare means for fishermen [18].

1.1.3 Tourism growth and community role

In the last two decades the tourism industry has shown significant growth worldwide [23]. In 1998, tourism in developing countries rose 23%, showing the importance of those countries in the market supply [24]. The World Tourism Organization, has estimated that between 2000 and 2010 tourism growth rate in all of the Americas will be 3.9% [4]. Moreover, in 2020, tourists will be one billion tourists.

Environmental impacts due to tourism growth include pollution, sedimentation, and erosion [22]. Tourism main pressures in the Wider Caribbean are deforestation, land reclamation, pollution and sewage.

90% of sewage directed to coastal areas in that region [22]. Sewage as well as fertilizers are the main source of eutrophication for coastal lagoons.

Agenda 21, recognized the need of new forms of tourism as a potential tool for sustainable development for rural communities, particularly in fragile environments through the conservation of nature thereby generating social benefit [25].

Ecotourism has arisen as a need for "understanding and appreciating the natural environment including the respect for host cultures" and generates local benefits [26]. Ecotourism criteria are conservation of the environment and minimization of impacts upon it, respect for local culture and welfare benefits for the communities involved.

Ecotourism is growing as an option for sustainability in local communities, especially in developing countries. The World Trade Organisation estimates that 7% of international trade is related to ecotourism [27].

Ecotourism has shown a growth rate of 10-15% a year, with demand principally from developed countries such as Germany, the United States, the United Kingdom, Canada, France, Australia, Netherlands, Sweden, Austria, New Zealand, Norway and Denmark [28, 29]. Developing countries with high biodiversity represent the main source of supply [29]. Kenya earns $350 million annually in tourism receipts, which are almost entirely due to wildlife tourism [30].

However, the industry is facing challenges related to the determination of minimum impacts, contribution to local welfare and integration within a regionally integrated management process. In order to address these problems, community participation and local knowledge are recognised as essential elements for building sustainable ecotourism projects.

The rationale that Renard (1991) proposes for developing Community Based Ecotourism Management (CBEM) is that it provides an opportunity for equity and democracy, could be economically and technically efficient, promotes responsibility, stability and commitment to management and permits adaptive management towards local, social and environmental conditions [31]. Therefore, CBEM ideally involves local benefits, local sovereignty and facilitation of local natural resource conservation.

In that sense, valuation of ecosystem services where CBEM projects are based is an important tool for supporting CBEM, regional development and policies for common property resources.

Environmental valuation in tourism destinations is needed, and in particular, environmental quality valuation since it has an influence on the quality of the experience which is crucial for ecotourism demand [32-34]. Since each individual has different preferences in recreation, they have different perceptions and interests with respect to the quality of the environment for tourist purposes. Different non market valuation techniques has been used for environmental valuation such as, travel costs and willingness to accept. Travel cost method assumes that the value of the tourist destination is equivalent to the cost that an individual incurs in order to visit this destination. The limits of this approach are that the method considers generally daily expenses, that travel expenses are not always included and costs need to be specific for the nature-based destination [35]. Contingent valuation assess stated preferences from questionnaires, in particular the willingness to pay for the existence of environmental attributes or the willingness to be compensated for conserving environmental attributes. Its main advantage is its flexibility and ability to deal with different use values. There is some concern about the validity and reliability of the results [36], due to various biases and errors. The main aspects of concern causing bias are: the sequence and type of questions, income and previous experience in similar ecosystems [36]. The limitations of contingent valuation are intrinsic to questionnaires methodologies and minimization of bias is explored [36, 37] in order to obtain more accurate results in the main technique used for valuing non market goods.

1.1.4 Water scarcity

Water has been highlighted as a key resource for ecosystem health and economic development. In particular, watershed hydrology is a key element. Fresh-water inputs in coastal lagoons, for example, represent a key factor for fisheries success. Moreover, overexploitation of water increases soil salinity affecting negatively crops cultivation.

In addition, urbanization depends directly on water supply. There is therefore, an intrinsic link between water and economic activities, showing that water scarcity is a pressure for the environment, and the need for internalizing the costs of its sustainable use.

The UNEP Vital Water Graphics report (2002) indicates that the total volume of water on Earth is around 1.4 billion km^3 and that the volume of freshwater resources is about 2.5% of the total volume. Of these freshwater resources, 68.9% is in the form of ice and permanent snow cover and 30.8% is stored underground in the form of groundwater. Freshwater lakes and rivers contain an estimated 105 000 km^3 or ~0.3% of the world's freshwater. The total usable freshwater supply for ecosystems and humans is ~200 000 km^3 of water, which is < 1% of all freshwater resources and only 0.01% of all the water on Earth [20].

In Mexico, the National Commission of Water[1] estimate that in 2001, 74 000 million cubic meters were extracted, of which 63% was from surface water and 37% from groundwater. Agriculture consumption is 80%, 13% is for public use and 7% for industry [38]. In addition, 60% of groundwater is exploited for agriculture and the number of aquifers exploited has been increasing (Table 1).

Table 1. Number of aquifers exploited in Mexico

1975	1981	1985	2001
32	36	80	97

Created from data published in [38]

Agriculture is one of the major activities demanding water supply, and the area in Mexico under irrigation increased from 750 000 ha in 1926 to 6.3 million hectares today. In Mexico, 88% of the population receives potable water and 76% have sewage infrastructure. In rural areas, 70% of the population has potable water and 37.9% sewage infrastructure, meaning that 80% of sewage water arrives eventually to the rivers or the sea [38].

Irrigation systems are inefficient since infrastructure is old and high amounts of water volumes are lost during irrigation.

[1] CNA part of the Ministry of Environment and Natural Resource is in charge of the administration of national waters, as well as, of the hydrological systems management and regulation, and promotion to social development.

The inefficiency of irrigation infrastructure (46% of efficiency), lack of control of water extraction, low costs of water pumps, poor water treatment infrastructure and a lack of culture of water payment are the major issues [38].

The following points have been highlighted as the main aspects related to water management in Chapter 18 in Agenda 21:

- Integrated water resources development and management;
- Water resources assessment;
- Protection of water resources, water quality and aquatic ecosystems;
- Drinking-water supply and sanitation;
- Water and sustainable urban development;
- Water for sustainable food production and rural development;
- The impact of climate change on water resources

In particular, water strategies for Mexico need to address water assessment, irrigation efficiency, potable water extension, sanitation and sewage treatment, as well as the promotion of integrated management between watersheds and coastal regions. Other aspects are also related to an adequate payment system for water services and environmental education.

1.2 Ecological-economic modelling for integrated management

Eighty percent of marine and coastal pollution is due to upland based sources [1]. To confront this issue it is essential to have an interdisciplinary approach linking political, social, scientific and economic aspects for an integrated river basin and coastal management.

The Global Program Action for Protecting the Oceans from Land-Based Activities (GPA) [1] is the international framework from which national and international initiatives are created. The GPA was proposed by the Joint Group of Experts on Scientific Aspects on Marine Environmental Protection (GESAMP). The GESAMP secretary is under UNEP and is in charge of promoting international, regional and sub-regional agreements, searching for international cooperation, and finance, creating an adequate institutional framework and organising periodic meetings. International Initiatives are, for example, Fresh Co Initiative, UCC-Water and White Water to Blue Water[2].

Integrated coastal zone management is a continuous and dynamic process by which decisions are made for the sustainable use, development and protection of the coastal zone [39]. In order to build an integrated management program, it is necessary to make an ecological and socio-economic diagnosis, in terms of socio-cultural characteristics and natural resource availability for economic growth.

Ecological-economic modelling links variables from each discipline in order to build an integrated diagnosis. Results from such analyses would support management policies that are based on the goal of non-declining of the capital stock and equity to sustain welfare [40]. Sustainable agriculture, for example, means maintaining the production in the long term, minimizing impacts to the environment, equitable distribution and local welfare [41, 42]. Ecological-economics is a discipline initiated around 1970 when it was recognised that natural resources were not infinite [43], and institutionalised with the creation in 1988 of The International Society for Ecological-economics [44]. The ecological-economic discipline is the outcome of: environmental issues, system ecology, scientific approach and economic concerns on pollution, development and scarcity [44]. In that sense, ecological-economic models have moved from a single species to an ecosystem approach, and from a single problem focus to a consideration of multi-factorial analysis and multidisciplinary groups. Ecological-economic models for fisheries are a good example since they have moved from single species to multispecies fisheries that consider trophic relationships [45].

Different spatial scales have been applied for the development ecological-economic models. A local scale generally would involve only one ecosystem, such as models linking mangrove or marshes to fisheries [46] [47].

In contrast, regional scales are more suitable for an integrated approach including more than one ecosystem. Some examples can be found for landscape and watershed planning [48] [49] [50].

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[2] Initiatives are the coordination between civil organisations, research institutes and the UNEP secretary. They define priorities, promote integrated watershed and coastal management, strategies for coastal evaluation and programs implementation.

The watershed is the most appropriate scale for an integrated approach since it is the natural ecological unit where everything is self-contained and connected by water flows and the processes are in general well-understood. Specifically, watershed approach allows to link upland socio-economic and ecological aspects to coastal ones.

Maintaining economic production in the long run while minimizing impacts to the environment requires firstly, an understanding of ecosystems ecology and secondly, an internalisation of ecosystems goods and services in the economy. In that sense, an ecological-economic model represents an option for linking ecological aspects for supporting economic growth. Understanding ecosystems for maintenance of its services, biodiversity and structural integrity implies the description of biomass flows between the different ecosystem elements [51]. That is, trophodynamic aspects are indicators for ecosystem diagnosis [51, 52]. Other indices have also been used for relating ecosystem aspects to environmental pressures but do not consider energy flows that are necessary for maintaining ecosystem integrity. For example, Hiddink and Kaiser (2005) pointed that abundance as an indicator of environmental stress need to be taken with caution when many factors might be involved for explaining abundance variations [53]. Therefore, a combination of trophic indicators to understand ecosystems would provide more elements for explaining ecological processes, even if presence of unknown elements is inevitable. In that sense, a combination of trophodynamic indicators have been used to assess ecosystem diagnosis in terms of ecosystem health. Constanza (1992) has described a healthy ecosystem where there is absence of disease, given by the presence of diversity or complexity, stability or resilience, vigor or growth, as well as, normal succession and balance between system components [54] [55]. Vigor, organization and resilience are the most important indices. Vigor is the flow of energy in the system and organization is related to complexity of trophic relations. The combination of both has been captured by Ulanowicz (1992) as ascendency [56]. Ecosystem flow studies have been carried out in order to link trophic relationships and energy fluxes to economic activities, such as fisheries [57] [58] [59]. Ecosystem health analysis is helpful to know if the system can support stress or impacts such as exploitation or pollution. Thus, this approach allows the exploration of the level to which ecosystems can be exploited without losing their integrity and functions. That means, that ecosystem goods and services can be maintained. On the other hand, conservation of goods and services provides sustainability if their values are internalized in the economy. Different valuation methods have been developed such as, production function analysis, travel cost methods, hedonic pricing and contingent valuation between others. The advantage of the production function analysis, is that it uses scientific knowledge for describing cause effect relationships between ecosystem services and the output level of the marketed commodity [60]. Therefore, economic output depends on ecosystem services, thus, the link between the ecosystem and the economy can be clearly established. The production function approach has been used for example, for valuing tropical wetlands in relation to the shrimp fishery [57] [61]. It has also been used for valuing the groundwater recharge function on agricultural production [48]. Other methods, such as, contingent valuation are useful for measuring preferences of non-market goods, but the production function approach is more appropriate for a regional scale and for planning.

Optimization of economic profits subject to environmental dynamics is also a common approach in welfare economics. It is a useful tool to analyze externalities and to obtain management recommendations [47].

Ecological-economic modeling is a potential tool for an integrated diagnosis because it links two scientific disciplines. The conjunction provides additional strength to any resulting management recommendations.

1.3. Aims and research questions

Integrating coastal and river basin management is required to establish better management programs and environmental policies. The aim of the thesis is to build an ecological-economic model as a tool for a holistic diagnosis in order to link coastal and watershed management. The research questions to be answered in order to reach the thesis aim are:

- Is it possible to link a production function approach to existing food web models, such as ECOPATH, in order to identify an optimal management strategy?

- Is it possible to apply such a model in Tonameca watershed, Oaxaca, Mexico in order to develop management policies for natural resource exploitation?

The thesis specific research questions are:

- Is water quality a useful variable for assessing the impacts from upland activities in coastal ecosystems?
- ECOPATH food web model could be linked to water quality?
- Is there a relationship between water quality, nitrogen run-off and water extraction?
- Environmental variables can be included to the agriculture, fisheries and ecotourism production ?
- Are there externalities between agriculture, fisheries and ecotourism?
- Is there an optimum point for developing fisheries, ecotourism and agriculture considering environmental aspects?

Chapter 2.

Description of the Tonameca watershed

2.1 Geographical description

The Tonameca watershed is located on the South Pacific coast of Mexico, one of the 12 mega diverse countries in the world [62]. The watershed is situated within the central coast of Oaxaca state, the most diverse in Mexico in terms of ethnic and biological diversity (28.5% of ethnic groups, 37% of reptiles species, and high endemism) [62] but one which also has a high degree of societal poverty.

The watershed covers 49 800 hectares and encompasses a population of 28 000, producing a population density of approximately 52 habitants per km^2 [63]. The geographical coordinates correspond to 4 limiting points 760 429; 1 733 388 UTM in the southeast, 753 954; 1 735 714 UTM in the southwest, 758 731; 1 768 337 UTM in the northwest and 776 897; 1 762 994 UTM in the northeast.

Six municipalities (the political division in Mexican states) exist in Tonameca catchment, although only a proportion of each falls exactly within the catchment boundaries: Santa María Tonameca, San Pedro Pochutla, Candelaria Loxicha, Pluma Hidalgo, Santo Domingo de Morelos, San Agustín Loxicha[3] (Fig. 1).

2.2 Hydrology and Climate

The National Commission of water divides the country in hydrological regions. The Tonameca watershed is located within the South Pacific region particularly in the 21 hydrological area, in the sub-region of Oaxaca coast [64].

The main river in the watershed is the Tonameca rising at 2382 meters of altitude and ending in the Tonameca coastal lagoon at sea level (field trip data obtained with a GPS).

Annual precipitation is approximately 1200 mm a year, giving a potential annual volume of 684 million cubic meters of water within the catchment

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[3] The municipalities have a code provided by the National Institute of Statistics, Geography and Information Technology (INEGI): Pluma Hidalgo (71), San Agustin Loxicha (85), Santo Domingo de Morelos (509), Candelaria Loxicha (12), San Pedro Pochutla (324) and Santa Maria Tonameca (439).

[65]. The annual volume of water is represented by the surface draining capacity (surface water volume) of 205 million cubic meters a year and 479 million m^3 of evaporation and infiltration [65]. The draining coefficient is the relation between the volume of water in the river and the volume of precipitation being 30% for the Tonameca [65]. The river is shallow with around one meter deep in dry season and around 3 meters deep in the rainy season.

The Tonameca hydrological characteristics indicate large draining volumes but high evaporation, with a rainy season and a dry season, common characteristics of a dry tropical forest. The annual average temperature is 28°C. The climate is tropical sub-humid with a rainy season from June to November [66].

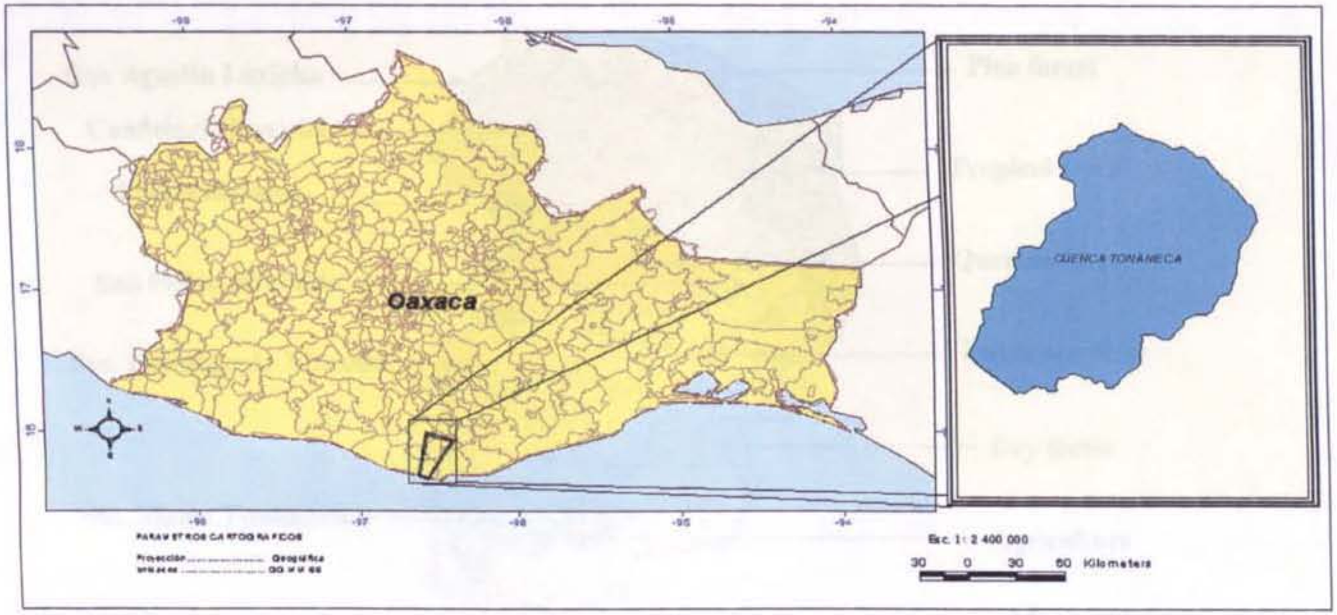
Southwest winds are dominant with an intensity around 1.8 and 3.3 m/s, with occasional winds from the south to the southeast with the same intensity [67]. Sea water exchange is once year during the rainy season between July and September. During those months the coastal lagoon receive fresh water from upland and sea water. The coastal lagoon is shallow (maximum 5 meters during the rainy season) thus stratification of the water column is not significant.

2.3 Flora and fauna

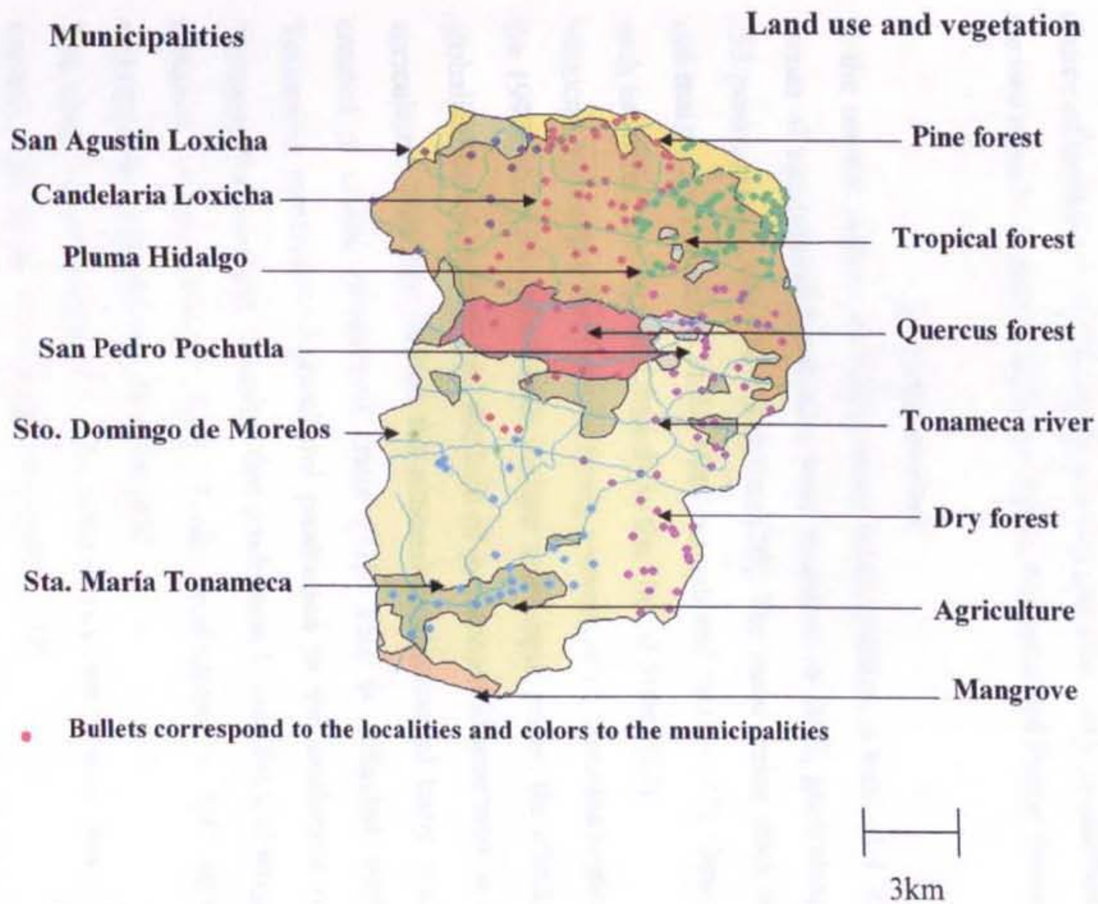
Oaxaca is the most biologically diverse state in Mexico with 8431 species of plants and 1431 vertebrate species, of which 702 and 128 respectively are endemic [62]. Vegetation within the catchment is composed from highest to lowest altitude, of pine forest, tropical forest (where shade coffee is grown), deciduous tropical forest and mangrove forest [64] (Fig 1). Different endangered species occur, such as sea turtles (*Lepidochelys olivacea, Dermochelys coriacea*), the American crocodile (*Crocodylus acutus*), the green iguana (*Iguana iguana*) [68] and the white-tailed deer (*Odocoileus virginianus*). The Oaxaca coast is important for marine turtle nesting [69] and adjacent to the main study area of Ventanilla (see below) is a government institute, the Mexican Center for Sea Turtle Conservation. The institution has a public aquarium for educational programs for tourists on sea turtles. In addition, the Center is responsible for the management of state sea turtle conservation camps.

Fig.1 Tonameca watershed location. a) Mexico and Oaxaca state location b) Tonameca watershed location in Oaxaca state c)Tonameca watershed, vegetation and municipalities

a) (Fig1)



b) (Fig.1)


Municipalities
Land use and vegetation
San Agustin Loxicha
Candelaria Loxicha
Pluma Hidalgo
San Pedro Pochutla
Sto. Domingo de Morelos
Sta. María Tonameca
Pine forest
Tropical forest
Quercus forest
Tonameca river
Dry forest
Agriculture
Mangrove
Bullets correspond to the localities and colors to the municipalities
3km

c) (Fig. 1)

2.4 Socio-economic factors

Within the catchment, 99% of land is held communally and poverty conditions are severe. Only 35% of household have electricity, 30% have water supply and 16.5% have sewage infrastructure [63]. Poverty affects health: 45% of deaths are caused by malaria and 30% by stomach diseases [65]. The percent of illiteracy in the region is high. In the Tonameca municipality, for example, 35% of adults and 20% of children are Spanish illiterate [65]. However, 42% of the total population speak an ethnic language and of those 49 % speak Zapotec [63]. Agriculture is the main source of revenue for 54% of the active population [63]. In addition, there are two main tourism resorts in the region, Huatulco and Puerto Escondido.

2.4.1 Agriculture

In the coastal region, including many municipalities, a total of 1 431 053 tonnes of agricultural production were produced in 2002, generating 1 594 258 pesos, around 144 932 US dollars [70]. The basic grains, such as beans and maize, are consumed in the Mexican national market [71]. Other crops, such as coffee, are exported, mainly to the United States [72].

Mexican agriculture has been suffering a severe crisis since the beginning of the 1990s, due to secular trends in input and output prices, the effects of the globalization of markets and the lack of governmental programs to support agriculture. This has limited the national production of basic grains and created a coffee production crisis [71]. This is reflected within the Tonameca catchment. Agricultural production in the catchment is called "temporal" agriculture, meaning that production is rain fed and irrigation is minimal or non-existent [65]. Thus, production is for subsistence consumption or for the local market [65].

The main crops cultivated in the coastal area are: maize, beans, coffee, sesame, chili and in minor proportion papaya [73].

Land use in the catchment depends directly on the type of vegetation. In the highest limit of the catchment, a small area of pine forest can be found, where forestry represents a small income for the catchment. In contrast, in the tropical forest shade coffee production is located representing one of the main economic activities in the Tonameca catchment.

Shade coffee production includes 3983 farmers (Unpublished information provided by the regional office of agriculture) covering 16 000 ha [73]. During the 1980's the coffee market was very successful, providing the second source of export for Mexico [71]. The International Organization of Coffee was responsible for regulating coffee prices and the Mexican Coffee Institute was in charge of technical support, subsides, credits and exports incentives [71]. But by the end of the 1990s, the globalization of markets provoked an economic crisis in the industry due to imports with low taxes and a decline in prices regulated thereafter by the New York stock exchange. For instance, the price decreased by 78% from 1985 to 1999 and Vietnam and Guatemala became the main competitors for Mexico in the international market [71].

Demand for organic coffee is an incentive for producing coffee with better quality and hence increasing the production value. In 2000, organic coffee production in Mexico was only 8.3% of the area under coffee cultivation [71]. Government programs are needed for promoting and supporting organic production. Tonameca coffee cultivation has suffered, reflecting the national crisis, often encouraging a land use change to other crops with better prices in the local market. Fortunately, the coffee crisis has been controlled with government subsidies stopping deforestation for growing other kinds of crops. Shade-grown coffee remains today one of the main crops in the Tonameca catchment but a small percent is organic.

In the dry forest, maize, sesame, melon, beans, banana and mango are the main crops cultivated [73] [70]. Production without irrigation represent 98% of the area cultivated in the municipalities included in the catchment [73] and productivity is not very high. For example, maize crops in the Tonameca municipality produce 1 ton/ha [65]. Livestock is present only in 23% of the area compared to 72% of agriculture [73].

2.4.2 Ecotourism

Mexico recognizes ecotourism as a way of expanding tourism to rural regions and the National Ecotourism Strategy published in 1994 is the first planning initiative [74]. The Ministry of Tourism published in 2001 a study of ecotourism potential in Mexico [75] which considered 20 tourist destinations and 19 activities. The document indicates that the annual demand generated more than 750 million pesos (68 181 818 US dollars) with 442 participating companies. International and national visitor expenditure are around 60% and 40% respectively [75]. Ecosystem and wildlife observation is a major aim for 16% of tourists and represents 19% of tourism revenues [75]. The study demonstrates that Mexico has high potential for nature tourism.

Following the ban on sea turtle exploitation in 1990, tourism became significant for the Oaxaca coast and nowadays represents one of the main sources of income for the coastal region, especially for Puerto Escondido and Huatulco [75]. After Cancun, Huatulco is the most important coastal resort in the region receiving 170 000 tourists a year that generate a state income of 530 million pesos a year [75]. In 2002, Huatulco received 273 777 tourists that contributed 38.6% of tourism state revenues, with Puerto Escondido generating only 7.5% [75]. Traditional tourism is very important in the region, but ecotourism is growing slowly [75]. The State Tourism Ministry promotes 5 regions within Oaxaca for ecotourism: the coast, the north and south sierras, the central valley and the Mixteca region [76]. The coastal region is promoted by the state government as a destination for ecotourism. Ecotourism coastal offer is composed by: 26 companies, 4 cooperatives and two coffee "fincas" in this area [76].

The Tonameca watershed is located between the tourist resorts of Puerto Escondido and Huatulco. Ventanilla is the only community in the catchment where ecotourism provides the population's main source of revenue. The Ventanilla community is located in the Santa Maria Tonameca municipality, the coastal municipality of the Tonameca watershed. Whilst traditionally a community whose livelihood was based on farming and fishing, today the Ventanilla community relies on ecotourism as the main source of revenue and includes 90% of the families [69]. Visitors to Ventanilla arrive for the day to watch wildlife (mangrove forest, birds, crocodiles, and iguanas) during a lagoon boat trip and sometimes for eating traditional food in the women-run community restaurant.

A mangrove nursery greenhouse, turtle eggs and juvenile crocodiles in captivity are shown as part of the conservation program. Adult crocodiles, deer, and raccoons, are also animals kept captive and were captured from illegal trade by the Environmental Protection Federal Mexican Agency (PROFEPA) and given to the community for conservation purposes.

Ventanilla has been registered since 2001 as a Unit of Management and Wildlife Conservation (UMA), a strategy of the Minster of Environment and Natural Resources to identify and support communities that use wildlife sustainably.

The community has demonstrated social cohesion, as well as a conservation commitment, as proven by the mangrove reforestation and crocodile population monitoring programs. Equity of benefit sharing, sovereignty of the cooperative (decision only taken by the members of the cooperative) and co-ordination with national, international and regional organizations and communities has been also demonstrated [69].

The Ventanilla initiative has evolved in different stages: an initial consolidation stage and recently, a maturity stage. In each stage, the community has had to confront and to solve problems such as social organization, financing and identity. The Ventanilla community represents for the region a successful example of ecosystem services use and a community project of sustainable wildlife exploitation. Ecotourism is an important activity for the catchment because it is a sustainable activity carried on by a cooperative that provides an example for many other communities elsewhere in Mexico wishing to start a similar ecotourism project.

The mangrove ecosystem at the coast receives upland pressures that could affect natural resources used in ecotourism, such as bird populations or the extent of the mangrove habitat. Thus, ecotourism needs to be seen as part of a wider regional strategy. Tourism and ecotourism development need to be planned in conjunction with other economic activities, such as fisheries and agriculture.

2.4.3- Fisheries

The commercial fishery in the area is mainly located offshore whilst coastal lagoon fisheries are artisanal and for self consumption. The Isthmus of Tehuantepec is the main Oaxaca coastal region, with an important fishery in the lagoons and Salina Cruz is the only important port in terms of commerce and engine fuel availability. Other villages, such as Puerto Angel are important for the local market or for specific markets, such as the shark fishery. The regional fishery is depleted due to overexploitation, incipient markets and a lack of integral exploitation of species [21]. In the Chacahua coastal lagoon, for example, shrimp production decreased considerably from 139 tonnes in 1963, to 83 tonnes in 1983 [77]. There is a lack of infrastructure for commercialization and processing and local markets therefore are dominant [78].

In the Tonameca catchment, the fishery is concentrated in the lagoon and is carried out with lines or nets used from the beach. Fishermen come mainly from the Tonameca municipality. The main genera in the Tonameca lagoon are *Centropomus*, *Lutjanus*, *Mugil* and *Gerrrides*.

The centropomidae sea fishery corresponding to the area of study represent 5.5% of the state fishery for this family of fish with around 50 tonnes a year, whilst the Lutjanidae fishery in the region is 8% of the state production, with around 600 tonnes a year. *Mugil* is another important species in the region representing 8% of the state production, with around 200 tonnes [21].

In 2002, the Puerto Escondido fishery office registered 7679 permits representing 2 802 tonnes of different species, with a value of 32 000 pesos. For each permit the production represents around 4296 pesos a year (Unpublished information from the Regional Government Office for Fisheries). Permits are given to cooperatives or individual boats. In Tonameca coastal lagoon there is no cooperative, however, in each village fishermen groups discuss specific aspects, such as, mesh size, lagoon mouth sedimentation and pollution.

The regional diagnosis indicates the depletion of fisheries along the Oaxaca coast [21]. Fisheries information is collected for the coastal region but considers only offshore fisheries. Therefore, specific information for artisanal fishery in the coastal lagoons needs to be collected.

2.5 Environmental pressures

The above description of the Tonameca catchment shows that agriculture, tourism and fisheries are the main economic activities.

Environmental pressures are here related with those activities. Forestry represents only a very small proportion of the catchment and it is though to create little environmental pressure. Agriculture is the main economic activity through much of the catchment and the pressure for land use change is severe, especially considering that most of the remaining forest is used for shade coffee cultivation. Coffee production is presently suffering a severe crisis due to world markets promoting deforestation of tropical forest for the cultivation of alternative crops. The dry forest is mainly deforested for self consumption agriculture. Agriculture promotes both deforestation and the run-off of artificial fertilizers, causing downstream sedimentation and pollution problems in the coastal lagoons. An intensification of fertilizer use on existing agricultural land and/or greater conversion rates of forest to agriculture would cause an increase in nutrient concentration in the coastal lagoons, in turn causing eutrophication, algal blooms and decreased fisheries and eco-tourist incomes.

Environmental pressures from fisheries are directly related to the number of fishermen engaged in fishing and the latter is growing due to an increase in the local population. Technological changes such as a switch to different types of gear are not thought to be an issue, since mainly line and nets with recommended mesh size are used. On the other hand, the lagoon fisheries, like other aspects of lagoon ecology are probably affected by sedimentation processes and pollution from upstream activities.

Sedimentation is due to land conversion to agriculture and to catastrophic natural events, such as hurricane Pauline (1997). Pollution is due to fertilizer use and urbanization. There are 219 localities in the catchment with Pochutla (Fig 1) one of the biggest with 12 000 habitants [65]. Villages are growing without planning and adequate services. For instance, water availability, distribution and treatment are recognized as key issues [65]. Particularly in the dry season (January to May), water is scarce and each year there is an increase in water demand. Pochutla, for example, extracts from the Tonameca river 1 442 000 litres per day and there is no waste water plant (personal communication with the person responsible for the water pump). Water is extracted also for agriculture and tourism (for Mazunte and Puerto Angel).

On the other hand, impacts from resort construction or operation are not significant within the catchment because the main tourism centers (Huatulco and Puerto Escondido) are located just outside of the catchment along the coast, an hour by car from the catchment. However, the number of tourists arriving in Ventanilla depends on those arriving in Huatulco and Puerto Escondido and if controls on numbers entering Ventanilla are not introduced, local problems will arise, such as erosion and pollution. Sewage is not a problem for the local community since they use dry toilets where solids are converted into soil and urine is filtered and used as fertilizer. Thus, the ecological impact of ecotourism is, for the moment, not significant.

In summary, the main socio-economic driving forces with respect to pressure on the catchment are agriculture and urbanization which generally cause water pollution and sedimentation. Fishery effort, water quality and sedimentation are the main pressures on fisheries production.

When dealing with environmental pressures it is necessary to make an integrated diagnosis of impacts and externalities, as well as developing regional planning for integrating agriculture, fisheries and ecotourism development. Water pollution from agriculture is the main pressure addressed in this thesis, since it represents the main external impact on both ecotourism and fishery, and rivers are the main natural component in watersheds. This thesis attempts to do this through the development of an ecological-economic model. The main foci of the model are water quality, fertilizer run-off and the structure and dynamics of the mangrove forest food web. Environmental quality is linked to the production of the different activities and the externalities internalized.

Chapter 3.
The ecological-economic model

3.1 General description

The ecological-economic model presented in this thesis is for a tropical coastal catchment. The catchment is the natural ecological unit, where everything is self-contained and joined by water flows. Thus, environmental pressures from upstream to downstream can be estimated more precisely on a catchment scale. Moreover, ecological and economic links are possible since the catchment processes are in general well-understood. The economic, social and ecological importance of coastal areas, as well as the environmental pressures described in the previous chapter, provide the reasons for developing the model in a tropical coastal watershed.

The model is applied to the Tonameca watershed, Oaxaca, Mexico. The Tonameca watershed, as mentioned in the previous chapter, contains different types of vegetation such as, tropical forest, dry forest and mangrove forest where a variety of potentially contrasting activities co-exist, such as agriculture, fisheries and ecotourism. Similar conditions could be found in other places of Mexico, Central America or other parts of the world. For instance, coastal effects of agriculture has been recognised as one of the main problems in the Indian and western Pacific [19]. Moreover, linkages between tourism and agriculture have been analysed in a small community in Thailand [79].

Ecotourism is carried out by the Ventanilla community and they are interested in the impacts from upland activities to the mangrove ecosystem where their community is located. This thesis, aims to generate useful knowledge for the Ventanilla community. Moreover, the size of the Tonameca watershed is appropriate for developing a model which is data demanding, especially, considering that coastal lagoons in Mexico and Central America have been studied for many years [80, 81].

Coastal environmental goods and services, such as the ones provided by the mangrove forest and by water, are inputs for fisheries, agriculture and tourism production. Maintenance of these goods and services in a coastal catchment requires sustainable activities and it is therefore important to establish the socially optimum level of exploitation of natural resources within the catchment. This in turn requires an understanding of the relationships between different components of the ecosystem, including their structure and function. Once an optimum level of exploitation is determined, the regulation of natural resource use within the catchment needs to be enforced, using a combination of legal instruments and economic incentives. To identify the socially optimal level of exploitation requires information on the value – the social opportunity cost – of the resources of the coastal catchment. Economic valuation of natural services is a valuable tool in this respect, especially for non-market goods [46, 57, 82].

