WHERE TO PUT MANGROVES?

A spatially explicit trade-off analysis of mangrove conservation and aquaculture in Vietnam

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...shrimp is the fruit of the sea.
You can barbecue it, boil it, broil it, bake it, sauté it.
There's shrimp-kebabs, shrimp creole, shrimp gumbo;
Pan-fried, deep-fried, stir-fried.
There's pineapple shrimp, lemon shrimp, coconut shrimp, pepper shrimp, cave shrimp, shrimp stew, shrimp salad, shrimp and potatoes, shrimp burger, cave shrimp. That... that's about it.

from *Forrest Gump*

Piove
in assenza di Ermione
se Dio vuole

"Piove", Eugenio Montale

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A Daniele, Gianfranco e Raffaele.

SUMMARY

The objective of the thesis is to assess the trade-offs between shrimp aquaculture production and the delivery of the nursery habitat function from mangrove forest in Vietnam. Trade-offs are analysed by mean of a spatially explicit bio-economic model. I develop a Mixed Integer Linear Programming model in GAMS that is employed to trace out the Production Possibility Frontier of the landscape. I formulated three scenarios. The “Benchmark” scenario solves a spatially explicit land allocation optimization problem. The “Lack of Spatial Information” scenario (LSI) shows how the lack of spatial information affects the trade-offs between the land uses. The “Non Spatial Management” scenario (NSM) is employed to compare the benchmark scenario with a non-spatial management.

The results show that is possible to substantially increase aquaculture production at the expense of minor changes in the provision of the nursery habitat service. Moreover, the comparison of the different scenarios shows that spatial attributes do matter. Both the LSI and the NSM scenarios lead to a lower level of the nursery habitat ecosystem service.

CHAPTER 1 - INTRODUCTION

1.1 Mangroves: an ecosystem at stake

Biodiversity and ecosystem protection are among the priorities of environmental policies worldwide. The undervaluation of ecosystem services, the lack of clearly defined property rights, and the frictions between long and short-term goals pose a severe challenge for the protection of biological resources. On the other hand, the economic literature highlights the importance of natural capital for the human wellbeing (Costanza et al., 1997).

Mangroves have faced major changes in the last decades worldwide; the current loss rate (1-2% per year) would make such an ecosystem disappear within 100 years (Duke et al., 2007). Located in coastal areas in tropical and sub-tropical regions around the world, they are threatened by development plans (Valiela et al., 2001). The problem is further exacerbated in developing countries, where more than 90% of mangroves are located (Duke et al., 2007).

Land conversions are the main driver of mangrove loss, and among them, aquaculture pond expansion plays a major role (Barbier and Cox 2003). Shrimp production is one of the most common outputs, given its export-oriented character it is an important source of foreign currency, hence becoming highly attractive, especially in developing countries (Barbier and Cox 2004). Aquaculture production requirements, like the ease of access to water, makes mangrove areas the preferred pond location (Barbier and Cox 2004). Shrimp aquaculture production is the main opportunity cost of mangrove preservation (Barbier and Cox 2003).

Despite the benefit of aquaculture, the mangrove loss rate is likely to be higher than what is socially efficient (Adger and Luttrell 2000). Mangroves provide ecosystem services such as storm buffer, biodiversity protection and the nursery habitat for several marine species that are commercially harvested (Millennium Ecosystem Assessment 2005). Focusing on the latter, the biological literature highlights the strong link between the presence of mangroves and the extent of the offshore population of shrimp (Manson et al., 2005). Based on the biological findings, several studies quantify the economic value of mangroves in supporting the fishery sector (Barbier 2000).

These elements depict a situation that requires a careful landscape planning, so that development plans are optimally balanced with mangrove preservation. It is necessary to assess the trade-offs between the different land use destinations in order to efficiently manage the landscape and to meet any given objective. Both activities are socially relevant. Especially in developing countries, where budget for conservation faces high opportunity costs, and ecosystem conversion pursues short term benefits at the expense of long term advantages, clearly quantifying land allocation trade-offs appears to be crucial.

Moreover, the analysis of such trade-offs should assume a spatially explicit perspective. Different empirical studies underline the importance of spatial attributes (such as the perimeter of the mangrove area) other than absolute extension in explaining the link between mangroves and the shrimp population offshore (Loneragan et al., 2005; Manson et al., 2005).

1.2 Research objective, research questions and methodology: a production possibility frontier to assess "where to put *mangrove*?"

The objective of this thesis is to assess the trade-offs between shrimp production from aquaculture ponds and from mangrove conservation. I formulated the following research questions:

1. What is the shape of the trade-off curve between shrimp aquaculture production and the provision of the shrimp nursery habitat service?
2. How does the availability of spatial information affect the trade-offs between shrimp aquaculture production and the provision of the shrimp nursery habitat service?
3. How does a spatially explicit management affect the trade-offs between shrimp aquaculture production and the provision of the shrimp nursery habitat service, compared to non-spatially explicit managements?

I address the questions by formulating a mathematical model aimed at solving a land allocation optimization problem. An optimization model in GAMS shows where to locate aquaculture ponds and where to prioritize mangrove preservation (focusing on the nursery habitat function), for any given production level demanded. The model is employed to compute the production possibility frontiers (PPF) of a mangrove area for different management scenarios (cf. Polasky et al., 2008).

The PPF -also called efficiency frontier (Polasky et al., 2008) or trade-off curve (Sanchirico and Springborn 2011)- shows the whole range of efficient outcomes, defined as combinations of service delivery where it is not possible to improve delivery of one service without reducing that of another. I trace out the PPF by calculating the maximum amount of nursery habitat service level provided by the landscape, for any given level of cultivated shrimp production.

I design three scenarios (three PPFs) to answer to the questions. The scenarios are formulated according to two elements: 1. the availability of spatial information, and 2. the specification of a spatially explicit management (Table 1). The Benchmark scenario addresses question 1. It entails a spatially explicit economic model to solve a land allocation optimization problem, where the manager of the landscape is aware of the spatially related mechanism, and spatial information is available. The Lack of Spatial Information (LSI) scenario relates to question 2: spatial information is lacking, but the manager is aware of the spatial attributes underlying the nursery habitat service. Finally, the Non-Spatial Management address question 3; the manager is interested in the absolute size of the protected area; no spatial attributes are taken into account.[1]

Table 1 - Scenarios

		Availability of spatial information?	
		Yes	No
Spatially explicit management?	Yes	Benchmark	LSI
	No	*not available*	NSM

The model is applied to the Ngoc Hien District, Ca Mau Province, Vietnam. The region is a mangrove area, which I choose for the availability of spatially explicit data regarding the nursery habitat function. (Phuong 2009).

[1] The design of the model makes it impossible to formulate the missing scenario, as it will be clear in the next sections.

[2] The structural complexity of mangroves and the presence of shallow and turbid water, impede

1.3 Contribution to the literature

The PPF is a common tool in the environmental economics literature with respect to landscape management. PPFs have been traced out to assess the trade-offs between conservation planning and economic output for several terrestrial ecosystems and landscapes (Nalle et al., 2004; Polasky et al., 2008). Ecosystem services are also introduced in trade-off analysis (Nelson et al., 2008). A number of studies take a spatially explicit approach, given the importance of spatial attributes for biodiversity protection and ecosystem services (Polasky et al., 2008; Groeneveld 2010).

However, to the best of my knowledge, while there are several economic analyses of mangrove forests, little attention has been paid to mangrove area trade-offs. The economic literature has focused mostly on the economic quantification of the ecosystem services, in particular on the nursery habitat service (Barbier and Strand 1998; Barbier 2000; Barbier 2007; McNally et al., 2011). These studies do not address the subsequent issue of the mangrove management.

Optimal land allocation of mangrove areas has been studied theoretically. The paper closest to the present research is by Sanchirico and Springborn (2011). They build a theoretical model to compute the trade-off (PPF) curve for a mangrove area. The relevant uses are the contribution of mangroves to the fishery sector, the development of the area (such as aquaculture ponds), and in-situ benefits (such as storm protection). However, my approach differs from theirs with respect to two elements: they do not take a spatially explicit approach, and they do not apply the model to a real case study.

1.4 Thesis overview

The thesis is developed as follows. In Chapter 2, I give more details about the problem of mangrove areas, by briefly reviewing the relevant literature. Aquaculture production, mangrove loss, the habitat nursery function, and the PPF literature are explained in more detail. Chapter 3 describes the model and the application to the real case study. First, I provide the mathematical structure of the model. Second, I describe the area I analyse and the data I employ. Third, I explain the scenarios analysed in this thesis. In Chapter 4 I present the main results of the research. Finally, in Chapter 5, I discuss the results and I draw the conclusion of the research.

CHAPTER 2 – ECONOMICS AND BIOLOGY OF LAND USE ALLOCATION IN MANGROVE AREAS

In this chapter I give more details on the problem faced by coastal areas in tropical and subtropical countries, by briefly reviewing the relevant literature. Section 2.1 focuses on the general problem of mangrove areas, in section 2.2 I describe the main driver of mangrove conversion, namely the expansion of aquaculture ponds. Section 2.3 discusses the nursery habitat ecosystem service, both from the biological and economic viewpoint. In section 2.4 I explain the issue of land allocation problems in mangrove area, by reviewing the existing studies on the topic. Moreover the importance of spatially explicit approach is also explained. Finally 2.5 provides some information on the specificity of the problem in Vietnam.

2.1 Ecosystem protection: mangroves

The term "mangrove" can refer to the whole ecosystem or to the vegetation that is present in the area (Kathiresan and Bingham 2001). According to Kathiresan and Bingham (2001), "Mangroves are woody plants that grow at the interface between land and sea in tropical and sub-tropical latitudes. These plants, and the associated microbes, fungi, plants, and animals, constitute the mangrove forest community or mangal". In this thesis the term "mangrove" refers to the whole ecosystem.

Coastal areas in tropical regions face the problem of optimally allocating land to mangrove conservation and land development plans. Mangroves are threatened by land conversion plans, mostly aimed at expanding aquaculture production. On the other hand there are several reasons to believe that the current rate of mangrove conversion is socially inefficient, and that wetlands benefits are often undervalued (Adger and Luttrell 2000). Mangroves provide several types of ecosystem services, such as storm buffer, biodiversity protection, and nursery habitat (Millennium Ecosystem Assessment 2005).

2.2 Mangrove conversion: aquaculture

The main driver of mangrove loss is land use change (Valiela et al., 2001; Duke et al., 2007). Among these activities, the expansion of aquaculture ponds is the most relevant, especially in countries with large remaining mangrove areas (Barbier and Cox 2003). The spatial requirement of aquaculture ponds and their economic attractiveness make aquaculture industry the main opportunity cost of mangrove conservation.

Mangrove and aquaculture compete for the same type of land. The brackish stagnant water that characterizes mangrove areas is ideal for aquaculture ponds (Barbier and Cox 2004). Giap et al. (2005) show with a GIS model that the areas along the coastline are the most suitable for aquaculture pond construction.

Barbier and Cox (2004) analyse the economic factors pushing the expansion of the aquaculture sector in Thailand. The authors build a theoretical model that is subsequently tested empirically. Aquaculture expansion is assumed to occur at the expense of mangrove area. They carry out a panel data analysis, taking into account as explanatory variables the price of shrimp, the input price, and the accessibility of the area (the distance from Bangkok). The results show that the relative price of shrimp has a positive and significant effect on deforestation. The effect is reduced the further away from the capital, showing that distance is also a powerful factor in determining pond location.

2.3 Mangrove ecosystem services: the nursery habitat service

Ecosystem services are the benefits that ecosystem provides to humankind (Millennium Ecosystem Assessment 2005). Among the various ecosystem services mangroves provide, in the current research I focus on the nursery habitat service for shrimp population.

Mangroves are a nursery habitat for several marine species, in particular fish and crustaceans (shrimp and crab species). Beck et al. (2001) defines the nursery habitat concept: "A habitat is a nursery for juveniles of a particular species if its contribution per unit area to the production of individuals that recruit to adult populations is greater, on average, than production from other habitats in which juveniles occur". Thus, the population of the adult marine species depends, among others, on the presence of a mangrove ecosystem providing the habitat for the juveniles. If the species is commercially harvested, e.g. shrimp, the link between the mangrove and the economy becomes clear: mangroves may affect the productivity of the fishery sector (Barbier and Strand 1998; Barbier 2000; Barbier 2007).

2.3.1 Biological mechanisms

The linkage between the presence of mangroves and marine fauna population size is widely accepted even if it is poorly understood from the ecological point of view (Manson et al., 2005). Shrimp is the species for which the strongest links have been found. Shrimp move into the mangrove in the post larvae phase; after a few months, they return to the ocean as adults (Manson et al., 2005). Mangroves are hypothesized to be the preferred shrimp nursery habitat because 1) they provide a refuge from predator, 2) they are characterized by abundance of food, 3) the vegetation traps in the area the larvae (Manson et al., 2005).[2]

The biological literature highlights two main characteristics that are relevant for this research. First, spatial characteristics such as perimeter (or the interface between land and water) have a stronger effect on the shrimp offshore population than the absolute size of the mangrove area (Manson et al., 2005). Second, the relationship is likely to be characterized by diminishing returns to scale (Loneragan et al., 2005).

The importance of spatial attributes in explaining the underlying mechanisms of the shrimp nursery habitat function is a common result in the biological literature. Testing the relationship between mangrove and coastal fisheries in Australia, Manson et al. (2005) find that mangrove spatial attributes (area and perimeter mostly) are important factors in explaining the differences in catches for mangrove related species such as shrimp. The result from a case study in western peninsula Malaysia shows that the extent and the ratio between mangrove area and coastline length significantly affect on offshore prawn harvest (Loneragan et al., 2005).

The presence of diminishing returns to scale in the relationship between mangrove areas and shrimp population is suggested by Loneragan et al. (2005). The authors find that there is little variation in the shrimp population when

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[2] The structural complexity of mangroves and the presence of shallow and turbid water, impede the movement of large predators. The high level of primary productivity and nutrient explains the abundance of food. The large abundance of food eases the life of the marine species that spend less energy in food research activities. All the three mechanisms are likely to play a role in the habitat nursery function Manson, F. J., N. R. Loneragan, B. D. Harch, G. A. Skilleter and L. Williams (2005). "A broad-scale analysis of links between coastal fisheries production and mangrove extent: A case-study for northeastern Australia." Fisheries Research **74**(1-3): 69-85..

regions in which the mangrove *buffer* along the coast is wide (100-200 m) are compared to those areas in which the mangrove buffer is narrow (5-10 m). On the other hand, a significant reduction in landing occurs when the mangrove has been cleared to build ponds for prawn aquaculture.

2.3.2 Economic evaluations

The biological/ecological understanding of the nursery habitat linkage has relevant implications for economic evaluation of mangrove ecosystems: two-thirds of the world harvested fish depend somehow on coastal habitats (Manson et al., 2005). Barbier (2000) categorizes the economic value of the nursery habitat ecosystem service as an "indirect use value", evaluated through the "production function approach". Mangroves are treated as an input in the production function of the fishery industry and evaluated for the contribution to the fishery output. These methods have been applied to evaluate empirically the economic benefit of mangroves.

Barbier and Strand (1998) assess the economic value of mangroves in Campeche region, Mexico, in sustaining the offshore shrimp fishery sector. The authors build a theoretical bio-economic framework based on a Gordon - Schaefer model of shrimp fishery in an open access environment. Fish growth is assumed to be dependent on the extent of the mangrove area, which affects the carrying capacity of the environment. By introducing the two long-run conditions (constant shrimp stock, and zero profits) they formulate a relationship between shrimp harvests, mangrove area extent and effort. The relationship is then empirically estimated by a time-series analysis (1980-1990) that shows the mangrove-output elasticity of 2.8. The deforestation of mangrove in that period is translated in a loss of US$ 139,352 on average for the fishery sector.

Sathirathai and Barbier (2001) evaluate mangrove conservation in southern Thailand. The extent of mangrove area has been dramatically reduced in the last years for development purposes such as shrimp aquaculture ponds. Depending on the management option for the fishery sector (open access or managed), they estimate the value of mangrove ranges between US$21 and US$69 per ha.

To slow the mangrove loss rate, the effort to preserve mangroves has led to the establishment of several protection areas around the world. While protected areas secure the long run viability of mangroves and of their related ecosystem services, they pose a threat to the locals that rely on mangroves for the extraction of fuel and wood related products. McNally et al. (2011) assess these temporal trade-offs by investigating the environmental and economics implications of Saadani National Park in Tanzania. It is one of the few examples, from the economic literature, in which spatially explicit approach has been employed. They combine georeferenced data about mangrove cover changes and household location with an econometric model. The results show that income from shrimping significantly increases twofold after a 10% increase in the mangrove cover area.

