The Utility of a Dynamic Model to Address Ecological-Economic Interactions: Shrimp Ponds and Mangroves in the Guayas River Estuary, Ecuador

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Increasingly resource managers and policymakers have come to understand that the sustainability of ecological and economic systems is intimately intertwined. However, in practice the complexity of the interactions may make intelligent, informed resource decision-making extremely difficult, particularly given the dynamic nature of ecosystems and the importance of scale. The nature of tropical ecosystems and the lack of knowledge about them further complicates matters for decision-makers there.

Ecosystems provide goods and services, whose mix and quantities can be varied (Gottfried 1992). Landscapes represent a mosaic of ecosystems, or a portfolio of multiproduct assets. However, the market fails to provide the socially optimal land use of landscapes because of the presence of external effects, the open access problem, and economies of configuration (Gottfried, et al. 1996). The latter represents the fact that all resource users jointly determine the configuration of land uses on the landscape, and therefore the mix of goods and services it provides. Unfortunately, the market offers no way to coordinate their decisions so as to provide the landscape they desire. Moreover, even should they coordinate, the decision-makers often lack information as to the impacts of their decisions given the uncertainty as to how the ecological and economic systems interact (Gottfried 1995; Gottfried, et al. 1996). It is clear that resource users generally will not conserve resources they use unless they realize that it is in their best interest to do so. When users fail to perceive their dependence on ecosystem environmental goods and services, they most likely will give those ecosystems little importance when they make their resource decisions.

Given the complexity of economic-ecological systems, understanding the ecological and socioeconomic impacts of land use calls for a tool that facilitates understanding that complexity and incorporates concepts fundamental to the decision-making process. Dynamic modelling provides one such tool.

This paper discusses the utility of a dynamic model of interactions between the estuarine/mangrove system of the Guayas River in Ecuador and the resident shrimp pond industry. The authors' working premises are that: 1) by demonstrating rigorously that shrimp pond profits depend to a greater or lesser extent upon mangroves, this information can be used to motivate decision-makers, whether public or private, to conserve mangroves; 2) the strength of this motivation may be spatially sensitive, implying that this approach may work best in certain targeted areas.

The next section discusses the model's conceptual framework and the concepts underlying it. The subsequent section then describes the case study area and the ecological components and economic components of the model. The next two sections present the results of simulations that demonstrate the utility of the modelling approach and discuss possible applications of the model. The concluding section provides a summary and discussion of future work.

Conceptual Framework

The model described below attempts to address the issue of mangrove deforestation in Latin America as the result of the rapid growth of the shrimp pond industry. It does so by addressing the case where mangroves reside in an estuary that is the target for siting shrimp ponds. The model includes only those functions of mangroves of particular relevance to shrimp ponds. In addition, the model includes shrimp ponds as part of the estuary so that the ecological interactions between the ponds and the natural system can be examined.

Figure 1 describes the conceptual framework for the model.[4] The large rectangle on the left represents the ecological processes occurring within the estuary. The estuary consists of three parts: 1) the bay, 2) the mangroves in the intertidal zone, and 3) the shrimp ponds that may be located within the intertidal zone, thereby replacing mangroves, or in the salt flats (*salinas*) behind the mangroves. The waters of the bay interact with both the mangroves and the ponds, connecting them directly and connecting the mangroves and shrimp ponds indirectly via the bay. Should ponds direct their effluent directly to the mangroves, then ponds also exert a direct effect on mangroves, as shown by the arrow enclosed by parentheses. For each component of the estuary Figure 1 includes processes of particular interest to shrimp ponds. The same is true for the rest of the diagram.

Forcing functions, or parameters, directly constrain, or affect, the estuarine processes. Solar energy, river flow, and tides all affect these processes and, therefore, the functioning of mangroves and ponds. Accordingly, their presence in the model underscores the importance of accounting for these constraints, as well as estuarine processes, when discussing the interactions between ponds and mangroves.

As a result of the environmental constraints and estuarine processes, the mangroves and ponds provide goods and services (functions) of interest to humans. The mangroves produce water quality while the ponds provide shrimp production and water quality (a good or "bad," depending upon their impact and the persons receiving the impact).

The prevailing human culture and socioeconomic system determines: 1) whether or not society recognizes the economic functions of mangroves and other ecosystems, 2) the tastes and preferences that determine price, and 3) the structure and policies of institutions that determine resource management decisions. Accordingly, markets determine the prices of shrimp and key inputs of shrimp pond production. Political processes drive government policy that, in turn, helps determine the relative profitability of the ponds. Exchange rate and trade policy determine the foreign exchange value of the industry’s output and the ease and cost of obtaining inputs. Monetary policy affects the availability of credit and the interest rate, affecting the

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[4] This figure is a modified version of Figure 7.11 that appeared in Twilley (1995).

ability and cost of establishing new ponds and the long-term value of these operations (via the discounting of future profits). Depending upon what the government taxes, and how much, the shrimp pond industry may find itself relatively favored or disadvantaged vis-a-vis other industries and international competitors. Similarly, the extent of the government's willingness to subsidize inputs (such as diesel or feed) or influence output prices affects firm profits. Finally, government land use policy restricting conversion of land, requiring permits and/or payment for access to land, and other coastal zone resource policies affect the costs of doing business and the location of the ponds.

Just as the model treats solar energy, river flow, and tides as forcing functions, treats these socioeconomic factors in the same way. These ecological and social forcing functions, along with estuarine processes, determine the value of mangroves and shrimp ponds. The output of mangroves, water quality, receives no explicit value in the model (the same as occurs in society). Mangroves are valued indirectly in terms of their contribution to shrimp pond profits. Shrimp profits represent the value of shrimp ponds by society.

These values contribute to management decisions that then feed back into the estuary in two ways. First, shrimp pond managers decide how to manage inputs for their ponds and, accordingly, affect the quality of water flowing back into the estuary. Second, based upon these values society chooses how to allocate land between competing uses in the estuary, thereby affecting the structure of the estuary itself.

In addition to stressing the importance of the forcing functions' influence on estuarine processes and on mangrove and shrimp pond values, the framework also addresses the importance of spatial relationships. The impacts of river and tides are felt differentially along an estuary. In the upper reaches of the estuary the effects of river discharge may dominate (assuming that a river(s) empties into the upper end of the estuary). At the lower end tidal effects may dominate, whereas in the middle the effects of river and tide may vary as the seasons change from dry to rainy. Also, should ponds decide to locate behind mangroves in the salt flats, the impact they have should differ greatly from the case where they replace mangroves. The spatial siting of ponds, therefore, by position in the bay and relative to mangroves should prove significant.