The thesis explores the potential of ecological-economic modelling for internalising the value of natural elements in the system within the production function of goods for optimising social welfare. The model involves three major stages in its construction (Fig. 2). The first stage is the determination of the linkages between the ecosystem and economic components within a tropical coastal catchment. A diagnosis of the ecological effects of economic activities is undertaken, in order to restrict the level of natural resources use for the production of goods. The second stage includes the effect of environmental externalities from one activity to the other. It is considered that environmental quality contributes positively to social welfare, since maintaining ecosystem services are required for sustainability [40]. For the purpose of the model, 90% of land is considered to be under a common property regime, as it is the case in many rural areas of Mexico and in Tonameca; meaning that the economic activities taken place in that land generates profits to local communities. On the other hand, coastal lagoons are a common resource where it is considered that ecotourism and fisheries take place in different parts of the lagoon. Ecotourism is carried on by a cooperative and fisheries by the fishermen located in the villages closed to the lagoon. Both social groups (the cooperative and fishermen) discuss internally and take decisions for improving their benefits. Thus, even if the lagoon is a common resource, its exploitation is undertaken by two organised groups. Therefore, maximising profits improves the welfare of people within the catchment. In the third stage, the Mexican socio-political framework, such as political structure, environmental regulations, land tenure and culture, needs to be considered in order to provide management recommendations for Tonameca watershed (Fig. 2).

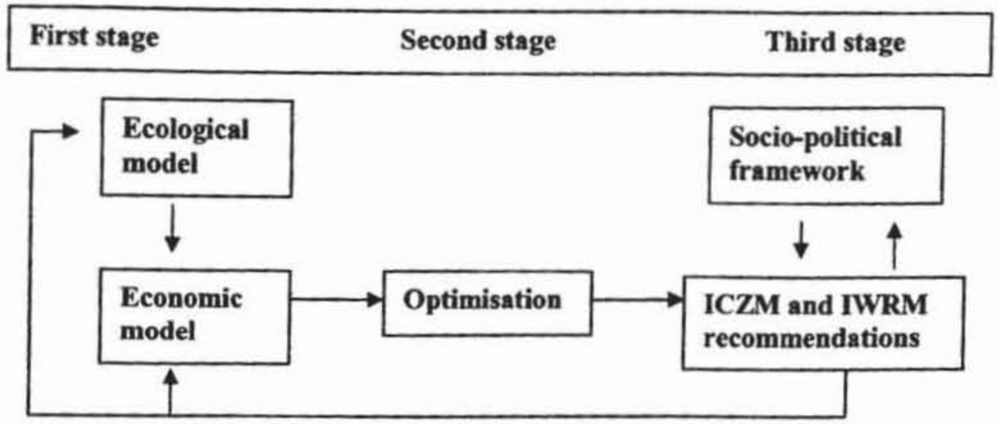


Fig. 2. Ecological-economic model stages

The theoretical relationships between agriculture, ecotourism, fisheries and ecosystem goods and services, are represented in figure 3[4]. Environmental inputs for agricultural production are water, land and fertilizers. Herbicides and pesticides are not included since their application is irregular (only when pests are present), no statistics are available and therefore it would be difficult to estimate the amount used for the catchment. On the other hand, in the area of study, the main chemical used is "Folidol", which is one of the less toxic pesticides and has been recommended by the National Institute of Ecology for cultivation of crops such as Opuntia [83]. Moreover, the Millenium ecosystem assessment has recognised that deforestation and nutrient loading are the main environmental effects from agriculture [84]. Coffee production, for example, uses specific pesticides for different types of pest [85]. In contrast, general fertilizers are applied to any crop in every season. Moreover, it has been shown that the use of fertilizers has been continually increasing [1]. Nutrient run-off from agriculture, reflecting additional loadings from fertilizers, can generate downstream changes in the estuary [8] and, in the case of the Tonameca watershed, changes in lagoon water quality due to an increase in concentrations of nitrogen and phosphorus. Changes in water quality can lead to biomass increases in the system, especially in phytoplankton [86, 87], with impacts on any economic

[4] Labour is an input for the production of ecotourism, agriculture and fisheries but only environmental inputs are included in the figure for simplification.

activities which depend on water quality, such as fisheries and ecotourism. In coastal watersheds, estuaries and lagoons are the downstream sinks of both local and upstream impacts. In this sense, lagoon water quality is in part a measure of the impacts of upland activities, especially if local impacts are minor or can be accounted for. Water quality influences mangrove and phytoplankton biomass in lagoons and coastal areas as shown in figure 3. At low levels of enrichment, phytoplankton increases, in turn zooplankton and fish biomass too, as well as the biomass of their predators, such as birds and crocodiles. Thus, fisheries and ecotourism are ultimately benefited. However, at high levels of nutrient inputs the phytoplankton biomass increases up to a level where oxygen is not sufficient for the system causing eutrophication and the death of organisms.

Coastal lagoons are complex ecosystems with multiple nutrients influencing phytoplankton growth. Phosphorous, silicon and nitrogen are the main nutrients but other aspects might also influence phytoplankton growth such as light. Flynn (2003) argues that even if light is a common aspect measured, the probability that light influences phytoplankton growth is low [87]. On the other hand, the model presented in this thesis uses phytoplankton growth as a measure of eutrophication. Rabalais (2002) indicates that phytoplankton biomass is the appropriate measure of eutrophication and nitrogen is the main nutrient limiting its growth [88].

On the other hand, water extraction from agriculture can cause hydrological changes in the long term as water flows to coastal areas are intercepted, leading in turn to effects on mangrove seedling recruitment and forest regeneration, [89-91] as well as on crocodile nestling success [92, 93] [94], both of which are markedly affected by water levels[5]. Long term data for crocodile populations and forest regeneration are not available for Tonameca, but if data become available this part of the model can be further developed as showed in figure 3.

It should also be noted that sea water exchange at the lagoon, at the terminus of the catchment is periodic. The lagoon is open to the ocean for only 2 or 3 months a year, when the flows of the river are sufficient to breach the beach barrier driven by the effects of wave action on the open coast. Thus, water

[5] Flooding changes soil salinity influencing mangrove seedling growth and crocodile hatchling. Crocodiles nests can not survive in areas where inundation is high level. Flooding also influence seeds dispersion and expansion of the forest area.

quality and water level measurements in the lagoon include the effects of this sea water exchange.

The ecological model constructed here includes an estimation of water quality in the river and lagoon influenced by fertilizer run-off, representing one of the main source of environmental pressures. The effects of water quality on mangrove and phytoplankton biomasses are also assessed.

These effects are then followed through the mangrove food web knowing the trophic relations, especially energy flow, between the key species, such as crocodiles, fish, mangrove and phytoplankton.

The economic component of the model is captured by the production functions for ecotourism, agriculture and fisheries, linked to changes in the ecological components. For instance, fish biomass depends on lagoon water quality in turn driven by fertilizer run-off from agriculture, so that fishery production is a function of fertilizer run-off and hence the fishery experiences an external effect from agriculture.

The externalities between activities are estimated as well as, the optimisation of profits as a measure of social welfare improvement.

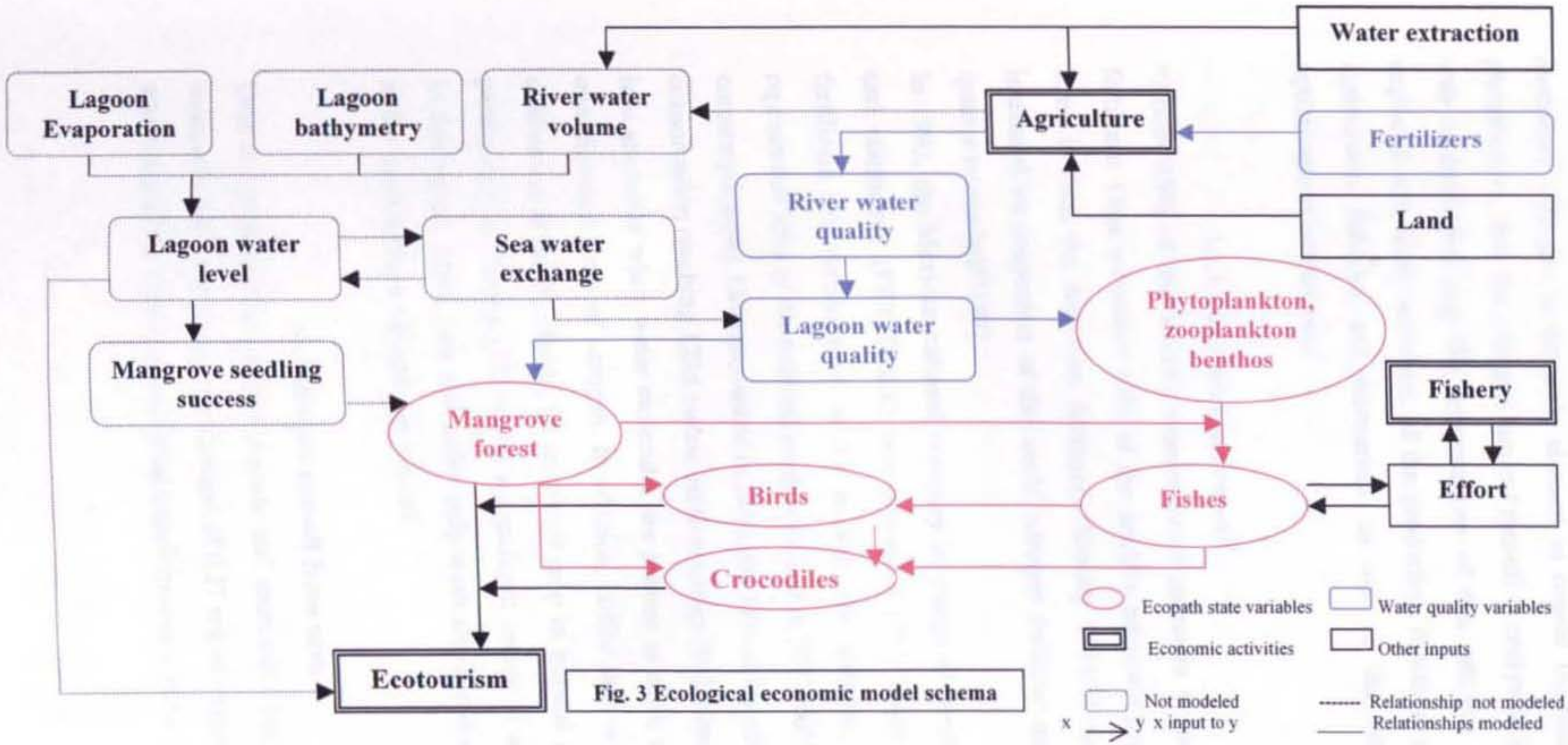


Fig. 3 Ecological economic model schema

3.2.- The ecological-economic model

There are three elements to the model. These are described below. First, the effects of nitrogen run-off on mangrove and phytoplankton biomass are described. Nitrogen is the main element in coastal lagoons compared to phosphorous, thus the nitrogen nutrient run-off is analysed. Second, a food web analysis allowing the repercussions of this nitrogen run-off to be explored and, third, estimates of the production functions and profits for agriculture, fisheries and ecotourism, as well as the externalities and optimisations estimations.

3.2.1 Total nitrogen run-off

"About 85% of the world's manufactured ammonia is used to produce fertilizer. Urea consumes 45% of the world's ammonia production" [95]. Urea is then the dominant fertilizer. "During 1973/74 to 1998/98 urea increased its proportion of the world nitrogen fertilizer market from one quarter to one half" [95].

In 1992, the Mexican national company in charge of fertilizer production and commerce (FERTIMEX) was privatised [96]. Since then, nitrogen fertilizers are predominant in the market. For instance, in 1995, urea represented 35% of the national production and in 1997, 90% of the national consumption [96]. Urea accounted in 2000, for 33% of the national fertilizers consumption reaching 1235 metric million tonnes [96]. Urea is transformed into ammonia when water molecules are present in soils, and ammonia is one chemical form of nitrogen. In addition, coffee pulp wash from coffee cultivation in the highlands, an important crop in tropical ecosystems, and particularly in Oaxaca [72] is also a significant source of nitrogen in rivers in this region. Thus, urea and coffee pulp wash are considered in the model as the main sources for nitrogen run-off.

a- Nitrogen run-off from urea

Urea is converted into carbon dioxide and ammonia (ammonium ions and ammonia gas) with an oxygen demand of 0.27 mg of oxygen per mg of urea according to the following chemical transformations in soil [97].

$$H_2NCON_2H \text{ (urea)} + 2\,H_2O \longrightarrow 2\,NH_4 + HCO_3$$

$$NH_4^+ \longrightarrow NH_3\,(g)\,H^+$$

$$HCO_3 + H^+ \longrightarrow CO_2\,(g) + H_2O$$

Ammonium can be very toxic for living organisms in the form of gaseous ammonia (NH_3), generated at high temperatures and high pH [97]. The transformation of urea into ammonia thus depends on the soil pH, temperature and the presence of urease enzymes [97]. Even when conditions are considered ideal for urea transformation, the maximum run-off estimated is 20% of the applied urea [97], similar to the estimations for temperate countries for other kinds of fertilizers. For instance, Colburn and Dowell (1984) estimated a run-off up to 20% of applied fertilizer for arable lands in Europe [97]. For the purpose of the model, the maximum urea run-off would be used, firstly because no minimum has been estimated and secondly because the precautionary approach indicates to consider the worst scenario. If the minimum value was used eutrophication might not be visible due to an underestimation of urea run-off. Moreover, soil pH data are not available. Thus, 20% of the urea recommended per crop (U_{c_t}), is used as an estimate of urea run-off :

$$\left(U_{c_t} * 20/100\right)$$

where U is urea (kg) and $_{c_t}$ is crop at time t

b- Nitrogen run-off from coffee pulp wash

The nitrogen from coffee pulp wash has been determined by the Environmental Agency of Cuba (EAC) [98] and their protocol is adopted here since the coffee harvest process is very similar in any country. The process includes harvest of beans, washing the flesh off, shelling, drying and grinding. The pulp wash can be done by a water wash or by fermentation of the crop.

During the water pulp wash the output of nitrogen estimated by the EAC is around 15 mg/L [98] and the nitrogen-rich effluent is usually deposited directly to the river without any prior treatment.

In the model adopted here, 15 mg/L is taken as a measure of nitrogen run-off, and the total nitrogen input from this source is simply this concentration times the volume of water used:

$$\left(W_{c_t} * 15\right)$$

where W_{c_t} is the amount of water used in litres (W) for coffee pulp wash at time t ($_{c_t}$), assuming that 20 litres of water are used per kg of coffee beans [98]

c- Total nitrogen run-off

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

(3.00)

$$R_t = \sum_{c}^{n}\left(U_{c_t} * 20/100\right)\left(H_{c_t}\right) + \left(W_{c_t} * 15\right)$$

where R_t = total nitrogen run-off at time t in t/yr, U_{c_t} = urea recommended per crop c in kg at time t, H_{c_t} = hectare of crop c and W_{c_t} = the total amount of water used for coffee production in litres.

3.2.2 Water quality, nitrogen run-off and water extraction relationship

Total nitrogen run-off has an impact on water quality and to measure the order of magnitude of it, water quality data (nitrogen concentrations) are necessary. On the other hand, nitrogen concentration in the river depends on the volume of water within the river system. In the dry season the concentration would be expected to be high due to low river flows (less dilution). However, in the lagoon system the nitrogen concentrations are not expected to be higher because the rain season is when the accumulation of nitrogen from upstream is conspicuous.

Water volume in the river decreases due to low volumes of rainfall but it also can be affected by water extraction. Water scarcity and pollution have been described as one of the main problems in the world in chapter 1, showing that agriculture is the primary source of water extraction [38]. During the dry season, surface water volume decreases and water extraction is low because water volumes in wells is low, increasing nutrient concentration in the river. If the surface water volume is enough for agriculture extraction, water extraction increases, decreasing the surface water level in the river. Water extraction is a variable included in the model in order to internalise the costs of water scarcity due to agriculture.

Water quality (here taken as nitrogen concentration in water) is related to nitrogen run-off and agriculture water extraction with the function H . Time is included as another variable in order to include the cumulative effect of nitrogen in the lagoon. For instance, it has been demonstrated that soil denitrification attains its maximum rate with 200 μM nitrate plus nitrite [99]. Thus, nitrogen is accumulated in soils when denitrification rate reaches its limit causing an increase of nitrogen in water.

(3.0)

$$N_t = \mathrm{H}(R_t, W_t, t)$$

where N_t = Nitrogen concentration in water a time t in mg/L, H = the function describing the relationship between variables, R_t = nitrogen run-off in t/yr, W_t = water extraction in litres, t = years

Water extraction W_t is estimated as a function of the annual draining volume V_t and water extraction for agriculture per municipality w_{i_t} as follows:

$$W_t = \frac{\left(\sum_i^n w_{i_t} + V_t\right)}{\sum_i^n w_{i_t}}$$

where i is the municipality and V_t is the annual draining volume

The annual draining volume is extracted from COPEI (2000) and was calculated based on the type of soil, area and average rainfall [100].

$$V_t = Pmm * A * Ce$$

and

$$Ce = \frac{S(Pmm - 250)}{2000} + \frac{S - 0.15}{1.5}$$

where, V_t = annual draining volume in cubic meters, Pmm = average rainfall from 1970 to 2000 in mm, A = catchment area in hectares, Ce = annual draining coefficient in cubic meters , S = 0.17 of soil absorption constant. Other constants in the formula were established by the authors.

Equation *(3.0)* is used to estimate the changes in nitrogen concentration in water after an increase in urea application, nitrogen run-off and water extraction. The new estimate for nitrogen concentration is then used to estimate changes in phytoplankton and mangrove biomass, as explained below.

3.2.3 Impacts of nitrogen run-off on mangrove and phytoplankton biomass

a.- Mangrove biomass variation

The effect of nitrogen concentration in water on mangrove biomass has not been explored fully, with most studies focussing on the nitrogen budget within the mangrove tree [88, 101, 102]. The nitrogen budget of the mangrove forest sediments is the balance between the input of nitrogen from water and the output from the mangrove tree consumption. Rates of accumulation of nitrogen are diverse and depend on the type of mangrove forest and soil [88, 101, 102]. Ammonification (transformation of organic nitrogen to ammonium), nitrification (transformation of ammonium to nitrite and nitrate) and denitrification (transformation of nitrate to nitrogen gas) are the main processes in the nitrogen budget and have been studied for different locations [101, 102] [88].

The nutrient concentration in mangrove soils has been related to seedling success, salinity and species composition [103] [90] [104] [105] . Biomass changes have been measured through productivity, leaf, root and branch growth [106] [107] [103]. 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, changes in mangrove biomass due to variations in water borne nutrients, particularly nitrogen, have not been explored much, with the exception of Onuf *et al* (1977) [108].

Onuf *et al* (1977) 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 birds guano. Onuf *et al* (1977) argues 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) [109]. The total production biomass of the mangrove tree due to the increase of ammonium showed a significant difference of 100 g dry weight per 1 cm of branch compared to 71.6 g dry weight at low concentrations. The total production biomass difference between the low and high ammonium soil concentration is therefore 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 is given by the following expression:

$$B_{m_{t+1}} = \frac{(30 * B_{m_t})}{100 + B_{m_t}}$$

where $B_{m_{t+1}}$ is biomass after a change in nitrogen in water in t/km^2,

and B_{m_t} is initial mangrove biomass in t/km^2

Thus, the general form for estimating a variation in mangrove biomass due to a change in nitrogen is:

$$B_{m_{t+1}} = \frac{(P * B_{m_t})}{100 + B_{m_t}} \quad (3.1)$$

where $B_{m_{t+1}}$ is the biomass after a change on nitrogen in water, P the percent of increase in biomass, and B_{m_t} is the initial mangrove biomass

b- Phytoplankton biomass variation

Monod (1942) first described the logistic growth of phytoplankton in relation to nutrient availability in water [86]. That is, the growth rate μ_t is a function of the nutrient concentration in water. Flynn (2003) showed that the Monod equation is appropriate for analysing the phytoplankton growth with respect to one limiting nutrient [87]. Moreover, as mentioned by

Rabalais (2002) nitrogen is the main limiting nutrient for phytoplankton growth [88] as discussed previously. Thus, in the model developed within this thesis, it is assumed that the most limiting nutrient in the coastal lagoon is nitrogen N_t, in common with the majority of estuarine and coastal studies [104]. The Monod equation is:

$$\mu_t = \mu_{\max}\left(\frac{N_t}{K_s + N_t}\right) \tag{3.2}$$

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.

The growth rate 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.

From the previous expression it is possible to re-write the relationship as:

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

Replacing μ_t with equation *3.2* we obtain:

$$B_{p_{t+1}} = B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{K_s + N_t}\right) \tag{3.3}$$

Taylor and Williams (1975) used nitrogen as a nutrient to grow two species of diatoms (phytoplankton) *Asterionella formosa* and *Cyclotella meneghiniana* to estimate K_s and $\mu_{\max}$ constants, obtaining 10 and 1 µg/l respectively [87]. Both species of diatoms are present in the Tonameca lagoon [81], therefore the values obtained for K_s and $\mu_{\max}$ by Taylor and Williams will be used.

Equation *(3.3)* is used to estimate phytoplankton biomass change following changes in nitrogen in water derived from the actual nitrogen in water and from nitrogen run-off from agriculture and water extraction rates estimated using equation *(3.0)*.

3.2.4 Food web analysis

The ecosystem approach has been recognized as a useful tool for understanding ecological relationships and adaptive management strategies. Over the last 30 years, ecosystem attributes have been studied based on Odum (1969), who distinguished a number of structural and functional attributes of natural systems, such as community structure, community energetics, life history traits, nutrient cycling and homeostasis [110].

Trophic fluxes (the energy moving between consumers and resources), assimilation efficiencies and energy transfers are characteristics which significantly contribute to system stability and function. Odum (1969) used such attributes to explore the differences between mature and immature ecosystem states, which provided insights into how structural and functional characteristics change as ecosystems mature through succession and how they might respond to disturbances. The approach also allows an exploration of how different parts of a food web respond to disturbances such as those caused by changes in over-fishing [16, 111] or nutrient enrichment. The ecosystem approach was therefore adopted here in order to understand how structural and functional aspects of the mangrove forest system, such as the energy flows and changes on biomass between species, might respond to changes in nutrients. A convenient way in which to carry out such an analysis is to construct a mass-balance trophic model using ECOPATH with ECOSIM 5 [45, 58]. As mentioned by Christensen and Walters (2004) ECOPATH with ECOSIM was initiated in the early 1980s, it is constantly being improved, and has been used in aquatic ecosystems, in 120 countries leading to 150 publications [112].

ECOPATH is a mass balance model where production and consumption are balanced, meaning that production is equal to the sum of all losses. ECOSIM is a dynamic version of ECOPATH; predicting consumption flows representing predator prey encounters and effects due to mass changes. Christensen and Walters (2004) discussed the capabilities and limitations of ECOPATH with ECOSIM [112]. They argue that the model bases the parametrization on an assumption of mass balance over a given time period with the possibility of varying the biomass accumulation during that period. Thus, the initial biomass can be different from the biomass at the end of that period for a specific group but the overall system returns to its initial biomass. In the same way, Pauly *et al* (2000) indicate that the model does not require a steady state condition, rather it requires that the system after a period returns to its earlier state (mass balance) [51]. The software allows also an open system because imports can be included, but ecosystems can develop in a mass balance condition by internalizing flows and recycling detritus [58]. The software presents trophic indicators and flows, thus the model provides an understanding of how the energy is transmitted within the system and allows to analyse the effects of species exploitation in the structural integrity of the system [51]. The trophic indicators do not provide a definite answer, they do provide ecosystem indices to describe the state of a system for strategic management answers.

ECOPATH provide different tools for minimizing uncertainty, the Ecoranger routine can eliminate parameter combination that violates thermodynamic rules and the Pedigree routine serves to assign confidence intervals to data based on their origin [112].

The program itself is based on linear regressions and was originally created in order to generate a global picture of food web interactions for determining fisheries yields, as well as changes at different trophic levels in response to fishing of certain key species. It has been used in Mexico, for the Yucatan Peninsula by Christensen and Pauly (1998), Perez-España and Arreguin (1999), Vega Cendejas and Arreguin (2001), Zetina-Rejón and Arreguin (2001) and also for Huizache Caimanero lagoon, in Sinaloa by Zetina-Rejón *et al* (2003) [58], [113] [59, 114] [115].

The general ECOPATH equation for each group is as follows:

$$B_{i_t}.(P/B)_{i_t}.EE_{i_t} - \sum B_{j_t}(O/B)_{ji_t}DC_{ji_t} - EX_{i_t} - BA_{i_t} = 0 \qquad (3.4)$$

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

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

The inputs for each group in the model are biomass B_{i_t}, $(P/B)_{i_t}$ total mortality and consumption biomass ratio $(O/B)_{ji_t}$.

The outputs describe the trophic structure and energy flows showing parameters (that were mentioned in chapter 1 and will be described in detail in the following chapter) such as trophic levels, respiration, energy flows, connectance, transfer efficiency and ascendency.

ECOPATH reveals the energy flows in the system and helps to understand the trophic relationships between the different groups. ECOSIM is a dynamic version of ECOPATH where changes in ECOPATH inputs can be seen in a long term. ECOSIM applications have been revised by Pauly *et al* (2000) showing the program has been widely used but further applications need to be explored. One of the main limits of the program is how to minimize uncertainty. In that respect, Pauly *et al* (2000) indicate that the quality of the input data and the application of the uncertainty routines (Ecoranger and Pedigree) are very important for minimizing uncertainty [51]. Other limits and advantages has been analysed suggesting that ECOSIM has many capabilities and potentials [112]. ECOSIM is used in this model, to simulate the biomass effects on different groups of the food web, when changing the mangrove and the phytoplankton biomass due to nutrients variations. The results are presented for several years. That is, it is possible to estimate what would be the biomass 10 years after a variation on phytoplankton biomass. Thus, ECOSIM provides information about the new biomass distribution within the trophic levels 10 years after a biomass variation in one trophic level. The ECOSIM equation for each group is as follows:

(3.5)

$$\frac{B_{i_{t+1}} - B_{i_t}}{B_{i_t}} = g_{i_t} \sum_j O_{ji_t} - \sum_j O_{ij_t} + I_{i_t} - (M_{i_t} + F_{i_t} + e_{i_t}) B_{i_t}$$

where, $\frac{B_{i_{t+1}} - B_{i_t}}{B_{i_t}}$ = growth rate during the time interval t for group i in terms of its biomass, g_{i_t} = net growth efficiency, M_{i_t} = natural mortality rate at time t, F_{i_t} = fishing mortality rate at time t, e_{i_t} = emigration rate in t/km^2 at time t and I_{i_t} = immigration rate in t/km^2 at time t, $\sum_j O_{ji_t}$ = total consumption by group i in t/km^2 at time t , $\sum_j O_{ij_t}$ = predation by all predators in group i in t/km^2 at time t .

The emigration and immigration rate are considered absent and fishing mortality is included in the total mortality, as well as, the natural mortality.

As mentioned before, it is possible to obtain changes in the food web biomass due to an increase or decrease in another group, such as phytoplankton. In that sense, it is possible to obtain with different phytoplankton biomass the variation in other groups biomass. A graph can be drawn, as well as an equation obtained, in order to relate groups biomass to an initial phytoplankton biomass (5 years before for example).

The changes in the biomass of groups obtained with the ECOSIM following changes in phytoplankton and/or mangrove biomass can be represented graphically or numerically.

3.2.5 Fisheries production and profit functions

a- Fisheries production function

The output of fisheries is the total harvest, defined as the total catch Fishermen use line and nets for fishing from the lagoon mouth as described in the previous chapter, thus no incidental catch is produced and mainly all catch is consumed. The Schaefer growth model (1954) is used to determine the production. The production function from one specie Q_{x_t} is a function of fishing effort, fish biomass and catchability. The Schaefer model for one species x of fish is as follows:

$$Q_{x_t} = \mathrm{q}\, E_t B_{x_t}$$

where q = catchability constant, E_t = fishing effort at time t, B_{x_t} = fish biomass of specie x

The four most important species in the region of study are included in the model and have the same catchability constant: *Mugil curema*, *Centropomus sp*, Gerrides, *Lutjanus sp*. Effort is considered to be the same for any of the four species, since fishermen spend the same amount of time for any specie, the fishery is not directed to a specific specie. The effort is independent to the amount or the specie collected.

The total fisheries production Q_{h_t} is given by the sum of the harvest of each species as follows:

(3.6)

$$Q_{h_t} = \sum_{x}^{4} Q_{x_t} = \sum_{x}^{4} \mathrm{q}\, E_t B_{x_t}$$

In order to simulate the change in harvest due to an increase or decrease on phytoplankton and mangrove biomass due to fertilizer run-off, it is assumed that there is a direct link between fish biomass, mangrove and phytoplankton. Fish biomass at any time t is a function of phytoplankton [116] and mangrove biomass [57] related previously to changes in nitrogen concentration in water [87, 108] . From equations *3.1* and *3.3* we obtain the fish biomass function F.

$$B_{x_t} = \mathrm{F}\left(B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{\mathrm{K}_s + N_t}\right), \left(\frac{\mathrm{P} * B_{m_t}}{100 + B_{m_t}}\right)\right)$$

On the other hand, fish biomass is also dependent on predation (by crocodiles, fishes or piscivorous birds for example). As expressed in the ECOSIM the expression $\sum_j O_{ji_t}$ means predation by all predators in group j at time t.

Therefore, fish biomass can be expressed as follows:

(3.7)

$$B_{x_t} = \mathrm{F}\left(B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{\mathrm{K}_s + N_t}\right), \left(\frac{\mathrm{P} * B_{m_t}}{100 + B_{m_t}}\right), \sum_j O_{xj_t}\right)$$

Thus, total production in equation *3.6* can be written using equation *3.7* as follows:

(3.8)

$$Q_{h_t} = \sum_{x}^{4} q\, E_t\, F_x \left(B_{p_t} + B_{p_t} \mu_{max} \left(\frac{N_t}{K_s + N_t} \right), \left(\frac{P * B_{m_t}}{100 + B_{m_t}} \right), \sum_j O_{xj_t} \right)$$

where q = catchability constant, E_t = fishing effort at time t, B_{p_t} = initial phytoplankton biomass, μ_{max} = maximum specific growth rate of phytoplankton, K_s = phytoplankton half saturation constant growth, N_t = nutrient concentration in water, B_{m_t} = initial mangrove biomass and $\sum_j O_{xj_t}$ = predation by all predators in group x at time t (all units have been presented in previous equations).

The fisheries production function is then a function of phytoplankton biomass and changes with respect to nitrogen concentration in water and hence with the use of fertilizer in agricultural systems in the catchment.

b- Fisheries profits

Fisheries profits Π_{x_t} generated from one species x depend on, production Q_{x_t} multiplied by the price of each species of fish P_{x_t} minus the costs of fishing. The model assumes an artisanal fishery that is based on a hook line fishery, where there are no motor boats and the fishing cost is equivalent to the opportunity cost of working in agriculture. That is, the cost of actually fishing correspond only to the cost of effort C_{E_t}. The cost of fishing line is insignificant as are the small boats without motors that are used for transportation. Fishing effort is measured in hours spent fishing. The cost of one hour of fishing is equivalent to the wage of one hour working in agriculture.

Fisheries profits (in pesos) for one specie at time t are given by the following expression:

$$\Pi_{x_t} = P_{x_t} Q_{x_t} - C_{E_t}$$

where P_{x_t} is the price of fish in pesos, E_t is the effort in hours

Fisheries production of one species has been expressed previously as follows:

$$Q_{x_t} = qE_t B_{x_t}$$

where q = catchability constant, E_t = fishing effort at time t,

B_{x_t} = biomass of one species of fish

Fishing costs (in pesos) are the price of one hour fishing P_{E_t} multiplied by the effort E_t as follows:

$$C_{E_t} = P_{E_t}.E_t$$

The profit function of fishing one species is then given by:

$$\Pi_{x_t} = P_{xt}qE_tB_{x_t} - P_{E_t}.E_t$$

The total profit is the sum of the profits generated by each species, *Mugil curema*, *Centropomus sp*, Gerrides, *Lutjanus sp,* where effort and catchability are assumed to be the same for any of the four species. Biomass of fish and fish price are variables. Therefore, total profits can be written as follows:

$$\Pi_{h_t} = \sum_{x}^{4} P_{xt} \sum_{x}^{4} qE_tB_{x_t} - P_{E_t}.E_t$$

Considering that the sum of price may be written as P_{h_t} and total harvest is Q_{h_t} total profits can also be written in the following forms:

(3.9)

$$\Pi_{h_t} = P_{h_t} \sum_{x}^{4} qE_tB_{x_t} - P_{E_t}.E_t$$

(3.10)

$$\Pi_{h_t} = P_{h_t} Q_{h_t} - P_{E_t}.E_t$$

On the other hand, fish biomass as shown in equation *3.8* is a function of phytoplankton, mangrove biomass and predation, thus profits can be expressed as follows:

(3.11)

$$\Pi_{h_t} = P_{h_t} \sum_{x}^{4} qE_t F_x \left(B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{K_s + N_t}\right), \left(\frac{P * B_{m_t}}{100 + B_{m_t}}\right), \sum_{j} O_{xj_t} \right) - P_{E_t}.E_t$$

Fishing profits depend on the price of fish, effort, phytoplankton biomass, nitrogen concentration in water, mangrove biomass, predation of fish and fishing effort costs. The value of the function F_x being given by the ECOSIM simulation results.

3.3.6 Agriculture production and profit functions

a- Agriculture production function

The basic agricultural inputs are generally labour, fertilizer and land. For the purpose of this model, water is also considered in order to internalize the costs of water scarcity. Agricultural inputs are then labour, water, fertilizer and land. Labour is given by the number of workers per type of crop and water is related to water extraction for agriculture, even though in the area of study a small percent of production counts with irrigation infrastructure, superficial wells are very common [7]. Fertilizer is an input for agriculture and urea is the main fertilizer considered in this thesis as it is the main compound used in the study area. The amount of urea used per type of crops is estimated in order to determine the amount of nitrogen run-off. Thus, nitrogen run-off is an indirect measure of urea consumption. In order to include the same environmental variable in all the activities for solving the maximisation problem as explained in following sections, nitrogen run-off is considered as a proxy of fertilizer use. That is, if more fertilizer is used an increase in nitrogen run-off is expected. Herbicides and pesticides are not considered in this model since their application is irregular as mentioned previously [85], and are therefore difficult to estimate. Land, in terms of hectares cultivated, is an input in agriculture production and is indirectly included in the equation. Labour, water extraction and nitrogen run-off depend on the number of hectares. Agriculture production Q_{a_t} is given by the function I as follows:

$$Q_{a_t} = I(L_{a_t}, W_{a_t}, R_t)$$

L_{a_t} = labour at time t, W_{a_t} = water extraction for agriculture at time t in cubic meters and R_t = nitrogen run-off at time t as a proxy for fertilizers use

Nitrogen run-off is estimated as explained in 3.2.1 point c, equation *3.00*. Water extraction is the extraction for agriculture in the watershed and labour is based on labour needed per type of crop.

(3.12)

$$L_{a_t} = \sum_{c}^{n} l_{c_t}$$

where l_{c_t} = labour per each crop

Agricultural output is then a function of labour, water extraction and fertilizers (estimated indirectly by nitrogen run-off). Using equations *3.12* and *3.00*, agriculture production is calculated as follows:

(3.13)

$$Q_{a_t} = I\left(\sum_{c}^{n} l_{c_t}, W_{a_t}, \sum_{c}^{n}\left(U_{c_t} * 20/100\right)\left(H_{c_t}\right) + \left(W_{c_t} * 15\right)\right)$$

The production function is used to estimate the effects of fertilizers and irrigation on output.

b- Agriculture profits

Profits Π_{a_t} from agriculture are obtained by multiplying agricultural production, Q_{a_t}, by the price P_{a_t} minus costs of production C_{a_t}.

(3.14)

$$\Pi_{a_t} = P_{a_t} Q_{a_t} - C_{a_t}$$

Price P_{a_t} is the average price of aggregate agricultural production in the catchment.

Costs include labour C_{L_t} and fertilizer C_{F_t} costs. That is, the price of labour $p_{l_{at}}$ per the number of workers required L_{a_t} and the price of fertilizer p_{F_t} per amount of it F_t used.

(3.15)

$$C_{a_t} = C_{L_t} + C_{F_t} = p_{l_t} L_t + p_{F_t} F_t$$

As shown in equation *(3.00)* nitrogen run-off is a measure of urea and coffee pulp wash. Therefore, nitrogen is considered as a direct measure of fertilizer use. Therefore, fertilizer can be replaced by nitrogen run-off as follows:

(3.16)

$$C_{a_t} = C_{L_{at}} + C_{R_t} = p_{l_{at}} L_{a_t} + p_{R_t} R_t$$

Using equation *3.13*, *3.15* and *3.16* the general equation for profits *3.14* can be written as follows:

(3.17)

$$\Pi_{a_t} = p_{a_t}\,\mathrm{I}\left(\sum_{c}^{n} l_{c_t}, W_{a_t}, \sum_{c}^{n}\left(U_{c_t} * 20/100\right)\left(H_{c_t}\right) + \left(W_{c_t} * 15\right)\right) - p_{l_{at}} L_{at} - p_{R_t} R_t$$

Agriculture profits are a function of price, labour, water extraction and fertilizer use minus costs of production.

3.2.7 Ecotourism

a- Ecotourism production function

The output of ecotourism is measured in terms of the number of tourists arriving at an ecotourism destination within the watershed. The production function Q_{v_t} depends on demand and other inputs. Demand Z_{v_t} depends on the socio-economic characteristics of tourists and the environmental attributes of the place. Studies show the environmental attributes are among the most important inputs for the tourist production function. Z_{v_t} is given by the function J as follows:

$$Z_{v_t} = \mathrm{J}\left(A_t, SE_t\right)$$

where A_t is the groups of ecological attributes and SE_t the visitors socio-economic variables.