2.4 Spatial land use allocation in mangrove areas

Summarizing the previous analysis, mangroves are threatened by the expansion of land allocated to aquaculture ponds; aquaculture is an important source of income. At the same time, mangroves are very rich ecosystems that provide public benefits that are likely to make the current rate of land conversion socially inefficient. Among these benefits, I focus on the nursery habitat service.

Many coastal areas in tropical and subtropical countries face competition between land use types:

- aquaculture ponds, mostly for shrimp farming;
- mangrove conservation areas for the nursery habitat service (that in turn would support the fishery sector).

The problem entails the presence of trade-offs that should be addressed to efficiently manage the landscape.

2.4.1 Computing PPF

A few studies have addressed the issue of the optimal land allocation between mangroves and alternative uses in coastal areas.

Parks and Bonifaz (1994) develop a conceptual model to identify the optimal mangrove deforestation rate. The authors assume a mangrove provides the post larvae shrimp (PLS) that is an input in the shrimp aquaculture production. The growth of PLS is assumed to be dependent on the extent of the mangrove area, and on the PLS stock. Moreover, they assume that fishermen collect the PLS and that collecting costs are decreasing in PLS stock. At the same time, aquaculture industry needs to clear (part of) the mangrove area to build the ponds. The more the mangrove is deforested, the less the post larvae can be collected. In an open access exploitation institutional environment, aquaculture producers do not take these costs into account; hence the private optimal deforestation rate is higher than the social planner deforestation rate. Temporal trade-offs are present; pursuing short term benefit (by converting mangrove) occurs at the expense of long term productivity (Parks and Bonifaz 1994).

Sanchirico and Springborn (2011) build a theoretical model to compute the tradeoff curve (PPF) for a mangrove area. The alternative outputs are the contribution of mangroves to the fishery sector, the development of the area (such as aquaculture ponds), and in-situ benefits (such as storm protection). A numerical example is employed to compute the trade-offs between the outputs and to draw the optimal path and the payments for ecosystem services needed to reach the frontier.

2.4.2 Spatial elements in the landscape management decision

There is more and more acknowledgment of the need for a spatial approach to ecosystem protection issues. With respect to biodiversity protection, spatial approaches have proved to increase in the efficiency of the preservation target (Groeneveld 2010). Species have *preferences* on habitat. Spatial characteristics provide constraint and opportunities for different species. Soil type, habitat and so on clearly affect the biodiversity present. It is not only a biological matter, but even economic. Soil type and water availability affect the return to land, thus the opportunity cost of biodiversity protection.

Addressing the spatial dimension is becoming a top priority also for ecosystem service management (de Groot et al., 2010). The spatial location is also determined by the societal demand for such services. The demand is determined by the answer to questions like "where are the people who use services, and how much do they use?" (Tallis and Polasky 2009). That is likely to lead to a different landscape management depending on which of the two goals the reserve land allocation is targeted.

This review of the biological literature on the nursery habitat function clearly highlights the importance of spatial attributes, other than absolute extension, in explaining the relationship between mangrove areas and offshore fishery productivity. Spatial factors are however rarely analysed in the economic literature. The usual approach is to assume a given form of dependence on the absolute extent of mangrove areas. Such an approach shows the societal importance of mangrove protection, but it gives little insight into how to manage mangroves at the micro/landscape scale.

However, several studies employed spatially explicit ecological economic models to compute the efficiency frontier of a given area, for other types of ecosystem. Among the others, Polasky et al. (2008) trace the PPF for the Williamette Basin in Oregon, USA. They develop a spatially explicit framework for both a biological preservation and economics model. The biological model includes the possibility that species are preserved even in a working landscape. In the economic branch of the model, the authors analysed production activities such as agriculture, forestry, and residential uses. Preservation is assumed not to provide economic benefits, even if theoretically it would be possible to include ecosystem service evaluations (Polasky et al., 2008). The comparison between the frontier and the actual situation illustrate the inefficiency of the actual management, and the potentiality of a careful spatial planning.

2.5 A spatially explicit framework for mangrove analysis in Ca Mau Province, Vietnam Vietnam

This literature review shows the importance of both mangrove areas and aquaculture production for coastal areas in tropical and subtropical countries. These elements are relevant for Vietnam, a developing country in which mangrove forest are present.

Vietnam is one of the largest shrimp producers worldwide, producing 249,000 tons (Anh et al., 2010). The aquaculture industry has experienced a great development in the coastal areas, at the expense of the mangrove areas (de Graaf and Xuan 1998). Supported by the government, shrimp aquaculture industry produces mostly the black tiger shrimp (Penaeus monodon), mainly in the Mekong Delta (Anh et al., 2010).

The nursery habitat service has been evaluated in Vietnam. De Graaf and Xuan (1998) analysed how the changes in the mangroves and in fishery effort (increase in the fleet) affect the fishery sector. According to their estimates, controlling for the fishing effort, 1 ha of mangrove contributes to the fishery sectory for 0.449 t/year of catch.

Moreover, Vietnam is the case study location for a spatially explicit analysis of the mangrove nursery habitat. Phuong (2009) develops a spatially explicit conceptual model in which the presence of shrimp in the mangrove depends on the possibility of access to the area. Tidal level and the elevation of the plots determine the extent of the area that is flooded, at any moment in time. That in turn affects the accessibility of shrimp into the mangrove. He applies the model to the Ngoc Hien District, Ca Mau Province, Vietnam. The result of the model is a suitability index for the area that shows the relative importance of plots as nursery habitat.

CHAPTER 3 – MODEL AND APPLICATION TO A REAL LANDSCAPE

In order to draw the efficiency frontier of the landscape, I first develop a Mixed Integer Linear Programming (MILP) model that is subsequently formulated in GAMS code. The model combines a biological part with an economic framework. Spatially explicit attributes are also introduced. In section 3.1 I describe the mathematical framework. The model is applied to draw the efficiency frontier for the Ngoc Hien district, in the Ca Mau province, Vietnam. Section 3.2 provides the description of the area; section 3.3 gives detailed information on the data employed in the model. Finally, in section 3.4 I formulate 3 scenarios to compare different management options.

3.1 Model description

I compute the efficient land allocation pattern, defined by the maximization of the biological production generated by the habitat (wild shrimp - kg), subject to a fixed level of production generated by the aquaculture activity (cultivated shrimp - kg). I draw the PPF by solving the maximization problem for the whole range of possible aquaculture production levels (Polasky et al., 2008).

Think of a coastal area in a tropical country and assume the landscape is divided in parcels (*p*) of equal dimension and shape. Following Sanchirico and Springborn (2011), I assume a benevolent social planner (named "manager" from now on) faces a maximization problem related to the allocation of the parcels ($D_{p,u} \in \{0,1\}$) to different activities (*u*), namely nursery habitat (named "habitat" from now on) for wild shrimp ($u \in \mathbf{N}$), and aquaculture ponds for cultivated shrimp ("pond" from now on - $u \in \mathbf{P}$). Consider habitat a subset of mangrove ecosystems that fulfil certain spatial requirements such that it is suitable for being a shrimp nursery habitat. Assume any parcel not allocated to either habitat or pond is mangrove.

The objective function is:

$$\Pi = \max_{D_{p,u}} \sum_{u \in \mathbf{N}} P_u \qquad (1)$$

where P_u is the production of wild shrimp generated by the habitat. The maximization problem is subject to the following constraints.

The production of cultivated shrimp must be greater than a given level $\bar{P}$.

$$\sum_{u \in \mathbf{P}} P_u \geq \bar{P} \qquad (2)$$

Land uses are mutually exclusive.[3]

$$\sum_{u} D_{p,u} \leq 1 \qquad (3)$$

[3] In this prospect, focusing on the specific ecosystem service of shrimp nursery habitat makes the problem different from a biodiversity protection issue, where a relevant attribute is the viability of certain species on working lands Polasky, S., E. Nelson, J. Camm, B. Csuti, P. Fackler, E. Lonsdorf, C. Montgomery, D. White, J. Arthur, B. Garber-Yonts, R. Haight, J. Kagan, A. Starfield and C. Tobalske (2008). "Where to put things? Spatial land management to sustain biodiversity and economic returns." Biological Conservation **141**(6): 1505-1524.. On the other hand, synergies in the provision of ecosystem services are likely to occur, e.g, between the nursery habitat and the storm protection service.

3.1.1 Modelling the nursery habitat service

I assume wild shrimp are harvested offshore from a fishery sector that is not explicitly defined. Spatial attributes are relevant with respect to the qualification of a parcel as habitat, and on the relative productivity in term of wild shrimp.

The benefits from the habitat are given by the production of the total area assigned to habitat in terms of wild shrimp (P_u) times the price of the shrimp (b_u - VND).

$$B_u = b_u P_u \quad \forall u \in \mathbf{N} \tag{4}$$

I formulate the relationship between the extent of the habitat and productivity of shrimp juveniles as characterized by diminishing return to scale, as suggested by the findings of Loneragan et al. (2005). The wild shrimp production function is modelled as a piecewise linear approximation of a version of the Beverton – Holt model (Guénette et al., 1998).[4]

$$P_u \le \frac{L}{1+\left(L/k\right)} \quad \forall u \in \mathbf{N} \tag{5}$$

The linear transformation takes the following shape: $P_u \le a_z + b_z L \;\; \forall z \in \mathbf{Z}, u \in \mathbf{N}$ where a_z and b_z are the relevant linear coefficients for any of the $\mathbf{Z}$ piecewise approximations.

Wild shrimp production depends on the landscape ecological quality (L), and on the carrying capacity of the population of recruits (k).[5] The equation depicts a situation where the contribution of the mangrove to the shrimp population is increasing in the extent of the habitat, at a decreasing rate.

L is given by the sum of ecological quality ($Q_{p,u}$) of each parcel allocated to habitat:

$$L = \sum_u \sum_p Q_{p,u} \quad \forall p; u \in \mathbf{N} \tag{6}$$

The ecological quality of the parcel depends on the shrimp density per parcel whether it is habitat ($p_{p,u}$):

$$Q_{p,u} = p_{p,u} D_{p,u} \quad \forall p; u \in \mathbf{N} \tag{7}$$

Shrimp density is defined by the physical characteristics of the landscape, such as elevation and the tidal level. These factors determine the extent of the area that is inundated, hence, that is accessible to shrimp (Phuong 2009).[6] Parcels are then heterogeneously contributing to the wild shrimp population.

A *mangrove* area becomes *habitat* if the spatial requirement of being connected to the watercourses is met. Recall that the presence of large pond areas are significantly related to a reduction in the mangrove-dependent marine population (Loneragan et al., 2005). Ponds are built buy enclosing the area with

[4] From the original model I substitute the number of adult shrimp with the total landscape quality.
[5] In mathematics terms, *k* represents the asymptote of the function.
[6] More details are provided in the data section (3.3).

dikes. The dikes prevent the natural flow of water, hence blocking the movement of shrimp inland, even in the area behind the pond. Any parcel of land becomes habitat if the adjacent parcel in the direction of the water is also habitat, in other words if the aquaculture ponds do not impede the tidal flow.[7] I assume unidirectionality in the movement of water inundating the land adjacent to the main watercourses. The assumption simplifies the reality of the issue, but it still captures the main idea that each parcel must be connected to water, in order to become suitable for habitat purposes.

Define $\mathbf{W}_p$ the set of parcels that are directly connected to water. These parcels can be allocated to habitat, with no additional requirements. Formally:

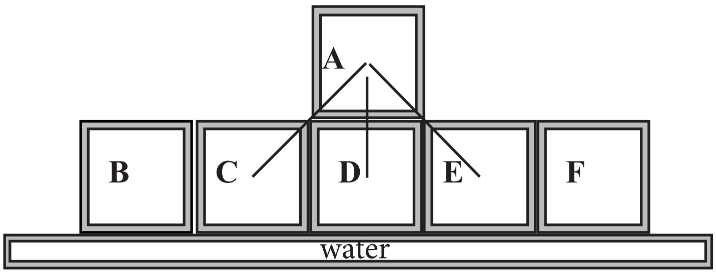
$$D_{p,u} \geq 0 \quad \forall u \in \mathbf{N};\ \forall p \in \mathbf{W}_p \tag{8}$$

Define $\mathbf{I}_p$ the parcels that are not directly connected to water and $\mathbf{G}_p$. The possibility that these parcels become habitat is constrained by the presence of habitat in the adjacent parcels that are immediately in the direction of the water (set of parcels $\mathbf{G}_p$). Figure 1 and Figure 2 illustrate equation (9) with a figurative example.

$$D_{p,u} \leq D_{j,u} \quad \forall u \in \mathbf{N};\ \forall p \in \mathbf{I}_p;\ \forall j \in \mathbf{G}_j \tag{9}$$

Figure 1 - Illustrating adjacency

The figure illustrates the assumption over the definition of adjacency. Parcel A is adjacent to parcel C, D, and E; it is not adjacent to parcel B and F.



[7] The logic is similar to the connectivity issue in the reserve design literature Williams, J., C. ReVelle and S. Levin (2005). "Spatial attributes and reserve design models: A review." Environmental Modeling and Assessment **10**(3): 163-181.. Among the various topics of the RSSP, the "stepping stone" selection is relevant here. Say that a species X is not able to move from reserve A to reserve B, given the distance A-B and the movement capacity of X. B becomes a suitable reserve area only if site C, within the range of the movement capacity of X, becomes a reserve area aimed at functioning as a stepping stone Groeneveld, R. A. (2010). "Species-specific spatial characteristics in reserve site selection." Ecological Economics **69**(12): 2307-2314.. The problem is easily solvable by employing MILP when the movement of the species is unidirectional, like, e.g., in the selection of stepping-stones for migratory flyways Williams, J. C., C. S. ReVelle and D. J. Bain (2003). "A decision model for selecting protected habitat areas within migratory flyways." Socio-Economic Planning Sciences **37**(4): 239-268, Groeneveld, R. A. (2010). "Species-specific spatial characteristics in reserve site selection." Ecological Economics **69**(12): 2307-2314..

Figure 2 - Application of adjacency to the definition of habitat

The figure illustrates when the model allows the allocation of land to habitat. Parcel A can be allocated to habitat since the adjacent parcels are already habitat (black squares). Parcel B cannot be allocated to habitat since the adjacent parcels are allocated to ponds (grey squares).

3.1.2 Modelling aquaculture

Spatial attributes matter also in the aquaculture sector, with respect to the transportation costs and to the reduction in the productivity as a function of the distance from the main watercourses.