The above conceptual framework carries embodied within it several concepts worth discussing. The framework stresses a holistic versus a reductionist approach to assessing the role mangroves play in the shrimp pond industry. This requires accounting for complex dynamic interactions as opposed to assuming that ecosystems comprise static systems whose values can be determined by characterizing them at one point in time. It also requires recognition of the fact that boundaries play a key role in ecosystem valuation. When significant interactions occur between ecosystems, considering them in isolation from the greater natural system of which they are a part introduces a serious bias (Gottfried 1992). Moreover, because ecosystems change over time, both as the result of changes in forcing functions and also as management and other impacts carryover from year to year, ecosystem management analyses must be careful to choose an appropriate time scale of analysis. Finally, ecosystems often possess thresholds such that, when disturbed beyond these levels, ecosystem processes change drastically and often (virtually) irreversibly. Sustainability requires recognizing this possibility and including it in resource management decision-making. The overexploitation of open access resources becomes doubly tragic when overexploitation leads to irreversible ecological change of potentially great economic importance.

The Model

Few ecological models of tropical coastal areas exist. Only recently have researchers constructed dynamic, or process-based models, to obtain a better understanding of landscape processes (Sobero-Chavez et al., 1988; Reyes et al. 1994). The model presented here is unique, to the authors' knowledge, in that it not only explicitly includes shrimp mariculture as an important component of the estuary, but that it also explicitly includes the economics of shrimp ponds. There exist few attempts to model aquaculture pond systems and to link them to the larger ecosystem in such a way as to permit analysis of landscape management (Hagiwara and Mitsch 1994). Moreover, in shrimp mariculture most environmental studies are directed to maintaining optimal conditions in the ponds for growth and development of shrimp post-larvae and for maximizing profits (Robertson and Phillips, 1995). No ecologically-based models currently exist to assess the impact of shrimp pond land use on a regional scale (Wang, 1990). Similarly, no existing models permit examination of possible negative feedbacks of pond management decisions on the shrimp pond industry via their environmental impacts. Most concern in this respect has centered around the loss of ecological functions of mangroves (Twilley 1988, 1995).

The authors have formulated the model without having data available to test all its aspects. They have chosen to continue because practically no information exists on the physical and chemical variables for shrimp ponds relative to nutrient cycling in the Guayas estuary and on the ecology of mangrove forests in the region. Yet, the importance of this estuary (see below), as well as the rapid conversion of mangroves in Latin America, urgently demands tools that decision-makers can use to address these resource management issues. The authors consider the model a tool to develop experimental designs to obtain the parameters needed to validate the model and as a "unit" model upon which to build more sophisticated dynamic and landscape models in the future, models necessary for developing management plans for the region, not just the Guayas estuary.

The case study area

The rapid growth of farmed shrimp production in Ecuador has made that country the second largest producer of farmed shrimp in the world (McPadden 1985). While

Ecuador produced less than 5,000 MT of shrimp from ponds in 1979, by 1991 it produced more than 100,000 MT (Southgate and Whitaker 1992). By 1990 Ecuador produced 76% of the western hemisphere's total shrimp production. After oil it provided Ecuador its largest source of foreign exchange (Argüero and González 1991; cited in González 1993, p. 2).

Major changes in land use have accompanied this tremendous growth. From 1980 to 1987, the last year for which comprehensive data are available, nearly 15,000 ponds per year received governmental authorization, resulting in about 125,000 ha. of ponds by 1987, 47% of which resided in the intertidal zone (Gonzalez 1993). By 1986 Guayas had 71% of all shrimp ponds in the country. Accordingly whereas Guayas province had 125,613 ha. of mangroves in 1969, that number fell 10% to 113,090 in 1987 (Gonzalez 1993).

The Guayas River estuary and the Gulf of Guayaquil form the largest estuarine ecosystem on the Pacific coast of South America (Cucalon 1984). Due to strong seasonal discharges from the river and high tidal amplitudes, water quickly flushes from the estuary in about 21 days (Murray et al. 1975). With a mean discharge of 1,144 m3/s, the Guayas River has the highest discharge of the thirty rivers of coastal Ecuador, representing 39% of all the discharge from this region (Stevenson 1981). The figure following Map 1 illustrates the dimensions of the estuary and its interrelationships with shrimp ponds (on the left of the diagram) and mangroves (on the right). The estuary serves as important habitat for economically important marine invertebrates.

The ecosystem model[5]

The main objective of the ecological model lies in evaluating the effects of shrimp mariculture on nitrogen cycling and on the transport of suspended sediments and salt in the Guayas River estuary. In particular, the model attempts to determine how the exchange of water between shrimp ponds and the estuary modify nitrogen enrichment in both, and how pond management decisions may affect ecological processes in the estuary. Within these objectives the model explores how the loss of mangrove areas may affect both nitrogen cycling in the estuary and total shrimp production in the ponds. The model was developed using Stella II version 3.0.5, a user-friendly object-oriented application for the solution of complex differential equations.

The authors structured the model to account for spatial effects by constructing the hydrologic submodel as a “box” model that divides the estuary into three zones: upper, middle, and lower. The model then determines the exchange, or net flow, of water, salt, nutrients, and other variables of interest between these zones. Each box, or zone, contains submodels for nitrogen cycling, total suspended sediments, dissolved oxygen, and salt in both the bay and shrimp ponds. When high rates of flushing in the

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[5] For more detail on the ecological model see Zhang, Rivera-Monroy, and Twilley (1996).

estuary exist, the large water fluxes between the zones generally determine the estuarine system's behavior

Water in the model flows, not only between the three zones, but between bay waters, shrimp ponds, and the surrounding mangroves within each zone. The model includes tidal inundation of mangroves in each zone. Mechanical pumps exchange water and water-borne constituents between the bay and the shrimp ponds. Mangroves capture some sediment and sediment also settles out in ponds. They also provide nitrogen to the estuary via their detritus as well as store nutrients in their biomass. Values for salinity, nitrogen, and total suspended sediments thus reflect the influence of the river and water exchange with coastal waters and ponds, and nitrogen and sediments levels reflect the impact of mangroves and ponds. Partitioning the estuary into only three zones sacrificed some precision, but allowed the authors to maintain a certain level of simplicity and effectiveness (Costanza and Sklar 1985).

The concentration of nitrogen in pond waters, a function of its level in the estuary and the rate of feeding and fertilization in the ponds, affects shrimp growth in two ways. The higher the amount of nitrogen, the faster shrimp grow. However, the higher the concentration, the more shrimp suffer the effects of eutrophication, including the effects of pathogens and environmental stress. As sediment levels in ponds fall, more sunlight enters pond waters and encourages algal blooms that, in turn, can promote diseases that affect shrimp mortality and quality. Thus, nitrogen concentrations in pond waters rise and sediment levels fall, shrimp profits become increasingly threatened.