The estimation of J would allow to distinguish which of the ecological attributes included in the function is significant for tourists. In this particular case, the ecological attributes are for example, the mangrove forest, crocodiles and birds. In order to specify the model, and considering that crocodiles is the most exotic specie in the area of study, suppose that the most significant attribute is crocodile population B_{c_t}, the production function Q_{v_t} is then given by the function G :

$$Q_{v_t} = \mathrm{G}\left(B_{c_t}, L_{v_t}\right)$$

where B_{c_t} = crocodiles biomass, L_{v_t} = labour

Crocodile biomass depends on the availability of food, therefore it is assumed in this model that an increase on crocodile biomass results from an increase in fish [117, 118]. Thus, it is possible to define crocodile biomass is a function of fish biomass given by the function V :

$$B_{c_t} = \mathrm{V}\left(B_{x_t}\right)$$

Using equation 3.7 describing fish biomass we obtain:

$$B_{c_t} = \mathrm{V}\left(\mathrm{F}_x\left(B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{\mathrm{K}_s + N_t}\right), \left(\frac{\mathrm{P} * B_{m_t}}{100 + B_{m_t}}\right), \sum_j O_{xj_t}\right)\right)$$

Replacing the previous expression in the ecotourism production function we have:

$$\mathrm{Q}_{v_t} = \mathrm{G}\left[L_{v_t}, \mathrm{V}\left(\mathrm{F}_x\left(B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{\mathrm{K}_s + N_t}\right), \left(\frac{\mathrm{P} * B_{m_t}}{100 + B_{m_t}}\right), \sum_j O_{xj_t}\right)\right)\right] \tag{3.18}$$

Ecotourism accordingly depends on labour, and biomass of crocodiles that is a function of fish biomass. Moreover, fish biomass is a function of nitrogen concentration in water due to urea run-off. Changes on mangrove biomass and predation on fish are also related to fish biomass and to crocodile biomass, thus to ecotourism production.

Demand model

Demand depends as mentioned previously on the ecological attributes of the place and the socio-economic characteristics of tourists. Other studies analyze demand in relation of ecological attributes of different destinations. By contrast, this model relates to a single site, and a single system, a mangrove ecosystem [119]. The ecotourism demand Z_{v_t} is estimated by analyzing the impact of environmental quality changes on visitors to a single site. This is a different approach from travel cost or contingent valuation methods where tourists are asked about their preferences even if they do not know the destination. The demand is conditioned by the probability that a tourist repeats a visit depending on environmental quality changes. Keane (1997) demonstrated that the reputation of a place is given by the repetition of a visit or recommendation of the place by another who had already experienced the site, as well as by environmental quality [120]. Moreover, it has been demonstrated that shifts in demand depend on management costs for conservation of natural resources and environmental quality [121]. Repetition of visits has not been explored for assessing shifts in demand. It has been used as a measure of reputation of a site. In this thesis the potential repetition of a visit is used as a mechanism for valuing shifts in demand due to environmental quality changes. A repetition of a visit is possible to address only if the person has already experienced the site.

Environmental quality effects on tourism have been observed by several authors, indicating that deterioration causes a decrease in tourism arrivals and profits for firms or regions [122] [123] [119].

Environmental quality has been valued for comparing different destinations, but the problem is that ecological attributes are not substitutes. That is, it is difficult to compare a mangrove forest to a perennial tropical forest. In other studies, the concept used is the quality of the experience that depends on one specific attribute, such as the amount of animals available for hunting [119]. Environmental quality is also valued by asking respondents for their willingness to pay for or accept a policy scenario, where a specific resource deteriorates or is conserved to a certain level [123] [122]. This thesis proposes to use for a single site, specific ranges of change for three attributes, to observe shifts in demand.

The probability of repeating a visit with respect to environmental quality changes is evaluated in Avila-Foucat and Eugenio-Martin (2004) [124].The authors consider that the decision to visit the site again is a binary choice, denoted by T_i, such that, $T_i = 1$ if a household or individual decides to visit the site again and $T_i = 0$ otherwise. They want to model the probability that $T_i = 1$, i.e. $\Pr(T_i = 1)$, assuming that $\Pr(T_i = 1)$ is linked to a set of exogenous variables. More precisely, for some appropriate function $g(\cdot)$:

(3.19)

$$\Pr(T_i = 1) = g\left(\alpha + \sum_{j=1}^{k} \beta_j SE_{ij} + \sum_{l=1}^{h} \beta_l A_{il}\right)$$

where $0 \leq g(\cdot) \leq 1$, α denotes a constant, SE_{ji} denotes j[th] socio-economic variable of individual *i*, A_{il} denotes the value of attribute l as seen by individual *i* as defined in figure 3. β_j and β_l denotes associated parameters to previous variables respectively.

The probability change of revisiting the site under a marginal change in an attribute is as follows:

(3.20)

$$\frac{\partial \Pr(T_i = 1)}{\partial A_{il}} = \phi\left(\alpha + \sum_{j=1}^{k} \beta_j SE_{ij} + \sum_{l=1}^{h} \beta_l A_{il}\right)\beta_l$$

where $\phi(z) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} z^2\right)$ is the probability density function of a standard normal distribution.

The ecological attributes are the number of crocodiles, the mangrove area and birds diversity. The interviewer is asked whether if under the current status of ecological attribute he/she will repeat their visit. If yes, a percent of deterioration willing to be accepted for returning is asked for. If the answer is no, a percent of improvement is asked for. The model presents scenarios of environmental quality change such as, 20%, 50%, 70% of improvement or deterioration for each attribute. The percentages of change are correlated with the percentage of change of mangrove and phytoplankton biomass affecting the mangrove food web when using ECOSIM.

The probability of repeating a visit depending on ecological attribute quality is used to estimate the number of arrivals for following years. Arrivals for the next year, are given by the number of visitors repeating their visit from one year to another given by the model, plus the current of arrivals in the region.

b- Ecotourism profits

Ecotourism profits are determined by the production function Q_{v_t}, the ecotourism experience price P_{v_t} minus costs C_{v_t}.

(3.21)

$$\Pi_{v_t} = P_{v_t} Q_{v_t} - C_{v_t}$$

Price is equivalent to the fee visitors pay for enjoying the place. In this model, it is assumed that ecotourism is run by a cooperative, thus the price is the fee for an ecotourism trip organised by the cooperative. Costs are related to labour, that is, the members of the cooperative and the workers.

(3.22)

$$C_{v_t} = P_{Lv_t} . L_{v_t}$$

Using equation *3.18* and *3.22* it is possible to write equation *3.10* as follows:

(3.23)

$$\Pi_{v_t} = P_{v_t} \mathrm{G}\left[L_{v_t}, \mathrm{V}\left(\mathrm{F}_z\left(B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{\mathrm{K}_s + N_t}\right), \left(\frac{\mathrm{P} * B_{m_t}}{100 + B_{m_t}}\right), \sum_j O_{xj_t} \right)\right)\right]$$
$$- P_{Lv_t} . L_{v_t}$$

Ecotourism profits are a function of price, labour, crocodile biomass and costs.

3.2.8 Profit maximisation for agriculture, fisheries, ecotourism

a. Maximisation of agriculture, fisheries, ecotourism

Social welfare is achieved by maximising the sum of all profits. Land resources are assumed to be subject to a regulated common property. The common property means that economic activities are carried on by the communities in their own land. Ecotourism and fishing take place in the coastal lagoon, which are normally an open access resource. Ecotourism is assumed to take place also on land with a common property regime.

In order to maximize the private communities benefits on the catchment, fisheries profits are maximised by choice of effort. Agricultural profits are maximised by choice of fertilizer, proxied by nitrogen run-off. Ecotourism profits are maximised by choice of labour. The specific forms of each function along with the first order conditions for their maximisation are specified in chapter 6.

Fisheries

The problem is the form:

$$\mathrm{Max}_{E_t} \Pi_{h_t} = P_{h_t} \sum_{x}^{4} qE_t B_{x_t} - P_{E_t}.E_t$$

and the first order conditions require that:

$$\frac{d\Pi_{h_t}}{dE_t} = P_{h_t} \sum_{x}^{4} qB_{x_t} - P_{E_t} = 0$$

implying that:

$$P_{h_t} \sum_{x}^{4} qB_{x_t} = P_{E_t}$$

i.e. that the marginal revenue is equal to marginal costs.

Agriculture

The problem is of the form:

$$\mathrm{Max}_{R_t} \Pi_{a_t} = P_{a_t} Q_{a_t} - p_{l_{at}} L_{a_t} - p_{R_t} R_t$$

The first order conditions include:

$$\frac{d\Pi_{a_t}}{dR_t} = P_{a_t}\left(\frac{dQ_{a_t}}{dR_t}\right) - p_{R_t} = 0$$

implying that

$$P_{a_t}\left(\frac{dQ_{a_t}}{dL_{a_t}}\right) = p_{R_t}$$

and that the marginal revenue production of fertilizer is equal to the marginal costs.

Ecotourism

The problem is of the form:

$$\mathrm{Max}_{L_{v_t}}\ \Pi_{v_t} = P_{v_t}Q_{v_t} - P_{v_t}L_{v_t}$$

and the first order conditions include:

$$\frac{d\Pi_{v_t}}{dL_{v_t}} = P_{v_t}\left(\frac{dQ_{v_t}}{dL_{v_t}}\right) - P_{v_t} = 0$$

implying that

$$P_{v_t}\left(\frac{dQ_{v_t}}{dL_{v_t}}\right) = P_{v_t}$$

i.e. that the marginal revenue production of labour is equal to the marginal costs.

b- Joint profit maximisation

A joint profit maximization is proposed to take into account the externalities from one activity on the others.

Joint profit is the sum of profits. Using equations *3.10* for fisheries, *3.14*, *3.16* for agriculture and *3.10*, *3.21* for ecotourism; the sum of profits can be expressed as follows:

$$\Pi = P_{h_t}\,\mathrm{Q}_{h_t} + P_{a_t}\,\mathrm{Q}_{a_t} + P_{v_t}\,\mathrm{Q}_{v_t} - P_{E_t}.E_t - p_{l_{a_t}}L_{a_t} - p_{R_t}R_t - P_{Lv_t}.L_{v_t}$$

The first order necessary condition for maximising joint profits with respect to ecotourism labour, fishing effort and fertilizer include the following:

Joint profit derived with respect to ecotourism labour

$$\frac{d\Pi}{dL_{v_t}} = P_{v_t}\left(\frac{d\,\mathrm{Q}_{v_t}}{dL_{v_t}}\right) + P_{a_t}\left(\frac{d\,\mathrm{Q}_{a_t}}{dR_t}.\frac{dR_t}{dL_{v_t}}\right) + P_{h_t}\left(\frac{d\,\mathrm{Q}_{h_t}}{dB_{x_t}}.\frac{dB_{x_t}}{dL_{v_t}}\right) - P_{Lv_t} = 0$$

The externality of ecotourism on fisheries$\left(\frac{d\,Q_{h_t}}{dB_{x_t}}.\frac{dB_{x_t}}{dL_{v_t}}\right)=0$ because the biomass of fish does not depend directly on the ecotourism labour.

Joint profit derived with respect to effort

$$\frac{d\Pi}{dE_t}=P_{h_t}\left(\frac{d\,Q_{h_t}}{dE_t}\right)+P_{a_t}\left(\frac{d\,Q_{a_t}}{dR_t}.\frac{dR_t}{dE_t}\right)+P_{v_t}\left(\frac{d\,Q_{v_t}}{dB_{c_t}}.\frac{dB_{c_t}}{dE_t}\right)-P_{E_t}=0$$

$$\text{where }\left(\frac{d\,Q_{v_t}}{dB_{c_t}}.\frac{dB_{c_t}}{dE_t}\right)\leq 0$$

The externality of fishing on ecotourism is negative because if fishing effort increases the biomass of fish decreases producing a decrease in the crocodile population and affecting ecotourism profits.

That is:

$$\frac{dQ_{v_t}}{dE_t}=\frac{dQ_{v_t}}{dB_{c_t}}.\frac{dB_{c_t}}{dB_{x_t}}.\frac{dB_{x_t}}{dE_t}\leq 0$$

Joint profit derived with respect to nitrogen run-off

$$\frac{d\Pi}{dR_t}=P_{a_t}\left(\frac{d\,Q_{a_t}}{dR_t}\right)+P_{v_t}\left(\frac{d\,Q_{v_t}}{dB_{c_t}}.\frac{dB_{c_t}}{dR_t}\right)+P_{h_t}\left(\frac{d\,Q_{h_t}}{dB_{x_t}}.\frac{dB_{x_t}}{dR_t}\right)-p_{R_t}=0$$

$$\text{where }\left(\frac{d\,Q_{v_t}}{dB_{c_t}}.\frac{dB_{c_t}}{dR_t}\right)\leq or \geq 0\text{ and }\left(\frac{d\,Q_{h_t}}{dB_{x_t}}.\frac{dB_{x_t}}{dR_t}\right)\leq or\geq 0$$

The externality of agriculture to ecotourism$\left(\frac{d\,Q_{v_t}}{dB_{c_t}}.\frac{dB_{c_t}}{dR_t}\right)$ and to fishing $\left(\frac{d\,Q_{h_t}}{dB_{x_t}}.\frac{dB_{x_t}}{dR_t}\right)$ can be positive or negative depending on the level of nitrogen run-off. Equation *3.6* shows that fishing production depends on phytoplankton and nutrients. Equation *3.18* shows that ecotourism production depends on fish biomass, phytoplankton and nutrients. Therefore, if nitrogen run-off is up to the ecosystem threshold, phytoplankton, fish and crocodiles population could be depleted (eutrophication). But if the level is below the limit, the externality can be positive since more nutrients are available in the system.

That is,

$$\frac{dQ_{v_t}}{dR_t} = \frac{dQ_{v_t}}{dB_{c_t}} . \frac{dB_{c_t}}{dB_{p_t}} . \frac{dB_{p_t}}{dR_t} \leq or \geq 0$$

$$\frac{dQ_{h_t}}{dR_t} = \frac{dQ_{h_t}}{dB_{x_t}} . \frac{dB_{x_t}}{dB_{p_t}} . \frac{dB_{p_t}}{dR_t} \leq or \geq 0$$

In the case of the joint profit maximisation, the externality between fishing and ecotourism can be regulated by applying a tax to fishing or a subsidy to ecotourism. The externality from agriculture to ecotourism and fisheries needs to be assessed in order to know the optimum level of nitrogen run-off. The optimum level of nitrogen run-off is equivalent to the intersection of marginal external damage and marginal net private benefit from fertilizer application.

Chapter 4.
Modeling the Ecosystem

The ecosystem model explores changes in water quality in relation to fertilizer run-off and the consequent effects on the mangrove food web.

4.1 Water quality

Lagoon and river water quality represent a key component of the model and especially eutrophication (nutrient enrichment). Eutrophication in coastal lagoons is due to an increase in nutrient concentration, causing blooms of algal and microbial material which cause anoxia and consequently death of other organisms, including fish. Phosphorus and nitrogen are the main nutrients involved in coastal eutrophication (although silicon may be a limiting factor for some diatom populations) and it is these nutrients that are the focus of this thesis. Light is not the main factor for phytoplankton growth [87] as discussed in the previous chapter. The lagoon and the river are shallow therefore, mixing processes and stratification are not considered as important factors to be measured. Nutrients were estimated in both the lagoon and the feeder river water.

4.1.1 Sampling nutrients

Water samples were taken along the river at 8 points corresponding to the different kinds of vegetation and economic activities within the catchment (Table 2). Samples were only taken in the main river, the Rio Grande, in order to avoid guerrilla activity located in the isolated forest and because access was possible from the road. The river has one of its origins in El Aguacate (where the first sample was taken).

The river starts at 1800 altitude, finishes in the coast (sea level) and passes through different types of vegetation, such as tropical forest, deciduous (dry) forest and mangrove. Towards the coast, the river divides into two coastal lagoons, the smaller Ventanilla lagoon and the larger Tonameca lagoon. Both lagoons are isolated from the ocean by a sand bar, which is breached each year in winter, allowing seawater exchange.

At the start of the rainy season, the Ventanilla lagoon receives first the water from the highlands but when water arrives at the Tonameca lagoon and its mouth is open, the water level within the Ventanilla lagoon drops until the mouth is closed by a sand bar movement.

Since the Tonameca and Ventanilla lagoons have different hydrology, water samples were taken from each lagoon.

In the river, two samples were taken at each station, from its origin in El Aguacate to the coast (Table 2) and sampling was repeated five days later. Samples were taken in 4 different periods of the year: at the end of the coffee harvest in February, during the dry season in April, at the beginning of the rainy season in June and after the period of application of fertilizers, during the rainy season at the end of July. In the Tonameca lagoon, data were collected in April and July because the Chacahuita community boat used for taking the samples was not available at other times.

A total of 100 samples were taken over a year (21 in February, 25 in April, 26 in June, 28 in July and August). Water quality samples were analyzed with a spectrophotometer HACH DR 2000[6]. Nitrites, nitrates, ammonium and phosphorus were the main nutrients measured. Temperature and pH were also measured in the field. Nitrite, nitrate and ammonium concentrations were determined in order to obtain the total nitrogen in the river and the lagoon.

Nitrate and ammonium are particularly relevant since they have been related to an increase on fertilizer use elsewhere [125]. For instance, in the Mississipi river plume conditions of hypoxia have been related to an increase in nitrogen, specifically nitrate, due to changes in land use over the last century [13]. Mitchell (2001) suggests an increase in nitrate concentration in water due to an increase in fertilizer use by 130%, in the Tully River, Australia [10].

[6] The Hach 2000 was provided by Arturo Ruiz, CIAD-Mazatlán and the samples were processed in the Mexican Center of Sea Turtles.

Table 2. Water samples location. Sampling points are located from the upper part of the watershed to the sea. The locality name is the name of the closest village to the sampling point, geographic coordinates are in Universal Transverse Mercator, and a description of how to reach that point is given as well as the type of vegetation and economic activity in the area.

Sampling Points	Locality Name	Location (UTM)	Description	Vegetation	Economic Activity
1	El Aguacate	772086; 1765008	River source, 30 min. walk from Finca el Pacífico	Tropical forest	Organic shade coffee
2	Finca El Pacífico	771062; 764164	Finca where coffee is washed and toasted	Tropical forest	Organic shade coffee
3	El Alacrán	769254; 1762720	Closed to the main road to Oaxaca 15 min. by car after la Finca	Tropical forest	Shade coffee
4	Chacala-pilla	769254; 1762720	Under the Chacalapilla bridge closed to the road 30 min. from la Finca	Tropical forest	End of the coffee plantations. Agriculture of other crops
5	Río Grande or Xonene	766078; 1745588	Around 30 min. from Pochutla and the main road to Oaxaca	Dry forest	Pochutla water pump. Agriculture
6	San Isidro del Palmar	755768; 1738615	Under San Isidro bridge in the road from Pochutla to Puerto Escondido	Dry forest and where the wetland starts	Agriculture Fishery
7	Ventanilla lagoon	759401; 1733732 759462; 1734030	In Ventanilla community	Mangrove	Agriculture Fishery
8	Tonameca lagoon	7542437; 17352318 755368; 1735059	Around an hour walk by the beach from Ventanilla community	Mangrove	Agriculture Fishery

In contrast, phosphorus concentrations in mangrove water are generally low and increase in fresh water [125] [101]. Thus, it is important to analyze the concentration of phosphorus especially in fresh water as a possible indicator of pollution in the river.

4.1.2 Water quality results

pH and temperature are similar over time and between localities. The Río Grande has the highest pH (8.9-9.5). Ventanilla had in June the lowest pH of 6.5. Water temperature showed a gradient of increase from 20 to 35 °C from the uplands to the coast.

Phosphorus is a key nutrient for fresh water production and in the Tonameca river concentrations were low (Fig. 4). In the dry season, phosphorus reaches a maximum at San Isidro (0.4 mg/L). At the beginning of the rainy season (in June), the concentration was maximum at Chacalapilla and El Alacrán (0.5 mg/L). In July, when the rainfall is more constant, the phosphorus is diluted. The river phosphorus concentrations are below the maximum allowed by national regulations (5 mg/L) [126]. Total phosphorus in the lagoons is 3.2 mg/L, also below the maximum recommended for estuaries in the national regulation (5 mg/L) but is higher than the values found for other lagoons [126]. In the Ebrié lagoon in the Ivory Coast, West Africa, the phosphorus had an average concentration of 56 mg/m^3 (0.056 mg/L) from 1985 to 2000, and the lagoon is much bigger than Tonameca measuring 130 km length and between 1 and 7 km in width [14]. In Mexico, coastal lagoons have been focus on many studies [125, 127, 128] and nutrient values are very diverse. For example, in the Mandinga lagoon the total phosphorus concentration is 2.2 μg-at/l (0.068 mg/L) and in Tamiahua lagoon 10.3 μg-at/l (0.319 mg/L) [125]. In the Yucatan Peninsula, the maximum total phosphorus concentration is 0.7 μmol/l (0.021 mg/L) [127].

In Tonameca, in June, phosphorus concentrations were highest for Ventanilla, probably because water from the uplands arrives here before entering the Tonameca lagoon, where the maximum is recorded later, in July.

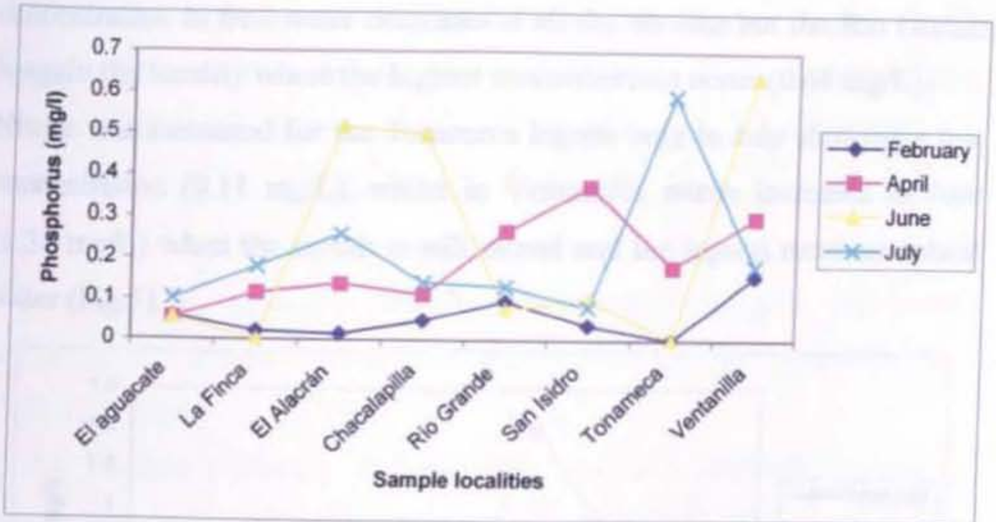


Fig 4. Phosphorus (P) concentrations (mg/L) in the Tonameca river and coastal lagoon, in 2003. February -April correspond to the dry season and June-July to the rain season. The graph shows the mean concentrations for each sampling point in each season. In June the concentration in la Finca is zero and for Tonameca no sample was taken.

Table 3 . Phosphorus (P) concentrations (mg/L) and standard deviation. The mean concentration is shown for each sampling point and month as well as the corresponding standard deviation. In Tonameca in February and June no sample were taken.

	February	April	June	July
El aguacate	0.057 (0.031)	0.054 (0.041)	0.055 (0.035)	0.102 (0.02)
La Finca	0.02 (0.005)	0.116 (0.006)	0	0.18 (0.127)
El Alacrán	0.014 (0.006)	0.138 (0.051)	0.517 (0.44)	0.259 (0.33)
Chacalapilla	0.048 (0.006)	0.114 (0.05)	0.497 (0.42)	0.142 (0.09)
Río Grande	0.097 (0.071)	0.266 (0.117)	0.077 (0.046)	0.132 (0.05)
San Isidro	0.037 (0.016)	0.374 (0.398)	0.102 (0.072)	0.083 (0.023)
Tonameca		0.18 (0.024)		0.593 (0.5)
Ventanilla	0.16 (0.16)	0.3 (0.3)	0.64 (0.4)	0.182 (0.039)

Nitrite (NO^{2-}) concentration in the river was the highest during the dry season (April), and the peaks are in the Río Grande (1.39 mg/L) and El Alacrán (0.59 mg/L) locations. During the rainy season, nitrite concentration in freshwater decreases at all the stations but the Río Grande is again the locality where the highest concentrations occur (0.64 mg/L). Nitrite was measured for the Tonameca lagoon only in July showing a low concentration (0.11 mg/L), whilst in Ventanilla, nitrite increases in June (1.35 mg/L) when the mouth is still closed and the lagoon receives upland water (Fig 5).

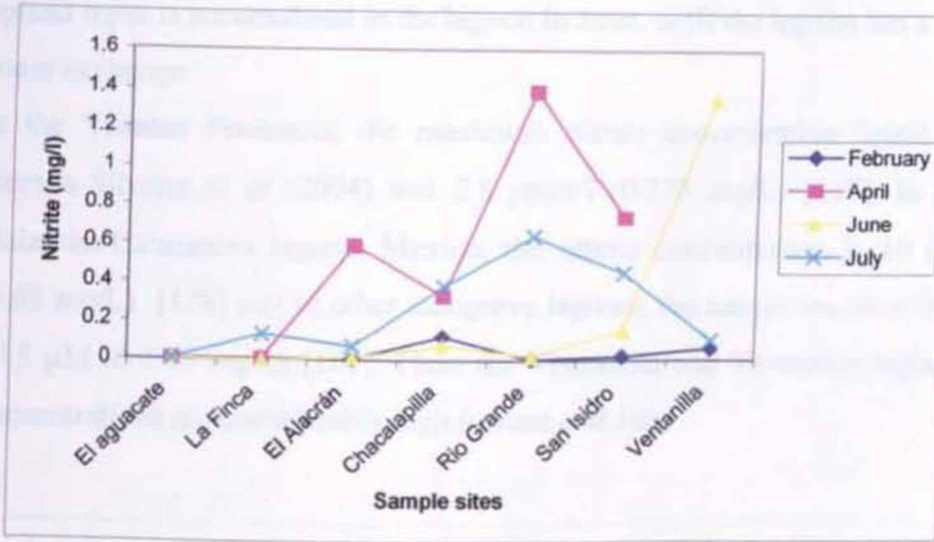


Fig 5. Nitrite (NO^{2-}) concentrations (mg/L) in the Tonameca river and coastal lagoon, in 2003. February -April correspond to the dry season and June-July to the rain season. The graph shows the mean concentrations for each sampling point in each season. Tonameca data were only taken in April and July.

Table 4. Nitrite concentrations (mg/L) and standard deviation. The mean concentration is shown for each month and sampling point as well as the corresponding standard deviation. No samples were taken in Tonameca in February and June

	February	April	June	July
El aguacate	0.06 (0.003)	0.004 (0.002)	0.007 (0.004)	0.007 (0.003)
La Finca	0.007 (0.005)	0.003 (0.000)	0	0.13 (0.013)
El Alacrán	0.006 (0.005)	0.59 (0.050)	0.015 (0.009)	0.07 (0.006)
Chacalapilla	0.12 (0.008)	0.33 (0.023)	0.073 (0.042)	0.38 (0.023)
Río Grande	0.005 (0.002)	1.39 (0.132)	0.02 (0.11)	0.64 (0.055)
San Isidro	0.02 (0.002)	0.74 (0.127)	0.152 (0.08)	0.45 (0.037)
Tonameca		0		0.11 (0.005)
Ventanilla	0.06 (0.06)		1.35 (1.24)	0.102 (0.009)

Similar trends for nitrate (NO^{3-}) concentrations are apparent. During the dry season in the river the concentration of nitrate was greatest for Río Grande (5 mg/L) and El Alacrán. In the Tonameca lagoon, nitrate concentration was measured in July showing a high value (12 mg/L). In the Ventanilla lagoon, the maximum concentration is obtained in June (22 mg/L) (Fig.6).

The increase in nitrate concentration in Ventanilla suggests that nitrate upland input is accumulated in the lagoon in June, until the lagoon has a sea water exchange.

In the Yucatan Peninsula, the maximum nitrate concentration found by Herrera-Silveira *et al* (2004) was 2.8 μmol/l (0.173 mg/L) [127]. In the Huizache-Caimanero lagoon, Mexico, the nitrate concentration is 10 μM (0.62 mg/L) [128] and in other mangrove lagoons the ranges are from 0 to 30.5 μM (0-1.89 mg/L) [101]. Thus, the Ventanilla and Tonameca lagoon, concentrations are considerably high in June and July.

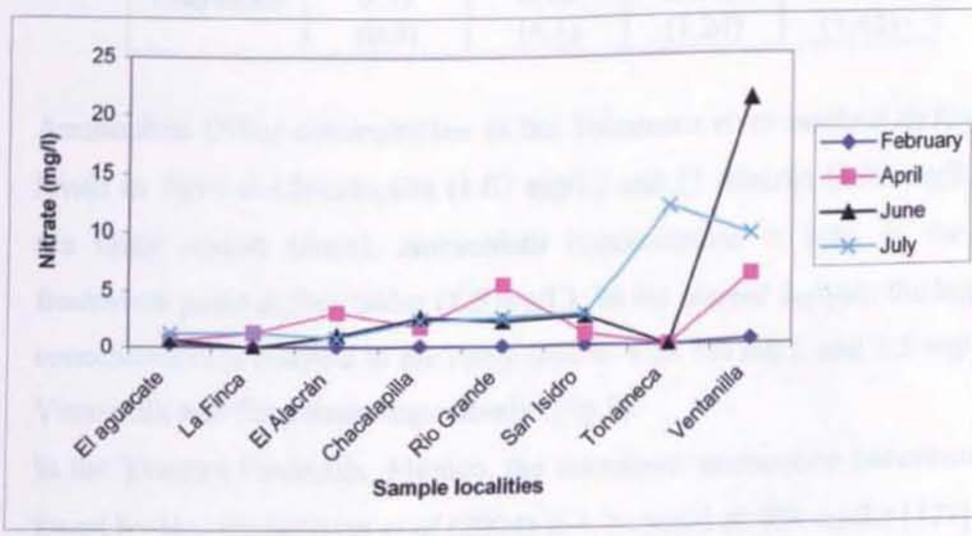


Fig. 6. Nitrate (NO^{3-}) concentrations (mg/L) in Tonameca river and coastal lagoon, in 2003. February -April correspond to the dry season and June-July to the rain season. The graph shows the mean concentrations for each sampling point in each season. Tonameca data were only taken in July.

Table 5. Nitrate concentrations (mg/L) and standard deviation.

The mean concentration is shown for each month and sampling point as well as the corresponding standard deviation. No samples were taken in Tonameca in February and June

	February	April	June	July
El aguacate	0.26 (0.41)	0.55 (0.660)	0.66 (0.42)	1.21 (0.42)
La Finca	0.04 (0)	1.32 (1.240)	0	1.32 (0.93)
El Alacrán	0.04 (0.036)	3.08 (3)	1.1 (0.6)	0.88 (0.35)
Chacalapilla	0.06 (0.05)	1.76 (1.52)	2.64 (1.52)	2.31 (0.9)
Río Grande	0	5.39 (5.2)	2.2 (1.45)	2.53 (2.16)
San Isidro	0.03 (0.04)	1.1 (1.040)	2.64 (2.09)	2.86 (1.27)
Tonameca				12 (1.5)
Ventanilla	0.39 (0.3)	6.16 (6.1)	21.12 (1.24)	9.57 (1.45)

Ammonium (NH_4) concentration in the Tonameca river reached its highest levels in April at Chacalapilla (1.07 mg/L) and El Alacrán (1.09 mg/L). In the rainy season (June), ammonium concentration is high in the last freshwater point at San Isidro (1.5 mg/L). In the coastal lagoons the highest concentration is reached in the rainy season with 5.6 mg/L and 3.5 mg/L in Ventanilla and Tonameca respectively (Fig 7).

In the Yucatan Peninsula, Mexico, the maximum ammonium concentration found by Herrera-Silveira *et al* (2004) is 4.7 μmol/l (0.084 mg/L) [127] and in the Bassin d´Archon, in France, 0.023 mg/L [11]. Nutrient concentrations are presented for several mangrove creeks and estuaries by Alongi *et al* (1992). For example, the Fly river in Papua New Guinea has ammonium concentrations ranging from 0.1 to 1.142 μM (0.0018 - 0.018 mg/L) and in Fiji the highest concentration is found (50.94 μM; 0.9 mg/L) [101]. The Ventanilla and Tonameca lagoons have high concentrations of ammonium in the rainy season in comparing with other places.

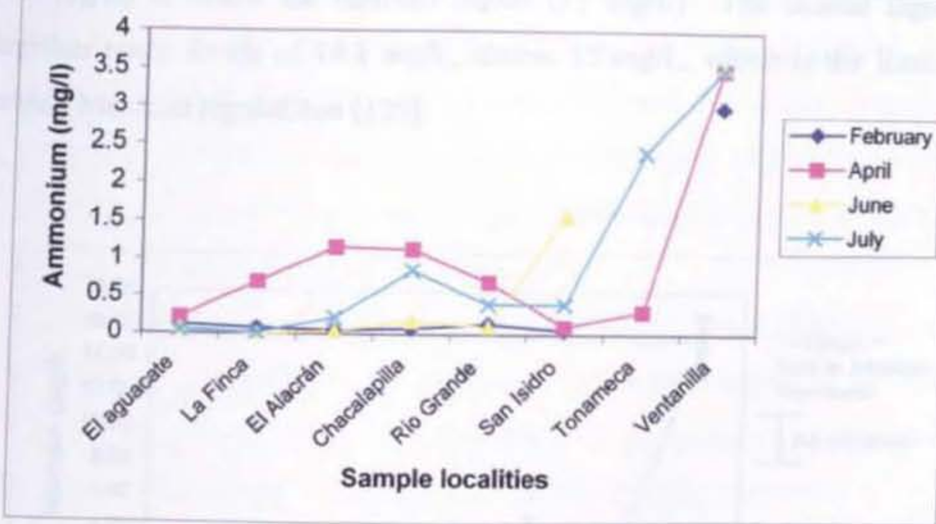


Fig 7. Ammonium (NH_4) concentrations (mg/L) in Tonameca river and coastal lagoon, in 2003. February -April correspond to the dry season and June-July to the rain season. The graph shows the mean concentrations for each sampling point in each season. Tonameca data were only taken in April and July

Table 6. Ammonium concentration (mg/L) and standard deviation. The mean concentration is shown for each month and sampling point as well as the corresponding standard deviation. No samples were taken in Tonameca in February and June

	February	April	June	July
El aguacate	0.116 (0.107)	0.214 (0.083)	0.073 (0.046)	0.055 (0.05)
La Finca	0.073 (0.05)	0.659 (0.980)	0	0.012 (0.009)
El Alacrán	0.049 (0.038)	1.098 (1.183)	0.037 (0.039)	0.211 (0.2)
Chacalapilla	0.073 (0.055)	1.07 (1.6)	0.165 (0.1)	0.817 (0.69)
Río Grande	0.128 (0.009)	0.668 (0.550)	0.098 (0.08)	0.378 (0.26)
San Isidro	0.055 (0.045)	0.101 (0.130)	1.495 (1.3)	0.448 (0.47)
Tonameca		0.287 (0.3)		3.35 (2.4)
Ventanilla	2.84 (3)	3.35 (3.5)	3.35 (3.5)	5.661 (3.5)

Total nitrogen is the sum of the average concentration along the year of the different forms of nitrogen (nitrate, nitrite and ammonium) (Fig 8). At the freshwater sites, the Río Grande had the highest concentration but the value

(1.4 mg/L) is below the national norms (15 mg/L)[7]. The coastal lagoons together reach levels of 14.8 mg/L, almost 15 mg/L, which is the limit set within Mexican regulations [126].

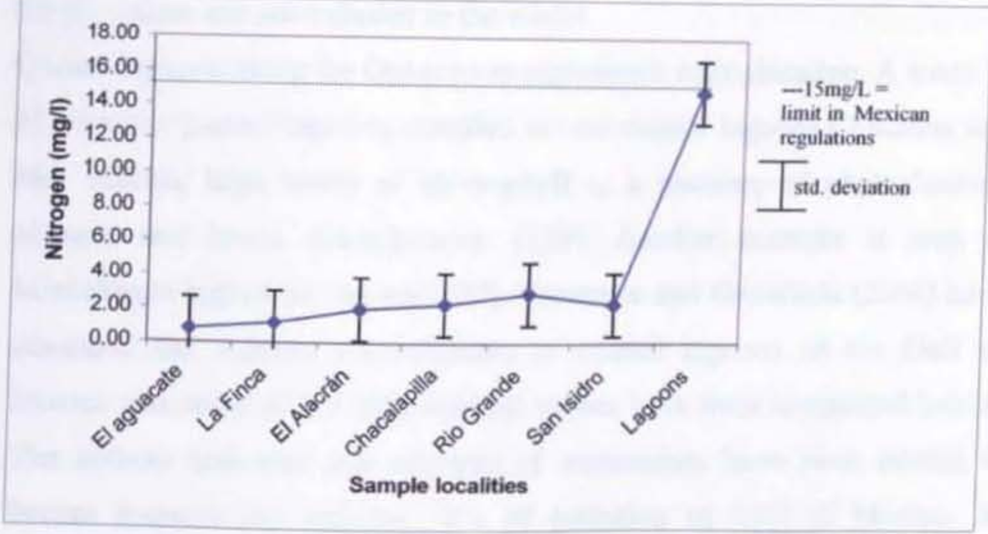


Fig 8 Total nitrogen (mg/L) in Tonameca catchment, in 2003. The figure show the sum of the average concentrations of nitrate, nitrite and ammonium for each sampling point and the corresponding standard deviation.