Benefits from aquaculture are given by the total production of cultivated shrimp times the shrimp price (b_u - VNP), minus the cost C_u (VNP):

$$B_u = b_u P_u - C_u \quad \forall u \in \mathbf{P} \tag{10}$$

Total aquaculture production is given by the aquaculture pond productivity (kg per parcel) times the number of parcels that are allocated to ponds.

$$P_u = \sum_p p_{p,u} D_{p,u} \quad \forall u \in \mathbf{P} \tag{11}$$

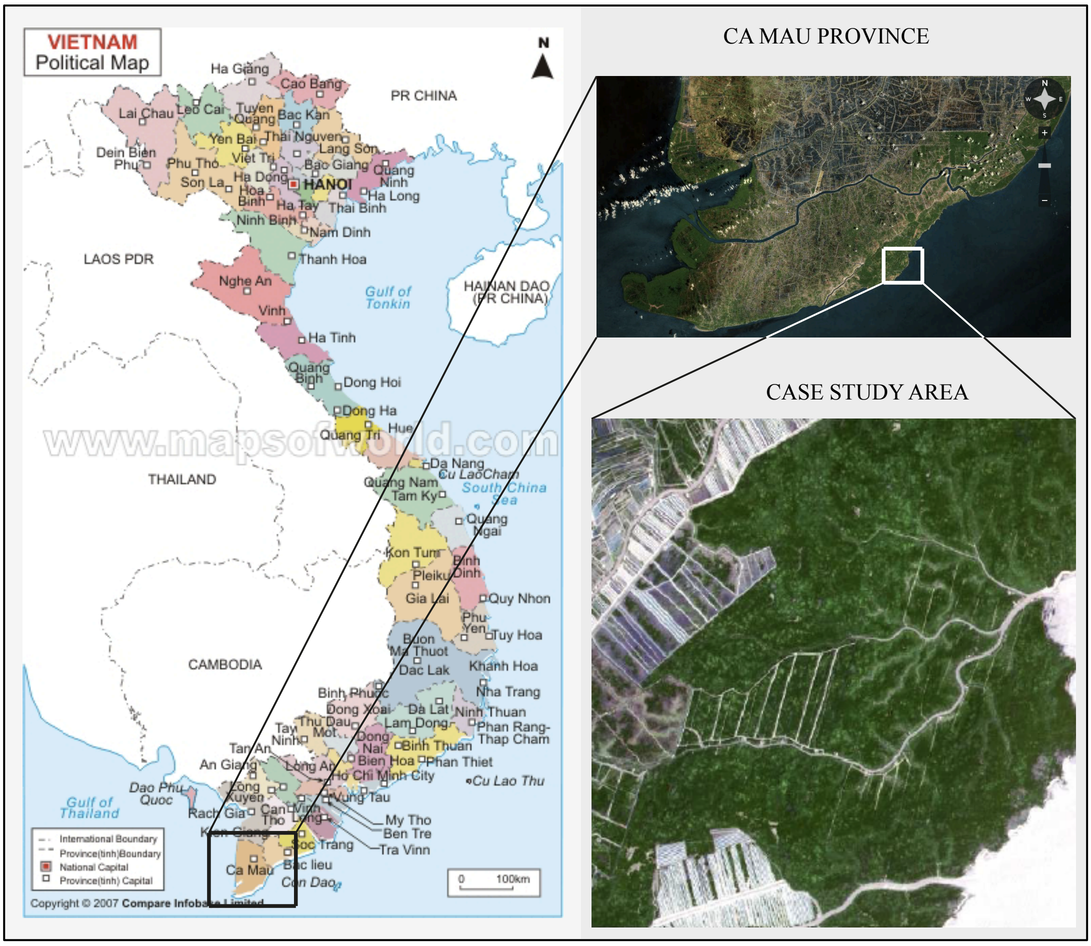
Finally, the costs are given by the transportation costs (VND per parcel). The literature review highlighted the importance of the distance from the markets as in the pond location decision (Barbier and Cox 2004; Giap et al., 2005). Assume waterways are the main infrastructure, so that the distance is computed by calculating the distance of each pond to the closest watercourse, and from there, to the exit of the landscape throughout the watercourses. Say $y_{p,w}$ is the distance (100 m) from each pond to the closest watercourse point (w), h_w is the distance from such a point to the exit (100 m), and t is transportation cost (VND/100 m). The parameter defining the transportation cost per parcel ($c_{p,u}$) is then given by $c_p = t(y_{p,w} + h_w)$.

$$C_u = \sum_p c_p D_{p,u} \quad \forall p,u \in \mathbf{P} \tag{12}$$

3.2 Area description

I apply the model to the In Ngoc Hien District, Ca Mau Province, Vietnam. The area has been chosen for the availability of data regarding the parcel shrimp density (see section 3.3 for more details). The district (743 km^2) is located in the southernmost area of the province. The area I analyse is a landscape surrounded by water for much of the perimeter, on the Northwest side by rivers, and on the east side by the ocean. Fully covered by mangrove, the area is flooded by the tidal regime (Phuong 2009). Rhizophora species is the dominant flora species.

Figure 3 – Study area, from Phuong (2009)



3.3 Data description

Georeferenced data of the area have been obtained from Phuong (2009). The map that was provided contains information over the shrimp density per location. Shrimp density values are the result of a theoretical model developed in order to assess the relative importance of mangrove area as nursery habitat. The value can be interpreted as a nursery habitat suitability index, obtained by taking into account elevation of the land and tidal level (Phuong 2009). The The elevation of the land has been simulated by the author, given the lack of data at the required resolution. Tidal level changes over time, thus I employ in my model the data for the maximum level of the tidal regime.

The raster map has been overlapped by a shapefile grid of 100 m per 100 m parcels, containing the shrimp density information. The water system was simplified to indicate the main watercourses, given the reduction in the resolution following the transformation of the map from raster to shapefile. The map is made of 1389 parcels, subdivided in 1125 parcels defined as “land” and 264 parcels defined as “water”.

I assume shrimp pond productivity takes the value of 600 kg/ha (Binh et al., 1997).[8] I assume the productivity is reduced the further away from the main watercourses so that it captures the problem of access to clean water, needed in the shrimp production process (Kautsky et al., 1997) Parcels are grouped in strips according to the distance from the main watercourses; the reduction in the productivity follows the scheme described in Table 2.

Table 2 – Pond productivity, watercourse distance adjustment

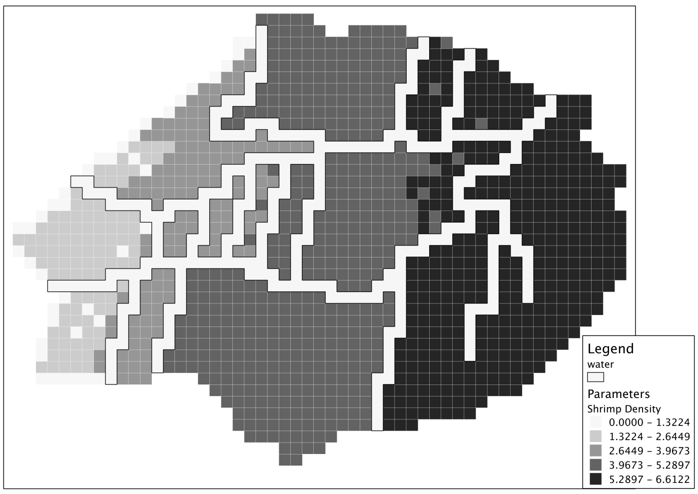
Distance from water	Productivity reduction (%)
$p < 100$m	0
100m $< p <$ 200m	0.01
200m $< p <$ 400m	0.05

For wild shrimp, the relationship between parcels and total production is more complex. Wild shrimp density (productivity) affects the habitat quality. That in turn determines the total contribution of the habitat to the wild shrimp production (see section 3.1). The shrimp density (nr. of shrimp per m^2) ranges from 2.19 to 6.01 (Figure 4).

The modified version of the Beverton - Holt model has been introduced as a piecewise linear approximation. To linearly approximate the curve, the relevant parameters are described next. I assume the carrying capacity (k) to be equal to the number of parcels defined as "land": $k = 1125$. Moreover, recall that the landscape quality is $L = \sum_p \sum_u Q_{p,u} = \sum_p \sum_u p_{p,u} D_{p,u} \quad \forall p,u \in \mathbf{N}$. $p_{p\,u}$ is the shrimp average of the area ($p_{p,u} = 5.068$). The curve has been approximated with 11 intersections.

Figure 4 – Shrimp density map

The density is illustrated by the variation in the grey colour, the darker, the higher the predicted shrimp density. In white, the main watercourses are indicated.

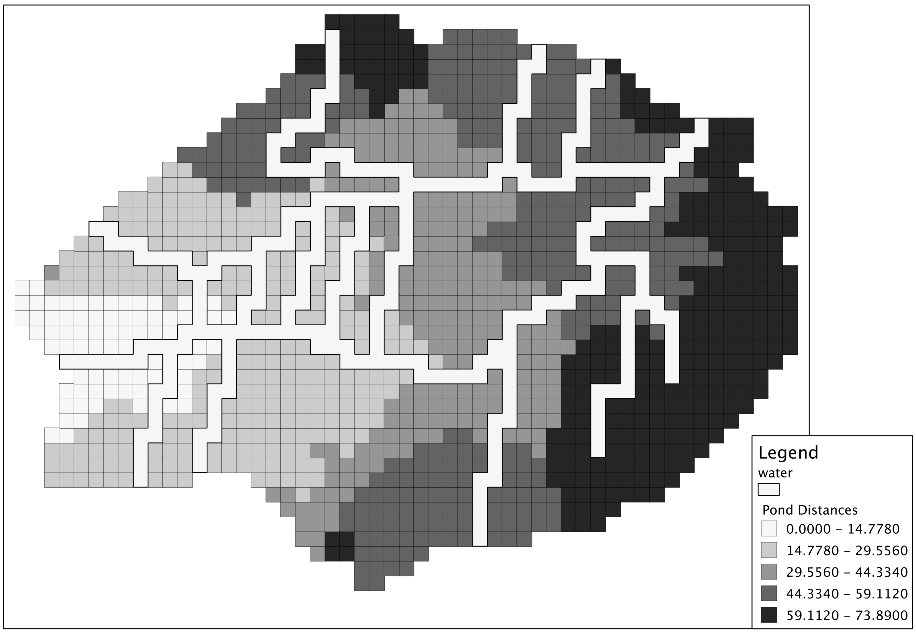


[8] The value is the maximum of the productivity range value. Shrimp productivity shows a great variability in time and farming practices Binh, C. T., M. J. Phillips and H. Demaine (1997). "Integrated shrimp-mangrove farming systems in the Mekong delta of Vietnam." Aquaculture Research **28**(8): 599-610..

The price of shrimp depends on the size of the harvested animal (NACA 2010). Cultivate shrimp price ranges from 90,000 VND/kg to 130,000 VND/kg; to run the model I use the average value, 110,000 VND/kg. Wild shrimp are usually smaller, thus the price ranges from 30,000 to 40,000 VND/kg, employing in the model the value of 35,000 VND/kg (Phung and van Dijk forthcoming).

No transportation costs were available; I assume a value of 1 VND/100 m. Pond distances are shown in Figure 5.

Figure 5 – Distances map



3.4 Scenarios formulation: comparing management options

I formulate three scenarios that are employed to address the three research questions. Recall I define "habitat" as a subset of "mangrove" that meets the spatial requirement of being connected to water, and I assume that any parcel that is not allocated to either habitat or pond is allocated to "mangrove".

3.4.1.Benchmark scenario

The benchmark scenario addresses research question 1, namely, the assessment of the trade-offs between aquaculture production and the shrimp nursery habitat function (see APPENDIX I for the GAMS code). It entails a spatially explicit optimal land allocation problem (equations 1 to 12), where a mangrove protection is aimed at habitat protection (connectivity to water) and the manager has spatially explicit information on the relative importance of parcels for nursery habitat service (shrimp density value).

3.4.2 Lack of Spatial Information scenario (LSI)

I frame the LSI scenario to observe the difference in the ecosystem service provision level when there is no available georeferenced information relative to the ecosystem services; hence these data are not taken into account in the optimization problem. The scenario is employed to answer to the second research question (see APPENDIX II for the GAMS code). In this case study, the relevant data is the shrimp density value per parcel.[9] I trace out the PPF by maximizing aquaculture production, given a fixed habitat size, for the whole range of possible habitat extension. The mathematical notation is as follows.

The objective function is:

$$\Pi = \max_{D_{p,u}} \sum_{u \in \mathbf{P}} P_u \tag{13}$$

where P_u is the production of cultivated shrimp generated by the ponds. The maximization problem is subject to the following constraints.

Call N_u the number of parcels allocated per use. The number of parcels allocated to habitat is equal to a given level N_u. The model is iterated for different values of N_u.

$$\sum_{p,u \in \mathbf{N}} D_{p,u} = N_u \tag{14}$$

Equations 3 to 12 apply here as well.

By setting the constraint on the number of parcels allocated to habitat (namely, absolute size of the habitat area), the manager leaves out from the maximization problem the shrimp density information. The potential differences show the value of goereferenced information for the management of the area.

3.4.3 Non Spatial Management scenario (NSM)

I formulate the NSM scenario to observe the differences in the PPF between a spatially explicit conservation management aimed at protecting habitat (the main model framework) and the effect of a conservation policy not aimed at conserving ecosystem services, and that does not take into account the relative spatial requirements (NSM). The relevant research question is the third one. The manager protects an area from development project (aquaculture pond land is limited), but not considering the nursery habitat service. To compare such a management with the main model, I trace out the PPF with a different setting, in a two steps procedure.

STEP 1: aquaculture production maximization (see APPENDIX IIIA for the GAMS code). I maximize aquaculture production subject to a fixed level of land allocable to aquaculture ponds. In mathematical terms:

$$\Pi = \max_{D_{p,u}} \sum_{u \in \mathbf{P}} P_u \tag{15}$$

The maximization problem is subject to the following constraints.

The number of parcels allocated to aquaculture ponds is equal to a given level N_u. The model is repeated for different values of N_u.

$$\sum_{p,u \in \mathbf{P}} D_{p,u} = N_u \tag{16}$$

Equations 3 to 12 apply here too.

STEP 2: habitat production maximization (see APPENDIX IIIB for the GAMS code). In the second step the model maximizes wild shrimp production

[9] Recall that density shrimp value is the result of a conceptual model, and it is determined by spatial attributes such as land elevation and tidal level.

from mangrove areas, given the parcels that are left "free" from step 1. That shows what is the level of nursery habitat service that *accidentally* is produced by the landscape. In mathematical terms:

$$\Pi = \max_{D_{p,u}} \sum_{u \in \mathbf{N}} P_u \qquad (17)$$

where P_u is the production of wild shrimp generated by habitat. The maximization problem is subject to the following constraint.

The parcels allocated to habitat are the parcels that are not allocated to aquaculture production in step 1, $H_{p,v}$ (both the number and the location of parcels are the same). The model is repeated for the different values of $H_{p,v}$.

$$D_{p,u} = H_{p,v} \quad \mathrm{u} \in \mathbf{N},\ v \notin \mathbf{P} \qquad (18)$$

CHAPTER 4 - RESULTS

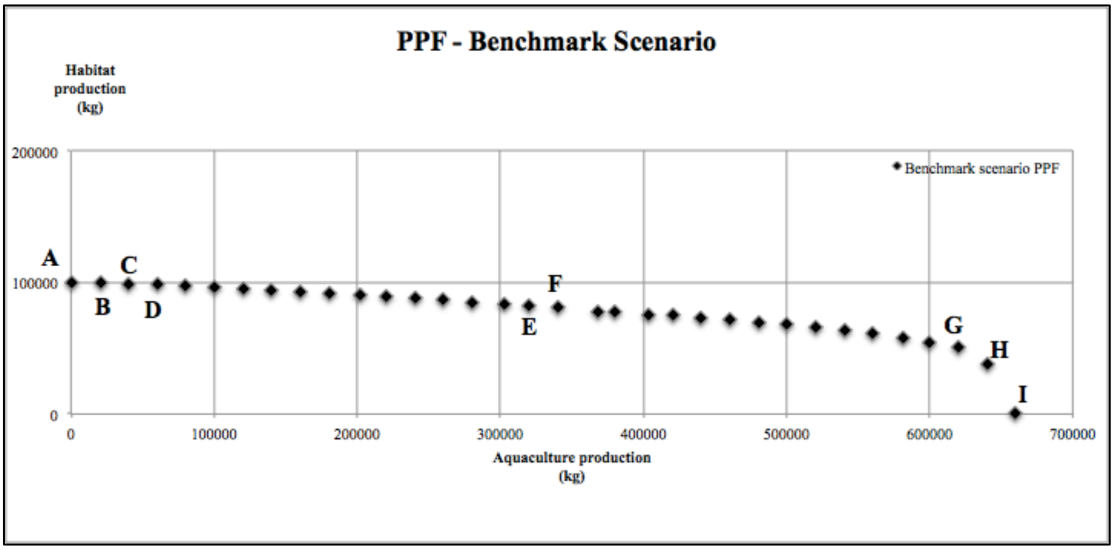
In this section I present the results of the scenarios that have been previously described. Differences in land allocation patterns, and in profits, are described (see APPENDIX IV for the complete result tables).

4.1 Land allocation patterns

4.1.1 Benchmark scenario

The Benchmark scenario implies the mangrove protection is aimed at preserving the nursery habitat, and the manager has full knowledge of the spatial dimension of the problem. GAMS provides the results that are employed to draw the landscape PPF, showing the trade-offs between the production of wild shrimp from habitat, and the production of cultivated shrimp from aquaculture ponds. The PPF of the landscape shows the usual concave shape from the origin (Figure 6). Each point on the PPF is the result of one of the 34 GAMS solutions, namely, each result is characterised by a minimum level of aquaculture production.

Figure 6 – PPF Benchmark scenario



I select some points on the PPF that are descriptive of the relevant trade-offs. Point A shows the maximum quantity of habitat production of the landscape. The level of wild shrimp is relatively low (≈100 t) compared to the maximum level of aquaculture production (point I), that is characterised by a production level of ≈ 6t.

The major trade-offs occur at the borders of the PPF, where small changes in the production level of one activity are translated in bigger change in the production level of the other activity. Moving from left to right (from B to C), large increases in aquaculture production levels (97%) occurs at a relatively small reduction in the ecosystems service levels (-1%). On the other side of the PPF, moving from right to left (from H - G), shows that great contributions to the habitat (25%) comes at the cost of a relatively low reduction in pond production (-3%). In the central part of the PPF, changes are more balanced, e.g., moving from E to F entails a reduction in the habitat production of 1%, balanced by an increase in pond production of 6%.