In its current stage of development the complete model simulates one 10 ha pond per zone, multiplying its effects by the number of ponds located in the zone. The model allows ponds to be located in the mangrove areas, thereby replacing mangroves, or behind them in the salinas. Because the ecological modelling of the ponds requires further development, the model whose results are simulated below treats ponds in a manner similar to mangroves. Each hectare of ponds or mangroves contribute a fixed amount of nitrogen or capture a fixed amount of sediments. Thus, the model simply models their interaction with the estuary via the use of coefficients.

The complete model simulates pond ecological processes and management. As feeding, pumping, and other management actions, and as shrimp growth and mortality vary according to water quality conditions, shrimp pond profits rise and fall. Shrimp take shorter or longer periods of time to reach the required size and shrimp yields differ. Accordingly, the revenue and costs of the pond vary as water quality varies. However, because the ecological processes cannot be modeled reliably in the current complete model, it cannot link costs and revenues to these processes. For purposes of this paper, then, rising nitrogen concentrations and falling sediment levels proxy falling profits (see the appendix for further details of the economic section of the complete model).

The hydrological model correctly simulates daily water fluxes and salinity oscillations in the estuary. The ecological processes of the shrimp ponds require further model development before their results can be considered reliable and, therefore, are not included in the model used for this paper.

Simulation Results[6]

The graphs for the simulation runs show the results of changing river flow, tidal exchange, and land use. Unless mentioned otherwise, the simulations are compared to the base case where all land is in mangroves and river flows and tidal exchange are at 100% of their actual levels (river:tide ratio of 100:100 and run S1). Note that there are graphs for the upper, middle, and lower bays.

Total nitrogen concentrations change with land use depending on the amount of river flow in the estuary (see the first three simulation graphs). With all mangroves and no shrimp ponds in each bay of the estuary (runs S1), as river flow decreases there is an increase in total nitrogen in the estuary in the upper and middle bays, but concentrations remain low in the lower estuary with all land use patterns (runs S1, 2, and 3). At 90 % reduction in river flow, total nitrogen concentrations increase by 5 fold in the upper and middle estuary (river:tide ratio of 10:100). In addition, with a reduction in mangroves and increased construction of shrimp ponds to a 50:50 distribution in each region of the estuary (run S2), concentrations of total nitrogen increase 30 fold in the upper estuary compared to 10 fold in the middle estuary (run S2 at 10:100 compared to 100:100 for run S1). Again, there is very little change in the total nitrogen in the lower estuary associated with land use change at reduced river flow. Extreme nitrogen concentrations is observed in the upper and middle estuary when all the mangroves are removed and replaced with shrimp ponds, with 60 and 30 fold increases, respectively (run S3 at 10:100). Peak concentrations, at nearly 600 uM of total nitrogen, are extreme eutrophic concentrations. Note that the middle bay shows about one-third of the increase the upper bay experiences. In sum, decreased river flow combined with the conversion of mangroves to shrimp ponds tends to increase nitrogen concentration markedly in the upper and middle bays, but not in the lower.

Changes in water quality as indicated by concentrations of total nitrogen are ecologically significant when ponds replace mangroves under estuary conditions of lower tidal exchange. Strong tides transport material long distances up the estuary, increasing their residence time in the system. In other words, strong tides tend to hold

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[6] In the scenarios of this model we only investigate two of the multi-product functions of mangroves relative to those of shrimp ponds. There are several other ecosystem products that must be evaluated. Mangroves remove nitrogen but ponds are a source of this nutrient due to fertilization. However, both mangroves and shrimp ponds remove sediment, thus they have no distinct function in the model (but different magnitude). Other attributes such as habitat value, hydrology, carbon or detritus, pesticides, and other nutrients such as phosphorus, need to be included in this analysis.

nutrients in the system. Under these conditions, when river flow decreases, these contaminants have a greater tendency to accumulate. But with very little tidal exchange, even reduced river flow is enough to flush them out of the estuary. Consider the case of an estuary with river flow 90% lower than the Guayaquil estuary but the same tidal exchange (10:100), and 50% or 100% of mangroves converted to ponds (runs S2 and S3). When the tide is reduced by 50% (river:tide of 10:50) nitrogen concentrations fall by about one-half. Estuaries with less tidal energy experience lower nitrogen concentrations than those with higher tides. Given Guayaquil's high tides, a decreased river flow combined with substantial mangrove conversion leads to high nitrogen concentrations.

Suspended sediment concentrations behave opposite to nitrogen concentrations. Mangroves remove sediments, and so do shrimp ponds. Thus, even though one of these ecosystems replaces the other, the function of the intertidal zone does not change- it remains a sediment sink. Thus, as mangroves are converted to shrimp ponds, the sediment sink function of the intertidal zone actually increases, because ponds are more efficient at accumulating sediment than are mangroves. Accordingly, the suspended sediment concentrations in the base run of normal river flow and tides with all mangroves in the intertidal zone (S1 at 100:100) yield suspended concentrations of 375 mg/L in the upper estuary compared to about 300 mg/L when the intertidal zone is all ponds (S3 at 100:100). The other factor that decreases sediment concentrations is the amount of river flow. At 90% reduction in river flow, suspended concentrations are only 5-20% of the base run concentrations because sediments have more time to settle out. Again, changes in suspended sediment are most apparent in the upper and middle regions of the estuary with little change in the lower estuary. Concentrations are most sensitive to the magnitude of river flow, rather than tidal exchange or land use.

With respect to total nitrogen and suspended sediments there exists an important interaction between mangroves and shrimp ponds. A decrease in suspended sediment concentration due to pond construction allows more light to penetrate the water column. This light is an important resource for the growth of phytoplankton in normally turbid river-dominated estuaries. Therefore, the reduction of suspended sediment alone will probably promote phytoplankton growth and the productivity of this pond/estuary ecosystem. But those scenarios that caused a reduction in suspended concentrations also resulted in increased total nitrogen concentrations as ponds enriched estuarine waters and mangroves no long removed nutrients. Thus, two these land use changes increased two resources: light and nutrients. The combination of these two factors should markedly change the productivity and potential for the eutrophication of the estuary.