The average total nitrogen in Ebrié lagoon, in the Ivory coast is 557 mg/m^3 (0.557 mg/L) [14]. Contreras and Castañeda (2004) presented the total nitrogen concentrations in Celestun (9.8 μg-at/l or 0.137 mg/L), in Mandinga lagoon (2.2 μg-at/l or 0.031 mg/L) and in Tamiahua lagoon (10.3 μg-at/l or 0.144 mg/L) [125]. The total nitrogen in the Tonameca lagoon is not very high compared to the Gulf of Mexico lagoons.

4.1.3 Water quality conclusions

My assessment of water quality shows that, as expected, there is an input of nutrients from the uplands when the rainy season starts, augmenting the nutrient concentration in the lagoons. In addition, it is clear that Ventanilla is the first lagoon to receive water from the uplands since there is an increase in nutrients in June at Ventanilla and in July for Tonameca. In contrast, the highest concentrations of nutrients in freshwater are during the dry season due to the lowest rate of dilution of nutrients in water.

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[7] The water pump for supplying of water to Pochutla is in Rio Grande. Thus, it might be that due to the surface water extraction, the volume of water is less in that part of the river and the concentration of nutrients increases.

Phosphorus and nitrogen concentrations in the river are below the 5 mg/L limit set by Mexican regulations [126]. In contrast, in coastal lagoons nitrogen concentration is very close to the limit (15 mg/L) proposed by Mexican regulation [126]. Phosphorus concentrations in the river were only important to measure in order to assess the level of pollution in freshwater, but the values are not included in the model.

Coastal lagoons along the Oaxaca can experience eutrophication. A study of 33 Mexican coastal lagoons, revealed in two coastal lagoons Chacahua and Mar Muerto, high levels of chlorophyll a, a measure of phytoplankton biomass and hence eutrophication [129]. Another example is seen in Manialtepec lagoon in Oaxaca [130]. Contreras and Castañeda (2004) have described the nutrient concentration in coastal lagoons of the Gulf of Mexico and some of the high nutrient values have been mentioned below. The authors indicates that nitrogen of ammonium have been related to human impacts and indicate 76% of pollution in Gulf of Mexico. In comparison to other coastal lagoons in Oaxaca, the Tonameca watershed does not seem as polluted. Neither compared to Latin America and the Caribbean water quality. Over the past 30 years, the water quality in Latin America and the Caribbean has decreased due to agricultural run-off and untreated urban and industrial water [1]. The excessive use of fertilizers in agriculture has raised the level of nitrates in the Amazon and the Orinoco as well as in underground sources [131]. In addition, in coastal areas the loss of fisheries and aquaculture has been enormous due to eutrophication [131].

4.2 Nitrogen run-off estimation and its relationship with water quality and water extraction

Nitrogen run-off from urea and coffee pulp wash is described in this section, in order to assess the externality from agriculture in the watershed. The relationship between the total nitrogen concentration in the river (described in the previous section), nitrogen run-off and water extraction is also presented allowing the contribution of each variable to be estimated. The relationship is then used to explore the impacts of nitrogen increase for the mangrove food web.

4.2.1 Nitrogen run-off from urea

Nitrogen run-off from urea is estimated from the product of the number of hectares under cultivation for each crop and the amount of fertilizer (urea) recommended for each crop. The number of hectares per crop is given per municipality. The Tonameca catchment embraces only a proportion of each municipality, so that it is necessary to estimate the area of each municipality that falls within the catchment.

a- Municipalities within the Tonameca catchment

A Geographic Information System (GIS) in Arcview was built to estimate the areas of each municipality that fall within the Tonameca catchment.

A Tonameca watershed GIS was created by digitizing land use, topographic and hydrological maps, (1:250 000 scale) published in 1995 by the National Institute of Statistics, Geography and Computing (INEGI). A polygon for each group of villages was drawn, defining the limits of each municipality. The polygons were overlain on a national map produced by the National Commission of Water (CNA) which contains the municipality boundaries (Table 7). The total area estimated to be covered by all the municipalities (660 km^2) is close to the independently estimated real catchment area (650 km^2), indicating that the GIS areas are sufficiently defined.

Table 7. Areas covered by each municipality in the Tonameca catchment. The municipality areas, the corresponding percent of each municipality within the catchment and the area of each municipality in the catchment are presented.

	Total area (km^2)	Percent of the municipality in the catchment (%)	Area in the catchment (km^2)
Santa María Tonameca	536	40	214.4
San Pedro Pochutla	400	40	160
Santo Domingo de Morelos	123	30	36.9
San Agustín Loxicha	320	10	32
Candelaria Loxicha	186	80	148.8
Pluma Hidalgo	114	60	68.4
Total			660.5

b- Amount of urea recommended for different crops

The amount of urea used in the catchment was estimated as the hectares under each crop type, multiplied by the amount of urea recommended for each crop type (Table 8). The average application rate was used, that is, if the range was stated as 400-500 kg/ha, the amount used was 450 kg/ha. The recommended amount of urea per type of crop is valid for self consumption agriculture.

Table 8. Recommended urea application rate for each crop type in the Tonameca catchment (extracted from www. corpmisti.com). Minimum and maximum values for each crop are presented.

Crop	Urea (kg/ha)
Maize	400-500
Beans	400-500
Tomato	450-550
Cucurbitacea	350-500
Citrics	300-600
Coffee	350-450
Banana	300-400
Mango	300-600

c- Urea run-off from agriculture

Urea run-off is estimated as described in chapter 3 in equation *3.00*. That is, the number of hectares per crop multiplied by 20% of the recommended amount of urea. Even when conditions are considered ideal for urea transformation, the maximum run-off estimated is 20% of the applied urea [97]. The hectares of each crop type and the number of producers using fertilizer were extracted from national statistics published in 1998 [73].

Those national statistics are the only published data showing information per municipality and the number of farmers using fertilizer, and were therefore the most appropriate statistics for the purpose of this section. Moreover, the Oaxaca coast statistics for 2002 show similar types of crop cultivated in the area [70].

The most important perennial and annual crops were considered when estimating urea run-off. These are: mango, banana, coffee and orange (perennials), maize and beans (annuals), representing 79% and 7.8% respectively for Tonameca.

Urea run-off is then finally adjusted to the areas estimated in Table 7 for each municipality (urea run-off in Tonameca table 9). The urea run-off results are shown in Tables 9 to 15.

Tables 9 to 14. Urea used is estimated per type of crop based on table 8 values, urea run-off is estimated as explained in chapter 3 and urea run-off in Tonameca is an estimation for the corresponding area of each municipality within the catchment.

Table 9. Urea run-off in the Tonameca catchment due to Maize cultivation.

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo
Maize Hectares	6 736	2 617	2 180	1 776	695	99
Urea used (kg)	3 031 200	1 177 650	981 000	79 920	312 750	44 550
Urea run-off (kg)	606 204	235 530	196 200	15 984	62 550	8910
Urea run-off in Tonameca (kg)	242 481	94212	58860	1598	50040	5346

Table 10. Urea run-off in the Tonameca catchment due to Beans cultivation

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo
Beans Hectares	235	122	85	823	695	21
Urea input (kg)	105 750	54 900	38 250	370 350	3 127 040	9 450
Urea run-off (kg)	21 150	1 098	7 650	74 070	625 408	1 890
Urea run-off in Tonameca (kg)	8 460	43 920	2 295	7 407	500 326	113 400

Table 11. Urea run-off in the Tonameca catchment due to Coffee cultivation

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo
Coffee Hectares	267	1760	14	4899	5637	5167
Urea used (kg)	106 800	704 000	5600	1 959 600	2 254 800	2 066 800
Urea run-off (kg)	21360	140 800	1120	391 920	450 960	413 360
Urea run-off in Tonameca (kg)	8544	56320	33600	39192	360768	248016

Table 12. Urea run-off in the Tonameca catchment due to Mango cultivation

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos
Mango Hectares	900	67	3
Urea used (kg)	4 050	30 150	1 350
Urea run-off (kg)	810	6 030	270
Urea run-off in Tonameca (kg)	324	2 412	81

Note: mango is not cultivated in San Agustín Loxicha, Candelaria Loxicha and Pluma Hidalgo

Table 13. Urea run-off in the Tonameca catchment due to Orange cultivation

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo
Orange Hectares	666	61	10	32	22	8
Urea used (kg)	299 700	27 450	4 500	14 400	9 900	3 600
Urea run-off (kg)	59 940	5 490	900	2 880	1 980	72 000
Urea run-off in Tonameca (kg)	23 976	2 196	270	288	1 584	43 200

Table 14. Urea run-off in Tonameca catchment due to Banana cultivation

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo
Banana Hectares	30	174	19	1 466	1 535	1 112
Urea used (kg)	10 500	60 900	6 650	513 100	5 37 250	389 200
Urea run-off (kg)	2 100	12 180	1 330	102 620	107 450	7 7840
Urea run-off in Tonameca (kg)	840	4 872	399	10 262	85 960	46 704

The total urea run-off is the sum of urea run-off per crop in each municipality (Table 15).

Table 15. Total urea run-off in the Tonameca catchment assuming that all the producers use fertilizers. Sum of the urea run-off per type of crop in each municipality

Urea run-off per crop (kg)	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo	Total
Banana	840	4 872	399	10 262	85 960	46 704	14 9037
Orange	23 976	2 196	270	288	1 584	43 200	71 514
Mango	324	2 412	81	0	0	0	2 817
Coffee	8 544	56 320	33 600	39 192	360 768	248 016	746 440
Beans	8 460	43 920	2 295	7 407	500 326	113 400	675 808
Maize	242 481	94 212	58 860	1 598	50 040	5 346	452 537
Total urea run-off for the catchment (kg/yr)	284 625	203 932	95 505	58 747	998 678	456 666	2 098 53

National statistics indicate that not all the producers use fertilizer, so that the proportion of producers using fertilizers was calculated for the catchment and the urea run-off re-estimated (Tables 16 and 17).

It is sensible to consider the number of producers using fertilizer, due to the poverty conditions in the catchment and the large amount of self consumption agriculture [65], suggesting that a low proportion of producers would use part of their income to buy fertilizers. Finally, the total nitrogen run-off is calculated assuming that only 46% of urea is nitrogen (Table 17).

Table 16. Proportion of producers using fertilizer

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo	Total
Total producers	1803	1641	993	2046	990	376	7849
Producers using fertilizer	183	24	135	102	51	37	533

Table 17 Total nitrogen run-off (NRO) from urea considering: 46% of urea as nitrogen and producers using fertilizer. Total urea run-off is the result of table 15, total NRO is the estimation considering 46% of urea as nitrogen, and the last row is the estimation of NRO considering only producers using fertilizer

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Candelaria Loxicha	Pluma Hidalgo	Total
Total urea run-off (kg/yr)	284 625	203 932	95 505	58 747	998 678	456 666	2098153
Total NRO (kg/yr)	130 927	93 808	43 932	27 023	459 391	210 066	965147
Total NRO with producers using fertilizer (kg/yr)	13 303	1372	5986	1348	23758	21 118	66 885

The total nitrogen run-off in Tonameca from urea is 66 885 kg/yr (66 t/yr), taking into account that 46% of urea is nitrogen as well as the number of producers using fertilizer.

This is a conservative approach. Other less conservative ones are explored in the next section when adding the nitrogen run-off from coffee pulp wash. Loading estimates have been published for several places [14] [11-13], however, none is specific for urea.

For example, in the Ebrié lagoon, in the Ivory coast, in 2000, 13 829 tonnes a year of nitrogen due to land run-off were estimated [14]. For the Mississipi river, 1.6 x 10^6 tonnes of nitrogen, from which 0.95 x 10^6 tonnes is nitrate have been recorded [13]. A low amount of nitrogen run-off for Tonameca is visible when comparing to the two examples cited.

4.2.2 Nitrogen run-off from coffee pulp wash process

Nitrogen run-off from the coffee pulp wash process is described in chapter 3 equation *3.00*. Coffee pulp wash produces 15 mg of nitrogen per litre and about 20 litres of water are used for producing one kg of coffee. The run-off from coffee pulp for the catchment is calculated from the proportion of each municipality in the catchment. Table 18 shows these calculations and the total run-off. The total nitrogen run-off from coffee pulp wash is 2 171 kg/yr.

Table 18. Nitrogen run-off (NRO) from coffee pulp in the Tonameca catchment. Coffee NRO is estimated as explained in chapter 3 and last row is estimated using the area of each municipality within the watershed.

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Cande-laria Loxicha	Pluma Hidalgo	Total
Coffee product-ion x 10^3 (kg/yr)	155	1 120	25	6 059	4 275	4 504	16 138
Water used x 10^6 (l/yr)	3. 1	22. 4	0.5	121. 18	0.5	9 008	9155.68
Coffee NRO (kg/yr)	46	336	7	1817	1282	1351	4 839
Coffee NRO in the catchment (kg/yr)	18	134	2	181	1 026	810	2 171

4.2.3 Total nitrogen run-off

Total nitrogen run-off is the sum of nitrogen run-off from urea and nitrogen from the coffee pulp wash (Table 19).

Table 19 Total nitrogen run-off (NRO) from coffee pulp wash and other crops in the Tonameca catchment. The first row correspond to the results presented in table 18, the second to table 17 and last row is the sum of previous rows.

	Santa María Tonameca	San Pedro Pochutla	Santo Domingo de Morelos	San Agustín Loxicha	Cande-laria Loxicha	Pluma Hidalgo	Total
NRO from coffee pulp wash (kg/yr)	18	134	2	181	1 026	810	2 171
NRO from other crops (kg/yr)	13 303	1 372	5 986	1 348	23 758	21 118	66 885
Total NRO (kg/yr)	13 321	1 506	5 988	1529	24 784	21 928	69 056

Three different approaches can be used for estimating the total nitrogen run-off taking into account nitrogen from urea and coffee pulp wash and the areas of each municipality that fall within the catchment.

The conservative approach considers that urea has 46% of nitrogen and the number of producers using fertilizer. Under this approach, the total nitrogen run-off for the catchment is 69 056 kg/yr, around 69 t/yr (Table 19).

A less conservative approach considers that urea has 46% of nitrogen and the total number of producers (Table 17), that is, not only the ones using fertilizer. The number of producers using fertilizer indicated in the National statistics are only the ones registered to receive the fertilizer subsidy. However, other producers that are not registered might use fertilizer. Under those circumstances total nitrogen run-off is 967 t/yr.

Lastly, a non conservative estimation takes into account the total number of producers and that all urea added is converted into nitrogen (Table 17). The last assumption is to suppose an extreme condition of high amounts of a form of nitrogen when for example urea is converted into gaseous ammonia generated at high temperatures and high pH in soils. In this case, the total nitrogen run-off is 2 100 t/yr.

De Wit et al (2001) showed for the Bassin d´Archon, a nitrogen run-off of 1 616 tonnes [11]. Scheren *et al* (2004) for the Ebrié lagoon, in the Ivory coast, showed for the lagoon area where agriculture is dominant, a nitrogen run-off of 6621 t/yr and for other areas 4549 t/yr. [14]. Other examples, show much higher values of nitrogen run-off but correspond to big areas such as the Mississipi river where nitrogen loads are 1.6x 10^6 tonnes [13]. The examples show that Tonameca watershed has in the conservative estimation low ranges of nitrogen run-off (69 t/yr or 967 t/yr), however, in the non conservative approach, nitrogen run-off (2 100 t/yr) is not negligible and even higher to the one proposed for the Bassin d´Archon.

4.2.4 Relationship between water nutrient concentration, nitrogen run-off and water extraction

The nutrient concentration measured in the field represents the total nitrogen from natural conditions plus that from fertilizer run-off.

In order to know the contribution made by fertilizer run-off it is important to establish a relationship between both variables. In addition, nutrient concentration in water depends on the water volume in the river. That is, in the dry season when the volume of water is less the concentration of nutrients increase. As shown in figures 5, 6, and 7, concentrations in the river are high in April, the dry season. Water volume can decrease also due to water extraction for agriculture or urban use. In order to estimate the influence of water extraction on the concentration of river nutrients the relationship H in chapter 3 equation *3.0* is proposed.

$$N_t = \mathrm{H}(R_t, W_t, t)$$

where N_t = Nitrogen concentration in water at time t , R_t = nitrogen run-off , W_t = water extraction, t = years

This relationship captures changes in nutrient concentrations in water due to an increase in fertilizer use and water extraction and this is used to explore changes in phytoplankton biomass and hence impacts on the mangrove food web. Water extraction W_t is estimated as presented in chapter 3 section 3.2.2, considering the annual draining volume V_t and water extraction for agriculture per municipality w_{i_t}. Annual draining volume and water extraction data were obtained for 1998 and for each municipality. Data were taken from the hydrological balance study carried out by Copei Ingenieros S. A. de C.V. for the National Water Commission [100]. Water extraction for each municipality was adjusted for the areas of each municipality within the catchment. The annual draining volume is calculated by the consultant agency as described in chapter 3, section 3.2.2. The total draining coefficient is 280 Mm^3 (255 Mm^3 for upland and 25 Mm^3 for the coast) and water extraction for agriculture in the catchment is 272 713 m^3. Table 20 shows the water extractions for each municipality.

Table 20. Water extraction for agriculture per municipality in the Tonameca catchment in 2003

	Santa Maria Tonameca	San Pedro Pochutla	Candelaria Loxicha	Pluma Hidalgo	Total
Agriculture water extraction (m^3)	145 058	16 813	26 652	49 436	272 713

Note: There are no water extraction permits registered in San Agustin Loxicha and Sto. Domingo de Morelos

Water extraction is assumed to be the same in 1999 and 1998. Water extraction in 2000, 2001 and 2002 is estimated from the hectares under agriculture for each year. Using the data collected on the average nutrient concentrations within each municipality, along with the data on water extraction by agriculture and run off from the combined crop types (967 t/yr), I carried out using the common software for econometric LIMDEP a fixed panel data analysis to obtain the results presented in table 21. A panel data set is constructed from repeated data from a population at a given time. Panel analysis is applied when data are available for some years instead of time series. The fixed method is used when information is not random, for example when information is for a state or a province [132].In order to obtain data for different years the values of each variable for one year are related to the hectares under agriculture in other year (26 868 ha in 1999, 26 822 in 2000, 25 396 ha in 2001 and 25 728 ha in 2002).

Table 21 Panel regression relating nitrogen concentration in water, years, nitrogen run-off and water extraction

Variable	Coefficient	(Std error)	P
Water extraction **	- 0.062	0.0032	0.03
Nitrogen run-off **	18.04	0.92	0.03
Years **	0.49	0.22	0.02
** significant at 5 %, R-squared = 0.99, Durbin-Watson statistics= 2.4			

Using the results of the regression a specific equation can be written as follows:

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

which is equivalent to:

$$N_t = 18R_t - 0.49W_t + 0.062t$$

The regression shows that if water extraction increases, the concentration of nutrients in the river decreases.

In contrast, nitrogen run-off is a positive variable, if there is an increase in the use of urea, the nutrient concentration would be higher.

This regression model is used to estimate change on nutrient concentration in the water arriving at the lagoon, due to an increase on nitrogen run-off and water extraction. This nitrogen fuels the growth of lagoon phytoplankton biomass which in turn impacts on the mangrove food web, as described below.

4.3 Mangrove food web analysis

4.3.1 Food web analysis using ECOPATH

The tropho-dynamic analysis described here concerns the mangrove forest, because it is the sink for impacts, or downstream effects, generated in upland areas in the catchment. In this sense, the mangrove forest is a key ecosystem indicator for the Tonameca watershed in general, because it integrates and reflects all upstream impacts. It is also the focus of much of the eco-tourist activity in the study area and as such may be considered as the key ecosystem within the Tonameca watershed. The specific approach taken here is ECOPATH with ECOSIM, a mass-balance modelling approach that provides information on indicators of ecosystem health, to be assessed through the quantification of trophic structures and energy flows, such as ascendancy, as well as the effects of disturbance on specific components of the food web [55, 56].

This approach was adopted for the Tonameca mangrove ecosystem in order to assess its current status and its behaviour under a range of nutrient-enrichment scenarios, based on the preceding analyses of land-use and nutrient run-off. The general approach and the ECOPATH equation have been described in section 3.2.4 and in order to understand the ECOPATH procedure and highlight the input needed, the equation is presented again as follows:

$$B_{i_t}.(P/B)_{i_t}.EE_{i_t} - \sum B_{j_t}(O/B)_{ji_t}DC_{ji_t} - EX_{i_t} - BA_{i_t} = 0$$

where, B_{i_t} = biomass in t/km^2, P_{i_t} = production t/km^2, $(P/B)_{i_t}$ = production /biomass ratio that is equal to the coefficient of total mortality in yr, EE_{i_t} = Ecotrophic efficiency that is the fraction of production that is consumed within or caught from the system, B_{j_t} = biomass of group j at time t in t/km^2, $(O/B)_{ji_t}$ = consumption/biomass ratio of group j, DC_{ji_t} = fraction of i in the average diet of j in biomass EX_{i_t} = export of group i, in biomass, BA_{i_t} = biomass accumulation in t/km^2. All the variables are expressed at time t.

The inputs for each group in the model are: the biomass B_{i_t}, the $(P/B)_{i_t}$ ratio and the consumption biomass ratio $(O/B)_{ji_t}$. Outputs describe the trophic structure and energy flows with respect to trophic level, respiration, consumption and energy flow, connectance, transfer efficiency and high-level network characteristics such as throughput, information content and ascendancy (defined below).

a- Input data for ECOPATH

The first step in constructing an ECOPATH model is to define the elements in the food web. These can be individual species, size classes within species, tropho-species (species grouped together on the basis of their shared predators and prey), higher taxonomic groupings (e.g "birds", "fish"), functional groups based on similar ecological roles or functions, or a mixture of all these.

As a general rule, it is impractical to resolve every trophic element to species level, due to the Herculean task of every species parameterisation (most mangrove webs have several thousand species). There is a trade-off between complexity against tractability. Thus several food webs can be constructed for a same location, and the difference reflects the information required. Thus, for the Tonameca mangrove food web, several different versions could be constructed differing in their complexity and the nature of the elements or groups. For the present investigation the following functional groups were selected to represent the Tonameca mangrove food web, on the following criteria:

- The species must be representative and abundant (rare species were not included)
- The species must have economic and social importance, relevant to the overall aims of the thesis
- The species must have been previously studied within the region (although not necessarily in the Tonameca forest), so that reliable data were available on abundance, diet, consumption and production.

Based on these criteria, 11 functional groups of species were selected to represent the main food web elements. These were: mangal (mangrove vegetation, including the dominant trees), phytoplankton, zooplankton, detritus, macro-benthos (invertebrates living in the lagoon sediment), insects, demersal (bottom-dwelling) and pelagic (water column-dwelling) fishes, and a key species for ecotourism, as well as being a top predator in the system, the American alligator (*Crocodylus acutus*). The fishes species (*Centropomus sp, Mugil curema, Lutjanus sp* and Gerrides) were selected mainly because of their fishery importance, but also because they are the most common and abundant species in the lagoon (personal communication with fishermen) and in other closer lagoons [133].

The Tonameca food web described here is the first mangrove web that incorporates *Crocodylus acutus* as the main top predator. Whereas previous studies on mangrove webs have incorporated birds, sharks, turtles, and dolphins, none have included crocodiles [114]. It is important to include crocodiles because their biological cycle is 90% in the lagoons and they play a dominant role as a top predator. But population data are not very common. In addition, the mangrove forest as a primary producer in the food web has not been included in ECOPATH models of mangrove systems. This is surprising because mangroves are a key contributor to detritus formation from fallen leaves that decompose in the mangrove sediments. Many mangrove studies have focussed on the energy flow and nutrient cycle to detritus [102, 105] and it is important therefore to consider the mangrove forest as a primary producer and make the link with water quality.

Clearly, in the Tonameca food web there are more than 11 "species" within the mangrove food web, many hundreds in fact. However, the intention of this analysis is to build a representative trophic model that allows us to understand how the system might behave when perturbed, rather than representing every component at the species level.

A diagrammatic representation of the Tonameca mangrove food web is shown in figure 9.

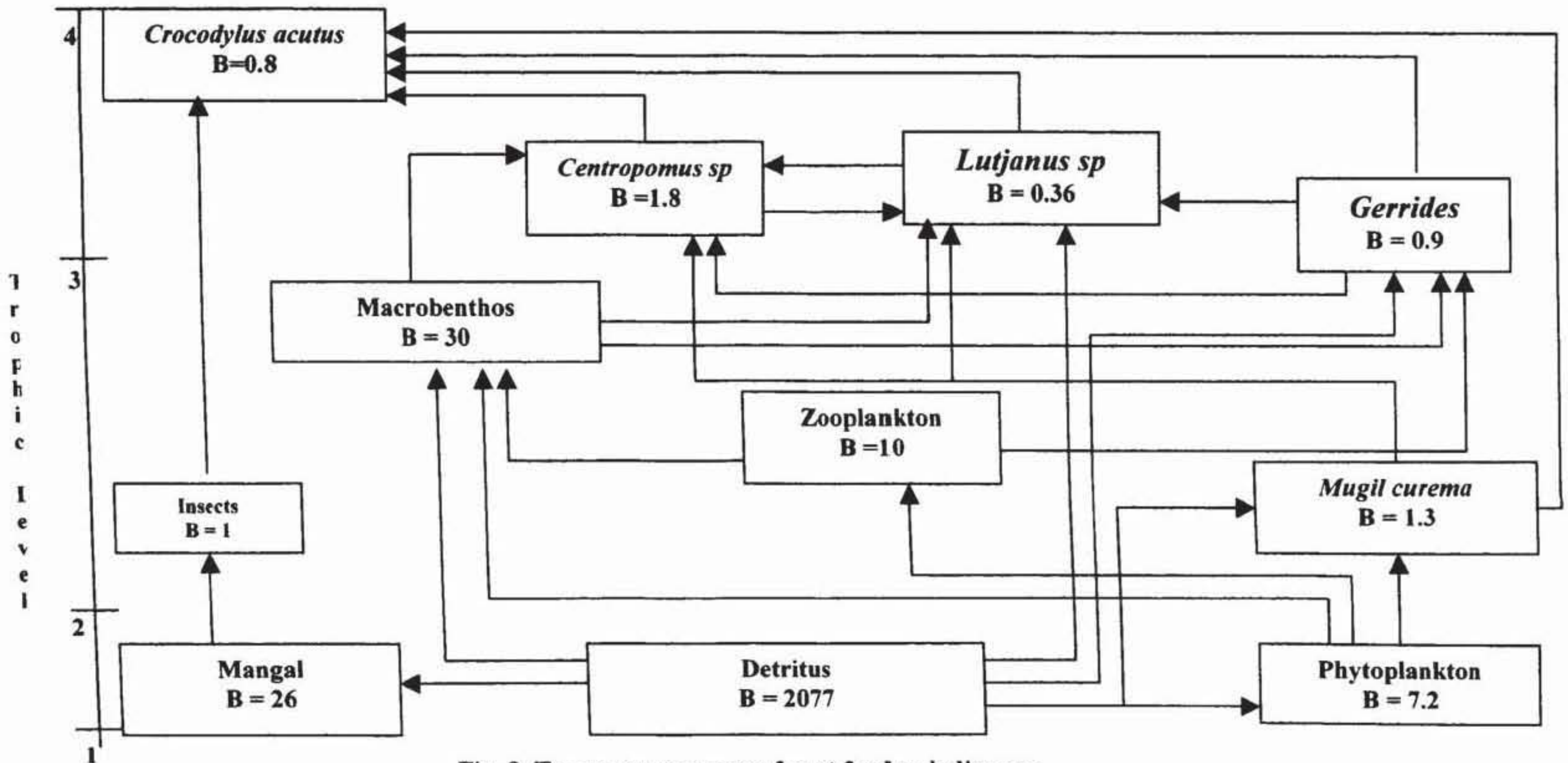


Fig. 9. Tonameca mangrove forest food web diagram.
B= Biomass and the values are obtained as explained in section 4.3.1, a. *i.*

i. Biomass input data

Data on the biomass (average annual, wet weight in tonnes/km^2) were determined in the field or extracted from other studies done previously within the Tonameca or in similar lagoons in Mexico (Table 22).

Fish and marine groups (phytoplankton, zooplankton, macro-benthos) biomass were extracted from previous studies on other coastal lagoons (Table 22), except for the fish Gerrides and *Centropomus sp* as well as for insects where biomass is estimated by the ECOPATH program during the mass-balance procedure. Using data from other locations generates a slant in the model, however, ECOPATH allows to include the level of accuracy of the data.

Table 22. Biomass data for ECOPATH

Groups	Biomass (t/km^2)	Geographic location	References
Phytoplankton	7.2	Gulf of Mexico Campeche	[59]
Zooplankton	10	Yucatan Peninsula	[59]
Macro-benthos	30	Pacific Huizache-Caimanero	[115]
Mugil curema	1.34	Pacific Huizache-Caimanero	[134]
Lutjanus sp	0.36	Pacific Chacahua	[133]

Mangal is the association of different species of plants in a mangrove forest and is taken as proportional to the mangrove tree biomass. Thus, if mangal is consumed by insects, it implies that insects (treated here as an herbivorous group) can eat any species of plant within the mangrove forest.

The mangrove biomass input was estimated directly in the field from the red mangrove biomass *Rizophora mangle*, the most abundant species in the Tonameca system.

Mangrove biomass was estimated in February 2003 using the point-centred quarter method [135]. The method consists of walking 3 transects of 15 meters length, located along the lagoon. On each transect, points are separated by 5 meters. A total of 20 points were sampled. At each point, an imaginary perpendicular line to the transect is drawn, in order to obtain 4 quarters. In each quarter, the distance to the closest tree was measured, as well as, the circumference at chest height (CCH) and the total height of the tree. Biomass is given as CCH^2 x height [136]. In the area sampled, only *Rizophora mangle* was found. An example of the kind of data collected is presented in table 23. The mangrove forest biomass thus obtained was 26 t/km^2.

Table 23. Example of field data collected for estimation of the mangrove biomass

Transect	Sampling point	Quarter	Species	Distance (m)	Height (m)	CCH (cm)
1	2	a	*Rizophora mangle*	7	10	30

Crocodile biomass was based on an annual population study, which had recorded the number of individuals within each *Crocodylus acutus* age class [137] (Fig 10 and table 24). To obtain the population biomass, the average weight of an individual crocodile in each age class was taken from the literature and multiplied by the number of crocodiles in each class. The biomass in each class and the total population biomass are presented in table 24. The total population biomass is 0.892 t/km^2.

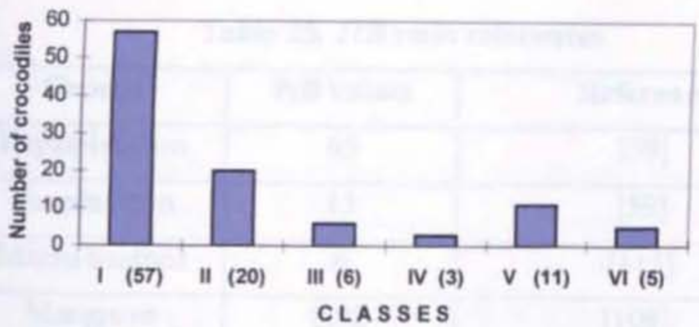


Fig 10. Size structure for Ventanilla *Crocodylus acutus* population, N= 102 (Numbers in brackets are the number of individuals in each class) Extracted from [137]

Table 24. *Crocodylus acutus* age structure and population biomass, in Ventanilla lagoon. The biomass is the number of crocodiles multiplied by the weight and divided by the lagoon area.

	Length scale (cm)	Mean weight (kg)	Number of crocodiles in age class	Total biomass (tonnes)	Biomass (t /km^2)
Class I	< 60	0.920	57	0.05	0.019
Class II	60 - 120	5.150	20	0.103	0.03
Class III	120 - 180	5.175	6	0.031	0.011
Class IV	180 - 240	29.25	3	0.087	0.033
Class V	240 - 300	95	11	1.05	0.4
Class VI	300 - 380	225	5	1.13	0.43
Total			102	2.45	0.9

Note: Number of crocodiles per age class extracted from [137] and biomass estimated.

ii. P/B input data

For insects the *P/B* ratio is calculated using the equation $P/B = 0.6457 \cdot W^{-0.37}$ as proposed by Banse and Mosher (1980) where W is the body mass [138]. Phytoplankton, zooplankton, mangrove and macro benthos P/B ratios were directly taken from the literature (Table 25).

Table 25. ***P/B*** **ratio references**

Groups	P/B values	Reference
Phytoplankton	65	[59]
Zooplankton	13	[59]
Macro benthos	6	[115]
Mangrove	0.92	[108].

The crocodile P/B ratio is based on the adult natural mortality rate of 0.8 adults per year, proposed by Kushland and Mazzoti (1989) [139]. The total adult population (classes V and VI) estimated by Espinosa (2000) is 16 individuals. The mortality rate of 0.8 means that one adult dies each year. Thus, the number of adults remaining in the study site after a year is 15 adults, plus juveniles. The mortality ratio is thus the weight in tonnes of one adult died in class VI (Table 24). Class VI was chosen since older individuals have a higher probability of death. The P/B ratio calculated in this way is 0.22.

Fish total mortality was estimated by summing natural mortality and fishing mortality. Natural mortality was taken from the literature for *Mugil curema* and calculated for Gerrides and *Lutjanus sp* using the Von Bertalanfy growth function (VBG):

$$M = K^{0.65} L_{\infty}^{-0.279} T^{0.463}$$

where, K is the curvature parameter for the VBGF,
L is the asymptotic length and T is the mean water temperature.

Table 26 shows the parameters values for each species.

Fishing mortality was estimated from structured questionnaires carried out in 2003, where 37% (n=26) of fishermen in the Tonameca municipality were interviewed (Appendix A). Fishing mortality was estimated as the average total catch over 6 years (1993, 1997, 2000, 2001, 2002, 2003) provided by the interviewees. The total catch was obtained by multiplying the catch per day by the number of days and divided by the biomass. Table 26 shows the fishing mortality for three species. For *Centropomus sp*, the P/B ratio was taken from Zetina-Rejón (2003) because length data for that species could not be obtained in the field [45].

Table 26. Natural and fishing mortality. Natural mortality is calculated for Gerrides and *Lutjanus sp* using the Von Bertalanfy growth function, fishing mortality is estimated from questionnaires and the total mortality is the sum of both.

	Natural Mortality	Reference	Fishing mortality	Total mortality (Z)
Mugil curema	0.262	[140]	0.599	0.861
Gerrides	1.2	$L_\infty = 0.44$ $K = -0.14$	0.54	1.74
Lutjanus sp	0.43	$L_\infty = 0.51$ $K = -0.53$	1.46	1.89

iii. Q/B input data

Q/B ratio is the intake of food by a group over its biomass for one year. The Q/B values and references for each group are presented in table 27.

Fish and zooplankton Q/B ratios are extracted from Zetina –Rejón (1999). The latter authors used an empirical Q/B ratio for fish developed by Palomares and Pauly (1998):

$\mathrm{Log}(Q/B) = 7.964 - 0.204 \log W_\infty - 1.965\, T + 0.083\, A + 0.532\, h + 0.398\, d$

where, W_∞ is the asymptotic weight, T is the mean annual temperature, A is the aspect ratio of the caudal fin ($height^2 / surface$), h and d are dummy variables, (1 for herbivores and 0 for detritivores or carnivores).

For zooplankton, the ratio was estimated using the relationship proposed by Viela (1995):

$$Q = (R + P) / EA$$

where R is respiration, P is production and EA is the assimilation efficiency, which is 0.2 for detritus, 0.5 for plants and 0.8 for animals.

Macro-benthos, insect and crocodile Q/B ratios were taken from the estimates provided by the Network Analysis of the Trophic Dynamics of South Florida Ecosystems [141]. The network has an Across Trophic Level System Simulation (ATLSS) carried on by the Centre for Environmental Science, at the University of Maryland [141].

Table 27. Q/B values and references

Groups	Q/B values	References
Zooplankton	84	[115]
Macro benthos	21	[115]
Insects	3.9	[141]
Mugil curema	4.273	[115]
Gerrides	5.108	[115]
Centropomus sp	2.513	[115]
Crocodylus acutus	6.5	[141]

iv. Diet composition input data

All consumer diet composition was taken from the literature (Table 28). The prey/predator matrix is showed in table 29 The table shows the proportion of the diet of each group. For instance, if zooplankton eats 90% phytoplankton, the value included in the table is 0.9.

Table 28. Diet composition data references

	Reference
Zooplankton	[59]
Macro benthos	[141]
Insects	[59] [141]
Mugil curema	[140] [116]
Gerrides	[141]
Lutjanus sp	[142] [141]
Centropomus sp	[143]
Crocodylus acutus	[117] [118]

Table 29. Prey predator matrix for the Tonameca mangrove food web.

The values represent the proportions of the diet composition of each group or specie (see table 28 for references). Each column need to sum 1.