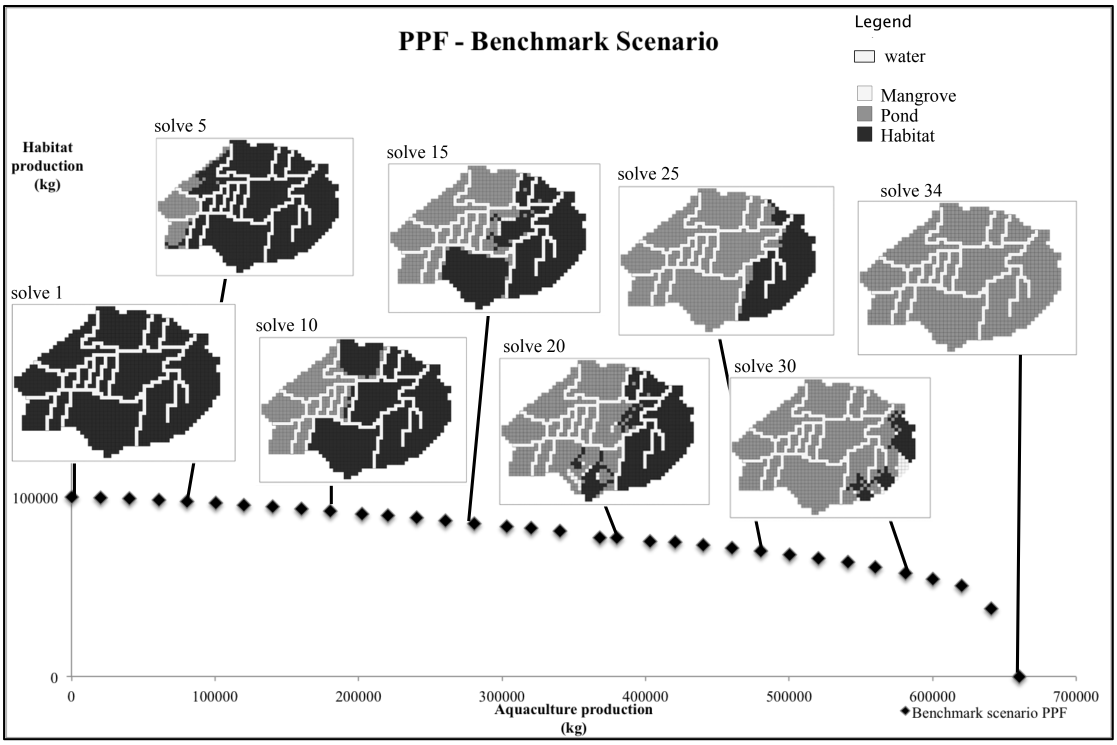
The shape of the curve reflects the diminishing returns to scale that characterises the link between habitat spatial characteristics and production of wild shrimp (equation 5). The first parcels allocated to habitat are highly productive in term of wild shrimp; further increases give a lower contribution to the ecosystem provision level.

Table 3 - % change for selected points

	% change in habitat production	% change in pond production
From B to C	-1%	97%
From C to D	-1%	51%
From E to F	-2%	6%
From G to H	-25%	3%

Recall that the model is spatially explicit; hence each point on the PPF is linked to a land allocation pattern. Figure 7 presents the land allocation patterns for some selected points identified with the GAMS solve order. Moving along the PPF from left to right is translated spatially in the expansion of aquaculture ponds from west to east, showing that habitat is prioritised on east side of the landscape, which is the closest to the coast, and the relatively more productive in term of nursery habitat function (compare with Figure 4, that shows the shrimp density distribution).

Figure 7 – PPF Benchmark scenario, land allocation patterns



4.1.2 LSI scenario

The Lack of Spatial Information scenario sketches a situation where the protection of mangrove is aimed at preserving the nursery habitat service, but the manager lacks the spatial information related to the shrimp density. I formulate the scenario to observe the potential value of the availability of spatially explicit information in the ecosystem service management. Figure 8 shows the LSI PPF in comparison with the Benchmark scenario PPF. Each point on the LSI PPF is characterised by the same extent for habitat area of the points on the Benchmark PPF, so the two curves can be directly compared.

Figure 8 – PPF LSI scenario

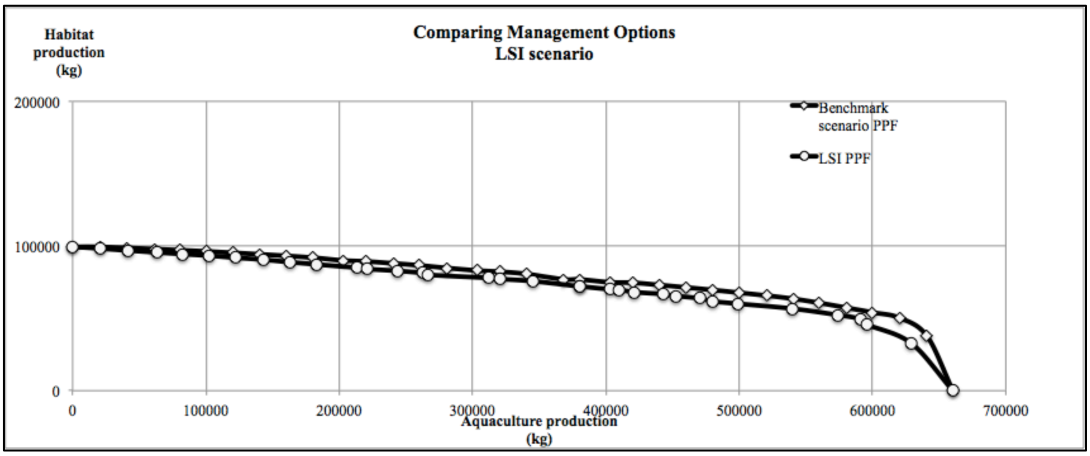


Figure 9 provides details on the habitat production levels among the scenarios. The comparison shows that the lack of spatial information leads to a lower level of habitat production holding constant the habitat area. Only reallocating land according to the shrimp density value (namely, passing from the LSI scenario management to the Benchmark scenario management) leads to an improvement in the habitat production level.

Figure 9 - Nursery habitat service level (kg) - scenarios comparison

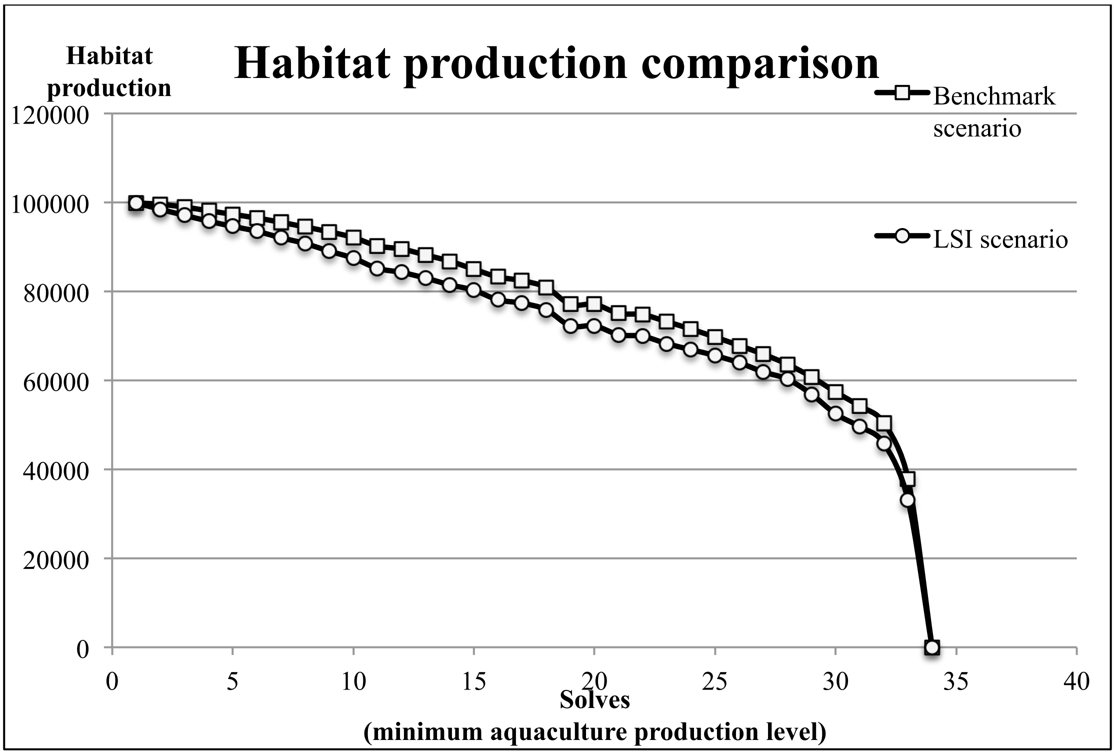
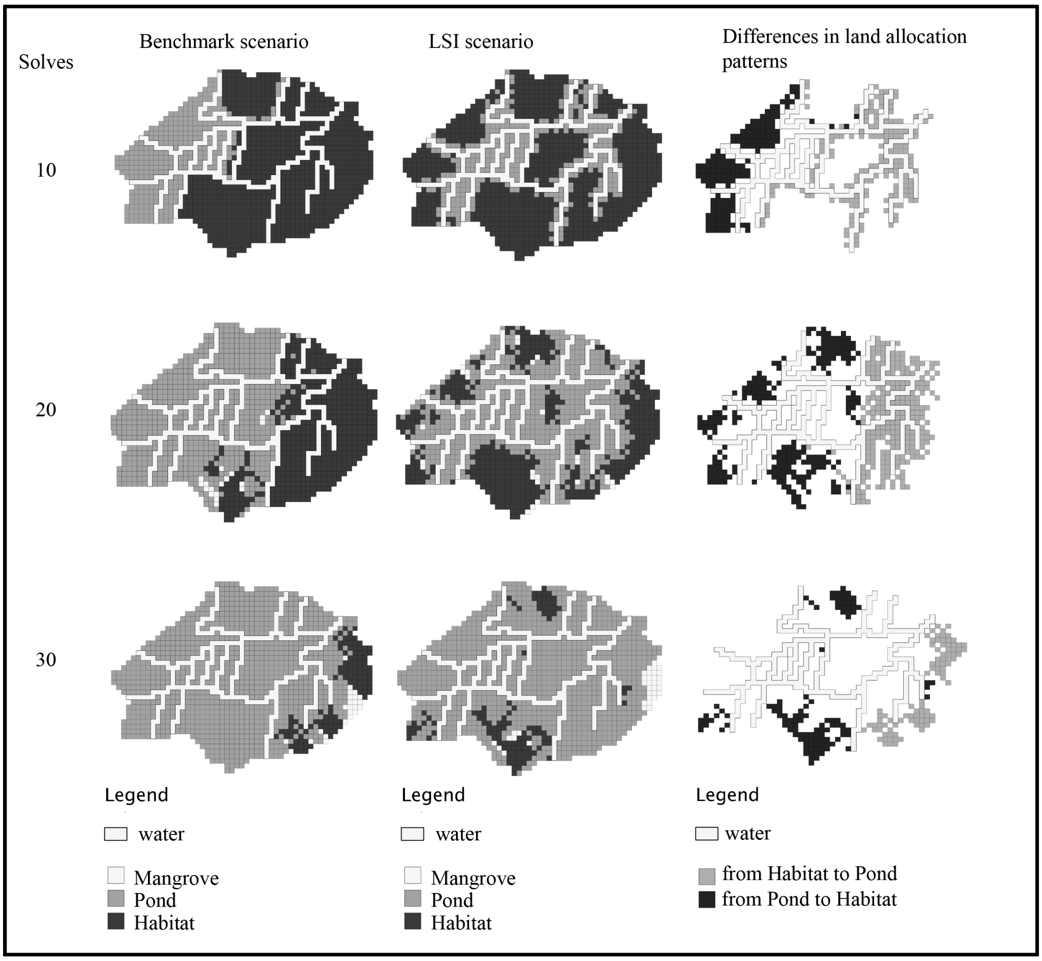


Figure 10 shows the differences in the land allocation between the scenarios, for three selected points on the PPF. The maps indicates that the lower level of habitat production in the LSI scenario is the result of a more evenly distributed land allocation that do not prioritize the location of habitat on the east side of the landscape.

Figure 10 – Land allocation patterns, comparison between Benchmark and LSI scenarios

The third column of maps highlights the parcels that change destination between the scenarios, from the Benchmark, to the LSI.

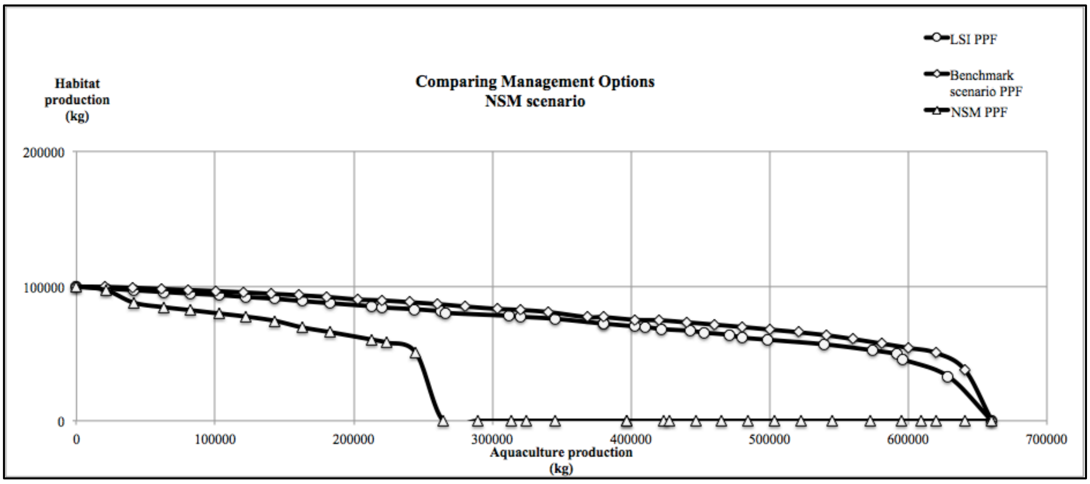


4.1.3 NSM scenario

The Non Spatial Management scenario simulates a situation where the ecosystem management is based on the absolute size of the area protected. No spatial information, nor the ecosystem service, is taken into account in the optimisation problem. However, it is still possible that such a management results in the provision of the shrimp nursery habitat service. I compare the NSM scenario with the Benchmark scenario to observe the differences in the level of nursery habitat service. The model is designed in such a way that the extent of the mangrove in the two scenarios is the same, so that the PPFs are directly comparable.[10]

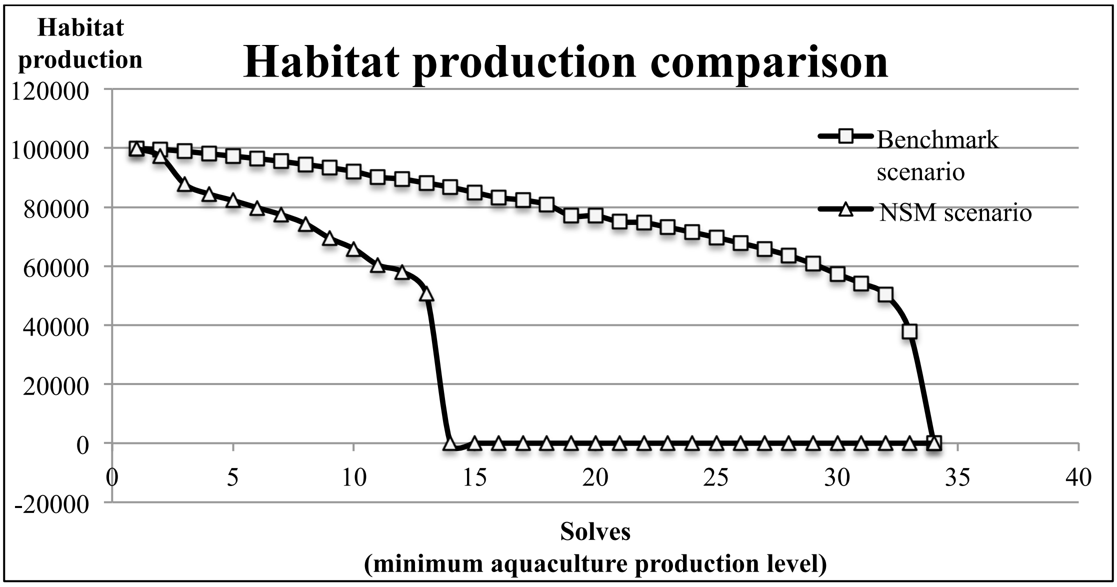
Here the PPF is remarkably different from the benchmark scenario (Figure 11). The characteristics of the optimisation problem are shaped in such a way that the aquaculture ponds are pushed towards the watercourses (pond productivity is higher, and transportation costs are lower, the closer to the watercourses) so that a larger and larger "pond buffer" is built around water, thus impeding the movement of shrimp inland, and the capacity of mangrove to act as nursery habitat.