The simulations indicate that the pond industry in the Guayas River has managed to sustain its productivity over time largely as the result of the large river discharge it experiences. That high outflow of water flushes nutrients out of the system, preventing significant eutrophication of waters. The government's construction of the Daule-

Peripa Dam upstream, however, threatens the estuary’s industry by reducing substantially the flow of the river, perhaps by about one-half. The model indicates that nitrogen concentrations will rise radically in the upper and middle bays, but little in the lower. Sediment concentrations similarly will fall differentially in the three bays when the dam is built. As discussed above, these changes threaten eutrophication of the estuary’s water and the profitability of the shrimp industry. When the shrimp pond submodel is completed, the synergistic effect of the changes in nitrogen and sediment levels on shrimp ponds can be examined to determine the full extent of the impact on profits by location.

The model further suggests that mangroves play a rather insignificant role in shrimp pond profits at the current time in the Guayas Estuary, but that the completion of the dam project will render their contribution much more significant, particularly as one moves further up the estuary toward the river. Their contribution lies in taking up nutrients that would lead to eutrophication and by contributing less to sediment retention than ponds. Replacing them with ponds, the alternative resource management option, tends to promote eutrophication.

Potential Applications of the Model

The simulations have demonstrated the sensitivity of key ecological/economic parameters to hydrologic and land use conditions. Differences in tidal energy affect the quality of estuarine waters and, therefore, the importance of mangroves to the shrimp pond industry. Similarly, the parameters of the estuary such as volume, length, width, depth, etc. play key roles in determining the rate at which nutrients, salt, and sediment move through the estuary. These parameters, in turn, will affect the role that mangroves play in determining industry profits at different points along the estuary.

Accordingly, the model may enable planners and conservationists to determine those estuaries, and particular locations within estuaries, where industry profits may be particularly vulnerable to the loss of mangroves due to the peculiar characteristics of those estuaries. One of the lessons of the simulations is that mangroves do not always play an important role in maintaining industry profits. Using self-interest as a motivation for maintaining mangroves will work best when self-interest can be demonstrated reasonably to pond owners. Unfortunately, the model suggests that it can only be so demonstrated under certain hydrological conditions.

Pond management strategies represent behavioral forcing functions that affect the functioning of the rest of the system. Pond inputs vary as one moves along the spectrum from extensive to intensive shrimp farming. When completed, the model can be used to explore the environmental and economic implications of the intensity of pond operations. Similarly, it can examine the impact of management strategies related to the response of pumping rates to water quality, of feeding rates to shrimp growth, of feeding rates to water quality, of fertilization to shrimp growth, and so forth.

Similarly, it can explore the different impacts of flushing pond effluent through the mangroves vs. directly into the bay.

Given the model's potential , the authors hope to be able to modify it as a generic model whose parameters can be altered to fit many estuaries. For instance, by changing the water volume of each of the estuary's three zones, the river discharge, and tidal flushing, the hydrological model can approximate many different estuaries. Similarly, by changing the amount and location of mangoves and shrimp ponds the model can be altered to fit a variety of circumstances.

This adaptability offers the opportunity of providing land use planners, coastal zone managers, conservationists, and shrimp pond owners a tool with which to address issues of mutual concern. Government agencies and conservation groups could identify mangrove areas whose preservation also carries great importance to local shrimp pond owners. By taking the model to the field with a laptop computer, professionals could demonstrate the importance of preserving key areas of mangroves. Also, they could discuss with pond owners on site the impacts on their profits of various shrimp pond management strategies as they feed back through the estuarine system. For instance, pond owners who may be tempted to increase feeding rates whenever shrimp growth is low could be shown that slow shrimp growth may be due to problems of low oxygen content in their water, a condition aggravated by mangrove loss and high feeding rates. By playing "games" on site with different feeding and pumping rates, as well as different amounts and locations of mangroves, owners could learn the extent to which their profits may be damaged by inappropriate management strategies and deforestation.

Because mangrove forests often resemble open access resources in practice, such demonstrations could provide the motivation for pond owners to work together to limit the degree of mangrove clearing in their estuary, and/or to cooperate with state and conservation agencies in coastal zone management efforts. This could improve the prospect for converting these open access resources into a form of common property arrangement or co-management scheme involving government and industry. Such a cooperative process has been occurring already under the aegis of the Proyecto de Manejo de Recursos Costeros (PMRC). Particularly along the northern coast of Ecuador the PMRC has had some success in educating and motivating pond owners to protect mangrove resources. Both the PMRC's and pond owners' interests in the model, and cooperation in its development, lead the authors to believe that it could prove valuable as both a planning and extension tool.[7]

The model also could permit examining the sustainability of the estuarine system and/or shrimp industry by means of sensitivity analyses that seek abrupt changes of system behavior and/or profitability. Running the model over many years further would

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[7] See, for example, Gill (1997) ,and Ive and Cocks, (1996), for examples of how computer models can aid in building consensus among various users of a resource.

allow an investigation of cumulative effects that may bring about thresholds in time. These simulations could inform and stimulate discussions of economic and environmental/land use, sustainability, management, and policy-making.

Finally, changes in key prices and governmental policies should greatly affect pond economics and industry sustainability. Should shrimp prices continue to fall, one could explore the impact on the industry, particularly in the face of changing environmental quality. The model could explore other questions, also. What impact might changes in input prices, and price variability, have on industry sustainability? Similarly, how might variations in post larvae availability and desubsidization of petroleum prices affect the industry under various scenarios? How could government exchange rate, interest rate, tax, and land concession policies affect environmental quality and the industry over time? Finally, how might changing the open access nature of the intertidal and salinas zones to one subject to rational management via internalization of externalities affect land use patterns and ecological and economic sustainability?

Summary and Conclusions

The model discussed above interrelates the three major components of the Guayas River estuary -- the bay, the mangroves, and the shrimp ponds -- within each of three, integrated spatial units: the upper, middle, and lower sectors of the estuary. Forcing functions such as river discharge, tidal exchange, temperature, shrimp prices, and pond input prices serve as parameters that constrain the system. The current model proxies shrimp pond interactions with the estuary via the means of fixed coefficients. Changes in nitrogen concentrations and sediment levels in estuarine waters serve as proxies for shrimp pond profits. A version of the model under development will model the ecological processes of the ponds themselves and permit a direct link to pond revenues and costs.

Simulation runs that involve changing tidal energy and river flow in the Guayas Estuary show that mangroves have an effect on pond profits depending upon the magnitudes of these parameters and on the location of the ponds in the estuary. Under current ecological conditions the water quality functions of the mangroves appear to be of little significance to the pond industry of this estuary. However, should the government complete plans to dam the river, this conclusion may prove change markedly.