	Prey/predator	3	4	5	6	7	8	9	10
1	**Mangal**			1					
2	**Phytoplankton**	0.9	0.23		0.8				
3	**Zooplankton**		0.181			0.308	0.004		
4	**Macro-benthos**					0.647	0.468	0.759	
5	**Insects**								0.121
6	***Mugil curema***							0.087	0.121
7	**Gerrides**						0.405	0.087	0.253
8	***Lutjanus sp***							0.068	0.126
9	***Centropomus sp***						0.037		0.379
10	***Crocodylus acutus***								
11	**Detritus**	0.1	0.588		0.2	0.046	0.086		

b. ECOPATH results

i. Balancing the model

The first step in the ECOPATH procedure is to balance the model, so that the biomasses of all elements can be supported by their consumption rates and the productivities of their prey. The criteria and the steps for balancing the model are:

- *P/Q* ratio values should be less than or around 0.3 (Table 30). This is because consumption generally needs to be about 3 to 10 times higher than production. In other words, organisms have to take in much more food for basic activities such as metabolism, than they require for growth and reproduction.

- Ecotrophic efficiency (EE) must be less than 1 (a species cannot produce more than it consumes). Ecotrophic efficiency is extremely difficult to calculate empirically for any organisms and is usually estimated by the program or assumed to be around 0.95 to 0.9 as proposed by Ricker (1968) in the ECOPATH manual,

-Respiration must be positive,

-Mortality by predation should be in accordance with diet composition,

-Diet composition must sum to 1 for each group,

-Pedigree data should be incorporated for diminishing uncertainty (accuracy of data). The data are assessed in terms of their origin, if they were collected in the field the value is higher that data coming from another location from the literature.

-Sensitivity analysis (Ecoranger) should be done to evaluate the accuracy of parameters estimated. The program assess the probability distribution for transformation of the input data using a Monte Carlo approach.

ii. Trophic structure and network analysis

The mangrove food web comprises 3 trophic levels and 7 sublevels (Fig 9. and table 30). *Crocodylus acutus* has the highest trophic level of 3.9 which is similar to other studies where top predators have a trophic level of 4.6 or 5 [142] [114]. The trophic level is slightly lower compared to the other studies because the Tonameca food web has less number of groups.

Mangrove plays an important role in detritus accumulation due to the large amount of leaf material that is incorporated within the soil. This detritus is utilised by several groups in the food web. Phytoplankton also has a primary role for the productivity of higher trophic levels that are dependent on detritus. Thus, it is relevant to analyse the influence of the two primary producers, phytoplankton and mangrove, in the coastal lagoon food web. The flows to detritus from phytoplankton and mangrove are similar in the Tonameca food web (Table 30), emphasising the important role that both groups play.

Table 30. Inputs and basic estimates for the mangrove food web in the Tonameca catchment. B=biomass, P= production Q=consumption, EE= ecotrophic efficiency. Habitat area, B, P/B, Q/B, EE are the inputs, P/Q and the trophic level values are estimated by ECOPATH as well as the numbers in (). Habitat area is one meaning that all the mangrove forest within the watershed is considered and inputs values correspond to that area.

	Group name	Trophic level	Habitat area (fraction)	B (t/km^2)	P/B (yr)	Q/B (yr)	EE	*P/Q*
1	**Mangal**	1	1	26	0.920	-	(1.6)	-
2	**Phytoplankton**	1	1	7.2	65	-	0.9	-
3	**Zooplankton**	2	1	10	13	84	(0.88)	*0.155*
4	**Macro benthos**	2.18	1	30	6	21	0.4	*0.286*
5	**Insects**	2	1	(1)	0.810	3.9	(0.875)	*0.205*
6	***Mugil curema***	2	1	1.340	0.861	4.270	0.95	*0.202*
7	**Gerrides**	3.07	1	(0.9)	1.740	5.1	0.95	*0.341*
8	***Lutjanus sp***	3.48	1	0.360	1.890	(5)	0.95	*0.378*
9	***Centropomus sp***	3.33	1	(1.8)	0.903	2.51	0.99	*0.361*
10	***Crocodylus acutus***	3.96	1	0.9	0.2	6.5	0.001	*0.034*
11	**Detritus**	1	1	2077	-	-	(0.9)	-

Table 31. Flow to detritus in the mangrove food web in the Tonameca catchment.

	Group name	Flow to detritus ($t/km^2/yr$)
1	**Mangal**	20.02
2	**Phytoplankton**	23.563
3	**Zooplankton**	182.552
4	**Macro benthos**	234
5	**Insects**	0.88
6	***Mugil curema***	1.2
7	**Gerrides**	0.996
8	***Lutjanus sp***	0.394
9	***Centropomus sp***	0.916
10	***Crocodylus acutus***	1.356
11	**Detritus**	0

The flows to detritus, from primary and second trophic levels, represent the main flow of energy in the food web. Particularly important is the flow from macro-benthos and zooplankton to detritus, which is 234 and 182.5 $t/km^2/yr$ respectively (Table 31). In other Mexican coastal lagoons, the high flow to detritus from zooplankton and benthic invertebrates has also been demonstrated [59].

The connectance index is the ratio of the number of actual trophic links to the number of possible links, assuming all species are connected. In Tonameca, the connectance index is 0.25 (or 25%), which is close to the value of 30% found for other areas (Table 32) [59]. The connectance index indicates that the links proposed in the model and the links existing between the functional groups are similar.

Transfer efficiency was 9.9%, close to 10%, meaning that the system is very efficient and may have greater potential to recover after disturbance [115].

Transfer efficiency declines at higher trophic levels, as expected and as also found in other studies [59, 115].

The total system throughput, primary production and biomass ratio, and ascendency are some of the most important parameters for evaluating ecosystem health and are explained in the following paragraphs [56, 144].

Here, each of these parameters was estimated and compared with those from two other coastal lagoons: Tamiahua lagoon located in Veracruz State, in the Gulf of Mexico and Huizache-Caimanero lagoon, in Sinaloa State, north Pacific coast of Mexico. The latter has a permanent open channel permitting the entrance of larvae and sea water.

Both lagoons are larger in size than Tonameca, but are fed by rivers, have mangrove forest and are relatively shallow, similar conditions to those at Tonameca. Huizache-Caimanero measures 175 km^2 and 65 km^2 in the dry season, more than 10 times the area of Tonameca lagoon.

The total system throughput is the total amount of energy that passes through the system from input to output, and is the transfer of energy between all groups [56]. If the total system throughput is high, it means that the system is capable of growth, implying that it is vigorous and healthy [55]. In the Tonameca system, the total system throughput is 2853 $t/km^2/yr$, a relatively high value considering the size of the lagoon and the intermittent connection with the sea. Other lagoons, have higher values (Table 32), for example, Huizache-Caimanero with 6618 $t/km^2/yr$ and Celestun (located in the Yucatan Peninsula) with a value of 4581$t/km^2/yr$.

Total flow to detritus is 465 $t/km^2/yr$, which is a large amount for Tonameca, for the same reasons as stated above (Table 32).

Total biomass and total system throughput ratio (TPP/R) shows similarities between Tonameca lagoon (0.028) and Tamiahua lagoon (0.026), but, the value for Huizache-Caimanero lagoon is higher (0.073), meaning that the total biomass for that lagoon is very high, due to its hydrology and aquaculture activity (Table 32). Compared to 4 other lagoons, Huizache-Caimanero had the highest throughput ratio [115].

Total primary production and respiration ratio is important since it shows the balance between production and consumption. Odum (1969) suggests that if the value is less than 1, the system is more mature because " ....the energy fixed tends to be balanced by the energy cost maintenance (that is, total community respiration).." [110]. A high TPP/R ratio can also indicate a high amount of organic matter due to pollution. For the Tonameca lagoon, the primary production to respiration ratio is less than 1, whilst in the two other lagoons the ratio exceeds unity (Table 32). Thus, the TPP/R ratio indicates that Tonameca lagoon is probably mature and with low level of organic matter.

Ascendency combines the diversity of the system (information content) and the total throughput of a system. It represents the degree of trophic organisation and the transfer of materials between compartments (groups). A healthy system requires a high diversity of compartmental transfers and a high mutual information content [56]. Ascendency has a value of 2909.4 t/km^2 (or 32.7%) which is a typical value for a mangrove or an estuary ecosystem. Ascendancy for Huizache-Caimanero lagoon is greater probably due to a larger number of groups (information content) and a higher throughput. Ascendency and other ecosystem health metrics are known to be sensitive to the number of groups used, since this affects the information content [56]. The Tonameca forest is only represented here by 11 elements. If more elements had been included, it is likely that ascendency would have been greater [56].

Table 32. Network results for three coastal lagoons in Mexico

Parameter	Tonameca Lagoon	Tamiahua lagoon	Huizache-Caimanero lagoon
Total system throughput (t/km^2/yr)	2853		6668
Sum of all flows into detritus (t/km^2/yr)	465.8		3471
Sum of all flows into detritus/ Total system throughput	0.16	0.22	0.5
Total biomass/ Total system throughput	0.028	0.026	0.073
Total primary production/ Total respiration	0.562	1.04	3.3
Connectance	0.25	0.38	0.3
Ascendency (Flow bits)	2909		6853
Number of groups	11		26

Note: Tamiahua and Huizache-Caimanero data from Zetina-Rejón *et al* 2003

In summary, the Tonameca mangrove ecosystem has a trophic structure with *Crocodylus acutus* as its top predator and two main sources of primary production, mangrove and phytoplankton. The flow to detritus is the main pathway for energy flow, as might be expected for a mangrove ecosystem. Ecosystems where the role of detritus is important, have a higher probability of being stable or healthy [110]. Connectance analysis indicates that the actual links realised are representative of the possible links in Tonameca food web. Total biomass and total system throughput ratio reveal a low biomass for Tonameca lagoon compared with other lagoons. A low ratio is characteristic of immature ecosystems [110]. Moreover, the total primary production and total respiration shows that production is low. Thus, the biomass and production are exceeded by respiration, which is representative of mature and low levels of organic matter [110] as shown also in the water quality analysis of the Tonameca lagoon (section 4.1).

Ascendency is relatively high for the Tonameca lagoon considering the limited number of groups included, the hydrological conditions and the lagoon size.

Ascendency is an indicator of ecosystem health since diversity and vigor allows more possibilities to react positively to stress and hence to be more stable [55, 56, 145].

It can be seen that the Tonameca lagoon has some characteristics of a mature system (respiration major than production, detritus based food web and ascendancy) as well as immature characteristics (low ratio of total biomass and total system throughput). Nevertheless, the Tonameca mangrove ecosystem appears relatively healthy.

In the following sections, this balanced system will be used as an experimental model for exploring the consequences of disturbances (using ECOSIM) due to nutrient enrichment on the system's elements, in particular fish and crocodiles, both of socio-economic importance to the area.

4.3.2 Impacts of nitrogen run-off on phytoplankton and mangrove biomasses

The effects of changes in nitrogen run-off on the mangrove food web are explored using ECOSIM. ECOPATH with ECOSIM has been used elsewhere including two locations of Mexico [142] for fisheries management where fish populations have decreased (due to over-fishing) and other trophic levels are affected [146]. ECOSIM has been also used for looking at the interactions between octopus and the red grouper [147] as well as, for analyzing harvesting strategies for the shrimp fishery [45].

In the present study, ECOSIM is used for exploring potential changes in fish and crocodile populations following changes in primary producer biomass due to water quality changes.

a- Effects on phytoplankton biomass

The procedure using the Monod equation for estimating the effects on phytoplankton biomass due to a change in nutrient concentration in water was explained in chapter 3 section 3.2.3 equation *3.3*. In the following section, two different approaches are used to explore nutrient impacts. The first deals with the changes in phytoplankton under the actual nitrogen concentration in the lagoons. The second, uses predicted estimates of the nitrogen concentration in water following changes in levels of water extraction and nitrogen run-off.

i Effects due to changes in water nitrogen concentration

Water quality assessments presented in section 4.1 indicate that the nitrogen concentration for Tonameca and Ventanilla lagoons is 14.8 mg/L for both lagoons. The initial phytoplankton biomass presented in the ECOPATH model is 7.25 t/km^2 taken from (Vega–Cendejas and Arreguín, 2001) [59]. Equation *3.3* from chapter 3 is as follows:

$$B_{p_{t+1}} = B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{N_t}{\mathrm{K}_s + N_t}\right)$$

where $B_{p_{t+1}}$ is the change in population growth, B_{p_t} is the initial phytoplankton biomass in t/km^2, K_s is half of the saturation constant growth, $\mu_{\max}$ is the maximum specific growth rate and N_t is the nutrient concentration in water in mg/L.

The critical nutrient ratios K_s and $\mu_{\max}$ have been determined for nitrogen in diatoms, as 10 μg/l and 1 respectively [87]. Replacing with the initial phytoplankton biomass and the nutrient concentration in water we obtain:

$$B_{p_{t+1}} = 7.2 + 7.2\left(\frac{14.8}{10+14.8}\right) = 11.6\text{t/km}^2$$

The result shows, as expected, an increase in the phytoplankton biomass.

ii-. Effects due to changes in water nutrients, nitrogen run-off and water extraction

The relationship between water nutrient, nitrogen run-off and water extraction is presented in chapter 3 in section 3.2.2 and was estimated in section 4.2.4. The relationship between these variables is as follows:

$$N_t = 18R_t - 0.49W_t + 0.062t$$

where N_t = Nitrogen concentration in water in (mg/L) at time t, R_t = nitrogen run-off in t/yr, W_t = water extraction in cubic meter, t = years

Using this expression (above), a new value of nitrogen concentration in water is calculated when varying the values of the variables, by different amounts (percentages) (Table 33). The new nitrogen concentration is then used to estimate the new phytoplankton biomass using the Monod equation, taking 7.2 mg/L as the initial biomass (Table 33).

Table 33. Phytoplankton biomass variation in the Tonameca coastal lagoon using the relationship between nitrogen concentration, nitrogen run-off and water extraction

R_t and W_t percent of change	R_t (t/yr)	W_t (m^3)	N_t (mg/L)	$B_{P_{t+1}}$ (t/km^2)
+70 %	1532	443946	59	13.45
+50 %	1351	391717	53	13.3
+20 %	1081	313374	44	13.16
-20 %	721	208916	31	12.75
-50 %	450	130572	23	12.32
-70 %	270	78343	18	11.91

Note: the coefficient of the variable "year" is very low so there was no difference between 2005 and 2010.

The results indicate that nitrogen concentration in water increases when nitrogen run-off R_t and water extraction W_t increases, as might be reasonably expected.

The relationship between nitrogen concentration in water and phytoplankton biomass, suggest that very large changes in water extraction and nitrogen run-off are required to significantly affect phytoplankton biomass (Table 33). The range of phytoplankton biomass (including the estimation with water nutrients concentration presented in section *i*) is from 11 to 14 t/km^2 and these figures are therefore used in the ECOSIM analysis in order to explore the impact on other groups in the mangrove food web. Phytoplankton biomass value obtained in the previous section *i* (11.6 t/km^2) is very similar to 11.9 t/km^2, thus in the ECOSIM analysis only 11.9 t/km^2 is used.

b- Effects on mangrove biomass variation

One of the few studies of the effects of nutrient change on mangrove biomass is Onuf (1977). He demonstrated a 30% increase in mangrove biomass following an increase of ammonium in soil (more than 1g/m^2/day) comparable to a high discharge of sewage [108]. Given this range of increase it is possible to consider also the same percentages of biomass increase as for phytoplankton, (20%, 50%, 70%) to explore the effects of mangrove biomass changes on the other trophic groups.

The increases were relative to the initial mangrove biomass of 26 t/km^2. The results obtained using equation *3.2* are presented in table 34.

Mangrove and phytoplankton initial biomasses used in the ECOPATH analysis were replaced by the new biomasses for the ECOSIM analysis and the effects on other groups of the food web observed, focussing most on fish and crocodiles because these groups are inputs to fisheries and ecotourism, respectively.

Table 34. Mangrove biomass change estimated in Tonameca. Values are estimated based on the initial mangrove biomass of 26 t/km^2

Percent change of the initial mangrove biomass	Mangrove biomass t/km^2
+70 %	44.2
+50 %	39
+30%	33.8
+20 %	31.2
-20 %	20.8
-50 %	13
-70 %	7.8

4.3.3 Mangrove food web simulations

Three types of simulation were undertaken: first, changing only the phytoplankton biomass, second, changing only the mangrove biomass and third, changing both phytoplankton and mangrove biomasses (Table 35).
For each group within the model, biomass was obtained for 5, 10, 15 and 20 years after a change in phytoplankton and /or mangrove biomass.

Table 35. Phytoplankton and mangrove biomasses in Tonameca used for ECOSIM simulations. Biomasses are estimated as explained in the previous sections and in chapter 3

R_t and W_t percent of change for phytoplankton biomass estimation	Phytoplankton biomass (t/km^2)	Percent of change for mangrove biomass estimation	Mangrove biomass (t/km^2)
0% (Initial biomass value)	7.25	0% (Initial biomass value)	26
+70 %	13.45	+70 %	44.2
+50 %	13.3	+50 %	39
+30%	-	+30%	33.8
+20 %	13.16	+20 %	31.2
-20 %	12.75	-20 %	20.8
-50 %	12.32	-50 %	13
-70 %	11.91	-70 %	7.8

The changes in fish and crocodile abundance over time are shown in figure 11. The trajectories of all groups are oscillatory, although the average and maximum biomass obtained differs between groups. For instance, the biomass of *Centropomus* increases slowly, but reaches its maximum biomass after 15 years compared to other fish species, where the maximum is reached at 10 years. Gerrides and *Mugil curema* show similar patterns of change but *Lujtanus sp*, has a low biomass over the time period. Crocodile biomass also oscillates, in an opposite pattern to *Mugil curema* or Gerrides, due to the importance of both species in the crocodile diet. Oscillatory biomass behaviour has been observed for fish biomass in the northern continental shelf of Yucatan, Mexico by Arreguín-Sánchez (2000) [147] and is believed to be due to ecosystem compensatory mechanisms that tend to maintain a thermodynamically stable condition. Moreover, this author also showed that effects of changes in any physical variable tends to be propagated through the food web, similar to the results for Tonameca with the oscillatory behaviour (frequency of waves) being greater for top predators [147].

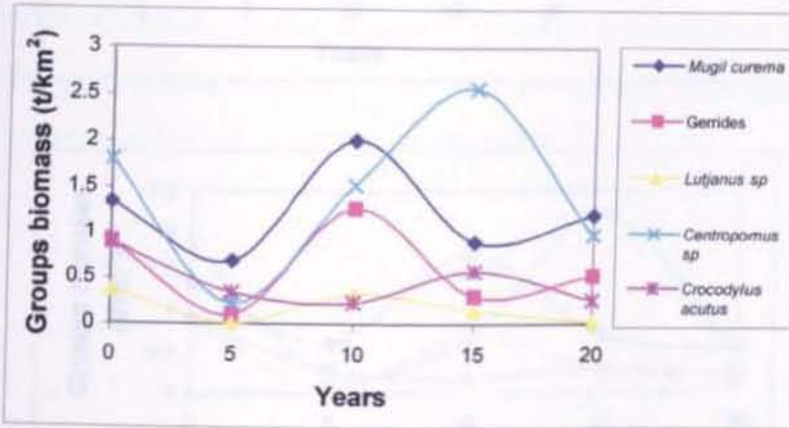
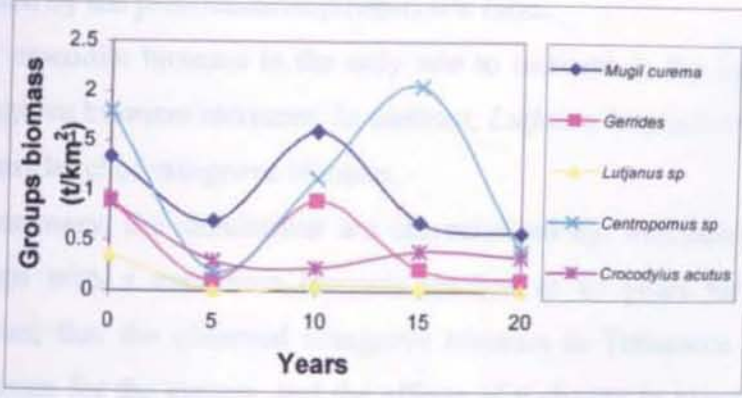


Fig. 11 Fish and crocodile biomass over time obtained with ECOSIM with initial mangrove and phytoplankton biomasses

a-The simulated effects of mangrove biomass changes

The effects on fish and crocodiles are only apparent at very high levels of mangrove biomass change (70%) (Figures 12 and 13). The behavior of the groups over time is similar to that in Fig 11, the majority of fish species and the crocodile population peaking at 10 years, but at 15 years for *Centropomus*. However, a slight decrease in biomass of all groups is observable after 10, 15 and 20 years compared to the initial biomass, for any change in mangrove biomass (except for crocodiles which increase after 20 years, when mangrove biomass increases) (Figures 12 and 13). These results suggest that the actual observed mangrove biomass could be the optimum for the system but it is necessary to remember that the relationship between mangrove and fish or crocodile is not direct and many processes are involved.



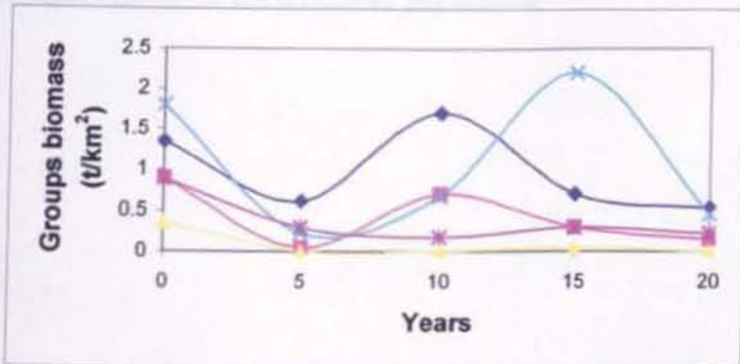


Fig 12 and 13. Fish and crocodile biomass in different years simulated in ECOSIM, when mangrove biomass is 44.2 and 7.8 t/km^2 respectively.

The biomass at 0 years correspond to the actual biomass of each group.

ECOSIM simulations are presented for each year (Fig. 14 to 17), figures were constructed using information from figures 11,12 and 13. Changes in the groups after 5 years indicate that the biomass increases slightly with higher biomass of mangrove.

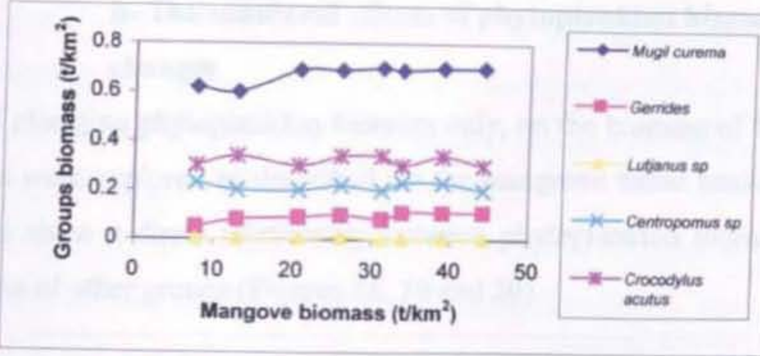
After 10 years the biomass of groups is maximal at any mangrove biomass, with *Mugil curema* and *Centropomus* having the highest biomasses (Fig. 15).

After 15 years, the maximum biomass is not so high as in previous years (Figure 16). *Centropomus* is the most abundant species and the other species decrease. Results are similar for any mangrove biomass implying that the role of mangrove in the food web dynamics does not seem to be important in this part of the analysis.

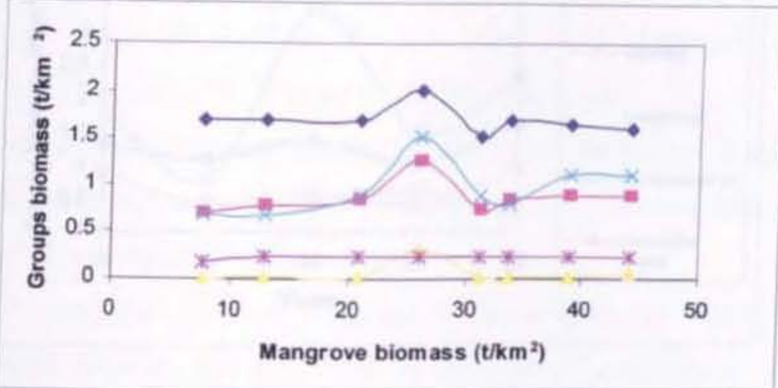
After 20 years, the biomass of groups other than mangrove declines slightly and it is noteworthy that the highest biomass in any year for all the species is associated with the actual observed mangrove biomass. This is consistent with the idea that the system is mature, as described also in the ECOPATH section by the production/respiration low ratio.

The crocodile biomass is the only one to increase in the long term when mangrove biomass increases. In contrast, *Lutjanus* biomass was always low for any level of mangrove biomass.

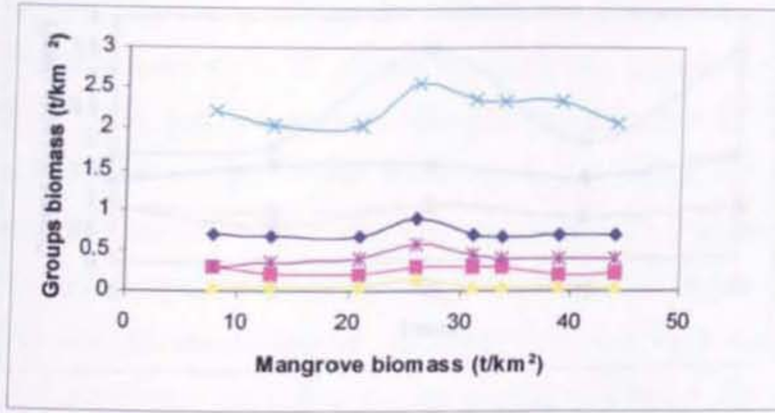
In summary, the simulations are characterized by: oscillatory behavior of groups with a maximum biomass reached at 10 years for most of the species; that the observed mangrove biomass in Tonameca might be the optimum for the system, and the effects of a change in mangrove biomass have slight effects on the crocodile population.



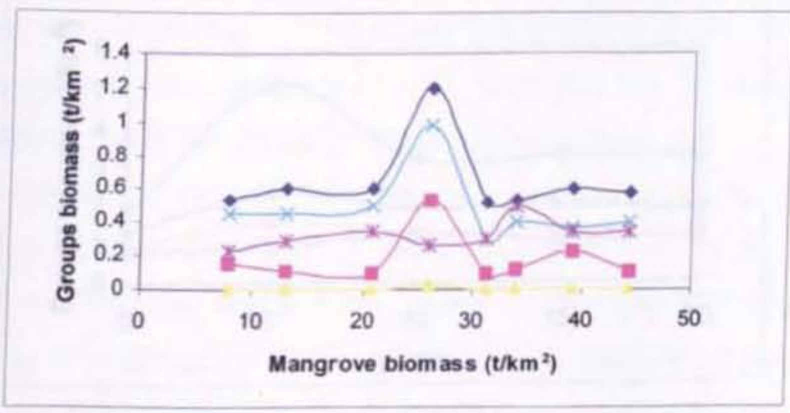
(Fig. 14)



(Fig. 15)



(Fig. 16)

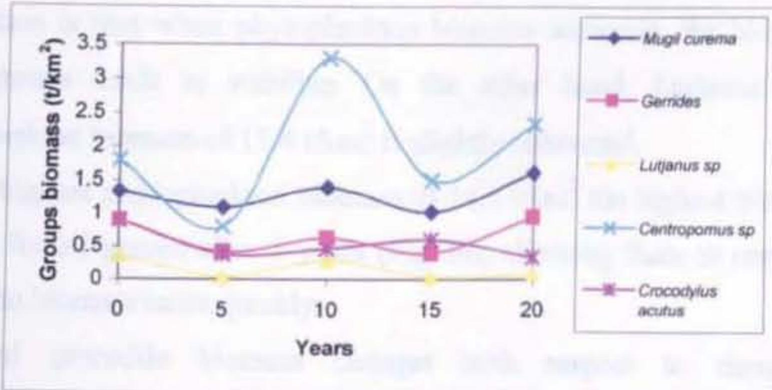


(Fig. 17)

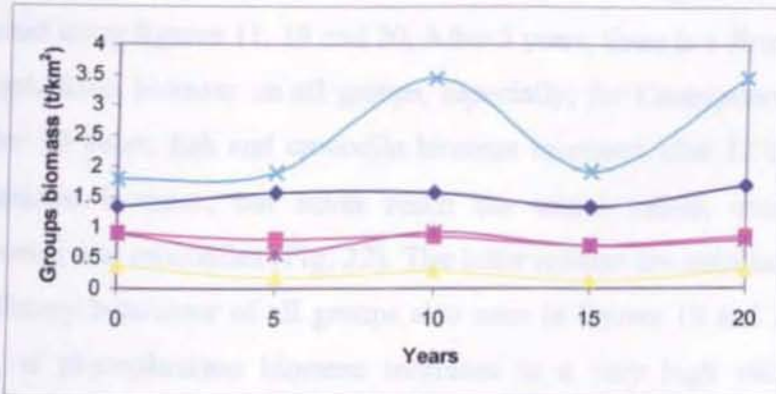
Fig. 14 to 17. Fish and crocodile biomass 5, 10, 15 and 20 years respectively after a change in the mangrove biomass. Curve peaks correspond to the actual mangrove biomass

b- The simulated effects of phytoplankton biomass changes

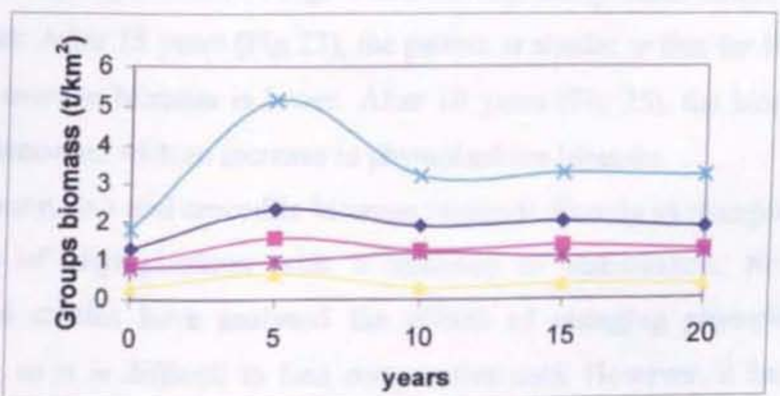
The effects of changing phytoplankton biomass only, on the biomass of fish and crocodiles were explored as described for the mangrove based analysis above. Results show a direct relationship between phytoplankton biomass and the biomass of other groups (Figures 18, 19 and 20).



(Fig. 18)



(Fig. 19)



(Fig. 20)

Fig. 18, 19 and 20. Fish and crocodile biomass in different years, when phytoplankton biomass is 11.9 , 13.4 and 14.5 t/km^2 respectively. The biomass at year 0 is the initial biomass of groups. A direct relationship between phytoplankton biomass and fish biomass is observable with a tendency to stabilisation..

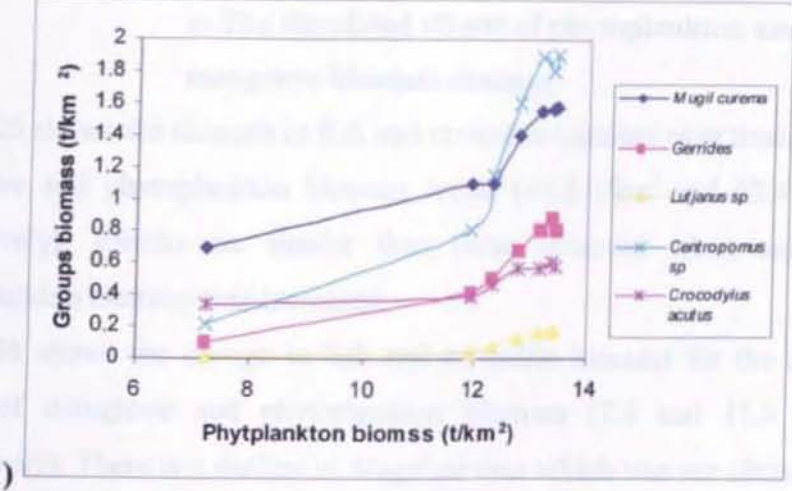
On average, the biomass of groups is directly linked to phytoplankton as it is shown comparing figure 18, 19 and 20. *Centropomus* had the highest biomass over the period followed by *Mugil curema* independently on the phytoplankton biomass.

If phytoplankton biomass is set at 13.4 t/km^2 or 14.5 t/km^2 biomass change is more stable and the oscillatory behaviour is not so marked. The overall implication is that when phytoplankton biomass increases, the biomass of other groups tends to stabilise. On the other hand, *Lutjanus* with a phytoplankton biomass of 13.4 t/km^2 is slightly recovered.

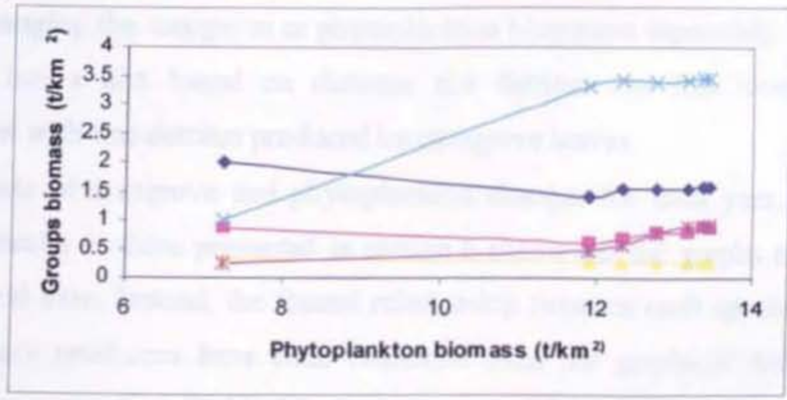
For the highest phytoplankton biomass of 14.5 t/km^2 the highest biomass is attained for all groups after 5 years (Fig 20), allowing them to reach their maximum biomass more quickly.

Fish and crocodile biomass changes with respect to changes in phytoplankton biomass are presented for each year in figures 21 to 24. constructed using figures 11, 19 and 20. After 5 years, there is a direct effect of phytoplankton biomass on all groups, especially, for *Centropomus* (Fig. 21). After 10 years, fish and crocodile biomass increases after 12 t/km^2 of phytoplankton biomass, but never reach the initial values, except for *Centropomus* and crocodiles (Fig. 22). The latter reflects the stabilisation of the oscillatory behaviour of all groups also seen in figures 19 and 20. For instance, if phytoplankton biomass increases to a very high value, the biomass of groups would be higher and the oscillatory effect would tend to disappear. After 15 years (Fig 23), the pattern is similar to that for 10 years, but the average biomass is lower. After 20 years (Fig 25), the biomass of groups increases with an increase in phytoplankton biomass.

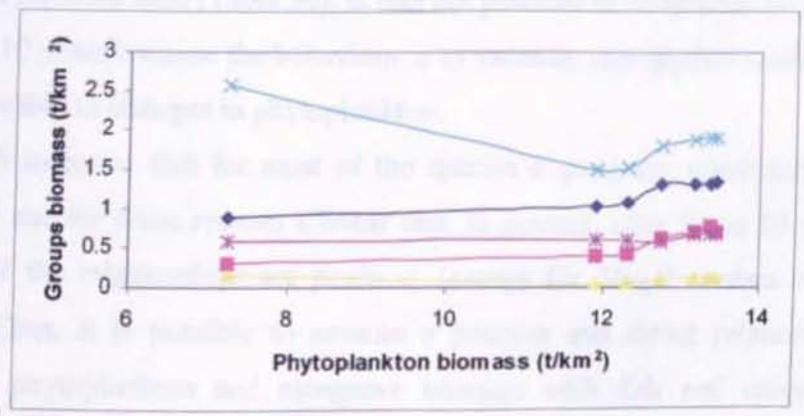
In summary, fish and crocodile biomass responds directly to changes in the biomass of phytoplankton with a tendency to stabilization. No other ECOSIM studies have analysed the effects of changing phytoplankton biomass, so it is difficult to find comparative data. However, it has been demonstrated that changes in biomass of certain groups affect the food web dynamics [146] [142, 147].



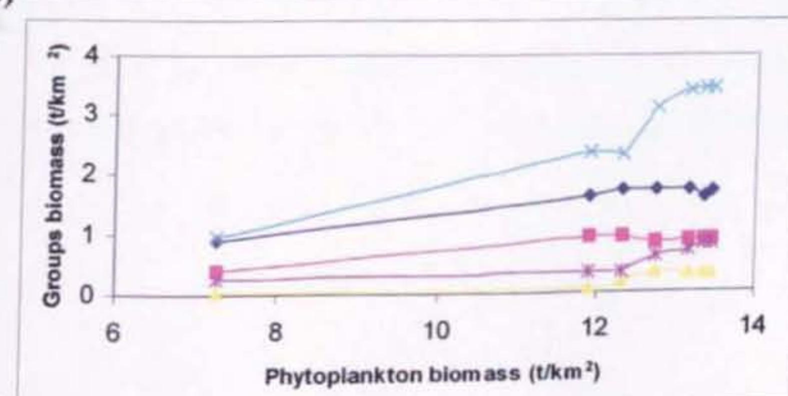
(Fig. 21)



(Fig. 22)



(Fig. 23)



(Fig. 24)

Fig 21 to 24. Fish and crocodile biomass 5, 10, 15 and 20 years respectively after a change in phytoplankton biomass. Actual phytoplankton biomass is 7.6 t/km².

c- The simulated effects of phytoplankton and mangrove biomass changes

Figure 25 shows the changes in fish and crocodile biomass over time, at the mangrove and phytoplankton biomass levels (44.2 t/km^2 and 13.4 t/km^2 respectively). Results are similar than those observed when only the phytoplankton biomass was increased.