Figure 11 – PPF NSM scenario



The extent of the protected area is the same between the Benchmark and the NSM for any point, but the habitat production is constantly lower; at solve 14 it reaches the level of 0, far before than in the Benchmark model (Figure 12).

Figure 12 - Nursery habitat service level (kg) - scenarios comparison

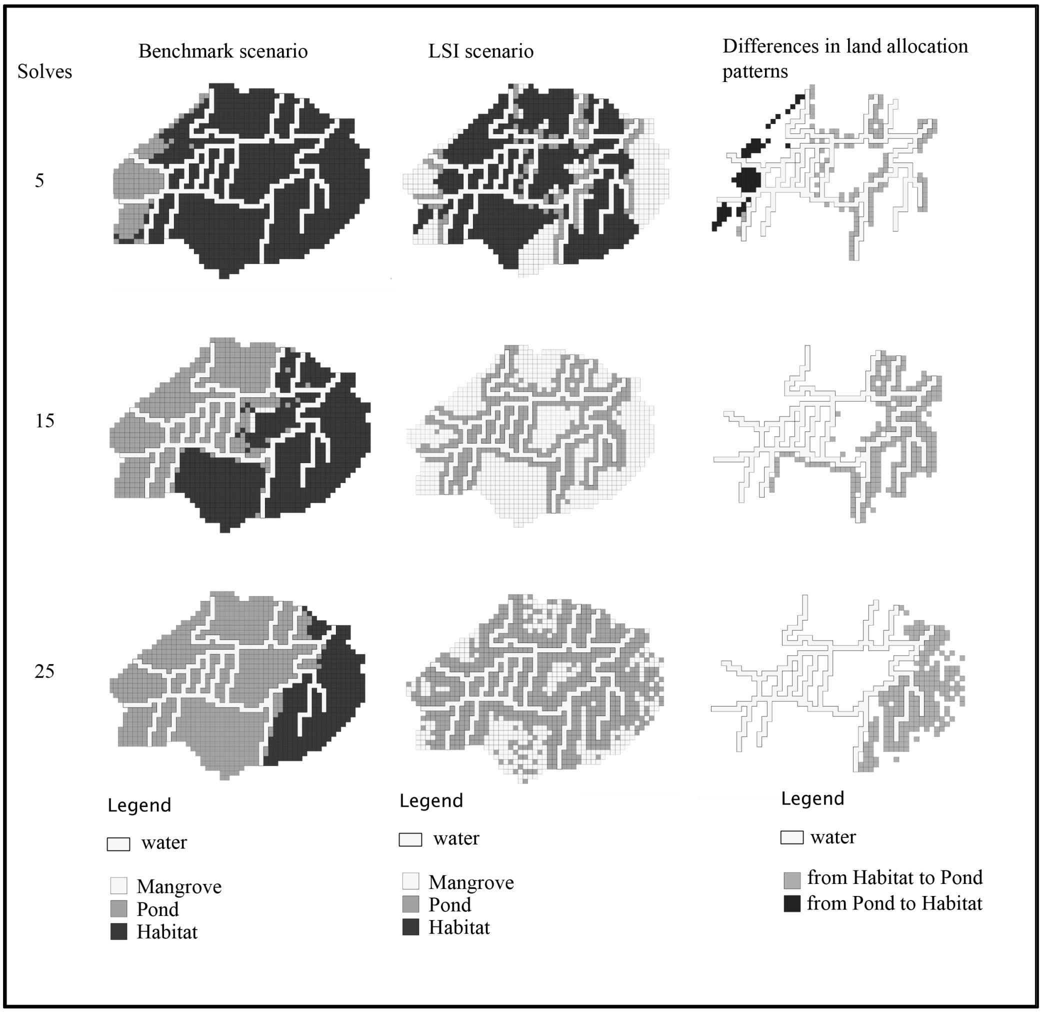


[10] In this case I speak in term of mangrove and not habitat because of the spatial requirements that the mangrove must meet so to become habitat.

Figure 13 clearly shows the differences in the land allocation patterns between the scenarios. More ponds are moved toward the watercourses, hence leaving out the possibility that mangroves provide the nursery habitat service.

Figure 13 – Land allocation patterns, comparison between Benchmark and NSM scenarios

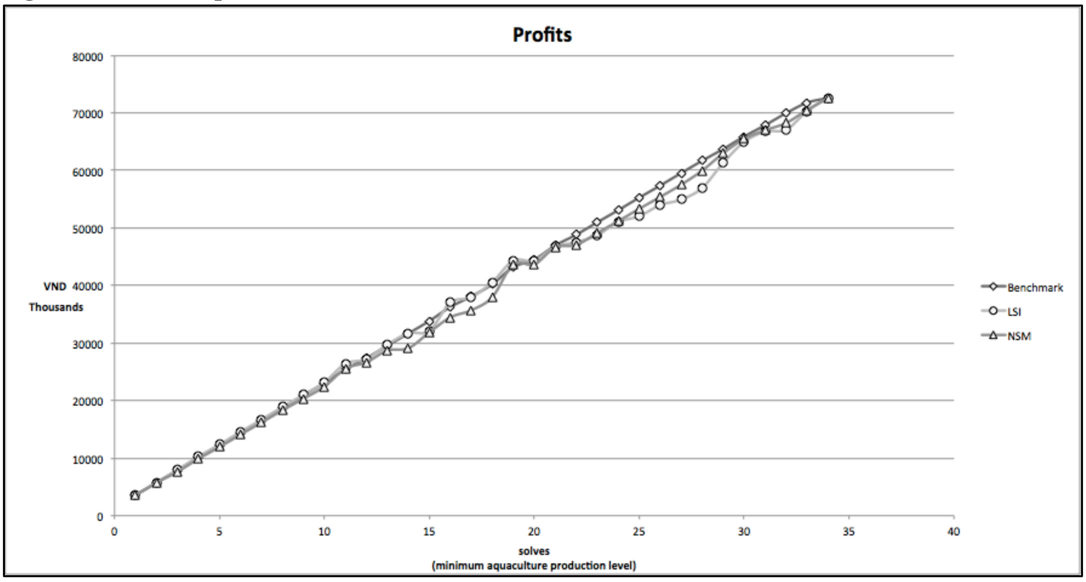
The third column of maps highlights the parcels that changes destination between the scenarios, from the Benchmark, to the NSM.



4.2 Profits

Profits do not differ remarkably among the scenarios. They range from 3.494.643 VND, when the whole area is allocated to habitat, to 72.582.844 VND, when aquaculture ponds occupy the entire landscape. In all cases, profits clearly increase with aquaculture production, showing that the optimal land allocation would entail the complete allocation of land to aquaculture ponds. The LSI scenario leads to profit levels that are constantly lower (but one case) than in the Benchmark scenario. The NSM scenario entails higher profits for the first solves (with respect to the Benchmark scenario), where the aquaculture ponds are allowed to enjoy a better location (so higher productivity and lower transportation costs), and the nursery habitat service is provided. Profits drops with the "collapse" of the nursery habitat service (Figure 14).

Figure 14 - Profits per scenario



CHAPTER 5 – DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

The economic literature highlights the economic value of mangroves, hence underpinning the base for their conservation (Barbier 2000; Millennium Ecosystem Assessment 2005). However, a few studies, and only at the theoretical level, address the issue of mangrove land optimal allocation (Parks and Bonifaz 1994; Sanchirico and Springborn 2011). Recall that most of mangroves are located in developing countries, and that aquaculture production is an important source of valuable currency. Balancing the land use types is crucial, especially at the micro/landscape level. The basic shape of the PPF is similar to other PPFs that are computed for terrestrial ecosystems (Naidoo and Ricketts 2006; Polasky et al., 2008).

Moreover, the biological literature shows the importance of the spatial dimension in the nursery habitat mangrove function (Loneragan et al., 2005; Manson et al., 2005), a dimension that is disregarded in the environmental economic literature with respect to mangrove (Barbier 2000; Sanchirico and Springborn 2011). However, the present study shows that a spatially explicit management makes the difference, and leads to a more efficient landscape outcome. The result is in line with other studies that focus on biodiversity protection issues (Groeneveld 2010) and on ecosystems services (Nalle et al., 2004; Naidoo and Ricketts 2006). The importance of georeferenced information matches the theoretical result regarding the reserve site selection problem of Polasky and Solow (2001).

However the present research have some limitations.

First of all, the mechanisms that underlie the nursery habitat function are still poorly understood, and that is mirrored in the assumptions regarding the relationship between the land allocated to habitat and production of wild shrimps. The results of the research are severely affected by any assumptions regarding such a mechanism. Assuming the nonlinearity of the nursery habitat function, characterised by diminishing return on the habitat extent, is likely to play a role in the optimal landscape management. Linearity in ecosystem service delivery is the common assumption, a simplification driven by the complexity of the ecological mechanisms underlying natural systems. But linearity leads to an “all or none” choice: either fully preserving or fully converting. As it is suggested by Barbier et al. (2008), assuming nonlinearity greatly influences the ecosystem service managements, that would result in the coexistence of ecosystem with development projects at the optimum.

Secondly, I include the fishery sector in the model as a black box, but that determines the value of the mangrove. Different fishery institutions and regulation, by affecting the value of the sector, also affect the optimal management of mangroves (Barbier and Strand 1998). Making the fishery sector explicit would improve the accuracy of the results.

Thirdly, I assume the aquaculture production has no relationship with mangrove forests, whereas in reality such a farming type is only one of the various typologies of aquaculture. Other farming practices involve mangrove as an input in the aquaculture production, the wild shrimps are used as the larvae for the cultivated shrimp (Kautsky et al., 1997; Anh et al., 2010). Moreover, I did not consider the ponds as a source of pollution, that in reality affects the ecological quality of mangroves (Kautsky et al., 1997).

Finally I neglected the temporal dimension and the relative temporal trade-offs. However those are likely to play a major role in developing countries, where mangrove loss is driven by short-term goals (McNally et al., 2011).

5.2 CONCLUSIONS

Coastal areas in many developing countries in tropical and subtropical regions face the completion between different types of land use: aquaculture pond expansion, an important source of valuable foreign currency, threatens the survival of mangrove forests. Mangroves provide several ecosystem services, such as the shrimp nursery habitat function: the mangrove loss rate is likely to be socially inefficient.

These elements require an assessment of the relevant trade-offs between the allocation of land for aquaculture pond production and the preservation of mangrove aimed at preserving the nursery habitat function. Both activities are important; these elements call for a careful landscape planning, so that coastal areas are efficiently managed balancing development with conservation projects. The mechanisms underpinning the nursery habitat function involve mangrove spatial attributes other than area extent; an assessment of the land allocation issue must take a spatially explicit approach.

In order to quantify the trade-offs between the two activities I formulated a spatially explicit land allocation optimization problem model. The model is employed to trace out the Production Possibility Frontier of the landscape. The model is solved in GAMS, for which I developed a Mixed Integer Linear Programming model. The model is applied to a real landscape, in the Ngoc Hien District, Ca Mau Province, Vietnam.

I formulate three research questions that have been answered by designing three scenarios that combines different spatial factors in the management of the landscape.

What are the trade-offs between shrimp aquaculture production and the provision of the shrimp nursery habitat service?

The Benchmark is the relevant scenario, it entails the solution of a land allocation optimization problem where habitat protection takes a spatially explicit approach and the manager has georeferenced information on the relative contribution of parcels to the habitat function. Results show that highest trade-offs are at the borders of the PPF, where increasing the aquaculture production level comes at a relatively low cost in term of habitat production (and the other way around). The shape of the curve mirrors the presence of diminishing return in the nursery habitat function with respect to the habitat size. Habitat is prioritized on the east side of the landscape, the closest to the coast.

How does the availability of spatial information affect the provision of the shrimp nursery habitat service?

I address the question designing the LSI scenario, which is characterized by the lack of georeferenced information on the contribution of each parcel to the nursery habitat service, while the mangrove protection is aimed at protecting the service. The comparison of the LSI PPF with the benchmark PPF highlights the importance of the availability of georeferenced information. Holding the habitat area the same, the LSI scenario constantly entails a lower provision level of the nursery habitat service. This negative outcome is the result of a more evenly distributed allocation of land in the landscape

How does a spatially explicit management affect the provision of the shrimp nursery habitat service, compared to non-spatially explicit managements?

The question is addressed by the NSM scenario in which the mangrove protection is based on the area extent, fully disregarding the spatial attributes. The location of the two land use types is driven by the pond spatial requirements, which results in a dike "buffer" along the watercourses, impeding the movement of the shrimp and severely affecting the mangrove capacity of acting as a nursery habitat. The nursery habitat service level is remarkably lower than in the benchmark scenario.

Summarizing, the results show that, given the presence of diminishing returns in the nursery habitat function, it is possible to convert part of the mangrove area into aquaculture ponds without severely affecting the nursery habitat function. Moreover, the spatial dimensions do matter. First, employing spatial information regarding the ecosystem service greatly contributes to the efficiency of the landscape management. Secondly, fully disregarding the spatial perspective results in a relevant efficiency loss, when the nursery habitat service is at stake. The results of the research advocate for a spatially explicit mangrove landscape management.

Some policy implications follow from the results. The maps show that if the protection of mangrove is aimed at sustaining the shrimp fishery sector, habitat conservation should be prioritized on the areas the closest to the coast, while keeping aquaculture ponds more inland. Moreover, they also suggest avoiding a situation where aquaculture ponds create a dike buffer along the watercourses, thus impeding the movement of shrimps in the mangrove. The results also suggest that improving and acquiring georeferenced information is worth, since it would lead to a more efficient landscape planning.

The present thesis leaves out many potentially important topics. Making explicit the fishery sector (that shapes the value of the mangrove with respect to the nursery habitat service) would give more insight on the landscape management. Moreover, the nursery habitat service is only one of the several ecosystem services delivered by mangroves. Assessing the trade-offs and the synergies among them would also lead to a more comprehensive and efficient land allocation patterns. Finally I completely neglected the temporal dimension and the relative temporal trade-offs. However those are likely to play a major role in developing countries and with respect to mangrove, a quickly restoring ecosystem.