When the authors have completed model development, they hope to train coastal zone resource planners and individuals in the shrimp mariculture industry in its use so that the model can be applied in the field. By taking the model to pond owners and others interested in environmental questions, resource managers at all levels can receive scientifically-based information about the environmental and economic impacts of various management approaches and policies. The authors hope that providing decision-makers with an interactive tool that facilitates exploring a variety of issues may alert users to the implications of resource management strategies that heretofore have been unappreciated or unknown. The authors further hope that the information may stimulate users to take individual and collective action to deal with their common concerns and may provide them with a common tool that facilitates their discussions. While not a panacea, such a model may promote better management by providing better information and, accordingly, greater motivation to act.

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Appendix: The economic model

The economic component of the complete model links the macroeconomy to the local ponds and the ponds to the ecological model. The model currently assumes that the ponds in the estuary cannot influence the price at which they sell their shrimp nor the prices of the inputs they purchase. Thus, as prices change in the larger economy, these changes affect the pond industry. For instance, in the past Ecuador has heavily subsidized the price of diesel, an important input to pond production. This government policy represents, in turn, a large subsidy to the shrimp mariculture industry. Similarly, pond profits depend directly upon the international price of shrimp, which has been falling since 1986 in real (inflation adjusted) terms (Southgate and Whitaker 1992). The model assumes a price of $2.00/lb.

The availability of postlarvae for pond stocking, as well as their price, can vary greatly. Prices in Ecuador gradually rose from $2.00/thousand in the later 1970's to over $4.00/thousand during the 1980's. During El Niño events postlarvae abound, causing prices to fall. At other times, prices can rise above $10.00/thousand. In 1985, for instance, prices peaked at $15.00/thousand, causing postlarvae purchases to account for 44% of the operating costs of a semi-extensive enterprise. In that year, and in 1990, postlarvae shortages idled many ponds (Southgate and Whitaker 1992). Although the model currently does not simulate wild or farmed postlarvae production, impacts of declining stocks or climatic events can be handled through price and limited availability.

Pond managers incur two types of costs: fixed or overhead costs, and operating or variable costs. The former occur as the result of clearing the land, if necessary, and then constructing the ponds themselves and then installing pumps and other equipment . Often ponds must be rebuilt periodically**.** Owners incur these costs whether or not their ponds are active. The current version of the model utilizes a daily fixed cost. This, and other shrimp pond costs, are based upon interviews with shrimp pond owners in Ecuador's Manabí province during January of 1993.

During operation pond managers incur variable costs. Throughout the operation they must hire labor. While the pond fills, pumps burn diesel fuel that must be purchased. When the pond is stocked, postlarvae and fertilizer must be purchased. Pumping during shrimp cultivation requires further diesel. Pump maintenance requires oil and filters, whose expenses in the model are assumed to be a function of the amount of pumping. Finally, while the pond is stocked, managers incur daily feed expenses.

The economic model links pond costs to the ecological model in several ways. First, shrimp growth depends upon water quality and the forcing functions that affect the estuary. The longer it takes the shrimp to reach harvestable size, and thereby bring in revenue, the more time that owners must pay daily fixed costs, feed, diesel, and labor. Thus, all other factors constant, slow shrimp growth implies higher costs and lower profits. Second, to the extent that managers increase pumping to counteract low dissolved oxygen in pond water, pumping costs (and indirectly, pump maintenance costs) depend upon the dissolved oxygen concentration of water pumped from the estuary and the pond processes that then affect dissolved oxygen in the pond. Third, the efficiency with which shrimp utilize artificial food, a factor affected by ecological conditions in the ponds, greatly determines the yield of shrimp per dollar expended on feed and, therefore, total feed costs. Fourth, should pond managers mismanage feeding, for instance, by applying more feed anytime they observe shrimp growth slowing, their costs will rise. This rise may be in response to ecological factors affecting shrimp growth. Finally, fertilizer and artificial feed applications in the ponds affect pond water quality. That water returns to the bay where it affects the quality of water there, water that then returns to the ponds and affects shrimp growth, dissolved oxygen, and profits.