Figure 26 shows the change in fish and crocodile biomass for the lowest values of mangrove and phytoplankton biomass (7.8 and 11.9 t/km^2 respectively). There is a decline in *Mugil curema* which was not observable when changing the mangrove or phytoplankton biomasses separately. *Mugil curema* has a diet based on diatoms and detritus and this would be consistent with less detritus produced by mangrove leaves.

The effects of mangrove and phytoplankton changes for each year, show similar results to those presented in section b above and the graphs are not reproduced here. Instead, the formal relationship between each species and the primary producers have been estimated from the graphical data and these are reported here (Table 36). It was not possible to do this for *Lutjanus sp* after 10 years because the behaviour is to variable, this species seemed to be vulnerable to changes in phytoplankton.

Table 36 indicates that for most of the species a quadratic relationship is obtained and for some species a linear one. In general, after 5 and 10 years slopes of the relationships are positive, (except for *Mugil curema* at 10 years). Thus, it is possible to assume a positive and direct relationship between phytoplankton and mangrove biomass with fish and crocodile biomass.

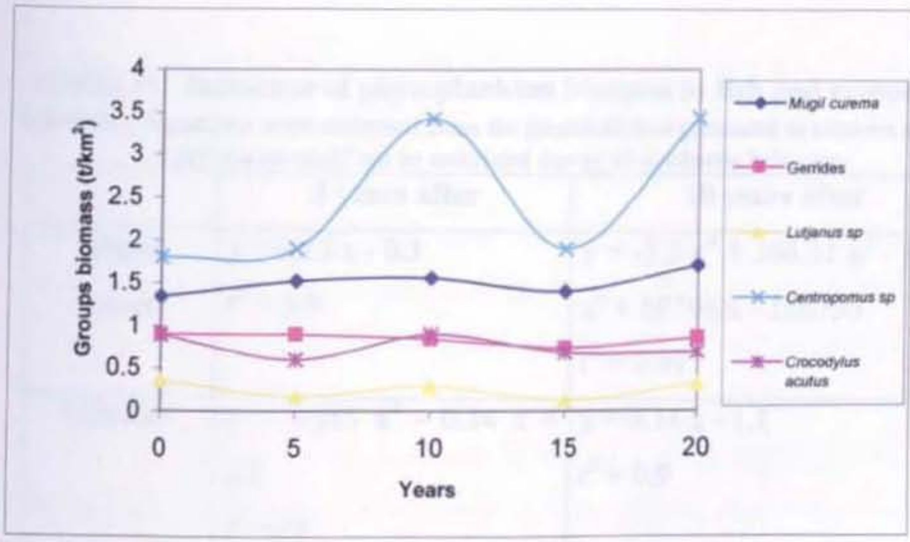


Fig 25. Fish and crocodile biomass in different years, when phytoplankton and mangrove biomass are 13.4 t/km^2 and 44.2 t/km^2 respectively.

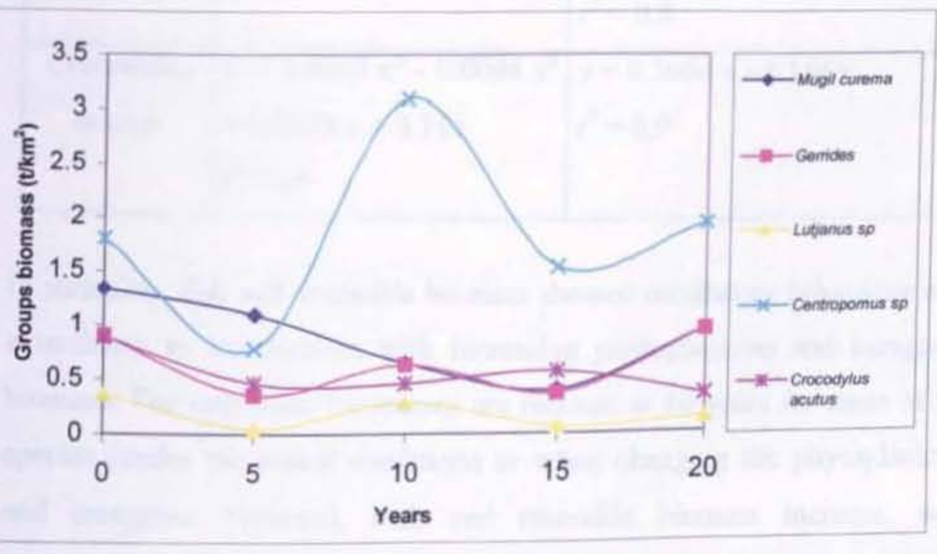


Fig 26. Fish and crocodile biomass in different years, when phytoplankton and mangrove biomass are 11.9 t/km^2 and 7.8 t/km^2 respectively

Table 36. Influence of phytoplankton biomass in fish and crocodiles biomass. Equations were estimated from the graphical data presented in sections a and b. Lutjanus sp could not be estimated due to its stochastic behavior.

y	5 years after	10 years after
Mugil curema	$y = 0.13\ x - 0.3$ $r^2 = 0.9$	$y = -7.2\ x^4 + 366.81\ x^3 - 7004\ x^2 + 59396\ x - 188756$ $r^2 = 0.97$
Gerrides	$y = 0.015\ x^2 - 0.14\ x + 0.3$ $r^2 = 0.8$	$y = 0.14\ x - 1.1$ $r^2 = 0.9$
Lutjanus sp	$y = 0.003\ x^2 - 0.03\ x + 0.07$ $r^2 = 0.95$	Stochastic behaviour
Centropomus sp	$y = 0.02\ x^2 - 0.2\ x + 0.4$ $r^2 = 0.9$	$y = 2.1\ x^3 - 81.6\ x^2 + 1042\ x - 4426.7$ $r^2 = 0.8$
Crocodylus acutus	$y = 0.0005\ x^3 - 0.0094\ x^2 + 0.0673\ x + 0.144$ $r^2 = 0.9$	$y = 0.3064\ x - 3.1965$ $r^2 = 0.9$

In summary, fish and crocodile biomass showed oscillatory behaviour with a tendency to stabilisation with increasing phytoplankton and mangrove biomass. The maximum biomasses are reached at 10 years for most of the species (under the actual conditions or when changing the phytoplankton and mangrove biomass). Fish and crocodile biomass increase, with increasing phytoplankton biomass. In contrast, the relationship is not linear with respect to mangrove biomass change. That is, it would appear that the actual (observed) level of mangrove biomass is the optimum for the system but it is important to note that the relationship between the biomasses of the different groups and mangrove is not direct, detritus formation being an important intermediary process.

The effects of changing mangrove biomass is much less than that of changing phytoplankton biomass. On the other hand, increasing phytoplankton and mangrove biomass by 70% causes a stabilisation of fish and crocodile population over time (smoothing the oscillatory behaviour).

That is, up to 70% of increase, the collapse of populations is not observable, as we could expect, in contrast, there is a stabilisation of the ecosystem, partly due to the logistic growth of phytoplankton and consistent with stabilisation processes as mentioned in Arreguín-Sánchez (2000) [147]. Thus, in order to have eutrophication the phytoplankton biomass needs to be very high. Therefore, nitrogen run-off would need to increase considerably in order to have eutrophication in the lagoons. But it is difficult to establish the limit to eutrophication because ECOPATH with ECOSIM does not include this process. Thus, the ecosystem stabilisation with 70% of increase in nitrogen run-off, might be interpreted as the limit to eutrophication. In contrast, if there is a considerable decrease on phytoplankton and mangrove biomasses, there would be severe impacts for the system.

4.4 Ecosystem assessment summary

The water quality results show that there is an accumulation of nutrients coming from upland activities, reflected in the high concentration in the last downstream fresh water localities, San Isidro and Río Grande and the increase in nutrients in coastal lagoons at the beginning of the rainy season. On the other hand, the nitrogen in coastal lagoons is very close to the limit (15 mg/L) proposed by the Mexican regulation [126].

Nitrogen run-off from agriculture and coffee pulp wash has been estimated using different approaches. The conservative one shows 69 t/yr of total nitrogen run-off, the second approach indicates a value of 967 t/yr and the non conservative shows 2100 t/yr of nitrogen run-off.

The relationship between nutrient concentration in water, water extraction and nitrogen run-off has been estimated. Results show an inverse relationship between nutrient concentration in water and water extraction. In contrast, there is a direct link between nutrient concentration and nitrogen run-off.

The mangrove food web includes for the first time *Crocodylus acutus* as top predator and mangrove as a primary producer. The food web relies strongly on detritus flows as expected for a mangrove ecosystem. The system shows some characteristics of maturity such as: respiration greater than production, detritus based food web and ascendency. On the other hand, the system shows an immature condition given by the low ratio of total biomass and total system throughput. In general terms, the Tonameca mangrove ecosystem seems relatively healthy.

The equation relating water quality to nitrogen run-off and water extraction was used for determining the phytoplankton biomass after a variation on the equation variables. Results are used for the ECOSIM simulation and compared to the actual conditions in Tonameca. ECOSIM simulations show that fish and crocodile biomasses have an oscillatory behaviour, with a tendency to stabilisation when phytoplankton and mangrove biomass are increased. The maximum biomasses are reached at 10 years for most of the species (under the actual conditions or when changing the phytoplankton and mangrove biomass). Fish and crocodile biomasses increase when phytoplankton biomass increases showing the dominance of phytoplankton, compared to mangrove. Biomass collapse is not observable even for a 70% phytoplankton increase.

Thus, in order for the lagoon to be eutrophic, the phytoplankton biomass needs to be very high and nitrogen run-off would need to augment considerably. In contrast, if there is a considerable decrease on phytoplankton and mangrove biomasses, these would be severe impacts.

The indicators of ecosystem maturity given by ECOPATH are confirmed in the ECOSIM simulations, since the system can support a high level of disturbance.

The ECOSIM analysis has shown that trophic dynamics might be changed when varying the biomass of different groups as it has been also demonstrated in other studies [45, 142, 146, 147].

The ecosystem analysis relies on field data, indirect sources and on the ECOPATH with ECOSIM software. The accuracy and reliance of the analysis has been explores in this chapter. Water quality assessment has been estimated in the field and nitrogen run-off has been presented under conservative and non conservative approaches for including different scenarios. Indirect sources for building the food web were taken as far as possible from near by areas and ECOPATH sensitive analysis was included. Other ECOPATH studies also use indirect sources and include input data from other years, from other places or other countries. For example, in Zetina-Rejón *et al* (2003) diet composition is extracted from other places and biomass from previous years [115] and in Vega-Cendejas *et al* (2001) production is extracted from other countries [59].

The ecosystem analysis presented in this chapter, indicates that Tonameca is relatively healthy, since water is not strongly polluted, and severe effects in food web dynamics and eutrophication require high amounts of nitrogen inputs.

Chapter 5.
Modeling the Economy

5.1. Agriculture production function and profits

5.1.1 The agricultural production function

The agricultural production function as presented in equation *3.13* includes the following inputs: labor, nitrogen run-off (as an indirect measure of fertilizer use) and water extraction (Table 37). Land is also an input for agricultural production, because labor, water extraction and fertilizer run-off depend on the number of hectares dedicated to agriculture. This has been used to interpolate between years for which observations on non-land inputs do not exist. Thus, in order to avoid autocorrelation between variables, land is not included as a variable in the regression.

State and regional statistics on the hectares used for agriculture are provided by the National Ministry of Agriculture [70]. The Ministry of Agriculture considers for Oaxaca State, 5 agricultural regions from which the coast correspond to the area of study. Coastal agricultural production is available for 1999 to 2002. On the other hand, municipal statistics available only for one year (1991) indicates the hectares used for agriculture. Using the number of hectares for agricultural production in the coast and in the catchment, it was estimated that Tonameca watershed represents 9.7% of the coastal hectares for agriculture [73]. Thus, the number of hectares used for agriculture in Tonameca for 1999, 2000, 2001 and 2002 correspond to 9.7% of the coastal production for each year.

The main crops cultivated in the catchment included in the coastal statistics are: sesame, coffee, maize, chili, beans, jamaica, mango and papaya [70].

Labor information used in this chapter has not been published and was obtained in the local office of agriculture located in Pochutla. Data include for 2001, labor costs for producing one hectare of 8 types of crop: jamaica, sesame, beans, coffee, papaya, melon, maize and water melon.

For instance, planting and harvesting are different activities requiring labor, but coffee harvest employs the twice the number required by maize harvest. A total cost per hectare was estimated in each municipality. An average labor for producing one hectare of any crop in the catchment was obtained considering that the 8 crops are representative of the case study. Finally, the average cost per hectare, was used to estimate the total cost per year as a function of the hectares cultivated.

The number of workers in agricultural production is obtained by dividing the labor costs in the catchment per year by the daily wage (100 pesos a day). It is assumed that the number of workers increase along the years in the same proportion of the cultivated hectares (Table 37).

Nitrogen run-off was estimated for 1991 in section 4.2.3 using hectares cultivated per municipality that include 8 types of crops. However, since coastal statistics include 16 crops, the value is re-estimated as a function of the number of crops and corresponding hectares (Table 37).

Water extraction data were estimated by COPEI consultancy using 1998 data and the same volume of water extracted is assumed for 1999 [100]. For the following years, 2000, 2001 and 2002 water extraction is estimated as a function of the number of hectares for agriculture. That is, it is assumed that if the number of hectares increase water extraction increases in the same proportion (Table 37).

A regression was run using the well known software for econometrics Limdep, in order to link agricultural production (tonnes) to labor, nitrogen run-off and water extraction. Input data and results are presented in table 37 and 38 respectively. The regression was adjusted to autocorrelation since the Durbin – Watson statistic was 1.3.

Table 37. Input data for the agricultural production function regression. Labor, water extraction and nitrogen run-off are the inputs to the production function and agriculture production dependent variable.

	Agriculture production (tonnes)	Labor (number of persons)	Water extraction (cubic meters)	Nitrogen run-off (tonnes/yr)
1999	160 956	1 570	239 136	2 509
2000	159 861	1 567	238 730	2 505
2001	156 253	1 484	226 039	2 372
2002	138 812	1 503	228 992	2 402

Table 38. Agriculture production function regression. Multiple regression estimated in Limdep indicates the coefficients of each variable and p-value indicating that all variables are significant at 1% and the r-square indicates a good fit of data. T-ratio is another statistic showing the coefficient fitness.

Production inputs	Coefficient	p- values	t-ratio
Labor*	12263	0.0004	3.5
Water extraction*	- 235	0.000	-11.6
Nitrogen run-off*	14828	0.000	7.4
Constant**	0.65	0.1386	1.4
R-square = 0.99, n = 4, *significant at 1%, ** significant at 10%			

The agriculture production function is then given by the following expression:

$$Q_{a_t} = 12263\, L_{a_t} - 235\, W_{a_t} + 14828\, R_t$$

where, Q_{a_t} = total tonnes of agriculture production, L_{a_t} =labor, W_{a_t} = water extraction for agriculture, R_t = nitrogen run-off.

The equation indicates production is increasing in labor and fertilizer use but decrease in water extraction. This is explained by the fact that 90% of production depends on rainfall [65]. Thus, if water extraction increases it is due to a low volume of rainfall and therefore the majority of the production is affected negatively.

The effect of nitrogen run-off and water extraction in the agricultural production is estimated using the equation presented above. For this purpose, 20%, 50% and 70% increase and decrease is simulated on labor, nitrogen run-off and water extraction (Table 39).

Table 39. Agriculture production after a change in inputs nitrogen run-off, water extraction and labor. Input were estimated using the percent of change in the 2002 values. The production is estimated using the regression obtained previously.

Percent of change	Nitrogen run-off (t/yr)	Water extraction (cubic meters)	Labor (number of persons)	Production (tonnes)
+70	4 083	389 286	2 555	399 543
+50	3 603	343 488	2 254	352 538
+20	2 882	274 790	1 803	282 031
-20	1 921	183 193	1202	188 021
-50	1 201	114 496	751	117 513
-70	720	68 697	451	70 508

Results show that there is a direct relationship between the inputs and the production, nevertheless the negative coefficient of water extraction.

The influence of nitrogen run-off and labor in the production is higher than water extraction.

5.1.2 Agriculture Profits

Profits, Π_{a_t}, are the difference between revenue (the average price of crops per year for the coast P_{a_t} to the production of each year minus costs C_{a_t}).

$$\Pi_{a_t} = P_{a_t} Q_{a_t} - C_{a_t}$$

Agricultural costs include fertilizer, labour and water extraction costs. Fertilizer costs were provided for 2001 by the local agriculture office. In order to estimate the equivalent fertilizer costs for other years, fertilizer use is assumed to depend on the number of hectares cultivated. In chapter 4.2 section 4.2.1, nitrogen run-off was estimated for the 46% of producers that use fertilizer. Fertilizer costs per crop were estimated for the same 46% of producers (Table 40).

Water extraction costs are equivalent to the number of permits of water extraction for agriculture (273 permits) [100] multiplied by the cost of permits in pesos (500 pesos).

Water extraction costs are obtained for 1999 and estimated for other years in proportion to the hectares used for agriculture in each year.

Finally, labour costs were estimated as explained in the previous section. Aggregate costs have been decreasing probably due to a decrease in the number of hectares cultivated.

Table 40 Total costs of agriculture production

Costs / Years	Labour (pesos)	Fertilizer (pesos)	Water extraction (pesos)
1999	2 230 201	359 412	600 873
2000	2 226 416	358 802	599 853
2001	2 108 058	339 728	567 964
2002	2 135 594	344 166	575 383

Aggregate profits per year are indicated in table 41.

Table 41. Aggregate profits from agriculture production from 1999 to 2002. (Production*price)-costs=profits

Years	Production (tonnes)	Average price of crops in the coast (pesos/tonnes)	Costs (pesos)	Profits (pesos)
1999	160 956	8 836	3 190 485	1 418 951 543
2000	159 861	7 111	3185 072	1 133 599 288
2001	156 253	5 393	3 015 751	839 662 697
2002	138 812	5 061	3 055 144	699 483 905

In 2002, aggregate profits from agriculture in the catchment were 699 483 905 pesos, implying that average profits per farmer were 89 117 pesos per year, or 7 426 pesos a month (675 dollars a month). This is double the average wage.

The agriculture production function presented below (section 5.2.1) was used to calculate the effect on the production of scaling levels of fertilizer use, water extraction and labor (Table 42). Aggregate profits are also recorded.

Table 42. Aggregate agricultural profits after change in nitrogen run-off, water extraction and labor. Production was estimated in table 39 and profits were estimated as in previous table using 2002 price and cost values

Inputs percent of change	Production (tonnes)	Profits (pesos)
+20	282 031	2 488 967 680
+50	352 538	3 111 971 950
+70	399 543	3 527 308 130
-20	188 021	1 658 295 320
-50	117 513	1 035 291 050
-70	70 508	619 954 870

In summary, production is positively related to fertilizer use and labor, and is negatively related to water extraction. Production and profits have both been decreasing as a consequence of the agricultural sector crisis, leading to a fall of land committed to agriculture [71]. The question here is what is the optimal level of fertilizer use given the externalities on Fisheries and ecotourism? In previous chapters it was demonstrated that at high levels of nitrogen run-off eutrophication of the coastal lagoon would be expected to occur. It was shown that a phytoplankton biomass of 14.5 t/km^2 corresponding to 70% of increase on nitrogen run-off, generates changes on the food web. Chapter 6 explores the effects of fertilizer run-off increases up to that level.

5.2 Fisheries production function and profits

5.2.1- Fisheries production function

The fisheries production function Q_{h_t} was described in chapter 3 section 3.2.5 equation *3.6*:

$$Q_{h_t} = \sum_{x}^{4} q\, E_t B_{x_t}$$

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

Mugil curema, Gerrides, *Lutjanus sp* and *Centropomus sp* are the species used for estimating the production. Those species were also used for the food web analysis and are common in the region. Information from 1993 to 2002 on effort, catch, length and weight were obtained with structured interviews (see survey method below).

a- Survey method

Interviews were carried out during February, July, August and September. February is the dry season and few fishermen were in the Tonameca river mouth fishing. July, August and September are the main months for the fishing season, because the lagoon mouth is open. In July, the interviews were done in the mouth of the river, however the number of fishermen was very low. Therefore, it was necessary to conduct the rest of the interviews in the villages close to the lagoon. The villages close to the lagoon were interviewed but only in 7 villages fishing is recognized as the main activity. In the other villages people interviewed said: "there are no fishermen in this village" and the income is based on agriculture or other activities. Occasional fishermen come from other places in the region, not necessarily closed to the lagoon (e.g. Tonameca). Thus, the number of interviews are representative of the fishermen in the catchment.

The villages selected are: El Venado, Chacahuita, Bajos del Palmar, Zapotal, Samaritan, Unión del Palmar and Laguna del Palmar. Men population with more than 18 years old in those villages represent the total number of fishermen. A total of 32 structured interviews were completed representing 14% of the number of fishermen in Tonameca. The fishermen leader was in charge of organizing a meeting with all the fishermen within the village. The questionnaire was then applied individually. Thus, the number of questionnaire is representative of the number of fishermen within each village.

The interview questions tackle the fishing relevance in the household economy, fishing areas (lagoon, mouth), species, seasons, effort, methods of fishing, changes on catch, prices and costs (Appendix A).

b- Descriptive statistics from questionnaires

The average age of interviewee was 38 years old and 46% had primary education. The most important economic activity for 34.6 % of the fishermen is agriculture and the second one is fishing for 23%.

Fishing represents 20% of the income for 61% of interviewees; confirming that the fishery is an important subsistence activity for the majority of the population. Income is less than 1000 pesos a month for 90% of the fishermen and none of the people interviewed was member of a fishing cooperative. The main sites for fishing are the lagoon and the lagoon mouth. Mullet (*Mugil curema*) is the must important species fished by 46% of the population and the second one for 15% of the interviewees. Mullets fishery is measured by dozens of fish, 2 or 3 dozens are obtained each session.

The species composition has not changed since 1993. However, fish were slightly bigger and two times more abundant at that time. Fishing effort in terms of hours fished per day has increased slightly but not the number of days per week. Effort is measured in hours because fishermen do not use boats for fishing. Effort is 3 days a week spending from 5 to 6 hours. The main method of fishing are line, "atarraya" or "trasmayo" nets with 2.5 or 2 inch.

Catch decrease was mentioned by 90% of the interviewees, harvest is less than 10 years ago, especially after hurricane Pauline in 1997. The indicators of production decrease are lower catches and smaller sizes, and the causes perceived are more fishermen, lower water quality and sedimentation.

Prices depend on the species. Fishing costs are low, because the boats are not used for fishing purposes, thus, only the opportunity cost of a day in agriculture is considered as a cost. Fishermen arrive to the lagoon mouth walking by the beach or using a small boat. Since the boat is not a necessary condition for fishing it is not considered as a cost.

c- Schaefer model method and results

The Schaefer model was used to estimate the production between 1993 to 2003. Production was projected to 2007 given changes in phytoplankton biomass.

To calculate the production between 1993 to 2002, biomass data are derived from ECOPATH (Table 43). Aggregate species biomass is used to calculate the total fishing production and is assumed to be constant.

The catchability constant (q) is 0.00003 as estimated for *Lutjanus* by the National Institute of Fishery [148] . The catchability constant (q) is the same for all the species since they have a similar size and the same type of fishing methods are used (Table 43).

Effort was obtained from the interviews and results presented in table 44.

Table 43. Fish biomass data and catchability constant value. See chapter 4 section 4.3.1 for data estimations

	Mugil curema	***Lutjanus sp***	**Gerrides**	***Centropomus sp***
q	0.00003	0.00003	0.00003	0.00003
Initial biomass (t/km^2)	1.34	0.9	0.36	1.8

Table 44. Fishing effort in Tonameca lagoon. Hours a week was obtained in the interviews. Hours a year are calculated considering that 3 months a year (dry months) there is no fishing activity

	1993	**1997**	**2000**	**2001**	**2002**
Hours per week	10.25	10.36	11.06	11.27	12.10
Hours a year	369.16	373.09	398.19	405.70	435.76
Total effort for 32 fishermen	11813	11939	12742	12982	13944

Production is calculated with the Schaefer model using effort, biomass and catchability constant (Table 45). Results show an increase in harvest, biomass and fishermen are constant and fishing effort increase.

The number of fishermen remained constant but the level of fishing effort increased.

Table 45. Total and specific harvest (tonnes a year) estimated with the Schaefer model. (See chapter 3 for more the model details). Biomass and number of fishermen are constant

	1993	1997	2000	2001	2002
Mugil curema	0.47	0.48	0.51	0.52	0.56
Lutjanus sp	0.13	0.13	0.14	0.14	0.15
Gerrides	0.32	0.32	0.34	0.35	0.38
Centropomus sp	0.64	0.64	0.69	0.70	0.75
Total harvest in tonnes	1.56	1.57	1.68	1.71	1.84

Fisheries production for 2007, was estimated using the equations applied in the ECOSIM simulations (chapter 4.3.3 point c table 36). The equations show fish biomass, 5 years after a change in phytoplankton biomass and results are presented in table 46. The increase in phytoplankton is due to variations on nitrogen run-off and water extraction (chapter 4 section 4.3). Phytoplankton biomasses correspond to the actual biomass (7.2 t/km^2), to 70% of increase (13 t/km^2) in nitrogen run-off and water extraction. An extreme situation of 3 t/km^2 phytoplankton biomass is also considered (Table 46). Fish biomass and harvest simulations for 2007 are presented in tables 46 and 47 respectively.

Table 46. Fish biomass in 2007 after changes in phytoplankton biomass. The actual phytoplankton biomass is 7.2 t/km^2, other phytoplankton values were estimated as explained in chapter 4 section 4.3 and fish biomass were estimated using the equation obtained in ECOSIM presented in table 36.

Phytoplankton biomass (t/km^2)	***Mugil curema* (t/km^2)**	***Lutjanus sp* (t/km^2)**	**Gerrides (t/km^2)**	***Centropomus sp* (t/km^2)**	**Total biomass (t/km^2)**
3	0.12	0.003	0	0	0.12
7.2	0.69	0.05	0.02	0.15	0.9
13	1.5	0.15	0.94	1.8	4.3

Fishing production for 2007, is projected to decrease (compared to 2002) with the 7.2 t/km^2 phytoplankton biomass (Table 47). In contrast, an increase in phytoplankton biomass causes a rise in tonnes in 2007 compared to the value with a lower phytoplankton biomass (Table 47).

Table 47. Specific and total fishing harvest in 2007 after a phytoplankton biomass change. Species harvest and total fishing harvest were estimated using the Schaefer model. The catchability constant is 0.00003, effort remain constant compared to 2002 (table 44) and biomass values are presented in table 46

Phytoplankton biomass (t/km^2)	*Mugil curema* harvest (tonnes)	*Lutjanus sp* harvest (tonnes)	Gerrides harvest (tonnes)	*Centropomus sp* harvest (tonnes)	Total fishing harvest (tonnes)
3	0.06	0.0008	0	0	0.03
7.2	0.35	0.014	0.1	0.04	0.25
13	0.75	0.04	0.27	0.51	1.23

5.2.2 Fisheries Profits

Profits are calculated multiplying the price and the production minus costs. Prices per year were extracted from the National Statistics Book [149] and it is assumed that the price for 2002 is the same than for 2001. The national statistics book indicates the prices per specie per ton and since fishermen catch is given in dozens of fish, tonnes were estimated considering the average weight and size of fish.

Fishing cost is the opportunity cost of an hour working in agriculture, that is, 12.5 pesos an hour. If fishermen spend 5 hours, the cost per day is 62.5 pesos. In a year, the total effort is equivalent to 18 000 pesos.

Fishermen have small boats without motor only to cross the lagoon to arrive to the mouth. They can also arrive to the mouth walking through the beach. Since, boats are not always used they are not considered as a cost. Costs are assumed to be constant over time, consistent with experience in the agricultural sector. The number of fishermen is also assumed to be constant.

Fishing profits have risen since 1993 due to increase in the price of fish and the level of effort (table 48).

Table 48. Fishing profits from 1993 to 2002

	1993	1997	2000	2001	2002
Profits (Pesos)	55 725	174 299	215 399	235 358	289 516
Per capita profit a year	1 741	5 447	6 731	7 355	9 047

Profits for 2007 were projected assuming that effort and price are the same as for 2002 (Table 49). Profits are projected to be lower, with a phytoplankton biomass of 7.2 t/km^2 compared to 2002 and profits are projected to be higher with a phytoplankton biomass of 13 t/km^2 (Table 49). Profits per capita are similar to these described for the Guerrero coast, in Mexico where the average gain per year per capita is 7855 pesos [150].

Table 49. Fishing profits in 2007 after a change in phytoplankton biomass

	Phytoplankton at 3 t/km^2	Phytoplankton at 7.2 t/km^2	Phytoplankton at 13 t/km^2
Profits in 2007 (pesos)	-12 289	28 296	193 656
Profits per capita per year	-384	884	6 052

In sum, production has been increasing from 1993 to 2000. Phytoplankton biomass increase causes a rise in fish biomass, and consequently on harvest and profits in the short run. By contrast, if phytoplankton biomass increases to 13 t/km^2 harvest is projected to fall relative to 2002: harvest in 2002 was 1.84 tonnes with 7.2 t/km^2 phytoplankton, and harvest in 2007 is projected to be 1.23 tonnes with 13 t/km^2 phytoplankton. This can be seen Fig 19. If harvest is analyzed after 10 years of phytoplankton variation, harvest would increase again (fig 19 and 20).

Per capita profits are lower than in agriculture, confirming that fishing is a subsistence activity. Per capita fisheries profits are 9 047 pesos a year, that is 35 pesos a day during the fishing season, which compares to 247 pesos a day from agriculture.

If phytoplankton increases due to an augmentation of fertilizer use, fishermen could benefit now, but not necessarily in 5 years time. If phytoplankton biomass falls there will be negative consequences for the fishery. In other words, increases in fertilizer use in agriculture can benefit in a short run the fisheries sector but not necessarily in a long run.

5.3 Ecotourism production function and profits

Ecotourism production is measured by the number of visitors to a destination, in this particular case the Ventanilla community. The number of arrivals depends on socio-economic characteristics of tourists, ecological attributes of the locality and other inputs such as labour. Therefore, two different factors matter. One is the level of demand, that is, tourist characteristics and preferences. A second is the level of tourism inputs such as, labour.

Demand analysis allows us to know ecological preferences that are part of the inputs used for the productions function. Two questions need to be answered in order to include preferences in the production function:

-What ecological attributes affect tourism arrivals?

-What impact has environmental quality changes on repeat visits?

Once the two questions are answered it is possible to estimate the relationship between arrivals to Ventanilla, tourism inputs and the ecological attributes that attract tourists.

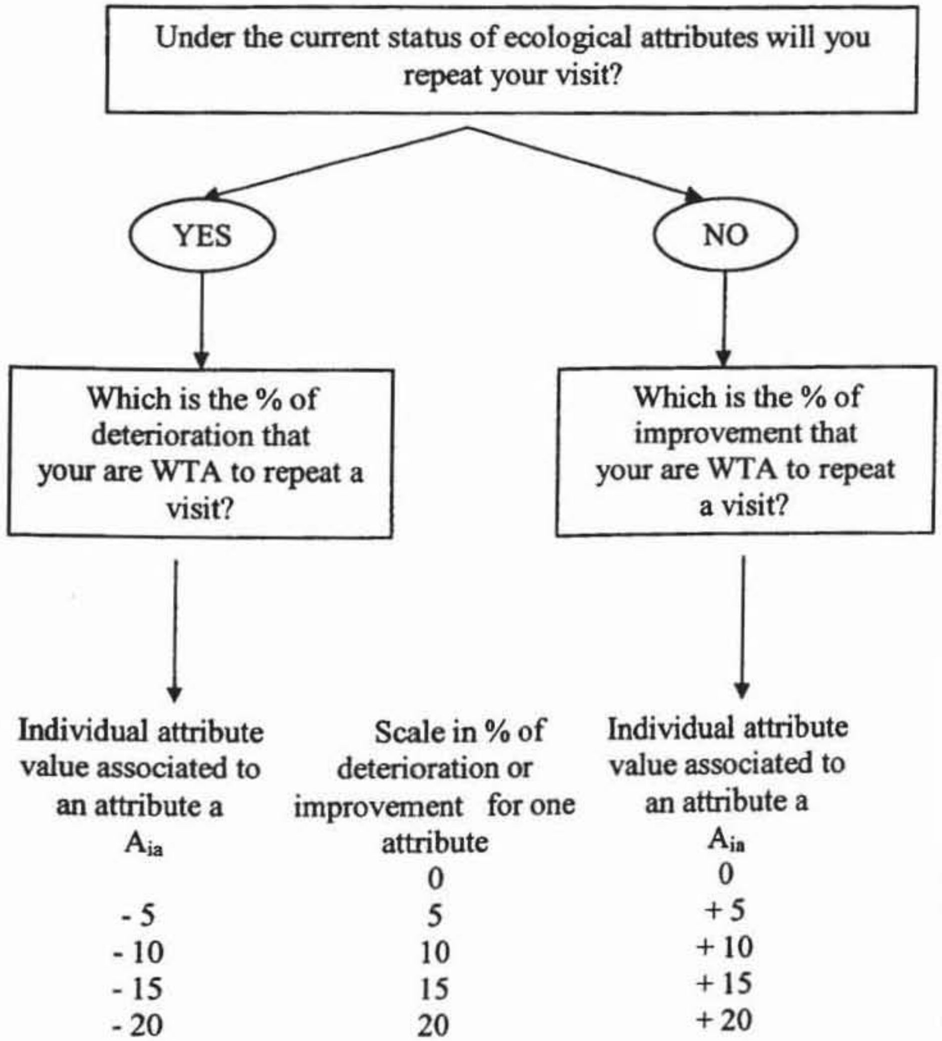
The details of the model are presented in chapter 3 section 3.2.7. The following sections, discuss the probability of repeat a visit depending on the ecological and socio-economic conditions. The production function is estimated as well as, the effect on profits when there is a decrease on environmental quality due to a high input on nitrogen run-off in the lagoon.

5.3.1 Importance of ecological attributes in the production function

The assessment of the main ecological attributes affecting tourism arrivals is based on the probability of repeating a visit in relation to changes on the environmental quality. It is based on a survey in Ventanilla and the method is described as well as the model results.

a. Survey method

A survey was carried out of Ventanilla visitors. A pilot survey of focus groups, was carried out during December 2002 and January 2003, with a total of nine groups and 84 persons. The survey was done during and after experiencing wildlife watching. One purpose was to determine how homogeneous visitors' perceptions of environmental quality were. For instance, the survey tested perceptions of abundance of birds or crocodiles. Results were used to develop the main survey in April and September 2003 and 552 structured questionnaires (Appendix B) were administered. The survey asks tourists about their socioeconomic profile, the effect of environmental changes on repeat visits. Both open and dichotomous questions were used in order to know socioeconomic characteristics of the individual, previous knowledge about Ventanilla, accommodation, length of stay, if they were in a tour, and if they had taken previous environmental courses. Respondents were asked to rank their reason for traveling (sun, hotel, nature, adventure) and nature preferences (mangrove, crocodiles, birds, community). Willingness to return despite a change in the environment was tested by asking respondents to consider a 20%, 50% and 70% increase or decrease in the mangrove area, in the abundance of crocodiles and birds (Fig 27). Other information was obtained on congestion, infrastructure opinion, income and travel expenses (travel cost to Oaxaca coast, trip cost to Ventanilla, expenses on accommodation, food and entertainment) (Appendix B). Results were analyzed using a the software for econometric analysis Limdep. A probit model was run, it is a model for binary response where the response probability is the standard normal distribution evaluated at a linear function of the explanatory variables [132]. The model is appropriate since we are trying to measure the probability of repeating a visit and the software is specific for econometric analysis providing specific information for economic analysis, such as elasticities.



For each individual *i* there is a value A_{ia} associated to attribute a. Since these are centered values the total value of an attribute $A_I = \Sigma A_{iI}$

Fig. 27 Willingness to accept an environmental quality change

b- Model results

i- Ecological attributes importance

Preferences for environmental attributes are related to four attributes: crocodiles and birds abundances, mangrove area and the fact that Ventanilla is a communitarian ecotourism cooperative. The willingness to repeat visits if there are changes in crocodiles, birds and mangrove are explored as shown in Figure 27.

General description of visitors:

Visitors' coming from Mexico was 86% compared to 6.5% coming from Europe. Specifically, 48% came from Mexico City and 13% from Oaxaca City. Visitors are mainly lodged in Huatulco (48%), followed by Puerto Escondido (12.45%). Accommodation in Ventanilla is non-existent but 35% of visitors are lodged in nearby villages such as Mazunte. Visitors arrive mainly by tours (41%) organized from Huatulco, by hotels or agencies for day trips to the region. Preferences for crocodiles, birds, mangrove and community were ranked between 4 and 1 from the most preferable to the least preferable. On average, visitors' preferred crocodiles (2.8) followed by mangrove, birds (2.4) and the ecotourism community (1.8).