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APPENDIX I – BENCHMARK GAMS CODE

```
*GAMS CODE BENCHMARK SCENARIO

* maximization of wild shrimp Production s.t to a minimum level
of aquaculture productions

*HABITAT FEATURES:
* - connectivity/access to the water way
* - suitability index (nr of shimp per parcel)
* - BH model that links the suitability index to the total
production of the landscape in term of wild shrimp

* AQUACULTURE FEATURE:
* - Productivity depending on the distance from the waterways
* - Distance (along the waterways) to the "exit of the
landscape"
*---------------------------------------------------------

SETS
p     parcels
s_water(p)  parcels defined as water
;
PARAMETER
p_Xcoor     parcels x coordinates
p_Ycoor     parcels y coordinates
p_ShrimpDensity   shrimp density per parcels (nr. Of shrimps per
squared meters)
p_ShrimpDensityAverage
;
* call external file GDX
$Gdxin mangrolfSD
$Load p
$Load s_Water
$Load p_Xcoor
$load p_Ycoor
*$load p_ShrimpDensity
$Gdxin

$Gdxin MZdensity
$load p_ShrimpDensity
$Gdxin

p_ShrimpDensityAverage=sum(p,p_ShrimpDensity(p))/1125;

*---------------------------------------------
* CODE PER BEVERTON HOLT MODEL
* computing parameters for the piecewise linear approximation of
the (non-linear) model
*1. the model computes for each 11 points how many shrimps there
are, according to the Beverton Holt Model
*2. the model then takes some points and it computes the line
parameters. It computes 11 lines

SET
s_CoeffBHmodel nr of lines /c1*c11/
;
PARAMETER
p_K carrying capacity /1125/
p_Juveniles(s_CoeffBHmodel) shrimps juveniles present in the
area - BevertonHoldModel(kg)
;
```

```
*y= mx + n
PARAMETER
p_MaxMangrov / 1125 /
P_mBHmodel(s_CoeffBHmodel)
P_nBHmodel(s_CoeffBHmodel)
x1
x2
y1
y2
yy1
yy2
xx(s_CoeffBHmodel)
;
xx(s_CoeffBHmodel) =
p_MaxMangrov*(ord(s_CoeffBHmodel)/card(s_CoeffBHmodel));
p_Juveniles(s_CoeffBHmodel)=p_ShrimpDensityAverage*(xx(s_CoeffBH
model))/(1+(p_ShrimpDensityAverage*xx(s_CoeffBHmodel)/p_k))
;
VARIABLE
dummy
m
n
;
EQUATION
* system of equations to find the parameter for the linear
approximation
q_retta1
q_retta2
q_Dummy
;
q_retta1..        x1*m+n=E=y1;
q_retta2..        x2*m+n=E=y2;
q_dummy..        dummy=E=0;
model lineareqfinder /all/;
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) eq 1),
x1=0;
y1=0;
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next model (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) ne 1),
x1=xx(s_CoeffBHmodel-1);
y1=p_Juveniles(s_CoeffBHmodel-1);
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next mdoel (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
display
P_mBHmodel
P_nBHmodel
p_Juveniles
p_ShrimpDensityAverage
;
* END CODE PER BEVERTON HOLT MODEL
*---------------------------------------------------------
```

```
* MODEL BENCHMARK PPF

SETS
sol   solves  /solve1*solve34/
U     land use                      /aqu, hab/
s_Nature(u) Nature land uses    / hab /
s_Pollut(u) Polluting land uses / aqu /
s_s   strips along watercourses/s1*s4/
;
ALIAS (u,v)
ALIAS (j,p)
ALIAS (q,j)
ALIAS (i,q)
ALIAS (z,i)
ALIAS (k,z)
;
SETS
*---MAPS OF SETS
m_ROWS(p, s_s)    mapping strips
m_Adjacency(p,j)  mapping adjacency 360 degrees
*---MAPPING CONNECTIVITY TO WATER------------
m_AdjacencyWater(p,j) mapping parcels adjacent to water
m_Catch(p) mapping parcels next to water - progressively
increases in a loop statement
m_TempCatch(p) saving result in the loop for m_Catch

*---MAPPING ADJACENCY WITH NO DIRECTION
m_AdjacencyInWaterNoDirection mapping adjacency for parcel in
river with downstream direction
m_AdjacencyTower(p,j)   adjacency not considering the diagonals
*---MAPPING adjacency WITH DIRECTION
m_AdjacencyInWater(p,j) mapping adjacency for parcel in river
m_RiverLenght(p)   mapping the river to compute the distance of
each river parcel to the end of the river
m_TempRiverLenght(p)    saving result for m_RiverLength
*---COMPUTING RIVER LENGTH
m_River(p)  landscape exit/p133/
m_RiverWay(p,j)
m_TempRiver(p)
m_TempAdj(p)
m_AdjNo
m_TempAdjNo
m_Route
m_TempRoute
m_RiverAdj
;
SCALAR
sc_SomeBigNr      big number /1000000000/
;
PARAMETER
p_Fixy to fix aquaculture production - it changes in the loop
statement
p_Constraint(sol) takes the value in the loop statement and it
give it to p_Fixy
p_CostPer100m cost per 100 m (VND per 100 m) /1/
p_Price(u)  price of activities (VND -1000- per kg)
         /
         aqu 110
         hab  35
         /
;
PARAMETERS
```

```
p_AbsDistBtwParcels     computing distances between parcels (100
m)
p_DistanceFromWater(p,j)      computing distances of each parcel
to each parcel that are water
p_DistanceMinFromWater(p)     computing the minimum distance to
water
p_TransportCost          computing transportation costs    (VNP
per 100 m)
p_DistanceP4
p_TempDistanceP4
;
p_AbsDistBTWParcels(p,j)= sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j))))/100;

p_DistanceFromWater(p,j)$s_Water(j)= sqrt(sqr((p_Xcoor(p)-
p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j))))/100;

p_DistanceMinFromWater(p)= smin(j$s_Water(j),
sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))+sqr((p_Ycoor(p)-
p_Ycoor(j))))/100);

*COMPUTING MAP SETS --------------------------------------------
-----

*ASSIGNING PARCELS TO STRIPS------------------------------------
-----
m_ROWS(p, "s1")= yes$(s_Water(p));

m_ROWS(p, "s2")= yes$((p_DistanceMinFromWater(p) GT  0) and
(p_DistanceMinFromWater(p) LE 1.5 ));

m_ROWS(p, "s3")= yes$((p_DistanceMinFromWater(p) GT  1.5) and
(p_DistanceMinFromWater(p) LE 2.9));

m_ROWS(p, "s4")= yes$((p_DistanceMinFromWater(p) GT  2.9))
*          and (p_DistanceMinFromWater(p) LE 3.606))
;
m_Adjacency(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1.5) and
(p_AbsDistBTWParcels(p,j)GT 0));

m_AdjacencyTower(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1) and
(p_AbsDistBTWParcels(p,j)GT 0));

* MAPPING CONNECTIVITY TO WATER---------------------------------
-----
*1. assigning parcels to set – It increasingly acquires the
parcels. start from the river, then the next strips, etc etc
m_Catch(p)= yes$(s_Water(p));
while(card(m_Catch) lt card(p),
*2. loop over the parcels that are catchment
         loop(p$m_Catch(p),
*3. defining the parcels that are adjacent to the catchment
parcels
                 loop(j$(m_Adjacency(p,j) and (not m_catch(j))),
                  m_AdjacencyWater(j,p) = yes;
*4. temporarily assiging these parcels to the catch
                        m_TempCatch(j)=yes;
                        );
                 );
         m_Catch(p)$m_TempCatch(p) = yes;
);
```

```
* end of the loop------------------------------------------------------
-----

* MAPPIGN ADJACENCY WITH NO DIRECTION----------------------------
----
m_AdjacencyInWaterNoDirection(p,j)=yes$(
                         (s_Water(p))
                         and (s_Water(j))
                         and  m_AdjacencyTower(p,j)
                                 );
*------------
* MAPPING adjacency in river from parcels in the river to
parcels in the river WITH DIRECTION downstream
*1. start of the river:
m_RiverLenght(p)=
yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2. loop over parcels in river
WHILE(card(m_RiverLenght) lt card(s_water),
*3. loop over parcels in river and not already assigned in the
river at 1.
loop(p$( (s_Water(p)) and not(m_RiverLenght(p))),
*4. loop over parcels that are in river and are adjacent to each
other
         loop(j$(m_RiverLenght(j) and m_AdjacencyTower(p,j)),
*5. mapping the adjacency
                 m_AdjacencyInWater(p,j)=yes$m_RiverLenght(j) ;
*6. temporarily assigning the parcels to the river
                 m_TempRiverLenght(p) = yes;
         );
      );
*7. adding these parcels to the m_TempRiverLenght, so that are
not used for the loop at point 4.
  m_riverlenght(p)= m_riverlenght(p)+ m_TempRiverLenght(p);
*8. end of the loop------------
);
*);
*------------
*COMPUTING DISTANCES ALONG THE RIVER----------------------------
-----
*1.
m_route(p)= yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2.
p_DistanceP4("p133")=0.5;
WHILE(card(m_route) lt card(s_water),
loop(i$m_route(i),
         loop(j$(m_AdjacencyInWater(j,i) and (not m_Route(j))),
                 p_DistanceP4(j)=
p_DistanceP4(i)+p_AbsDistBTWParcels(j,i);
                 m_TempRoute(j)= yes;
                 );
         m_route(p)$m_TempRoute(p) = YES;
);
);
*--------------------------------------------------------------
-----
SETS
m_ParcelWaterTranspConn(p,j)   defining the closest parcel in
water for each parcel that is not in water
;
parameter
p_Distance(p)  distance per aquaculture pond (100 m)
p_BioProductivity(p,u) biological productivity in term of shrimp
per land use (10.000 nr of shrimp per ha)
```

```
p_PondProductivity pond productivity /600/
p_NrOfShrimpPerKg /65/
p_PondProductReductionCoeff(s_s) the biological procuctivity per
aquaculutre pond depends on the distance from the water (
         /
         s1 = 0
         s2 = 0
         s3 = 0.01
         s4 = 0.05
         /
;
* MAPPING M_PARCELWATERTRANSPCONN-------------------------------
-----
*1 checking all the parcels that are inland
loop(p$(not s_Water(p)),
*2 cheking all the parcels that are in water
         loop(j$s_Water(j),
*3 assigning m_ParcelWaterTranspConn if the absolute distance
between the p and j is equal to the minimum distance from water
(previously computed)
*4 warning, the code finds multiple parcels that comply with the
requirements
                  m_ParcelWaterTranspConn(p,j) =yes$(
p_AbsDistBTWParcels(p,j) eq p_DistanceMinFromWater(p));
                          );
         );
* COMPUTING THE DISTANCE----------------------------------------
-----
*because of 4, among m_ParcelWaterTranspConn the code chooses
the minimum among p_DistanceP4 (previously computed, it's the
distance for each parcel
* in the water to a given parcel(p133))
p_Distance(p)= smin(j$m_ParcelWaterTranspConn(p,j),
p_DistanceP4(j))+ p_DistanceMinFromWater(p)
         ;
* COMPUTING THE BIOLOGICAL PRODUCTIVITY PER AQUACULTURE
PRODUCTION
* the productivity gets lower the further away from water ways
loop(m_Rows(p, s_s),
*loop(s_s,
*         loop(p$(m_Rows(p, s_s)),
         p_BioProductivity(p,u)$(s_Pollut(u))=
p_PondProductivity* (1-p_PondProductReductionCoeff(s_s))
);
* ASSIGNING THE BIOLOGICAL PRODUCITIVITY PER WILD SHRIMP--------
----
p_BioProductivity(p,u)$(s_Nature(u))= p_ShrimpDensity(p);
VARIABLES
v_Profits  profits (VND)
v_CostAqu  cost of aquaculture ponds (VND per pond)
v_Production (p,u)   production for parcel and land use type
(kg)
v_Objective   the variable that is maximized (habitat from
benefit)
v_TotBenefit  tot benefit per land use (VND)
v_HabitatLandscapeQuality   total score in term of biological
quality for the area
;
POSITIVE VARIABLES
v_HabitatQuality    score in term of biological quality per
parcel
v_TotProduction (u) total production per type of shrimp (kg)
v_Benefit(p,u)  benefit per parcel and land use type  (VNP)
```

```
;
BINARY VARIABLES
b_Dest(p,u)   land use type
;
EQUATIONS
*HABITAT MODEL STRUCTURE----------------------------------------
-----
Q_River     impeding allocation of uses on water
Q_HabitatQuality   habitat quality for parcels on river
Q_HabitatLandscapeQuality     total score in biological quality
Q_HabitatConnect1 parcels must have access to water
Q_HabitatConnect2 parcels must have access to water
Q_BHmodel   production function - linear equations that
approximate the Heverton Holt Model
Q_HabitatBenefit  monetary benefit from habitat

*AQUACULTURE MODEL STRUCTURE------------------------------------
-----
Q_AquaPondProduction    production per parcel allocated to pond
Q_AquapondCost    cost of aquaculture depending on distance from
water
Q_AquaPondBenefit net benefits from aquaculture ponds
Q_AquacultureProduction total aquaculture production
Q_AquacultureBenefit    total aquaculture benefits

Q_UseConstraint   one use for each parcel
Q_Constraint      constraining benefits from aquaculture
Q_Profits   profits
Q_Objective objective function
;

*HABITAT MODEL STRUCTURE----------------------------------------
-----
Q_River(p)$(s_Water(p))..     sum(u, B_Dest(p,u)) =L= 0;

Q_HabitatConnect1(u,p, s_s)$(s_Nature(u) and m_ROWS(p, "s2"))..
b_Dest(p,u)=G= 0;

Q_HabitatConnect2(u,p, s_s)$(s_Nature(u) and not s_Water(p) and
not m_ROWS(p, "s2"))..  b_Dest(p,u) =L=
sum(j$m_AdjacencyWater(p,j),b_Dest(j,u));

Q_HabitatQuality(u,p)$(s_Nature(u))..
v_HabitatQuality(p,u) =E= p_BioProductivity(p,u)*b_Dest(p,u);

Q_HabitatLandscapeQuality..
v_HabitatLandscapeQuality =E=
sum(u$s_Nature(u), sum(p,v_HabitatQuality(p,u)));

Q_BHmodel(u, s_CoeffBHmodel)$(s_Nature(u))..
v_TotProduction(u) =L=
p_NrOfShrimpPerKg*(P_mBHmodel(s_CoeffBHmodel)*v_HabitatLandscape
Quality+P_nBHmodel(s_CoeffBHmodel));

Q_HabitatBenefit(u)$(s_Nature(u)).. v_TotBenefit(u)
=L= v_TotProduction(u)*p_Price(u);

* AQUACULTURE MODEL STRUCTURE-----------------------------------
-----
Q_AquaPondProduction(p,u)$s_Pollut(u)..   v_Production (p,u) =E=
p_BioProductivity(p,u)*b_Dest(p,u);

Q_AquaPondCost(p,u)$s_Pollut(u)..   v_CostAqu(p) =E=
```

```
(p_CostPer100m*p_Distance(p)*b_Dest(p,u));

Q_AquaPondBenefit(p,u)$s_Pollut(u)..      v_Benefit(p,u) =E=
p_Price(u)*v_Production(p,u) - v_CostAqu(p);

Q_AquacultureProduction(u)$s_Pollut(u)..  v_TotProduction(u) =E=
sum(p, v_Production(p,u));

Q_AquacultureBenefit(u)$s_Pollut(u)..     v_TotBenefit(u) =E=
sum(p, (v_Production(p,u)*p_Price(u))-v_CostAqu(p));

* GENERAL STRUCTURE
Q_UseConstraint(p)..    sum(u, b_Dest(p,u)) =L= 1;

Q_Profits.. v_Profits =E= sum(u, v_TotBenefit(u));

Q_Constraint(u)$s_Pollut(u).. v_TotProduction(u) =G= p_Fixy;

Q_Objective..     v_Objective =E=
sum(u$s_Nature(u),v_TotProduction(u))
;
PARAMETER
*saving results for each solve
p_CompParc(u,sol) saving nr of parcels allocated per land use
p_Profits(sol)    saving profits
p_Benefit(p,u,sol)      saving benefits per parcel and land use
p_TotBenefit(u,sol)     saving benefits per land use
p_TotProduction(u,sol)  saving production per land use
p_LandUse(p,sol)  saing land use per parcel and solve
p_Constraint(sol)
p_HabitatLandscapeQuality(sol)
;
* SOLVE CODE
p_Constraint(sol)=0;
MODEL ParcelConfiguration /ALL/;
loop(sol,
p_Fixy = p_Constraint(sol);
SOLVE ParcelConfiguration  USING mip MAXIMIZING v_Objective;
*      saving results
         p_CompParc (u,sol)= sum (p, b_Dest.l(p,u));
         p_Profits(sol)  = v_Profits.l;
         p_Benefit(p,u,sol) = v_Benefit.l(p,u);
         p_TotBenefit(u,sol) = sum(p, v_Benefit.l(p,u));
         p_TotProduction(u,sol)= v_TotProduction.l(u);
         p_HabitatLandscapeQuality(sol)=
v_HabitatLandscapeQuality.l;

* parameter used in the maps:
*         p_LandUSe=0 -> river
*         p_LandUSe=1 -> aquaculture
*         p_LandUse=2 -> mangrove

p_LandUse(p,sol)= sum(u, b_Dest.l(p,u))
                 + sum(u$(s_Nature(u)),b_Dest.l(p,u))
;
p_Constraint(sol+1)=p_Fixy+20000;
);

DISPLAY
p_HabitatLandscapeQuality
p_BioProductivity
m_ParcelWaterTranspConn
p_CompParc
```

```
p_Ycoor
p_Xcoor
p_AbsDistBTWParcels
p_DistanceFromWater
p_DistanceMinFromWater
m_ROWS
m_Adjacency
m_AdjacencyWater
m_Catch
m_AdjacencyInWater
m_AdjacencyTower
m_RiverLenght
m_TempRiverLenght
p_DistanceP4
p_Distance
p_LandUse
;

*OUTPUT FILE CREATION-------------------------------------------
-----
FILE OutputFileBenchmarkMAP/ OutputFileBenchmarkMAP.txt/;
put OutputFileBenchmarkMAP;
OutputFileBenchmarkMAP.pc=0;
OutputFileBenchmarkMAP.pc=6;
put "p"; put "xcoor";put "ycoor";loop(sol, put sol.tl; ) put/;
put//;
loop(p, put p.tl;put p_xcoor(p);put p_ycoor(p); loop(sol, put
p_LandUse(p,sol););); put/);

*---------------------------------------------------------------
-----
FILE OutputFileBenchmarkPPF/ OutputFileBenchmarkPPF.txt/;
put OutputFileBenchmarkPPF;
put "profits    productionAqu   productionHAB     nr. of parcel
per Aqu       nr. of parcel per HAB"; put/;
loop(sol, put sol.tl, put p_profits(sol); loop(u,put
p_TotProduction(u, sol));loop(u,put p_CompParc(u, sol));put/;);
*---------------------------------------------------------------
-----
FILE PondProductivityMap/ PondProductivityMap.txt/;
put PondProductivityMap;
put"p:    xcoor:    ycoor:  pdistance: p_PondProduct:"; put//;
loop(p, put p.tl;put":"; put p_xcoor(p);put":";put
p_ycoor(p);put":"; put p_Distance(p)put":";; put
p_BioProductivity(p,"aqu");put":";; put/;);
*---------------------------------------------------------------
-----
* creating GDX file
parameter
ParcelLocationPerHab_from_10_18_EfficiencyFrontier(sol);
ParcelLocationPerHab_from_10_18_EfficiencyFrontier(sol)=
p_compParc("hab", sol)
Execute_Unload
'ParcelLocationPerHab_from_10_18_EfficiencyFrontier',
ParcelLocationPerHab_from_10_18_EfficiencyFrontier;
parameter
p_LandUseFrom_10_18_EfficiencyFrontier(p,sol);
p_LandUseFrom_10_18_EfficiencyFrontier(p,sol)=p_LandUse(p,sol);
Execute_Unload 'LandUseFrom_10_18_EfficiencyFrontier',
p_LandUseFrom_10_18_EfficiencyFrontier;
```