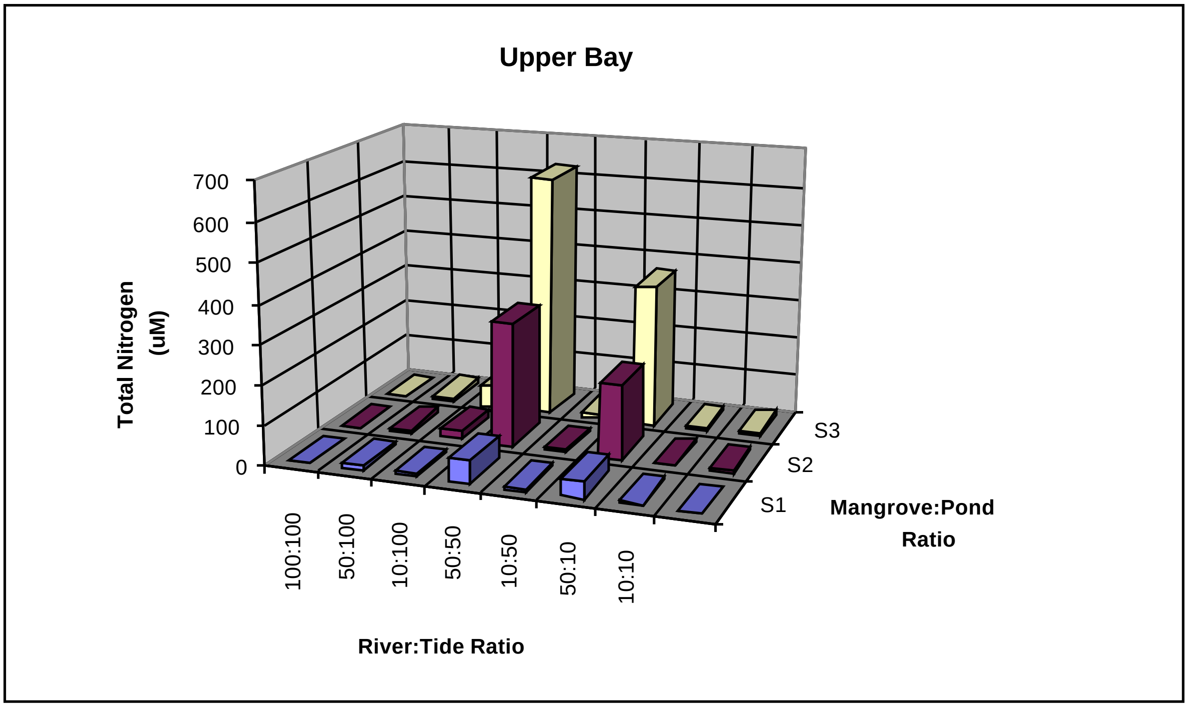
SIMULATION RESULTS

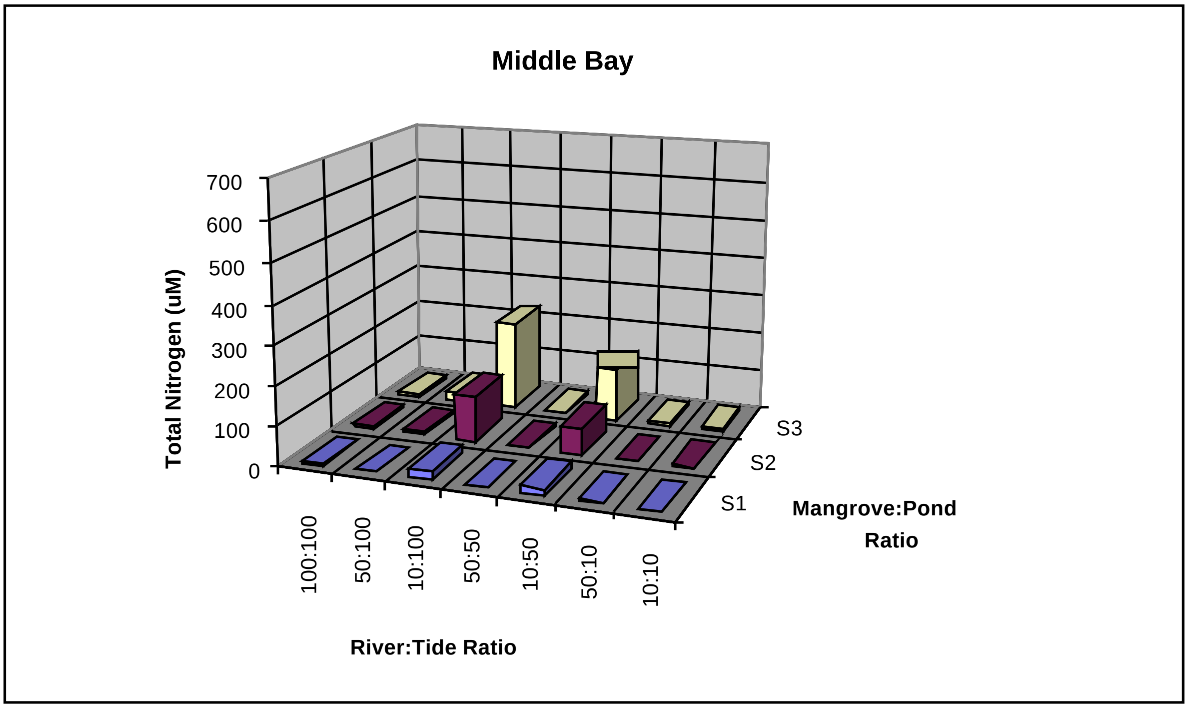
General Figure Legend:

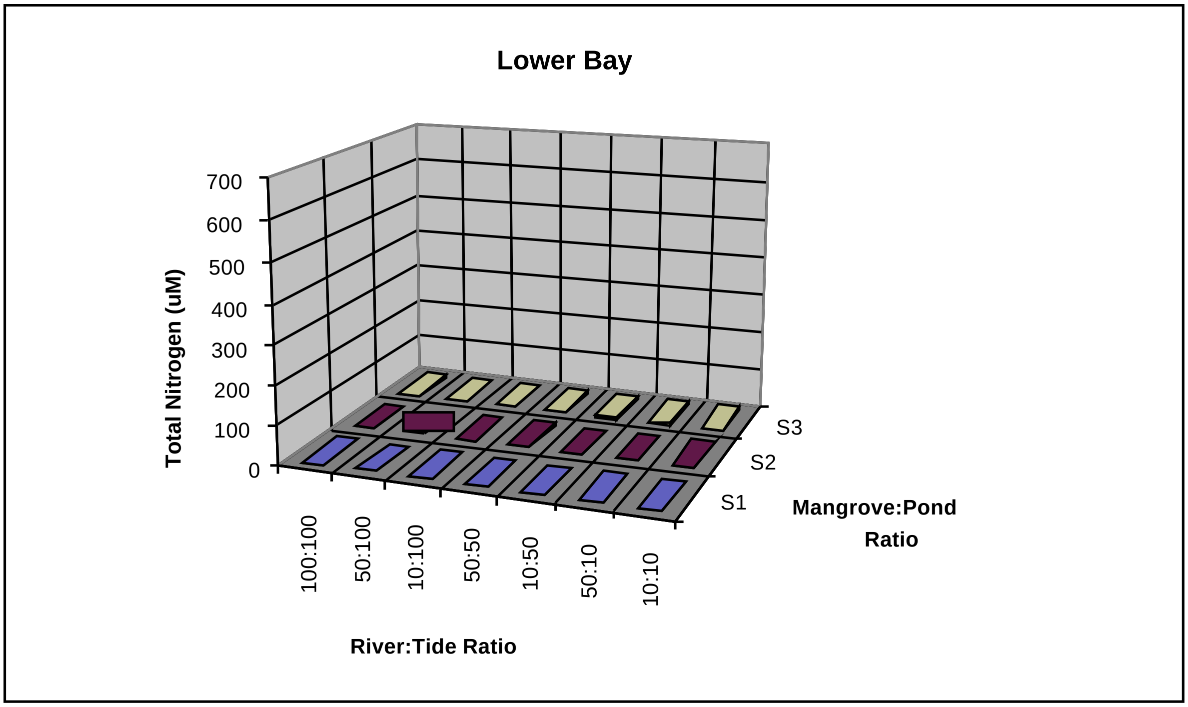
Simulation results of the box model of the Guayas River estuary showing the three land use scenarios at different ratios of river flow and tidal exchange. The river and tide simulations are percentage of the baseline run of 100 % using values for discharge and salinity distribution for 1987.