Probit model results:

The results from estimating the model are given in Table 50. Amongst more than 40 variables considered originally (Appendix B), the variables shown in this table are the most relevant for the repeat visit decision. Preferences, willingness to accept changes in environmental quality and socio-economic variables are presented. The estimation was obtained by maximum likelihood method and the number of well predicted cases was 85.67%. The key findings are that crocodiles were the only aspect relevant to tourists willing to repeat a visit. Those visitors who valued the presence of crocodiles over birds or vegetation were more likely to revisit the site. However those who preferred birds or vegetation were not so enthusiastic to repeat a visit.

The mean values for the willing to accept changes in the environment presented in table 50 show that, visitors were willing to accept a 3% of deterioration in the mangrove forest, but looked for an increase by 5% in the number of crocodiles and 3.1% in the number of birds if they were to repeat their visit.

Table 50. Probability regression (Probit model) results.

Variable	Mean	Parameter estimates
Preferences		
Preferences on crocodiles	2.77	0.2621 (3.648)
Preferences on birds	2.42	-0.1390 (-1.879)
Preferences on community	1.81	-0.1808 (-2.737)
Preferences on mangrove	2.52	-0.039 (-0.054)
Purpose of visit: hotel	1.76	-0.2179 (-2.182)
Purpose of visit: nature	4.16	0.2971 (2.973)
Willingness to accept changes in environmental quality of		
Mangrove	2.95	0.0086 (2.016)
Crocodiles	-4.98	0.0134 (2.985)
Birds	-3.08	-0.001 (-0.125)
Socio-economic characteristics		
Age	29.53	0.0354 (2.917)
Income (pesos)	13 769	-0.0000162 (-1.595)
Travel cost (pesos)	880	-0.000115 (-1.881)
Daily expenses (pesos)	870	0.000244 (1.603)
Total cost / Income	0.16	0.00236 (2.053)
Staying in Huatulco	0.44	0.5200 (1.909)
Staying in Pto. Escondido	0.11	0.4781 (1.409)
Previous knowledge about the existence of turtles in Ventanilla	0.18	0.8881 (2.777)
Ecological courses taken	0.40	0.4920 (2.237)
Log likelihood function Number of observations Actual 1s and 0s correctly predicted t-ratios in parenthesis		-100.182 321 85.67%

The marginal effects are calculated in the probit model as the percentage change in the probability of repeat visits resulting from a marginal change in the variable. Thus, a 1% change in the number of crocodiles will vary the probability of repeating the visit by 0.18%. Similarly, a 1% mangrove biomass change would affect the probability of repeating a visit by 0.12%, whereas changes in the number of birds had no significant effect. The number of crocodiles is the only significant environmental attribute whereas changes in the current number of birds and mangrove size are not so relevant for the decision of repeating the visit. It indicates that the presence of crocodiles in the site is the main attraction for visitors and that special emphasis needs to be put on their conservation.

ii. Other aspects of demand

Among the socio-economic variables we consider age, travel costs and income. Prices are divided into travel cost to the coast of Oaxaca, travel cost to Ventanilla and average daily expenses in food, entertainment and accommodation. Total costs with respect to income is considered in order to find out if the visit to Ventanilla is considered as a normal or inferior good.

The three main parts of tourism demand are distributed such that, 11% of visitors are repeaters, 47% arrive by recommendation and 42% are visiting for the first time Ventanilla without any kind of previous experience or recommendation. From the survey, we obtained the number of visitors in each of the three categories (Table 51). Assuming the proportion of visitors repeating their visit and arriving by recommendation is constant overt time, the proportion of revisiting the site is 57.74%. This percentage represents the part of the demand for which changes in environmental quality will have a further impact. Hence, from the total number of visitors in 2002 (34,712 visitors), 20,042 visitors would repeat their visit in 2003.

Table 51. Potential repetition of visitors

Demand components	Values for each component
Number of visitors in 2002	34, 712
% of visitors repeating visit	10.58 %
% of visitors visiting by recommendation	47.16 %
Repetition rate	**57.74 %**
Potential visitors for 2003	**20, 042**

In terms of the purpose of the visit, two kinds of tourists can be distinguished: those who are interested in hotel entertainments and those who are keen in having contact with nature. Nature was extremely or very important for 78.9% of visitors. Hotel entertainment was not important for 48%. Moreover, 30% of visitors had already visited another coastal lagoon before and 41% had attended an ecological course. Interviewees were asked to rank their purposes of visit. Enjoying being in a hotel with entertainments was negatively related with repeat visits, whereas those who were willing to have contact with nature was positively related with repeat visits.

Both were ranked variables from 1 to 5, and a discrete change from one rank to another has a marginal change in the probabilities of repeating the visit of –3% and 4.1% respectively. Hence, we can distinguish two kinds of visitors with different willingness to repeat the visit, representing different market segments.

As expected, the length of the stay matters. Those tourists who had a longer stay of a month in Oaxaca were more likely to repeat the visit than those who have short stays.

Another interesting aspect of the study relates income and demand. 71% of visitors had low earnings. 38% had income less than $5 000 pesos per month, and 33% had income between $5 000 and $10 000 pesos per month. The study shows that recreation in the site may became inferior good because the parameter associated with income is negative and the parameter associated with the ratio between price and income is positively related with repeating visit. That is, visitors with low incomes were more likely to repeat the experience (measuring income in absolute terms and relative to price). Those people with high incomes were interested on alternative leisure options.

As expected, travel cost is negatively related with demand, but those visitors who spend more in a daily basis are more likely to come back. Both elasticities were very low, -0.016 and 0.034 respectively, but were not significant at the 5% level.

Since elasticity of income is also very low (-0.036), demand is inelastic with respect to changes in income and prices.

The insensitivity of demand to changes in the price (with respect to income) and the inverse relationship between repeat visits and income, may help for improve understanding of the implications of changes on the fee.

5.3.2. Ecotourism production function

Demand analysis shows that crocodile abundance is the main ecological attribute for visitors. The number of tourists Q_{v_i} depend biomass of crocodiles, which is proportionally related to the number of crocodiles that can be observed by visitors. A regression model was estimated in order to relate the number of arrivals, labour and biomass of crocodiles. The number of arrivals was extracted from the Ventanilla cooperative handbook for arrivals registration. Similarly, labour data were extracted from the Ventanilla cooperative costs handbook and includes the number of both members and workers.

Crocodile biomass for 2000 was estimated using information derived from a local population study [137] and for the following years the biomass was taken from the ECOSIM simulations. Input data are presented in table 52.

Table 52. Ecotourism production function inputs.

Year	Number of visitors	Number of workers and cooperative members	Crocodile biomass (t/km^2)
2000	26138	10	0.9
2001	32457	15	0.85
2002	34712	20	0.58

The regression shows a positive relationship between the number of arrivals and crocodile abundance as shown in table 53.

Table 53. Ecotourism production function results

Variable	Coefficient	t-ratio
Labour	1317	42.7
Crocodile biomass	14611	24
R-squared =0.99, F = 319, Autocorrelation: 2.9 n =3		

The estimated model is given by the following expression:

$$Q_{v_t} = 14611B_{c_t} + 1317L_{v_t}$$

where L_{v_t} is labour and B_{c_t} is the crocodile biomass at t in t/km^2

In order to relate ecotourism to the impacts from agriculture, the biomass of crocodiles was related to fish, phytoplankton and nitrogen variations as in chapter 3 section 3.2.7. The equation is as follows:

$$B_{c_t} = V\left(F_x\left(B_{p_t} + B_{p_t}\mu_{max}\left(\frac{N_t}{K_s + N_t}\right), \left(\frac{P*B_{m_t}}{100 + B_{m_t}}\right), \sum_j O_{xj_t}\right)\right)$$

where B_{p_t} is phytoplankton biomass in t/km^2, N_t is nitrogen concentration in water in mg/L, P* B_{m_t} is the percentage of mangrove biomass and $\sum_j O_{xj_t}$ is the predation of fish in t/km^2.

The crocodile biomass results are given by ECOSIM and presented in table 54.

Table 54. Crocodile biomass estimation after a change environmental quality Nitrogen concentration, phytoplankton and mangrove biomass are estimated as shown in chapter 3 and 4. Crocodile biomasses are given by the ECOSIM.

Percent of change	Nitrogen concentration in water (mg/L)	Phytoplankton biomass (t/km^2)	Mangrove biomass (t/km^2)	Crocodile biomass after 5 years (2007) (t/km^2)	Crocodile biomass after 10 years (2012) (t/km^2)
+20	44	13.16	31.2	0.56	0.85
+50	53.5	13.3	39	0.58	0.92
+70	59.3	13.45	44.2	0.6	0.9
-20	31.4	12.75	20.8	0.57	0.7
-50	23.3	12.32	13	0.46	0.57
-70	18	11.91	7.8	0.46	0.46

An increase in nitrogen, phytoplankton or mangrove initially has little effect on crocodile biomass but after 10 years, 50% increase in nitrogen and phytoplankton leads to an increase in crocodile biomass. Output in 2007 and 2012 was estimated using the regression model and the simulated crocodile biomass. Results are presented in table 55 where an increase in arrivals is related to the percent of change in crocodile biomass.

Table 55. Ventanilla arrivals in 2007 and 2012 after a change in crocodile biomass. Arrivals are estimated using the ecotourism production function. Labour remains constant

Equivalent percent of change in crocodile biomass	Arrivals in 2007	Arrivals in 2012
+20	34 522	38 759
+50	34 814	39 782
+70	35 107	39 490
-20	34 668	36 568
-50	33 061	34 668
-70	33 061	33 061

5.3.3 Ecotourism profits

Cooperative profits were estimated using tourism arrivals Q_{v_t} multiplied by the price of the boat trip P_{v_t} minus costs C_{v_t}, as follows:

$$\Pi_{v_t} = P_{v_t} Q_{v_t} - C_{v_t}$$

Average labor costs per year were extracted from Ventanilla cooperative costs handbook (2000 to 2003 data) (Table 56). Cost increases related to because the number of workers. Price is the price of the trip in the boat which is 35 pesos per person. The effect on profits are presented in table 57.

Table 56. Ecotourism cooperative labor costs

Year	Costs (pesos)
2000	48 096
2001	140 109
2002	147 075

Table 57. Ventanilla cooperative profits

Years	Profits (pesos)
2000	736 044
2001	833 601
2002	1 067 845

Table 57 shows an increase in profits over time, implying that the number of arrivals have been increasing more than proportionately to costs. Profits for 2007 and 2012 are showed in table 58.

Table 58. Profits 5 and 10 years after a change in crocodile population biomass

Equivalent percent of change in crocodile biomass	Profits after 5 years (2007)	Profits after 10 years (2012)
+70	1 081 656	1 235 072
+50	1 071 428	1 245 299
+20	1 061 201	1 209 502
-20	1 066 314	1 132 795
-50	1 010 062	1 066 314
-70	1 010 062	1 010 062

Profits increase proportionally to tourist arrivals and the crocodile biomass. After 5 years, arrivals and profits increase when the crocodile population increases by 50%, and by 20% after 10 years. But population growth depends on the lagoon area. In contrast profits are affected after 5 years when decreasing the crocodile population by 20% and after 10 years when decreasing the population by 50%. Cooperative profits are high related to rural conditions in Oaxaca. In 2002, profits were 1 067 845 pesos, implying a gain per capita of around 7400 pesos a month, which is 247 pesos a day similar to the gain by agriculture.

In sum, crocodiles are the main attraction for tourists and changes on crocodile population would affect ecotourism arrivals. There is no willingness to accept deterioration and ecotourism is an inferior commodity. In the ECOSIM simulation, it was shown that crocodiles are affected after 10 years when phytoplankton and mangrove decrease by 70%. Under those conditions, the crocodile population would decrease and would affect ecotourism arrivals. In extreme conditions of pollution, eutrophication of the lagoon would cause the death of fish which would affect crocodiles as shown in the ECOPATH results. However, crocodiles could vary their diet to include birds or turtles or even migrate. However, it does require an increase in nitrogen run- off 70% to affect ecotourism arrivals.

Chapter 6.

Profit maximization and externalities

Maximization of the net benefits of agriculture, fisheries and ecotourism separately serves the interests of each activity, but ignores the effects that any one activity has on the others. This is the problem addressed in this chapter.

6.1 Profit maximisation: the "private" problem

6.1.1 Fisheries

Fishermen are assumed to maximise profits by choosing the level of fishing effort. The problem is of the following form:

(6.0)

$$\text{Max}_{E_t}\ \Pi_{h_t} = P_{h_t}\, Q_{h_t} - P_{E_t}.E_t$$

P_{h_t} is the average price of fish, Q_{h_t} is output, P_{E_t} is the price of effort, E_t is the effort.

The fishery profit function was described in chapter 3, equation *3.6* as follows:

(6.1)

$$\Pi_{h_t} = P_{h_t} \sum_{x}^{4} qE_t B_{x_t} - P_{E_t}.E_t$$

Since output is assumed to depend on catchability, effort and stock size, the first order conditions for fishing profits to be maximised include:

$$\frac{d\Pi_{h_t}}{dE_t} = P_{h_t} \sum_{x}^{4} q\, B_{x_t} - P_{E_t} = 0$$

implying that:

$$P_{h_t} \sum_{x}^{4} q\, B_{x_t} = P_{E_t}$$

In other words the marginal benefit of fishing effort should be equal to the marginal costs.

6.1.2 Agriculture

Agricultural profits are assumed to be maximised by choice of fertilizer applications, here approximated by nitrogen run-off. Other inputs are assumed to be in fixed proportions. This enables us to focus on the source of the external effect of agriculture on both fisheries and tourism. The farmer's problem is accordingly of the following form:

(6.2)

$$\mathrm{Max}_{R_t}\, \Pi_{a_t} = P_{a_t}\, Q_{a_t} - P_{l_t} L_{a_t} - P_{R_t} R_t$$

where P_{a_t} is the sum of the price of each crop cultivated in the catchment, Q_{at} is the production function, P_{l_t} is price of labour, L_{a_t} labour, P_{R_t} is the price of fertilizer and R_t is our indirect measure of fertilizer use.

Given the linear form of the production function:

(6.3)

$$Q_{a_t} = \beta_{L_t} L_{a_t} - \beta_{W_{a_t}} W_{a_t} + \beta_{R_t} R_t$$

Profits can be written using the equation *6.3*:

(6.4)

$$\Pi_{a_t} = P_{a_t}\left(\beta_{L_{a_t}} L_{a_t} - \beta_{W_{a_t}} W_{a_t} + \beta_{R_t} R_t\right) - P_{L_{a_t}} L_{a_t} - P_{R_t} R_t$$

In order to maximize profits it is necessary to satisfy the following first order condition:

$$\frac{d\Pi_{a_t}}{dR_t} = P_{a_t}\left(\beta_{R_t}\right) - P_{R_t} = 0$$

Implying that:

$$P_{a_t}\left(\beta_{R_t}\right) = P_{R_t}$$

Once again, this requires that the marginal benefits of fertilizer use are equal the marginal private cost of fertilizer.

6.1.3 Ecotourism

Ecotourism profits are maximised by choosing to the labour committed to tourist activities.

The tourist operator's problem accordingly has the following form:

(6.5)

$$\mathrm{Max}_{L_{v_t}}\, \Pi_{v_t} = P_{v_t}\, Q_{v_t} - P_{Lv_t} . L_{v_t}$$

where P_{v_t} is price of the trip, Q_{v_t} is output, measured in terms of tourists, P_{Lv_t} is the price of labour and L_{v_t} is labour.

Tourism output is assumed to be a linear function of crocodile biomass and labour as follows:

$$Q_{v_t} = \beta_{c_t} B_{c_t} + \beta_{L_{v_t}} L_{v_t} \tag{6.6}$$

where B_{c_t} is the crocodile biomass

Using this expression the problem can be written as:

$$\text{Max}_{L_{v_t}} \Pi_{v_t} = P_{v_t}\left(\beta_{c_t} B_{c_t} + \beta_{L_{v_t}} L_{v_t}\right) - P_{Lv_t} L_{v_t} \tag{6.7}$$

Once again the first order conditions require that:

$$\frac{d\Pi_{v_t}}{dL_{v_t}} = P_{v_t}\beta_{L_{v_t}} - P_{Lv_t} = 0$$

Implying that:

$$P_{v_t}\beta_{L_{v_t}} = P_{Lv_t}$$

The marginal revenue product of tourism labour is equal to its marginal cost.

In each case – fisheries, agriculture and tourism – these specifications of the production function assume that the activities are independent. In reality, they are not. The next step is to re-specify the problem in a way that acknowledges the existence of interdependency between the activities.

6.2 Agriculture, fisheries and ecotourism joint profit maximization

A joint profit maximization problem for agriculture, fisheries and ecotourism was described in chapter 3. Joint profit is the sum of each activity profits. In this section we consider a joint profit function in which the interactions between activities reflect the effect of nutrient loading on fish and crocodile biomass. In particular, fish and crocodile biomass depend on phytoplankton biomass, which in turn depends on nutrient loads.

Phytoplankton biomass $B_{p_{t+1}}$ is given by the equation as follows:

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

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 section 4.2.4 nitrogen concentration was assumed to bear a linear relation to nitrogen run-off, water extraction and time:

$$N_t = \beta_{R_t} R_t - \beta_{W_t} W_t + \beta_t t \, .$$

Replacing N_t in the phytoplankton $B_{p_{t+1}}$ equation we obtain:

$$B_{p_{t+1}} = B_{p_t} + B_{p_t} \mu_{\max} \left(\frac{\beta_{R_t} R_t - \beta_{W_t} W_t + \beta_t t}{\mathrm{K}_s + (\beta_{R_t} R_t - \beta_{W_t} W_t + \beta_t t)} \right)$$

where the term in brackets is denoted J

(6.8)

$$B_{p_{t+1}} = B_{p_t} + B_{p_t} \mu_{\max} J$$

Using equation *6.8* the profit functions now take the following form for each activity:

Agriculture profit function (equation *6.4*) is as follows:

$$\Pi_{a_t} = P_{a_t} \left(\beta_{L_{a_t}} L_{a_t} - \beta_{W_{a_t}} W_{a_t} + \beta_{R_t} R_t \right) - P_{L_{a_t}} L_{a_t} - P_{R_t} R_t$$

Fisheries profit function

Fisheries production depends on fish biomass given by equation *3.7*:

$$B_{x_t} = \mathrm{F}\left(B_{p_t} + B_{p_t} \mu_{\max} \left(\frac{N_t}{\mathrm{K}_s + N_t} \right), \left(\frac{\mathrm{P} * B_{m_t}}{100 + B_{m_t}} \right), \sum_j O_{xj_t} \right)$$

The function $\mathrm{F}(.)$ was estimated in section 4.3.3 using ECOSIM. Simulations in ECOSIM allow variations in phytoplankton, mangrove biomass and fish predation. The equations obtained using ECOSIM relate fish biomass and phytoplankton in a quadratic function for the majority of species. Therefore, it is assumed that for any of the four species of fish, there is a quadratic relationship between phytoplankton and fish biomass as follows:

(6.9)

$$B_{x_t} = \mathrm{a}\left(B_{p_{t+1}} \right)^2 + \mathrm{b} B_{p_{t+1}} + \mathrm{c}$$

where B_{x_t} is the fish biomass, $B_{p_{t+1}}$ is the phytoplankton biomass after a change in nitrogen concentration in water.

Since $B_{p_{t+1}}$ depends on nitrogen run-off as shown in equation (*6.8*), fish biomass also depends on nitrogen run-off $B_{x_t}(R_t)$.

Replacing $B_{P_{t+1}}$ in equation *6.9* using equation *6.8* we obtain:

$$\Pi_{f_t} = P_{f_t}\sum_{x}^{4} \mathrm{q}E_t\left(\mathrm{a}\left(B_{P_t}+B_{P_t}\mu_{\max}J\right)^2+\mathrm{b}\left(B_{P_t}+B_{P_t}\mu_{\max}J\right)+\mathrm{c}\right)-P_{E_t}E_t$$

and simplifying the expression knowing that the equation in parenthesis is $B_{x_t}(R_t)$ we obtain:

(6.10)

$$\Pi_{f_t} = P_{f_t}\sum_{x}^{4} \mathrm{q}E_t B_{x_t}(R_t)-P_{E_t}E_t$$

Ecotourism profit function

Ecotourism depends on two things: crocodile biomass and labour (as shown in equation *6.7*). The ECOSIM simulation reported in section 4.3.3 shows the relationship between crocodile biomass, mangrove and phytoplankton biomass. The general form of the equation is as follows:

(6.11)

$$B_{c_t} = \mathrm{s}\left(B_{P_{t+1}}\right)^3+\mathrm{m}\left(B_{P_{t+1}}\right)^2+\mathrm{n}\left(B_{P_{t+1}}\right)+\mathrm{z}$$

Since phytoplankton depends on nitrogen run-off as shown in equation *6.8* crocodile biomass also depends on it : $B_{c_t}(R_t)$

Thus, using equation *6.12* in equation *6.7* we have an ecotourism profit function that includes, as an argument, nitrogen run-off.

$$\Pi_{v_t} = P_{v_t}\left[\beta_{c_t}\left[\begin{matrix}\mathrm{s}\left(B_{P_t}+B_{P_t}\mu_{\max}J\right)^3+\mathrm{m}\left(B_{P_t}+B_{P_t}\mu_{\max}J\right)^2+\\ \mathrm{n}\left(B_{P_t}+B_{P_t}\mu_{\max}J\right)+\mathrm{z}\end{matrix}\right]+\beta_{L_{v_t}}L_{v_t}\right]-P_{Lv_t}L_{v_t}$$

Simplifying the expression replacing the term in brackets by $B_{c_t}(R_t)$ we obtain:

(6.12)

$$\Pi_{v_t} = P_{v_t}\left[\beta_{c_t}\mathrm{B}_{c_t}(\mathrm{R}_t)+\beta_{L_{v_t}}L_{v_t}\right]-P_{Lv_t}L_{v_t}$$

Joint profits

Joint profit is the sum of the profits of each activity as follows:

$$\Pi_{s} = \Pi_{f_t}+\Pi_{a_t}+\Pi_{v_t}$$

Using equations *6.4* for agriculture, *6.10* for fisheries and *6.12* for ecotourism the sum of profits is as follows:

$$\Pi_t = P_{h_t}\sum_{x}^{4} q E_t B_{x_t}(R_t) + P_{a_t}\left(\beta_{L_a} L_{a_t} - \beta_{W_a} W_{a_t} + \beta_R R_t\right) + P_{v_t}\left[\beta_{c_t} B_{c_t}(R_t) + \beta_{L_v} L_{v_t}\right]$$
$$- P_{E_t} E_t - P_{L_w} L_{a_t} - P_{R_t} R_t - P_{Lv_t} L_{v_t}$$

For a social optimum, the first order necessary conditions require that the derivatives of the social profit function with respect to fertilizer use, fishing effort and tourism labour be equal to zero. More particularly, they require that:

$$\frac{d\Pi}{dE_t} = P_{h_t}\sum_{x}^{4} q\, B_{x_t}(R_t) - P_{E_t} = 0$$

$$P_{h_t}\sum_{x}^{4} q\, B_{x_t}(R_t) = P_{E_t}$$

It can be seen that profits in tourism and fisheries are a quadratic function of phytoplankton. Thus, profits increase with phytoplankton growth up to some maximum point of phytoplankton growth, after that, profits will decrease.

There are two externalities. The first is from fertilizer use to both fisheries and tourism. The second is from fisheries to tourism.

Since the biomass of fish is quadratic with respect to phytoplankton, the externality of agriculture on both fisheries and tourism is positive up to some maximum and negative after that.

Since, crocodile abundance is directly related to fish biomass, the externality of fishing effort on ecotourism works through the abundance of fish.

In Tonameca, fishing and ecotourism take place in different parts of the mangrove system. Ecotourism take place in the smaller lagoon and fishing in the main lagoon. The lagoons are connected via the mangrove area when river flooding is high. Therefore, the effects of fishing effort on tourism might be expected to be only intermittent.

In the tourism sector since

$$\frac{d\Pi}{dL_{v_t}} = P_{v_t}\beta_{L_{v_t}} - P_{Lv_t} = 0$$

there is no externality from ecotourism to fishing or agriculture. Ecotourism does not affect either fishing or fish biomass. If motor boats were used, pollution produced could represent an externality but this is not the case in Tonameca.

To see the impact of agriculture on fisheries and ecotourism profit, those sectors are expressed firstly in terms of phytoplankton biomass, and secondly in terms of nitrogen run-off.

(1) Equation *6.10* expresses fisheries profits as a function of phytoplankton biomass as follows:

$$\Pi_{h_t} = P_{h_t}\sum_{x}^{4} \mathrm{q}\, E_t\left(\mathrm{a}_x\left(B_{p_{t+1}}\right)^2 + \mathrm{b}_x\left(B_{p_{t+1}}\right) + \mathrm{c}_x\right) - P_{E_t}.E_{x_t}$$

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

$$\frac{d\Pi_{(h)_t}}{dR_t} = \frac{d\Pi_{h_t}}{dB_{p_{t+1}}}.\frac{dB_{p_{t+1}}}{dR_t}$$

$$\frac{d\Pi_{(h)_t}}{dR_t} = P_{h_t}\sum_{x}^{4} \mathrm{q}\, E_t\left(2\mathrm{a}_x\left(B_{p_{t+1}}\right) + \mathrm{b}_x\right).\frac{dB_{p_{t+1}}}{dR_t}$$

(2) Its impact on ecotourism profits is derived in the same way:

$$\Pi_{v_t} = \left(P_{v_t}\beta_{c_t}\left(\mathrm{s}\left(B_{p_{t+1}}\right)^3 + \mathrm{m}\left(B_{p_{t+1}}\right)^2 + \mathrm{n}\left(B_{p_{t+1}}\right) + z\right) + \beta_{L_{v_t}}L_{v_t}\right) - P_{Lv_t}.L_{v_t}$$

$$\frac{d\Pi_{v_t}}{dR_t} = \frac{d\Pi_{v_t}}{dB_{p_{t+1}}}.\frac{dB_{p_{t+1}}}{dR_t}$$

where

$$\frac{d\Pi_{v_t}}{dR_t} = P_{v_t}\beta_{c_t}\left(3\mathrm{s}\left(B_{p_{t+1}}\right)^2 + 2\mathrm{m}\left(B_{p_{t+1}}\right) + \mathrm{n}\right).\frac{dB_{p_{t+1}}}{dR_t}$$

(3) The derivative of agriculture with respect to nitrogen run-off is:

$$\frac{d\Pi_{a_t}}{dR_t} = P_{a_t}\beta_{Rt} - P_{Rt}$$

To get the overall impact of fertilizer applications, we sum of the derivatives (1)+(2)+(3) to get:

$$\left[P_{h_t}\sum_{x}^{4} \mathrm{q}\, E_t\left(2\mathrm{a}_x B_{p_{t+1}} + \mathrm{b}_x\right) + P_{v_t}\beta_{c_t}\left(3\mathrm{s}\left(B_{p_{t+1}}\right)^2 + 2\mathrm{m}B_{p_{t+1}} + \mathrm{n}\right)\right].\frac{dB_{p_{t+1}}}{dR_t} + P_{a_t}\beta_{Rt} - P_{Rt}$$

where

$$B_{p_{t+1}} = B_{p_t} + B_{p_t}\mu_{\max}\left(\frac{\beta_{R_t}R_t - \beta_{W_t}W_t + \beta_t t}{\mathrm{K}_s + (\beta_{R_t}R_t - \beta_{W_t}W_t + \beta_t t)}\right)$$

Since the derivative of phytoplankton biomass $B_{P_{t+1}}$ with respect to nitrogen run-off is:

$$\frac{dB_{P_{t+1}}}{dR_t} = B_{P_t}\mu_{\max}\frac{\beta_{R_t}K_s}{\left(K_s + (\beta_{R_t}R_t - \beta_{W_t}W_t + \beta_t t)\right)^2}$$

we have that:

$$\frac{d\Pi_t}{dR_t} = \left[\left(P_{x_t}qE_t\sum_{x}^{4}2a_x\left(B_{P_{t+1}}\right)+b_x\right)+\left(P_{v_t}\beta_{B_{ct}}\left(3s\left(B_{P_{t+1}}\right)^2+6sm\left(B_{P_{t+1}}\right)+3sn\right)\right.\right.$$

$$\left.\mu_{\max}\frac{B_{P_t}\beta_{R_t}K_s}{\left(K_s+\beta_{R_t}R_t-\beta_{w}W_t+\beta_t t\right)^2}\right]+\left(P_{a_t}\beta_{R_t}-P_{R_t}\right)$$

Since fertilizers have both positive and negative (external) effects, the socially optimal level of fertilizer applications requires that the marginal benefits of fertilizer applications be equal to the marginal costs. From the joint profit function

$$\Pi_t = P_{x_t}\sum_{x}^{4}qE_tB_{x_t}(R_t)+P_{a_t}\left(\beta_{L_w}L_{a_t}-\beta_{W_a}W_{a_t}+\beta_{R_t}R_t\right)+P_{v_t}\left[\beta_{c_t}B_{c_t}(R_t)+\beta_{L_{v_t}}L_{v_t}\right]$$
$$-P_{E_t}E_t-L_{t_w}L_{a_t}-P_{R_t}R_t-P_{L_{v_t}}L_{v_t}$$

it follows that the socially optimal level of R_t should be selected to satisfy:

$$\Pi_t = P_{x_t}\sum_{x}^{4}qE_t\frac{dB_{x_t}(R_t)}{d(R_t)}+P_{a_t}\frac{dQ_{a_t}(R_t)}{dR_t}+P_{v_t}\left[\frac{d\beta_{c_t}B_{c_t}(R_t)+\beta_{L_{v_t}}L_{v_t}}{d(R_t)}\right]-P_{R_t}=0$$

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 find the optimal value of R in terms of the expressions obtained from the ECOPATH specification of the relation between crocodile, fish and phytoplankton biomass and fertilizer run-off, Mathematica 5 was used to obtain the following cumbersome expression:

(6.13)

$$R_t = -\frac{1}{3s\beta_{B_{ct}}\beta_{R_t}K_s\mu_{\max}{}^2B_{P_t}^2P_{v_t}}+D+M$$

where

$$D = 3sm\beta_{R_t} K_s \mu_{max}^2 B_{P_t}^2 + 3s\beta_{B_{ct}} \beta_{R_t} \beta_t t K_s \mu_{max}^2 B_{P_t}^2 P_{V_t} - 3s\beta_{B_{ct}} \beta_{R_t} \beta_w W K_s \mu_{max}^2 B_{P_t}^2 P_{V_t}$$
$$+ a_z \beta_{R_t} K_s q P_{h_t} E_t B_{P_t}^2 \mu_{max}^2$$

and

$$M = \sqrt{\begin{array}{l} \mu_{max} B_{P_t} (-3s^2 \beta_{B_{ct}} \beta_{R_t} K_s \mu_{max} B_{P_t}^2 P_{V_t}^2 + \mu_{max} B_{P_t} (3sm\beta_{R_t} K_s \mu_{max} B_{P_t} + a_z K_s \mu_{max} q P_{h_t} E B_{P_t})^2 \\ -3s\beta_{B_{ct}} \beta_{R_t} K_s \mu_{max} B_{P_t} P_{V_t} (3sn\beta_{R_t} K_s \mu_{max} B_{P_t} + 6sm\beta_{R_t} K_s \mu_{max} B_{P_t}^2 + \beta_{R_t} P_{a_t} + 2a_z (b_z + B_{P_t}) \\ \beta_{R_t} K_s q P_{h_t} E_t \mu_{max} B_{P_t} - P_{R_t})) \end{array}}$$

and the constant values are as follows:

$s=0.0005$, $m=-0.009$, $n=0.06$, $\beta_t=0.49$, $\beta_{B_{ct}}=14611$, $\beta_w=0.062$, $\beta_{R_t}=18.04$,

$a_z=0.024$, $b_z=-0.21$, $K_s=10$, $\mu_{max}=1$

6.3 Social welfare

At the optimal levels of effort, E_t*, labour, L_t* and fertilizer use, R_t*, described in the previous section, social welfare is maximised.

The optimal level of fertilizer use is indicated in Figure 28. This shows the range of values of R_t at which the effects of fertilizer use on other sectors is negative. It also shows the level of R_t at which the marginal net private benefits of fertilizer use equal the marginal external cost.

R_t solution is the optimal point R_t* between the marginal damage of fertilizer use and the marginal benefit of agriculture.

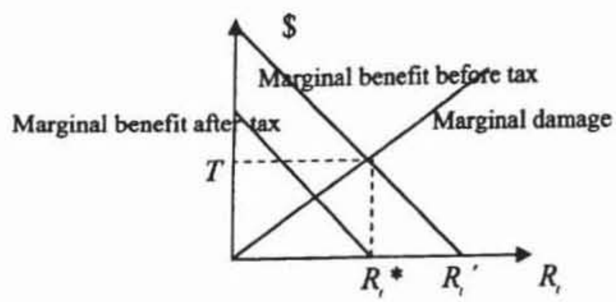


Fig 28. Optimum level of nitrogen run-off. R_t is nitrogen run-off at time t, R_t' is the nitrogen run-off at the maximum benefit before paying a tax, R_t* is the optimum nitrogen run-off, that is when marginal benefit equal marginal damage. The marginal damage at the optimal level of fertilizer use is the shadow price for an efficient rate of emission tax T.

If fertilizer use is less than the efficient level of pollution R_t* the marginal benefit of pollution is more than the marginal damage. But if the level of fertilizer use is more than R_t* the marginal benefit is less than the marginal damage from pollution.

The marginal damage at the optimal level of fertilizer use is T. T is equivalent to the shadow price for an efficient rate of emission tax or subsidy. It is also called the shadow price of the externality.

The shadow price can be applied as a tax (or subsidy) for agriculture for using less (or more) fertilizer.

It also can be used as an indirect measure of the value of conserving water as an ecosystem service. Ecotourism and fisheries are benefited when water quality is consistent with levels of fertilizer use that are less than R_t*. In that case, agriculture producers can be compensated by the fishermen and the ecotourism cooperative. The shadow price is the value that ecotourism and fisheries would have to pay to agriculture for not polluting water.

Joint profit maximisation also shows the optimum point for effort E_t* and labour L_t*.

Neither fisheries nor ecotourism are thought to have any external effects on the other. At the optimum level of effort, E_t* (Fig 28.), the marginal private net benefits are equal to zero. In this case T can be used as the compensation value from farmers to fishermen. Since fishing does not take place in the same part of the Tonameca lagoon where ecotourism is carried on, there is no negative externality of fisheries on tourism and the value is not assessed.

In the case of ecotourism L_t* is reached when marginal costs equal marginal revenues of ecotourism and no externality is observed to fishing or agriculture.

This chapter shows that when farmers, fishers and tour operators optimise their profits independently, the effects from one activity to the other are ignored. Lastly, given the relation between phytoplankton, fish, crocodiles and fertilizer, the optimal level of fertilizer application in agriculture is actually greater than the current level of fertilizer use. In order to understand the robustness of this result, it is important to remember that phytoplankton biomass is estimated using water quality data collected for one year and an estimation of nitrogen run-off from national statistics. Moreover, other social and political aspect, mentioned in the last chapter, need to be considered before implementing an environmental policy.

Chapter 7.

Implications for the Management of the Tonameca Watershed and Conclusions

7.1 The Mexican framework for watershed and coastal management

Coastal management in Mexico is designed (a) to protect the quality and productivity of coastal waters, (b) to encourage an ecosystem approach and (c) to address issues such as fisheries and coastal land development [151]. Similarly, watershed management aims to protect the quality and productivity derived from freshwater [151], focusing exclusively on water management and administration instead of promoting an integrated use of natural resources [152].

Coastal and watershed management are linked in an integrated way in terms of natural resources, socio-economics and institutions. Thus, upstream and coastal areas share natural resources such as water and have socioeconomic links such as the externalities between activities of fishing, tourism and agriculture. Both topics have been addressed in this thesis. Institutional links are also very important since different ministries, laws and programs are involved in the management process. Planning, regulations and economic instruments are similar for coastal and watershed management (Table 59) and national environmental instruments can be applied to the Tonameca watershed.

The legal framework can be divided into 4 main areas (Table 59): natural resources use, rural development, federal fees and agrarian rights. In some cases, the law is not sufficiently clear and this generates confusion in institutional functions. In order to properly integrate coastal and watershed management, the coastal zone can be delimited from the upper limit of the watersheds to the sea.