APPENDIX II – LSI GAMS CODE

```
*GAMS CODE LSI SCENARIO

* maximization of wild shrimp Production s.t to a minimum level
of aquaculture productions

*HABITAT FEATURES:
* - connectivity/access to the water way
* - suitability index (nr of shimp per parcel)
* - BH model that links the suitability index to the total
production of the landscape in term of wild shrimp

* AQUACULTURE FEATURE:
* - Productivity depending on the distance from the waterways
* - Distance (along the waterways) to the "exit of the
landscape"
*---------------------------------------------------------

SETS
p     parcels
s_water(p)  parcels defined as water
;
PARAMETER
p_Xcoor     parcels x coordinates
p_Ycoor     parcels y coordinates
p_ShrimpDensity   shrimp density per parcels (nr. Of shrimps per
squared meters)
p_ShrimpDensityAverage
ParcelLocationPerHab_from_10_18_EfficiencyFrontier
;
*call external file GDX
$Gdxin mangrolfSD
$Load p
$Load s_Water
$Load p_Xcoor
$load p_Ycoor
*$load p_ShrimpDensity
$Gdxin

$Gdxin MZdensity
$load p_ShrimpDensity
$Gdxin

p_ShrimpDensityAverage=sum(p,p_ShrimpDensity(p))/1125;

*----------------------------------------------
* CODE PER BEVERTON HOLT MODEL
* computing parameters for the piecewise linear approximation of
the (non-linear) model
*1. the model computes for each 11 points how many shrimps there
are, according to the Beverton Holt Model
*2. the model then takes some points and it computes the line
parameters. It computes 11 lines

SET
s_CoeffBHmodel nr of lines /c1*c11/
;
PARAMETER
p_K carrying capacity /1125/
p_Juveniles(s_CoeffBHmodel) shrimps juveniles present in the
area - BevertonHoldModel(kg)
```

```
;
*y= mx + n
PARAMETER
p_MaxMangrov / 1125 /
P_mBHmodel(s_CoeffBHmodel)
P_nBHmodel(s_CoeffBHmodel)
x1
x2
y1
y2
yy1
yy2
xx(s_CoeffBHmodel)
;
xx(s_CoeffBHmodel) =
p_MaxMangrov*(ord(s_CoeffBHmodel)/card(s_CoeffBHmodel));
p_Juveniles(s_CoeffBHmodel)=p_ShrimpDensityAverage*(xx(s_CoeffBH
model))/(1+(p_ShrimpDensityAverage*xx(s_CoeffBHmodel)/p_k))
;
VARIABLE
dummy
m
n
;
EQUATION
* system of equations to find the parameter for the linear
approximation
q_retta1
q_retta2
q_Dummy
;
q_retta1..        x1*m+n=E=y1;
q_retta2..        x2*m+n=E=y2;
q_dummy..        dummy=E=0;
model lineareqfinder /all/;
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) eq 1),
x1=0;
y1=0;
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next model (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) ne 1),
x1=xx(s_CoeffBHmodel-1);
y1=p_Juveniles(s_CoeffBHmodel-1);
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next mdoel (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
display
P_mBHmodel
P_nBHmodel
p_Juveniles
p_ShrimpDensityAverage
;
* END CODE PER BEVERTON HOLT MODEL
*---------------------------------------------------------
```

```
* MODEL PER LACK OF SPATIAL INFORMATION SCENARIO LSI

*CALL GDX FILE
$Gdxin ParcelLocationPerHab_from_10_18_EfficiencyFrontier
$Load ParcelLocationPerHab_from_10_18_EfficiencyFrontier
$Gdxin
*-----------------------------------------------------------------
-----


SETS
sol   solves  /solve1*solve34/
U     land use                      /aqu, hab/
s_Nature(u) Nature land uses    / hab /
s_Pollut(u) Polluting land uses / aqu /
s_s   strips along watercourses/s1*s4/
;
ALIAS (u,v)
ALIAS (j,p)
ALIAS (q,j)
ALIAS (i,q)
ALIAS (z,i)
ALIAS (k,z)
;
SETS
*---MAPS OF SETS
m_ROWS(p, s_s)    mapping strips
m_Adjacency(p,j)  mapping adjacency 360 degrees
*---MAPPING CONNECTIVITY TO WATER------------
m_AdjacencyWater(p,j) mapping parcels adjacent to water
m_Catch(p) mapping parcels next to water - progressively
increases in a loop statement
m_TempCatch(p) saving result in the loop for m_Catch

*---MAPPING ADJACENCY WITH NO DIRECTION
m_AdjacencyInWaterNoDirection mapping adjacency for parcel in
river with downstream direction
m_AdjacencyTower(p,j)   adjacency not considering the diagonals
*---MAPPING adjacency WITH DIRECTION
m_AdjacencyInWater(p,j) mapping adjacency for parcel in river
m_RiverLenght(p)   mapping the river to compute the distance of
each river parcel to the end of the river
m_TempRiverLenght(p)    saving result for m_RiverLength
*---COMPUTING RIVER LENGTH
m_River(p)  landscape exit/p133/
m_RiverWay(p,j)
m_TempRiver(p)
m_TempAdj(p)
m_AdjNo
m_TempAdjNo
m_Route
m_TempRoute
m_RiverAdj
;
SCALAR
sc_SomeBigNr      big number /1000000000/
;
PARAMETER
p_Fixy to fix aquaculture production - it changes in the loop
statement
p_Constraint(sol) takes the value in the loop statement and it
give it to p_Fixy
```

```
p_CostPer100m cost per 100 m (VND per 100 m) /1/
p_Price(u)  price of activities (VND -1000- per kg)
         /
         aqu 110
         hab  35
         /
;
PARAMETERS
p_AbsDistBtwParcels     computing distances between parcels (100
m)
p_DistanceFromWater(p,j)      computing distances of each parcel
to each parcel that are water
p_DistanceMinFromWater(p)     computing the minimum distance to
water
p_TransportCost          computing transportation costs    (VNP
per 100 m)
p_DistanceP4
p_TempDistanceP4
;
p_AbsDistBTWParcels(p,j)= sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j)))))/100;

p_DistanceFromWater(p,j)$s_Water(j)= sqrt(sqr((p_Xcoor(p)-
p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j)))))/100;

p_DistanceMinFromWater(p)= smin(j$s_Water(j),
sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))+sqr((p_Ycoor(p)-
p_Ycoor(j)))))/100);

*COMPUTING MAP SETS --------------------------------------------
-----

*ASSIGNING PARCELS TO STRIPS------------------------------------
-----
m_ROWS(p, "s1")= yes$(s_Water(p));

m_ROWS(p, "s2")= yes$((p_DistanceMinFromWater(p) GT  0) and
(p_DistanceMinFromWater(p) LE 1.5 ));

m_ROWS(p, "s3")= yes$((p_DistanceMinFromWater(p) GT  1.5) and
(p_DistanceMinFromWater(p) LE 2.9));

m_ROWS(p, "s4")= yes$((p_DistanceMinFromWater(p) GT  2.9))
*         and (p_DistanceMinFromWater(p) LE 3.606))
;
m_Adjacency(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1.5) and
(p_AbsDistBTWParcels(p,j)GT 0));

m_AdjacencyTower(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1) and
(p_AbsDistBTWParcels(p,j)GT 0));

* MAPPING CONNECTIVITY TO WATER---------------------------------
-----
*1. assigning parcels to set – It increasingly acquires the
parcels. start from the river, then the next strips, etc etc
m_Catch(p)= yes$(s_Water(p));
while(card(m_Catch) lt card(p),
*2. loop over the parcels that are catchment
         loop(p$m_Catch(p),
*3. defining the parcels that are adjacent to the catchment
parcels
                 loop(j$(m_Adjacency(p,j) and (not m_catch(j))),
```

```
                  m_AdjacencyWater(j,p) = yes;
*4. temporarily assiging these parcels to the catch
                         m_TempCatch(j)=yes;
                         );
                 );
         m_Catch(p)$m_TempCatch(p) = yes;
);
* end of the loop---------------------------------------------------
-----

* MAPPIGN ADJACENCY WITH NO DIRECTION---------------------------
----
m_AdjacencyInWaterNoDirection(p,j)=yes$(
                         (s_Water(p))
                         and (s_Water(j))
                         and  m_AdjacencyTower(p,j)
                                 );
*------------
* MAPPING adjacency in river from parcels in the river to
parcels in the river WITH DIRECTION downstream
*1. start of the river:
m_RiverLenght(p)=
yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2. loop over parcels in river
WHILE(card(m_RiverLenght) lt card(s_water),
*3. loop over parcels in river and not already assigned in the
river at 1.
loop(p$( (s_Water(p)) and not(m_RiverLenght(p))),
*4. loop over parcels that are in river and are adjacent to each
other
         loop(j$(m_RiverLenght(j) and m_AdjacencyTower(p,j)),
*5. mapping the adjacency
                 m_AdjacencyInWater(p,j)=yes$m_RiverLenght(j) ;
*6. temporarily assigning the parcels to the river
                 m_TempRiverLenght(p) = yes;
         );
      );
*7. adding these parcels to the m_TempRiverLenght, so that are
not used for the loop at point 4.
  m_riverlenght(p)= m_riverlenght(p)+ m_TempRiverLenght(p);
*8. end of the loop------------
);
*);
*------------
*COMPUTING DISTANCES ALONG THE RIVER----------------------------
-----
*1.
m_route(p)= yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2.
p_DistanceP4("p133")=0.5;
WHILE(card(m_route) lt card(s_water),
loop(i$m_route(i),
         loop(j$(m_AdjacencyInWater(j,i) and (not m_Route(j))),
                 p_DistanceP4(j)=
p_DistanceP4(i)+p_AbsDistBTWParcels(j,i);
                 m_TempRoute(j)= yes;
                 );
         m_route(p)$m_TempRoute(p) = YES;
);
);
*---------------------------------------------------------------
-----
SETS
```

```
m_ParcelWaterTranspConn(p,j)   defining the closest parcel in
water for each parcel that is not in water
;
parameter
p_Distance(p)  distance per aquaculture pond (100 m)
p_BioProductivity(p,u) biological productivity in term of shrimp
per land use (10.000 nr of shrimp per ha)
p_PondProductivity pond productivity /600/
p_NrOfShrimpPerKg /65/
p_PondProductReductionCoeff(s_s) the biological procuctivity per
aquaculutre pond depends on the distance from the water (
         /
         s1 = 0
         s2 = 0
         s3 = 0.01
         s4 = 0.05
         /
;
* MAPPING M_PARCELWATERTRANSPCONN------------------------------
-----
*1 checking all the parcels that are inland
loop(p$(not s_Water(p)),
*2 cheking all the parcels that are in water
         loop(j$s_Water(j),
*3 assigning m_ParcelWaterTranspConn if the absolute distance
between the p and j is equal to the minimum distance from water
(previously computed)
*4 warning, the code finds multiple parcels that comply with the
requirements
                 m_ParcelWaterTranspConn(p,j) =yes$(
p_AbsDistBTWParcels(p,j) eq p_DistanceMinFromWater(p));
                         );
         );
* COMPUTING THE DISTANCE----------------------------------------
-----
*because of 4, among m_ParcelWaterTranspConn the code chooses
the minimum among p_DistanceP4 (previously computed, it's the
distance for each parcel
* in the water to a given parcel(p133))
p_Distance(p)= smin(j$m_ParcelWaterTranspConn(p,j),
p_DistanceP4(j))+ p_DistanceMinFromWater(p)
         ;
* COMPUTING THE BIOLOGICAL PRODUCTIVITY PER AQUACULTURE
PRODUCTION
* the productivity gets lower the further away from water ways
loop(m_Rows(p, s_s),
*loop(s_s,
*         loop(p$(m_Rows(p, s_s)),
         p_BioProductivity(p,u)$(s_Pollut(u))=
p_PondProductivity* (1-p_PondProductReductionCoeff(s_s))
);
* ASSIGNING THE BIOLOGICAL PRODUCITIVITY PER WILD SHRIMP--------
----
p_BioProductivity(p,u)$(s_Nature(u))= p_ShrimpDensity(p);
VARIABLES
v_Profits  profits (VND)
v_CostAqu  cost of aquaculture ponds (VND per pond)
v_Production (p,u)   production for parcel and land use type
(kg)
v_Objective   the variable that is maximized (habitat from
benefit)
v_TotBenefit  tot benefit per land use (VND)
```

```
v_HabitatLandscapeQuality   total score in term of biological
quality for the area
;
POSITIVE VARIABLES
v_HabitatQuality    score in term of biological quality per
parcel
v_TotProduction (u) total production per type of shrimp (kg)
v_Benefit(p,u)  benefit per parcel and land use type  (VNP)
;
BINARY VARIABLES
b_Dest(p,u)   land use type
;
EQUATIONS
*HABITAT MODEL STRUCTURE----------------------------------------
-----
Q_River     impeding allocation of uses on water
Q_HabitatQuality   habitat quality for parcels on river
Q_HabitatLandscapeQuality     total score in biological quality
Q_HabitatConnect1 parcels must have access to water
Q_HabitatConnect2 parcels must have access to water
Q_BHmodel   production function - linear equations that
approximate the Heverton Holt Model
Q_HabitatBenefit  monetary benefit from habitat

*AQUACULTURE MODEL STRUCTURE------------------------------------
-----
Q_AquaPondProduction    production per parcel allocated to pond
Q_AquapondCost    cost of aquaculture depending on distance from
water
Q_AquaPondBenefit net benefits from aquaculture ponds
Q_AquacultureProduction total aquaculture production
Q_AquacultureBenefit    total aquaculture benefits

Q_UseConstraint   one use for each parcel
Q_Constraint      constraining benefits from aquaculture
Q_Profits   profits
Q_Objective objective function
;

*HABITAT MODEL STRUCTURE----------------------------------------
-----
Q_River(p)$(s_Water(p))..     sum(u, B_Dest(p,u)) =L= 0;

Q_HabitatConnect1(u,p, s_s)$(s_Nature(u) and m_ROWS(p, "s2"))..
b_Dest(p,u)=G= 0;

Q_HabitatConnect2(u,p, s_s)$(s_Nature(u) and not s_Water(p) and
not m_ROWS(p, "s2"))..  b_Dest(p,u) =L=
sum(j$m_AdjacencyWater(p,j),b_Dest(j,u));

Q_HabitatQuality(u,p)$(s_Nature(u))..
v_HabitatQuality(p,u) =E= p_BioProductivity(p,u)*b_Dest(p,u);

Q_HabitatLandscapeQuality..
v_HabitatLandscapeQuality =E=
sum(u$s_Nature(u), sum(p,v_HabitatQuality(p,u)));

Q_BHmodel(u, s_CoeffBHmodel)$(s_Nature(u))..
v_TotProduction(u) =L=
p_NrOfShrimpPerKg*(P_mBHmodel(s_CoeffBHmodel)*v_HabitatLandscape
Quality+P_nBHmodel(s_CoeffBHmodel));

Q_HabitatBenefit(u)$(s_Nature(u)).. v_TotBenefit(u)
```

```
=L= v_TotProduction(u)*p_Price(u);

* AQUACULTURE MODEL STRUCTURE-----------------------------------
-----
Q_AquaPondProduction(p,u)$s_Pollut(u)..   v_Production (p,u) =E=
p_BioProductivity(p,u)*b_Dest(p,u);

Q_AquaPondCost(p,u)$s_Pollut(u)..   v_CostAqu(p) =E=
(p_CostPer100m*p_Distance(p)*b_Dest(p,u));

Q_AquaPondBenefit(p,u)$s_Pollut(u)..      v_Benefit(p,u) =E=
p_Price(u)*v_Production(p,u) - v_CostAqu(p);

Q_AquacultureProduction(u)$s_Pollut(u)..  v_TotProduction(u) =E=
sum(p, v_Production(p,u));

Q_AquacultureBenefit(u)$s_Pollut(u)..     v_TotBenefit(u) =E=
sum(p, (v_Production(p,u)*p_Price(u))-v_CostAqu(p));

* GENERAL STRUCTURE
Q_UseConstraint(p)..    sum(u, b_Dest(p,u)) =L= 1;
Q_Profits.. v_Profits =E= sum(u, v_TotBenefit(u));
Q_Constraint(u)$s_Nature(u).. sum(p, b_Dest(p,u)) =E= p_Fixy;
Q_Objective..     v_Objective =E=
sum(u$s_pollut(u),v_TotProduction(u))
;



parameter
*saving results for each solve
p_CompParc(u,sol)         saving nr of parcels allocated per
land use
p_Profits(sol)            saving profits
p_Benefit(p,u,sol)       saving benefits per parcel and land use
p_TotBenefit(u,sol)      saving benefits per land use
p_TotProduction(u,sol) saving production per land use
*p_CompParcII
p_LandUse(p,sol)
p_Constraint(sol)
p_HabitatLandscapeQuality(sol)
;

MODEL ParcelConfiguration /ALL/;
loop(sol,
p_Fixy =
ParcelLocationPerHab_from_10_18_EfficiencyFrontier(sol);
SOLVE ParcelConfiguration  USING mip MAXIMIZING v_Objective;
*      saving results
         p_CompParc (u,sol)= sum (p, b_Dest.l(p,u));
         p_Profits(sol)  = v_Profits.l;
         p_Benefit(p,u,sol) = v_Benefit.l(p,u);
         p_TotBenefit(u,sol) = sum(p, v_Benefit.l(p,u));
         p_TotProduction(u,sol)= v_TotProduction.l(u);
         p_HabitatLandscapeQuality(sol)=
v_HabitatLandscapeQuality.l;
* parameter used in the maps next parameter:
*         p_LandUSe=0 -> river
*         p_LandUSe=1 -> aquaculture
*         p_LandUse=2 -> mangrove
         p_LandUse(p,sol)= sum(u, b_Dest.l(p,u))
                 + sum(u$(s_Nature(u)),b_Dest.l(p,u))
;
```

```
*        p_CompParcII(u,sol) = sum (p$s_NorthSouth("north",p),
b_Dest.l(p,u));
p_Constraint(sol+1)=p_Fixy+100;
);
*-----------------------------------------------------------------
-----
file OutputFileLSIMAP/OutputFileLSIMAP.txt/;
put OutputFileLSIMAP;
OutputFileLSIMAP.pc=0;
OutputFileLSIMAP.pc=6;
put "p"; put "xcoor";put "ycoor";loop(sol, put sol.tl; ) put/;
put//;
loop(p, put p.tl;put p_xcoor(p);put p_ycoor(p); loop(sol, put
p_LandUse(p,sol););  put/);
*-----------------------------------------------------------------
-----
file OutputFileLSIPPF/ OutputFileLSIPPF.txt/;
put OutputFileLSIPPF;
put "profits    productionAqu   productionHAB     nr. of parcel
per Aqu       nr. of parcel per HAB"; put/;
loop(sol, put sol.tl, put p_profits(sol); loop(u,put
p_TotProduction(u, sol));loop(u,put p_CompParc(u, sol));put/;);
*-----------------------------------------------------------------
-----
p_LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ(p,sol);
p_LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ(p,sol)=p_LandUs
e(p,sol);
Execute_Unload 'LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ',
p_LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ;
```