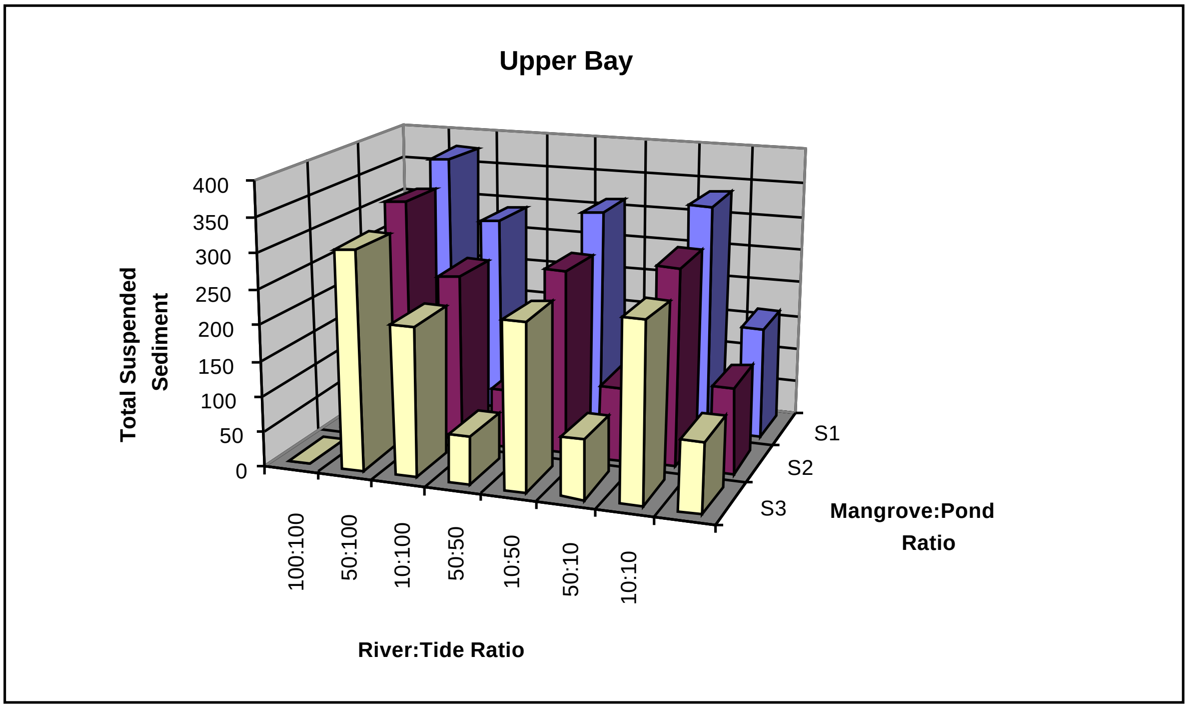
In S1, the entire intertidal area is considered mangroves whereas none is in ponds (100:0), in S2 the area is equally distributed between mangroves and shrimp ponds (50:50), and in S3, all of the intertidal area is converted to shrimp ponds (0:100). The table below gives the intertidal area in km^2 that is used in each simulation run for each bay of the estuary. When 100% of the estuary is in mangroves, the area in mangroves is as shown in the 100% column, with no km^2 in ponds. This is used for runs S1. If mangroves are 50% and ponds 50%, of the intertidal area, each has an area as shown in the second column (run S2). Similarly, if mangroves comprise only 10% of the area, they have the areas shown in the 10% column, with the difference between those numbers and the 100% column being in ponds (S3).

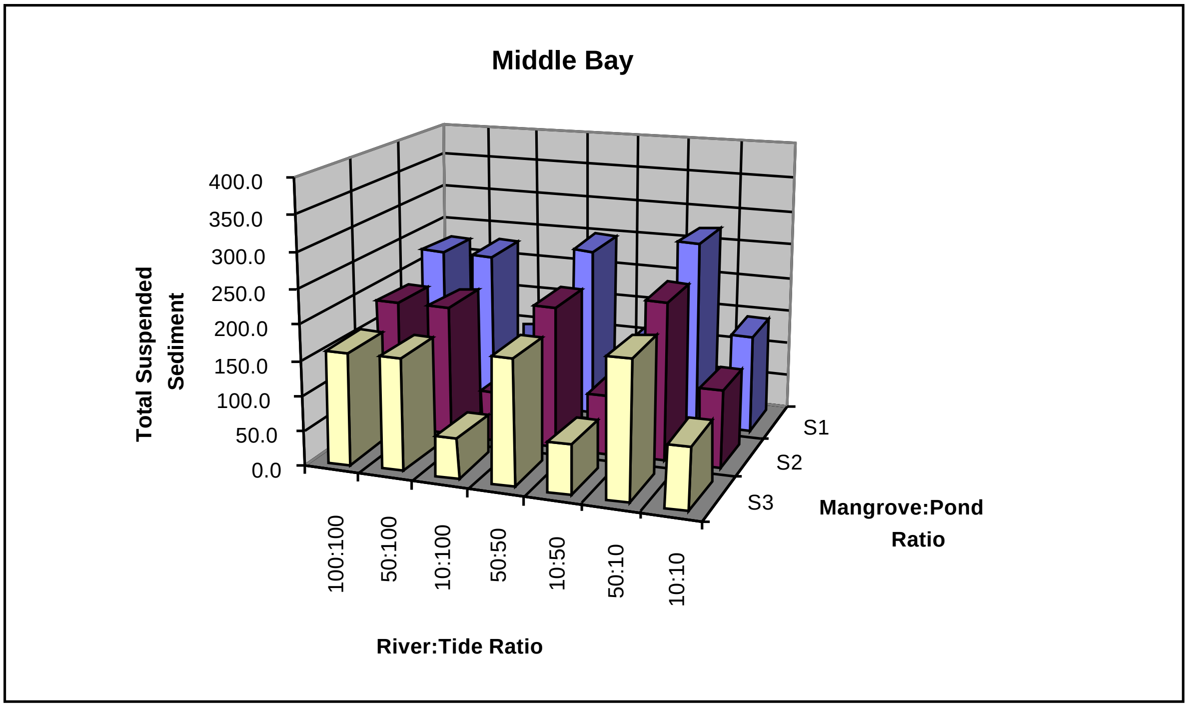
	100 %	50 %	10%
Upper	230	115	23.0
Middle	155	77.5	15.5
Lower	195	97.5	19.5