Table 59. Coastal and watershed management instruments, ministries involved and main problems

	Integrated coastal zone management (ICZM)	Integrated watershed management (IWM)
Definitions	Continuous and dynamic process by which decisions are made for sustainable use, development and protection of the coastal zone [39]	Organized and coherent management of all the components of a territory, articulated by an hydrological system defined by the watershed limits [153]
Natural habitats	Coastal lagoons, mangrove, coral reefs, islands, beach, sea, dry forest, dunes, tropical forest	All kinds of forests, deserts, dunes, lakes
Main activities	Fisheries, tourism, oil exploitation, wildlife use	Mining, agriculture, wildlife use, freshwater fisheries, tourism, forestry
Laws	General Law of the Ecological Equilibrium and Environmental Protection (LEGEEPA), National Waters Law (Ley de Aguas Nacionales), Fisheries Law (Ley de Pesca), National Goods Law (Ley de Bienes Nacionales), Law of Sustainable Rural Development (Ley de Desarrollo Rural Sustentable), General Law of Wildlife (Ley de Vida Silvestre), Federal Law of Rights (Ley Federal de Derechos), Law of Human Settlements (Ley de Asentamientos Humanos), Law of Agrarian Reform (Ley de la Reforma Agraria) Forestry Law (Ley Forestal) Federal Tourism Law (Ley Federal de Turismo) Public Constructions Law (Ley de Obras Publicas) Expropriation Law (Ley de expropiación) Only for ICZM: Federal Law of the Sea (Ley Federal del Mar) Ports Law (Ley de Puertos) Navigation Law (Ley de Navegación)	
Planning Instruments	Ordinance of the territory Natural Protected areas Use and Conservation Wildlife Units (UMA) Sectors Programs	
Instruments for Regulation	Norms Environmental impact assessments Permits Concessions Rights of access Closure season and areas National Fisheries Chart	

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(Table 59 cont.) Economic instruments	Fiscal: natural protected areas fees, fees for natural resources use, depreciation for polluting infrastructure, none tariff to non polluting infrastructure, environmental services payments Financial: funds, fiduciary, SWAPS (credits, deposits, insurances)Market: concessions, certifications, fare trade	
Social participation instruments	Fisheries State Committees State Councils of Sustainable Development	Watershed councils State Councils of Sustainable Development
Main Ministries	Ministry of Environment and Natural Resources (SEMARNAT) Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) Ministry of Communications and Transport (SCT) Ministry of Social Development (SEDESOL) Ministry of Tourism (SECTUR) Ministry of Agrarian Reform (SRA) For ICZM: Ministry of Marine Affairs (SEMAR)	
Specific problems	-Legal definition of coastal zone -Lack of a coastal law -Lack of coordination and clear institutions functions -Management process monitoring -Lack of political strategies for conflicts zones -Lack of an integrated use of instruments	-Legal definition of watershed limits -Lack of coordination and clear institutions functions -Management process monitoring -Lack of political strategies for conflicts zones -Lack of watershed local authorities, -Watershed councils auto-financing -Water councils and watershed councils are homologous instead of having different roles. -Lack of an integrated use of instruments

Sources: [154-156]

A range of environmental planning instruments are used for Integrated Coastal Zone Management (ICZM) and Integrated Watershed Management (IWM) (Table 59).

The Ecological Ordinance of the Territory (OET) determines the economic activities and development based on the physical, ecological and social characteristic of a region [156]. In México, 118 OETs exist and 31 have being decreed [156]. The OET is an instrument that is used in combination with other planning instruments such as natural protected areas, but can also be a regulation instrument in itself if it is decreed. The OET has been developed on occasions for one sector, such as the fisheries ordinances, but the approach has been criticized [154] and more flexible and social participation has been recommended [156]. The OET has been used at the local scale through Community Land Ordinances (OCT). In Oaxaca, 36 OCTs covering 400 000 hectares have been supported by non-governmental organizations and federal government programs [157]. OCTs have been used by communities with ecological projects or with certified organic production. The OCT allows planning and regulation of natural resource use at a local scale and has been used successfully by communities in Oaxaca for sustainable resource management [157]. The OCT can be applied to the Tonameca watershed especially to the Ventanilla community but the OET would provide a regional approach.

Natural protected areas aim to preserve natural resources and genetic diversity as well as to maintain their sustainable use. In Mexico, natural protected areas have zones designated for preservation whilst others are reserved for sustainable exploitation. The implementation of management programs associated with natural protected areas is difficult because of the lack of institutional capacity for vigilance and enforcement and for financing alternative productive projects. Moreover, entrance fees to natural protected areas do not reflect the ecosystem values and are not directly administered by the park, the fees being directed to the Ministry of Finance [156]. In the Tonameca watershed no natural protected areas exist and no areas reach the national criteria in terms of biodiversity for establishing one.

The Use and Conservation Wildlife Units (UMAS) is a scheme for the sustainable production and commercial exploitation of wildlife species. In addition, the program regulates the production, use and commercialization of endangered species.

It provides an incentive for diversifying production in rural areas, since it is possible to commercially produce an endangered species but a management program must be in place and sometimes repopulation is required. The UMAS can be operated by a person or an organization. Intensive and extensive units exist for different purposes such as commercialization, ecotourism and conservation. The implementation of UMAS in Tonameca is discussed below.

There are many government sector programs. The most important ones concern topics such as water use, wildlife use, natural protected areas, national development program, environment programs, rural development programs and many others. Water use and treatment is an important factor for establishing integrated management programs. Agriculture is the main activity which consumes water and urban discharges represent the primary source of water pollution [38]. The National Commission of Water (CNA) is in charge of applying the regional program of hydraulic planning, to increase the area of irrigation, as well as the infrastructure for potable water and sewage treatment. The program emphasizes the need for a sustainable use of water but at the same time recognizes the necessity of increasing irrigation for agricultural production. The hydraulic program recognizes that the main problems are the inefficient use of water, a lack of sewage treatment plants and water balance studies as well as integrated watershed management programs (see www.cna.gob.mx). Thus, the government is aware of the water problems in Mexico but the continued increase in the area under irrigation is a contradiction. It is clear that technological advances are needed for an efficient consumption of water and for regulating the expansion of irrigation areas.

Rural development programs have been identified in many sectors, where incentives and subsidies are used as a common economic instrument. Rural development programs can be considered as an important tool for diversifying activities and are expanded on later.

Instruments for regulation, such as norms, are applied at a national scale, but others such as permits, depend on the species and regions where scientific information is scarce and the application of those regulation instruments becomes difficult. Norms, laws, and permits are all used in the Tonameca watershed.

Environmental impact assessment is an instrument for mitigating activities that can affect negatively the environment, such as forestry, oil exploitation, construction and aquaculture [156]. Generally, EIA does not take a regional approach and is flexible in mitigating impacts that are harmful to the environment. The procedures for an EIA are not always very clear, and some technical aspects are difficult to measure such as carrying capacity or ecosystem values [156]. EIA applications need to be verified and evaluated.

Closed areas, closed seasons and rights of access are used generally for regulating hunting and for fisheries. Hunting is not an important activity in Oaxaca compared to the North of Mexico. Closed seasons and the National fisheries charter are used to regulate the fishery along the Oaxaca coast.

Economic instruments can be divided into: fiscal, financial, and market instruments. In Mexico fiscal instruments are mainly fees for discharges, for access to natural protected areas or for exploiting natural resources. A main concern with fees is that they do not usually represent the value of natural resources and ecosystem services.

The environmental services payment is an instrument that has been used for the forest conservation. The payment is made to communities who demonstrate a sustainable use of the forest and comes from water users, as explained further below.

Financial instruments are funds or administrative schemes for funds for supporting conservation, research and sustainable projects. Market instruments are almost non-existent in Mexico. Concessions are also considered regulation instruments [156].

Organic coffee is probably the best example of certified organic products and fair trade. In Oaxaca State, the State Coordination of Coffee Producers (CEPCO) integrates 41 local organizations covering 11 761 hectares and 70% of its production is certified organic coffee [157]. Economic instrument development and application need to be developed in Mexico for pollution regulation, wildlife and water use, and ecosystem services markets. In the Tonameca watershed, environmental service payments, organic certification, plastic recycling incentives (deposit-refund), alternative technology incentives (solar energy, dry toilets) might have potential.

Social participation is based on councils, a group of people representing different sectors of society. Non-governmental organizations, communities and the private sector are invited to be part of the councils. Watershed management councils are mainly created for water administration and the government aim is to have a watershed authority for water management [153]. Watershed councils have been difficult to implement due to a lack of clear institutional roles. Moreover, water administration and management need to be separated from watershed management that includes other natural resource uses [152].

Various ministries are responsible for different resource types. The Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) is responsible for agriculture and fisheries. Ecotourism and tourism are managed by the Ministry of Tourism (SECTUR). The Ministry of Environment and Natural Resources (SEMARNAT) is in charge of the use of natural resources and biodiversity conservation. The Ministry of Social Development (SEDESOL) and the Ministry of Agriculture are responsible for rural development and the Ministry of Agrarian Reform (SRA) for land property rights. Ministry coordination for defining national priorities, programs aims and criteria, are the most important issues that need to be resolved at these administrative and political levels.

Whilst there is a broad range of legal, planning and regulation instruments available for managing catchments such as the Tonameca, economic and social instruments are few. ICZM and IWM can be integrated for the Tonameca using environmental instruments but specific problems identified in Table 59 need to be solved. These include: watershed and coastal limit definitions; efficient management and appropriate involvement of stakeholders; integrated diagnosis including socioeconomic and environmental externalities; environmental services valuation; monitoring of the management process. Water management needs technological advances to reduce water consumption, for water quality monitoring including for microorganisms, water balance, private investments but not privatization, dam planning, risk assessments and conflict management strategies [38]. There is a need for coordination and cooperation between ministries, as well as more efficient social participation schemes. The instruments and laws mentioned are applicable at a national, regional, state and municipality scale. Other state and municipal instruments include programs of urban development, and land use authorization [156].

At the level of the municipality, whether there is an office in charge of environmental aspects depends on political interests. In order to have long term planning of programs in a locality it is crucial to support community-based projects and rural development programs.

7.2 Diversification of natural resource use and rural development programs

Rural development is intrinsically linked to the diversification of natural resources apart from other needs such as health, education, and living infrastructure. In Mexico, government programs exist for rural development and diversification of activities but there is an urgent need for homogenous criteria at a national level for selecting priority areas and applying subsidies. Coordination between ministries is urgently required for an integrated regional development [152] [154].

The Ministry of Social Development (SEDESOL) is in charge of health, education and living infrastructure and the inclusion of women into a productive sector in conjunction with other ministries (Table 60).

Natural resources subsidies have been created to support alternative productive projects but most do not have clear sustainable criteria. The agricultural program (PROCAMPO) started in 1994 as a response to the crisis generated to imports following free trade commerce initiatives with the United States and Canada. The program is mainly based on a subsidy for agricultural production but sustainable projects evaluated by the Ministry of Environment can also receive support from the fund. In this sense, the program can be used to ensure sustainable production. The PROCAMPO subsidy is directly given to the producer who decides to buy grain or fertilizer, but no particular incentive exists for fertilizer use.

Table 60. Diversification of natural resource use and rural development programs			
Aspects of diversification and rural development	**Ministry**	**Programs Name**	**Description** (For details see: www.semarnat.gob.mx , www.sedesol.gob.mx, www.sagarpa.gob.mx. www.sra.gob.mx, www.se.gob.mx)
Living conditions	SEDESOL	Opportunities	Subsidy for health, education and food
Agriculture	SAGARPA	Agricultural and Fisheries Products Commerce Program (PROMOAGRO)	Incentive for commerce and exports for small enterprises
		Agricultural Program (PROCAMPO)	Subsidy for rural producers, specific amount per hectare is given for basic crops production
		Production Transformation Program	Amount equivalent to the value of petrol for operating tractors or other infrastructure
		Livestock Productivity (PROGAN)	Subsidy for livestock production
Fisheries	SAGARPA	Fisheries and Aquaculture Program	Payment to fishermen or fisheries organizations (cooperatives) for small boats petrol.
		Fisheries and Aquaculture Program	Support to aquaculture infrastructure, training, and implementation of projects.
		PROMOAGRO	Incentive for commerce and exports for fishermen and fisheries organizations
Productive project funds	SEDESOL	Co-investment	Support to government, non government, academic and other organizations for productive projects
		Program for Local Development (Micro-regions)	Local investment in poor regions for health, education, infrastructure for basic living needs and for productive projects (fisheries, forestry, agriculture)

(Table 60 cont.)		Temporal employment program (PET)	Employment payment for local projects equivalent to a minimum wage
Productive projects funds with an environmental aim	SEMARNAT	Regional Sustainable Development Program (PRODERS)	Support institutional synergies, specific productive programs, regional sustainable development councils, financing, capacity building.
		Wildlife conservation and use units (UMA)	Registration to a wildlife conservation and use system units.
		National Program for Reforestation (PRONARE)	Support for buying infrastructure, plants and other inputs for reforestation
		Program for supporting commercial plantations (PRODEPLAN) Program of forestry development (PRODEFOR)	Subsidies for sustainable forestry including plants, infrastructure, training, management programs.
		Project for conservation and sustainable management of forests (PROCYMAF)	Support sustainable use of the forest, environmental services payment.
	SAGARPA	Rural Development Program	Subsidy to sustainable productive projects and capacity building
		Fund for productive projects	Subsidy to coffee, tourism, indigenous projects, agriculture commercialization and young entrepreneurs training

		Funds for the stabilization, strengthens, and reorganization of coffee production	Subsidy for compensating the losses of coffee price decrease
		Fund for social organization	Subsidy for promoting social organization, and capacity building
	SRA	Young rural enterprising	Support to young people living in rural regions for project implementation, infrastructure and trainning
(Table 60 cont.)		Productive projects fund (FAPPA)	Support to sustainable productive projects for diversification of the rural sector
		Women development in the agricultural sector program	Support to women or women micro-companies for agricultural projects
Training and micro-companies consolidation	LABOUR MINISTRY (STPS)	Employment support (PAE)	Training, productive projects, transport, unemployment support
		Training support program (PAC)	Training support such as scholarships, diploma, masters for the government workers
	ECONOMY MINISTRY (SE)	Micro financing fund for rural women (FOMMUR)	Monetary subsidy for infrastructure, training and implementation of productive projects of rural women or women rural associations
		National fund for enterprises in solidarity (FONAES)	Monetary support for infrastructure and technical aspects to private or social organizations

(Table 60 cont.)		Women development in the agricultural sector program (PROMUSAG)	Monetary support for infrastructure and technical aspects to women private or social organizations

Fisheries programs are almost non-existent. Table 60 shows incentives for petrol and aquaculture but environmental criteria are not emphasized. The fishery sector has been in crisis since 2000, when it was transferred from the Ministry of Environment to the Ministry of Agriculture.

Tourism is an economic activity that is not normally subsidized. Tourism development is linked to resort construction with private and government investment [158]. That is, in Mexico tourism is mainly based on traditional and beach tourism (Cancun, Huatulco) which benefits only the private sector. Generally, for resort construction community land is expropriated and the corresponding indemnity is not provided as happens in port constructions or hydroelectric plants [18]. Ecotourism is beginning to be recognized as an alternative form of tourism in Oaxaca State, and Ventanilla is identified as a successful case [158], but there are no incentives for promoting communities for building community- based ecotourism.

Programs that include environmental criteria are the ones proposed by SRA, SAGARAPA and SEMARNAT. Communities with high levels of poverty and migration are prioritized in most of those programs.

The Ministry of Environment and Natural Resources (SEMARNAT) has created different programs for promoting the diversification of rural production and sustainable use of natural resources: the Program for Regional Sustainable Development (PRODERS), part of the National Commission for Protected Areas (CONANP), and the Units of Management and Use of Wildlife (UMAS). Natural protected areas and PRODERS regions represent the priority areas for conservation. PRODERS is applied at different levels: regional, municipal and community.

The PRODERS program aims to generate institutional synergies, specific productive programs at different levels, regional sustainable development councils, financing programs and capacity building. The program is mainly oriented to poor regions with high levels of biodiversity. There are no PRODERS in the Tonameca catchment.

The UMAS have been described above as one of the national planning instruments (around 700 species of plants and fauna are included in UMAS). On the other hand, the National Commission of Forestry has different programs promoting reforestation and sustainable use of the forest.

The program for supporting commercial plantations (PRODEPLAN) is seeking to decrease the importation of wood and promote reforestation. PRONARE is also a subsidy for reforestation. The program of forestry development (PRODEFOR) gives direct subsidies to producers and communities (35% of the subsidy is from the state) for training, management programs and impact assessment, and provides recommendations for diversification. Moreover, the forest resources project of conservation and sustainable management (PROCYMAF) has created a scheme for environmental services payments. Around 200 million pesos coming from public water payments have been re-directed to 271 land owners of 127 000 hectares of forest for water. Watersheds that are overexploited and which have a population more than 5000 are prioritized in this scheme. 80% of the forest needs to be conserved over 5 years, in order to receive an annual payment of 300 or 400 pesos per hectare. Pluma Hidalgo and San Pedro Pochutla are two of the Tonameca watershed municipalities in this program (for more information see www.conafor.gob.mx, www.ine.gob.mx). SEMARNAT programs support mainly forest management and the budget is not sufficient for sustainable wildlife exploitation.

SAGARPA provides funds for productive projects, coffee subsidies and training.

The Ministry of the Agrarian Reform (SRA) provides incentives for young people to work in agriculture: migration to the United States is very common in rural areas, resulting in abandonment of agricultural land [71]. The FAPPA program supports ecotourism and sustainable wildlife use projects.

The Ministry of Economy (SE) finances small-enterprises, cooperatives and other organizations for implementing productive projects and specific activities for women (Table 60).

The programs described above provide sufficient incentives and subsidies for diversifying rural production but coordination is needed for an efficient distribution of funds. Social and anthropological research is also recommended to identify the communities with characteristics that might determine the success of a project. In this sense, it is important to assess heterogeneity, social capital and community institutions [159].

Rural development programs and diversification of economic activities involve subsidies for infrastructure, training, capacity building, women and young population inclusion into the productive sector.

The national framework for watershed-coastal management and rural development programs are tools that can be used for management of the Tonameca watershed.

7.3 The Tonameca watershed: findings and specific management recommendations

The ecological-economic model constructed in this thesis has revealed specific findings that can be used to justify the need for the application of legal, planning and economic instruments within the Tonameca watershed. These finding are summarized in table 61.

Table 61. Tonameca watershed ecological-economic model summary results

Modeling the Ecosystem results	
Water quality	➢ nitrogen input from upland ➢ coastal lagoons are close to the limits proposed by the Mexican Regulations (15 mg/L of nitrogen).
Nitrogen Run-off	Approaches: conservative (69 t/yr), the intermediary (967 t/yr) and non conservative one (2100 t/yr).
Relationship between nitrogen run-off, water extraction and water quality	Direct relationship between water quality and nitrogen run-off and an inverse relationship with water extraction
Food web	Healthy ecosystem showed by: respiration more than production, detritus based food web and ascendency
Mangrove and Phytoplankton changes	➢ Oscillatory biomass behavior with maximum points at 15 and 20 years. ➢ Stabilization of the food web when increasing phytoplankton biomass more than 70%. ➢ The effects of phytoplankton are dominant compared to the mangrove effects. ➢ ECOSIM simulation shows that a high amount of fertilizer is needed to affect strongly the ecosystem

(Table 65 cont.) Modeling the Economy results	
Agriculture	Fertilizer is the main input for production and profits are sufficient to support basic needs
Fisheries	➢ Fisheries is a self consumption activity ➢ Direct effect of phytoplankton on fish biomass ➢ Positive effect of nitrogen run-off increase on fisheries profits in a short period of time but not in a long run
Ecotourism	➢ Crocodiles are the main attraction ➢ Visitors are not willing to accept deterioration for repeating a visit ➢ Tourists are mainly coming from Huatulco and consider ecotourism as an inferior good. Thus, a diversification of activities and prices is viable ➢ Ecotourism profits are affected slightly by a decrease in the crocodile population ➢ The effects of a high nitrogen run-off on ecotourism profits is visible only in a long run
Externalities	Externality from agriculture to fisheries and ecotourism

The ecosystem diagnosis provides information on water quality, water extraction, land use changes and mangrove food web dynamics. Water quality analysis indicates that nutrients levels in the lagoon are close to the limit, thus organic agriculture is recommended to be promoted. Other inputs to water quality that were not measured here are sewage discharges and a treatment plant is required closed to La Florida to avoid microbial pollution. Water extraction is mainly for agriculture and urban consumption. The water balance analysis carried out here did not indicate severe problems of water scarcity but a constant monitoring program of water quality and hydrology would be prudent. Sedimentation, organo-biocides and heavy metals should also be assessed.

The mangrove food web appears to be a healthy ecosystem that can accommodate higher levels of nitrogen than it receives at present. However, land use analysis indicates that the number of hectares under agriculture has decreased (chapter 5) due to low land productivity, conversion to livestock and young people migrating to the United States [160]. Low productivity is partly due to the intensive the low soils productivity due to an intensive use of fertilizers. Thus, an increase on fertilizer use is not recommended. The externality of increasing fertilizer use to fisheries and ecotourism is positive in the short term (as overall production is increased) but may not be in the long term. There is a significant crisis in the agricultural sector in Mexico, but subsidies such as PROCAMPO are still distributed in many regions. Other subsidies can be used for Tonameca for promoting wildlife use, organic production and ecotourism (Table 60). Coffee cultivation is also in crisis due to global market competition and prices, but instruments are used in the area already. The environmental services payment (Pluma Hidalgo), organic certification and the subsidy compensating the loss due to the low prices of coffee need to be expanded to include small coffee producers.

Land use changes are also visible in the upper part of the watershed, in the pine forest. Legislation for forestry needs to be enforced in order to avoid deforestation, whilst reforestation programs from SEMARNAT can be applied. The environmental service payment scheme might be implemented in that region.

In the tropical forest, land owners grow much fruit for self consumption, such as "mamey" or "guanabana"; that have commercial potential in the region. Multi-species cultivation and agro-forestry would help for an integrated use of the forest. Wildlife use (UMAS) represents another kind of forest use diversification. For example, orchids grow naturally in the tropical forest and they could be sustainably exploited. Ecotourism could also be developed, since the vegetation and insects, especially in the rainy season, are abundant. SEMARNAT and possibly SAGARPA programs provide support for such integrated use of the forest.

In the dry forest, traditional agriculture is the main livelihood and only patches of dry forest remain today which can be conserved. Intensification of agriculture has been already rejected as a management recommendation (see above). Subsidies for organic production and reforestation could be used, but dry forest is not an easy ecosystem to restore. Diversification of economic activities can be promoted using subsidies, such as FAPPA or Micro-regions programs (Table 60). UMAS can be promoted in the region, so that iguana or deer species can be consumed. The main challenge for promoting production diversification is the inertia of traditional production, such as cultivation forms (slash and burn) and subsidies given by the government (PROCAMPO subsidy).

The mangrove forest in Ventanilla has been conserved but in other areas close to Tonameca deforestation occurs for agriculture and livestock. Ecotourism and UMAS are instruments used by the Ventanilla cooperative to conserve the mangrove forest. Other subsidies have been used, such as the CONAFOR subsidy for reforestation of the mangrove forest.

Ecotourism in the mangrove forest appears to be a successful case of community-based management where crocodiles are the main attraction, visitors are not willing to accept environmental deterioration, and other environmental education activities can be developed. The Chacahuita community (close to Ventanilla) has initiated an ecotourism project but they have been facing organizational problems. Community organization, consolidation and success need to be reinforced by municipalities. Table 60 shows a high diversity of government programs that can be used in rural places but there is no efficient communication with peasants and rural communities. Municipalities need to promote the existing programs and application procedures, as well as promote rural development and diversification of economic activities.

Fisheries are a self consumption activity and no programs exist for an artisanal fishery. Aquaculture might be an option but only if this is not at the expense of the mangrove and it is promoted under sustainable criteria. Restoration of coastal lagoons is an important issue that no government institution is leading. The Tonameca lagoon fishery is not an economic activity, it is a traditional activity. The fishery cannot be replaced by agriculture because it is part of the community's culture and artisanal fisheries require support from national programs. Further studies on artisanal fisheries are needed in the region.

Watershed councils or committees have been created in other regions for management purposes, as a scheme for negotiation, public participation and integration of different sectors. However, in many cases the committees are represented by government sectors, non-governmental organizations, or local leaders but not really by the communities. In the Tonameca, a water management council and watershed council are recommended.

The findings of this thesis, and in particular the ecotourism analysis in Ventanilla, have been presented to the community in a workshop. The community was interested in the impacts of upland activities and is interested in organizing other activities in the area. Thus, the ecological-economic model presented in this thesis has provided insights and finding that can be helpful for providing to communities in regional perspective of the environmental situation and for specific recommendations on their activities.

7.4.Conclusions

The ecological-economic model developed in this thesis reveals the potential for linking ecological tropho-dynamic analyses to the economic production function approach, in order to explore scenarios and move towards optimum watershed management. The ecological-economic model is applicable for other tropical coastal watersheds.

The ecological-economic model seeks to integrate environmental variables into models of economic production. Agriculture production is limited by water extraction and nitrogen run-off, ecotourism production is constrained by the crocodile biomass and fishery is constrained by fish biomass. In addition, the model explores the willingness to accept an environmental quality change for repeating a visit as an alternative approach for analyzing ecotourism demand. The elements for establishing management recommendations are provided by establishing, the optimum levels of ecotourism, fisheries and agriculture production, as well as the externalities from one activity to the other.

The ecological-economic model shows that nitrogen from agriculture has an impact in phytoplankton and mangrove biomass and consequently in the mangrove food web. Changes in agricultural policy and production can thus be linked directly to coastal biodiversity, fisheries and tourism. In addition, the food web model used here, ECOPATH with ECOSIM, is useful for assessing ecosystem health and allows the simulation of the effects of environmental quality changes due to different economic activities. With regard to this specific ecosystem, further research is needed on linking mangrove biomass and water quality changes, mangrove dynamics and lagoon dynamics to watershed hydrology. The eutrophication process also needs to be better represented in the ECOSIM. It should be noted that anthropological and social diagnosis are not included within the currently analysis and needs to be done for identifying the communities where alternative projects might be successful.

The Tonameca ecological-economic model indicates that the mangrove ecosystem food web can support further inputs of nitrogen. The fishery is affected positively by nitrogen inputs causing an increase in phytoplankton biomass only in the short run. Crocodile population is the main attraction for ecotourism and nitrogen increase effects are visible mainly in a long run. Moreover, ecotourism price diversification is advisable. In contrast environmental deterioration affects negatively fisheries and ecotourism. It has been shown that there is an externality from agriculture to fisheries and ecotourism.

Policy implications of those results indicate that in the long run an increase on fertilizer use would affect negatively fisheries. Ecotourism is slightly benefited in the long run when increasing fertilizer use, due to a fish biomass increase. However, crocodile population growth is limited by the coastal lagoon area. Moreover, the hectares for agriculture have been decreasing due to an overexploitation of soils and people migration. Thus, land for agriculture is overexploited and fertilizer increase would not solve social and economic problems of the sector. Other recommendations for diversification of rural production are given and organic agriculture, wildlife use, environmental services payments and ecotourism are proposed.

Availability of data is an important issue for building models as is the case here, but at the same time environmental planning is needed in places where no times series are available and ecological information exist only for a limited number of ecological groups. Modeling gives the opportunity to generate recommendations even when information is scarce, but results must be interpreted with cautiously.

A management program would have different stages: a diagnosis, strategies and activities program, program implementation and monitoring of the management process. The ecological-economic model presented in this thesis is part of the diagnosis and provides recommendations that can be integrated within the Tonameca management program. The model can be used as a planning instrument and is a complement of national Mexican instruments for environmental planning such as, the ordinance of the territory.

The Tonameca ecological-economic model presented in this thesis reveals the potential for linking ecological tropho-dynamic models and economic models in order to give management recommendations for environmental planning.

Appendices

Appendix A. Fisheries interview

1.- General information per individual (control characteristics)

Date

Municipality ______________ Locality

____________ Location____________

Name

Age

Origin

Occupation Profession______ Student______

Religion

Education

2.- Does fishing represents a high, medium or low part of your income?

1.- Low (20%)

2.- Medium (50%)

3.- High (90%)

3.- Does agriculture represents a high, medium or low part of your income?

1.- Low (20%)

2.- Medium (50%)

3.- High (90%)

4.- In which of the following locations do you fish?

1.- Tonameca mouth _____ 2.- Tonameca lagoon ______ 3.-Open sea_______

4.- Tonameca river_________ 5.-Other lagoons__________ 6. Other ______

5.- Which are the three main species that you catch and how much do you catch a year?

1.- ______ ________

2.- ______ ________

3.- ______ ________

6.- Which is the best month for fishing each of the three species?

1.- ______ ________

2.- ______ ________

3.- ______ ________

7.- For each of the three species, how many times a week do you fish and how many hours per session do you spend?

	Times a week	Hours
1		
2		
3		

8- Please tell me the species, the amount and the effort of fishing in previous years

	1993	1997	2000	2001	2002
Specie					
Catch					
Effort					

9.- What do you use for fishing? Please mention the number, size and date of acquisition.

	Number	Size	date
Panga with motor			
Panga without motor			
Atarraya			
Line			
Other net			

10- Which is the value in the local market of the 3 main species that you catch?

1.- ______ ________

2.- ______ ________

3.- ______ ________

11- Which are the costs of a day of fishing?

12.- If there are changes in the catch, why do you think this is happening?

13.- How many times a year and in which month is there a sea water exchange?

14.- Are you part of any cooperative?

15.- Could you give an average of your income per month?

16.- How many persons live in your house?

17.- How many persons under 18 live in the house?

Appendix B. Ecotourism questionnaire

Dear Ventanilla visitor:

The Cooperative Society for Ecoturistic Services la Ventanilla, contributes to the environment protection, reforesting the mangrove forest and conserving its wildlife. The community represents a sustainable example for rural development in Mexico.

If you would like to help Ventanilla project and its wildlife conservation, please answer the following questionnaire. The aim is to know your perceptions and opinions about Ventanilla.

The information derived from the questionnaire would be very useful for the community and would be analyzed as part of a research project.

Thank you for your collaboration, sincerely,

The Cooperative Society for Ecoturistic Services la Ventanilla and MSc. Sophie Avila Foucat (savila_1@yahoo.com.mx).

General information

Name	
Age	
Gender	1.-Female ______ 2.- Male ______
Country and place of origin	
Occupation	
Is it your first time in Oaxaca?	1.-Yes_____ 2.-No_____
Is it your first time in Ventanilla?	1.-Yes_____ 2.-No_____

1.- Where is your accommodation located ?

1.- Mazunte _______ 2.- Huatulco __________ 3.- Ventanilla ________

4.- Puerto Escondido______ 5.- Other _________

2.- How long will your visit to Oaxaca last for?

1.- Less than a week_____ 2.- A week ________3.- Two weeks_____

4.- More than two weeks________ 5.- Months______

3.- How long are you staying in Ventanilla?

1.- One day_______ 2.- More than a day______

4.- Are your traveling as part of a tour?

1.-Yes_____2.-No_____

5.- Please indicate which of the following statements most closely represent your view for the reasons of your trip.

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Enjoy the beach and sun	1	2	3	4	5
Enjoy being in a hotel with entertainments	1	2	3	4	5
Contact with nature	1	2	3	4	5
Contact with local people	1	2	3	4	5
Adventure	1	2	3	4	5

6.- Did you know about Ventanilla before leaving your country of origin?

1.-Yes____ 2.-No_____

What did you know or heard about Ventanilla?
1.- Crocodiles __________
2.- Community project __________
3.- Mangroves __________
4.- Birds __________
5.- Turtles __________

7.- How did you know about Ventanilla?

1.- Recommendation______2.- Hotel information________

3.- Travel agency________4.- Other________

8.- Have you been in another mangrove lagoon before?

1.- Yes______ 2.- No_______

Ecological preferences

9.- Please rank in order of importance the attributes in Ventanilla that you enjoyed the most .

	1(the most important)	2	3	4
Mangrove forest				
Crocodiles				
Birds diversity				
Community organization				

10.- Will you visit Ventanilla again if its environmental attributes are conserved as today?

1.-Yes______ 2.-No______

How much more of each attribute would you like to see for coming back to Ventanilla?

	Mangrove	# Crocodiles	# Birds
20% more			
50% more			
70% more			

11.-Please indicate for each of the following attributes, the percent of deterioration that you accept for visiting Ventanilla again.

	Mangrove forest	# Crocodiles	# Birds
20% less			
50% less			
70% less			

Services and infrastructure

12.- Please indicate if the trip fee in Ventanilla corresponds with the amount that you be willing to pay?

1.- Yes______ 2.-No______

How much and how would you be willing to pay?

Pesos	In which form?
1.- 0 – 35	a.- Fee entrance
2.- 35 – 70	b.- Donation
3.- 70 – 140	c.- Donation for a specific project
4.- 140 – 260	
5.- more than 260	

13.- How would you grade the infrastructure and services in Ventanilla?

	Bad	Moderate	Good	Very Good
Boat	1	2	3	4
Road	1	2	3	4
Toilets	1	2	3	4
Restaurants	1	2	3	4
Accommodation (if applying)	1	2	3	4

14.- Please indicate if you consider that waste management is a problem in Ventanilla

1.-Yes______ 2.-No_______

15.- Please indicate if you waited for a long time for taking the boat trip.

1.-Yes ______ 2.-No_______

16.- Would you consider staying more days in Ventanilla if you could do other environmental activities?

1.-Yes______ 2.-No________

Which topic would you prefer?
1.-Wildlife conservation _______
2.- Waste management________
3.- Local culture and projects ___________

17 - Have you ever attended any environmental course?

1.-Yes ______ 2.-No ______

18.- Are your part of an ecological organization?

1.-Yes______ 2.-No______

Trip expenses and income

19.- Please indicate your average trip expenditures in pesos OR dollars.

	Total amount spent
Transport to the coast	
Transport to Ventanilla	
Food expenses per day	
Entertainment per day	
Accommodation expenses per day	

20.- What is your approximate household income a month in dollars OR pesos?

Pesos	Dollars
1.- less than 5000	1.- less than 1000
2.- 5000-10 000	2.- 1000- 2000
3.- 10 000 –20 000	3.- 2000- 4000
4.- more than 20 000	4.- more than 4000

We are thankful for your participation and we would be grateful to receive any comments:

Thank you !

Appendix C. Symbols Glossary

U_{c_t} urea recommended per crop in Kg

W_{c_t} amount of water used in litres (W) for coffee pulp wash at time t ($_{c_t}$)

R_t total nitrogen run-off at time t in t/yr

H_{c_t} hectare of crop c

N_t nitrogen concentration in water at time t in mg/L

W_t water extraction at time t in liters

H function describing the relationship between nitrogen concentration, total nitrogen run-off and water extraction

V_t annual draining volume in cubic meters

Pmm average rainfall from 1970 to 2000 in mm

A catchment area in hectares

Ce annual draining coefficient in cubic meters

S soil absorption constant

$B_{m_{t+1}}$ biomass after a change in nitrogen in water in t/km^2

B_{m_t} initial mangrove biomass t/km^2

μ_t phytoplankton growth rate

K_s half of the saturation constant growth of phytoplankton

μ_{max} the maximum specific growth rate of phytoplankton

B_{p_t} the initial phytoplankton biomass in t/km^2

$B_{p_{t+1}}$ the change in population growth in t/km^2.

B_{i_t} biomass of group i in t/km^2 at t

$B_{i_{t+1}}$ biomass of group i in t/km^2 at t +1

P_{i_t} production of group i t/km^2 at t

$(P/B)_{i_t}$ production /biomass ratio of group i that is equal to the coefficient of total mortality in yr at time t

EE_{i_t} Ecotrophic efficiency of group i that is the fraction of production that is consumed within or caught from the system at time t

B_{j_t} biomass of group j at time t in t/km^2,

$(O/B)_{jt_t}$ consumption/biomass ratio of group j at time t

DC_{ji_t} fraction of i in the average diet of j in biomass at time t

EX_{i_t} export of group i in biomass at time t

BA_{i_t} biomass accumulation in t/km^2 at time t (per year)

$\frac{B_{i_{t+1}} - B_{i_t}}{B_{i_t}}$ growth rate during the time interval t for group i in terms of its biomass

g_{i_t} net growth efficiency (constant)

M_{i_t} natural mortality rate at time t

F_{i_t} fishing mortality rate at time t

e_{i_t} emigration rate in t/km^2 at time t (per year)

I_{i_t} immigration rate in t/km^2 at time t (per year)

$\sum_j O_{ji_t}$ total consumption by group i in t/km^2 at time t (per year)

$\sum_j O_{ij_t}$ predation by all predators in group i in t/km^2 at time t (per year)

Q_{x_t} specie x fisheries production or catch in tonnes

q catchability constant

E_t fishing effort at time t in hours

B_{x_t} fish biomass of specie x of fish in t/km^2

F function describing the relationship between fish biomass, phytoplankton, mangrove and predation

Q_{h_t} total harvest in tonnes

Π_{x_t} profits of fishing specie x in pesos

P_{x_t} price of specie x of fish in pesos

P_{E_t} is the price of one hour fishing in pesos

C_{E_t} fishing costs, cost of effort in pesos

Π_{h_t} total fisheries profits in pesos

P_{h_t} sum of the prices of fish species in pesos

Q_{a_t} agriculture production in tonnes

I the function describing agriculture production

L_{a_t} labour for agriculture at time t in number of persons

W_{a_t} water extraction for agriculture at time t in cubic meters

l_{c_t} labour per each crop in number of persons

Π_{a_t} agricultural profits in pesos

P_{a_t} average price of aggregate agricultural production in the catchment in pesos

C_{a_t} agricultural costs in pesos

C_{l_t} labour costs in pesos

C_{F_t} fertilizer costs in pesos

$p_{l_{at}}$ price of labour per the number of workers required in pesos

p_{F_t} price of fertilizer in pesos

F_t amount of fertilizer used in tonnes

Z_{v_t} ecotourism demand in number of tourists

A_t groups of ecological attributes

SE_t visitors socio-economic variables

J function describing the demand

B_{c_t} crocodiles biomass in t/km^2

L_{v_t} ecotourism labour in number of persons

V function describing the relationship between crocodile biomass and fish biomass

G function describing the ecotourism production

P_{v_t} ecotourism experience price in pesos

C_{v_t} ecotourism costs in pesos

Π_{v_t} ecotourism profits in pesos

P_{Lv_t} price of ecotourism labour in pesos

L_{v_t} ecotourism labour in number of persons

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