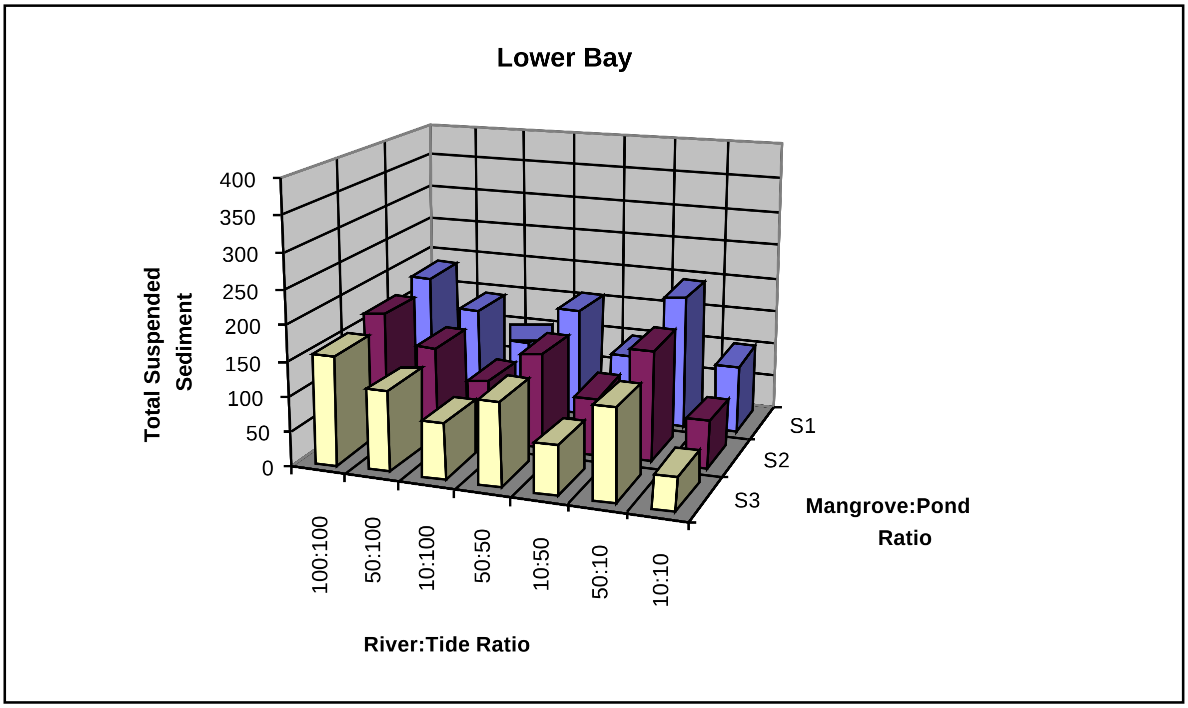

Upper Bay
Total Nitrogen (uM)
0
100
200
300
400
500
600
700
100:100
50:100
10:100
50:50
10:50
50:10
10:10
River:Tide Ratio
S1
S2
S3
Mangrove:Pond Ratio


Middle Bay
Total Nitrogen (uM)
0
100
200
300
400
500
600
700
100:100
50:100
10:100
50:50
10:50
50:10
10:10
River:Tide Ratio
S1
S2
S3
Mangrove:Pond Ratio


Lower Bay


Upper Bay


Middle Bay
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Total Suspended Sediment
100:100
50:100
10:100
50:50
10:50
50:10
10:10
River:Tide Ratio
S1
S2
S3
Mangrove:Pond Ratio


Lower Bay
400
350
300
250
200
150
100
50
0
Total Suspended Sediment
100:100
50:100
10:100
50:50
10:50
50:10
10:10
River:Tide Ratio
S1
S2
S3
Mangrove:Pond Ratio

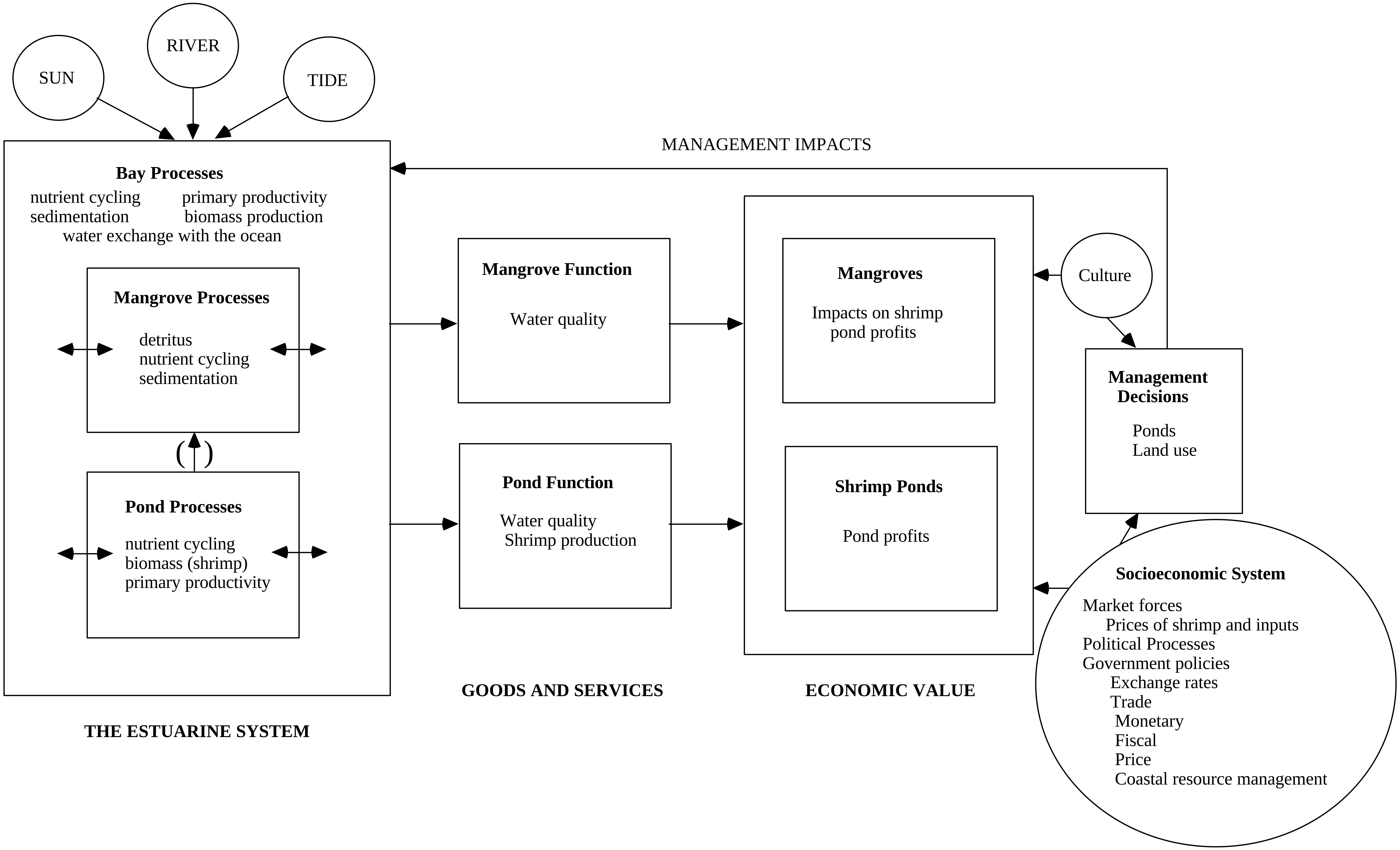


Figure 1. Conceptual framework