APPENDIX IIIA – NSM FIRST STEP GAMS CODE

```
*GAMS CODE NSM - step 1 SCENARIO

* maximization of wild shrimp Production s.t to a minimum level
of aquaculture productions

*HABITAT FEATURES:
* - connectivity/access to the water way
* - suitability index (nr of shimp per parcel)
* - BH model that links the suitability index to the total
production of the landscape in term of wild shrimp

* AQUACULTURE FEATURE:
* - Productivity depending on the distance from the waterways
* - Distance (along the waterways) to the "exit of the
landscape"
*---------------------------------------------------------

SETS
p     parcels
s_water(p)  parcels defined as water
;
PARAMETER
p_Xcoor     parcels x coordinates
p_Ycoor     parcels y coordinates
p_ShrimpDensity   shrimp density per parcels (nr. Of shrimps per
squared meters)
p_ShrimpDensityAverage
;
* call external file GDX
$Gdxin mangrolfSD
$Load p
$Load s_Water
$Load p_Xcoor
$load p_Ycoor
*$load p_ShrimpDensity
$Gdxin

$Gdxin MZdensity
$load p_ShrimpDensity
$Gdxin

p_ShrimpDensityAverage=sum(p,p_ShrimpDensity(p))/1125;

*----------------------------------------------
* CODE PER BEVERTON HOLT MODEL
* computing parameters for the piecewise linear approximation of
the (non-linear) model
*1. the model computes for each 11 points how many shrimps there
are, according to the Beverton Holt Model
*2. the model then takes some points and it computes the line
parameters. It computes 11 lines

SET
s_CoeffBHmodel nr of lines /c1*c11/
;
PARAMETER
p_K carrying capacity /1125/
p_Juveniles(s_CoeffBHmodel) shrimps juveniles present in the
area - BevertonHoldModel(kg)
;
```

```
*y= mx + n
PARAMETER
p_MaxMangrov / 1125 /
P_mBHmodel(s_CoeffBHmodel)
P_nBHmodel(s_CoeffBHmodel)
x1
x2
y1
y2
yy1
yy2
xx(s_CoeffBHmodel)
;
xx(s_CoeffBHmodel) =
p_MaxMangrov*(ord(s_CoeffBHmodel)/card(s_CoeffBHmodel));
p_Juveniles(s_CoeffBHmodel)=p_ShrimpDensityAverage*(xx(s_CoeffBH
model))/(1+(p_ShrimpDensityAverage*xx(s_CoeffBHmodel)/p_k))
;
VARIABLE
dummy
m
n
;
EQUATION
* system of equations to find the parameter for the linear
approximation
q_retta1
q_retta2
q_Dummy
;
q_retta1..        x1*m+n=E=y1;
q_retta2..        x2*m+n=E=y2;
q_dummy..        dummy=E=0;
model lineareqfinder /all/;
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) eq 1),
x1=0;
y1=0;
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next model (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) ne 1),
x1=xx(s_CoeffBHmodel-1);
y1=p_Juveniles(s_CoeffBHmodel-1);
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next mdoel (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
display
P_mBHmodel
P_nBHmodel
p_Juveniles
p_ShrimpDensityAverage
;
* END CODE PER BEVERTON HOLT MODEL
*---------------------------------------------------------
*CALL GDX FILE
```

```
$Gdxin ParcelLocationPerHab_from_10_18_EfficiencyFrontier
$Load ParcelLocationPerHab_from_10_18_EfficiencyFrontier
$Gdxin

SETS
sol   solves  /solve1*solve34/
U     land use                     /aqu, hab/
s_Nature(u) Nature land uses    / hab /
s_Pollut(u) Polluting land uses / aqu /
s_s   strips along watercourses/s1*s4/
;
ALIAS (u,v)
ALIAS (j,p)
ALIAS (q,j)
ALIAS (i,q)
ALIAS (z,i)
ALIAS (k,z)
;
SETS
*---MAPS OF SETS
m_ROWS(p, s_s)    mapping strips
m_Adjacency(p,j)  mapping adjacency 360 degrees
*---MAPPING CONNECTIVITY TO WATER------------
m_AdjacencyWater(p,j) mapping parcels adjacent to water
m_Catch(p) mapping parcels next to water - progressively
increases in a loop statement
m_TempCatch(p) saving result in the loop for m_Catch

*---MAPPING ADJACENCY WITH NO DIRECTION
m_AdjacencyInWaterNoDirection mapping adjacency for parcel in
river with downstream direction
m_AdjacencyTower(p,j)   adjacency not considering the diagonals
*---MAPPING adjacency WITH DIRECTION
m_AdjacencyInWater(p,j) mapping adjacency for parcel in river
m_RiverLenght(p)   mapping the river to compute the distance of
each river parcel to the end of the river
m_TempRiverLenght(p)    saving result for m_RiverLength
*---COMPUTING RIVER LENGTH
m_River(p)  landscape exit/p133/
m_RiverWay(p,j)
m_TempRiver(p)
m_TempAdj(p)
m_AdjNo
m_TempAdjNo
m_Route
m_TempRoute
m_RiverAdj
;
SCALAR
sc_SomeBigNr      big number /1000000000/
;
PARAMETER
p_Fixy to fix aquaculture production - it changes in the loop
statement
p_Constraint(sol) takes the value in the loop statement and it
give it to p_Fixy
p_CostPer100m cost per 100 m (VND per 100 m) /1/
p_Price(u)  price of activities (VND -1000- per kg)
         /
         aqu 110
         hab  35
         /
```

```
;
PARAMETERS
p_AbsDistBtwParcels     computing distances between parcels (100
m)
p_DistanceFromWater(p,j)      computing distances of each parcel
to each parcel that are water
p_DistanceMinFromWater(p)     computing the minimum distance to
water
p_TransportCost          computing transportation costs    (VNP
per 100 m)
p_DistanceP4
p_TempDistanceP4
;
p_AbsDistBTWParcels(p,j)= sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j)))))/100;

p_DistanceFromWater(p,j)$s_Water(j)= sqrt(sqr((p_Xcoor(p)-
p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j)))))/100;

p_DistanceMinFromWater(p)= smin(j$s_Water(j),
sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))+sqr((p_Ycoor(p)-
p_Ycoor(j)))))/100);

*COMPUTING MAP SETS --------------------------------------------
-----

*ASSIGNING PARCELS TO STRIPS------------------------------------
-----
m_ROWS(p, "s1")= yes$(s_Water(p));

m_ROWS(p, "s2")= yes$((p_DistanceMinFromWater(p) GT  0) and
(p_DistanceMinFromWater(p) LE 1.5 ));

m_ROWS(p, "s3")= yes$((p_DistanceMinFromWater(p) GT  1.5) and
(p_DistanceMinFromWater(p) LE 2.9));

m_ROWS(p, "s4")= yes$((p_DistanceMinFromWater(p) GT  2.9))
*          and (p_DistanceMinFromWater(p) LE 3.606))
;
m_Adjacency(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1.5) and
(p_AbsDistBTWParcels(p,j)GT 0));

m_AdjacencyTower(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1) and
(p_AbsDistBTWParcels(p,j)GT 0));

* MAPPING CONNECTIVITY TO WATER---------------------------------
-----
*1. assigning parcels to set – It increasingly acquires the
parcels. start from the river, then the next strips, etc etc
m_Catch(p)= yes$(s_Water(p));
while(card(m_Catch) lt card(p),
*2. loop over the parcels that are catchment
         loop(p$m_Catch(p),
*3. defining the parcels that are adjacent to the catchment
parcels
                 loop(j$(m_Adjacency(p,j) and (not m_catch(j))),
                  m_AdjacencyWater(j,p) = yes;
*4. temporarily assiging these parcels to the catch
                        m_TempCatch(j)=yes;
                        );
                 );
         m_Catch(p)$m_TempCatch(p) = yes;
```

```
);
* end of the loop---------------------------------------------------
-----

* MAPPIGN ADJACENCY WITH NO DIRECTION---------------------------
----
m_AdjacencyInWaterNoDirection(p,j)=yes$(
                         (s_Water(p))
                         and (s_Water(j))
                         and  m_AdjacencyTower(p,j)
                                 );
*------------
* MAPPING adjacency in river from parcels in the river to
parcels in the river WITH DIRECTION downstream
*1. start of the river:
m_RiverLenght(p)=
yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2. loop over parcels in river
WHILE(card(m_RiverLenght) lt card(s_water),
*3. loop over parcels in river and not already assigned in the
river at 1.
loop(p$( (s_Water(p)) and not(m_RiverLenght(p))),
*4. loop over parcels that are in river and are adjacent to each
other
         loop(j$(m_RiverLenght(j) and m_AdjacencyTower(p,j)),
*5. mapping the adjacency
                 m_AdjacencyInWater(p,j)=yes$m_RiverLenght(j) ;
*6. temporarily assigning the parcels to the river
                 m_TempRiverLenght(p) = yes;
         );
      );
*7. adding these parcels to the m_TempRiverLenght, so that are
not used for the loop at point 4.
  m_riverlenght(p)= m_riverlenght(p)+ m_TempRiverLenght(p);
*8. end of the loop------------
);
*);
*------------
*COMPUTING DISTANCES ALONG THE RIVER----------------------------
-----
*1.
m_route(p)= yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2.
p_DistanceP4("p133")=0.5;
WHILE(card(m_route) lt card(s_water),
loop(i$m_route(i),
         loop(j$(m_AdjacencyInWater(j,i) and (not m_Route(j))),
                 p_DistanceP4(j)=
p_DistanceP4(i)+p_AbsDistBTWParcels(j,i);
                 m_TempRoute(j)= yes;
                 );
         m_route(p)$m_TempRoute(p) = YES;
);
);
*---------------------------------------------------------------
-----
SETS
m_ParcelWaterTranspConn(p,j)   defining the closest parcel in
water for each parcel that is not in water
;
parameter
p_Distance(p)  distance per aquaculture pond (100 m)
```

```
p_BioProductivity(p,u) biological productivity in term of shrimp
per land use (10.000 nr of shrimp per ha)
p_PondProductivity pond productivity /600/
p_NrOfShrimpPerKg /65/
p_PondProductReductionCoeff(s_s) the biological procuctivity per
aquaculutre pond depends on the distance from the water (
         /
         s1 = 0
         s2 = 0
         s3 = 0.01
         s4 = 0.05
         /
;
* MAPPING M_PARCELWATERTRANSPCONN------------------------------
-----
*1 checking all the parcels that are inland
loop(p$(not s_Water(p)),
*2 cheking all the parcels that are in water
         loop(j$s_Water(j),
*3 assigning m_ParcelWaterTranspConn if the absolute distance
between the p and j is equal to the minimum distance from water
(previously computed)
*4 warning, the code finds multiple parcels that comply with the
requirements
                 m_ParcelWaterTranspConn(p,j) =yes$(
p_AbsDistBTWParcels(p,j) eq p_DistanceMinFromWater(p));
                         );
         );
* COMPUTING THE DISTANCE----------------------------------------
-----
*because of 4, among m_ParcelWaterTranspConn the code chooses
the minimum among p_DistanceP4 (previously computed, it's the
distance for each parcel
* in the water to a given parcel(p133))
p_Distance(p)= smin(j$m_ParcelWaterTranspConn(p,j),
p_DistanceP4(j))+ p_DistanceMinFromWater(p)
         ;
* COMPUTING THE BIOLOGICAL PRODUCTIVITY PER AQUACULTURE
PRODUCTION
* the productivity gets lower the further away from water ways
loop(m_Rows(p, s_s),
*loop(s_s,
*         loop(p$(m_Rows(p, s_s)),
         p_BioProductivity(p,u)$(s_Pollut(u))=
p_PondProductivity* (1-p_PondProductReductionCoeff(s_s))
);
* ASSIGNING THE BIOLOGICAL PRODUCITIVITY PER WILD SHRIMP--------
----
p_BioProductivity(p,u)$(s_Nature(u))= p_ShrimpDensity(p);
VARIABLES
v_Profits  profits (VND)
v_CostAqu  cost of aquaculture ponds (VND per pond)
v_Production (p,u)   production for parcel and land use type
(kg)
v_Objective   the variable that is maximized (habitat from
benefit)
v_TotBenefit  tot benefit per land use (VND)
v_HabitatLandscapeQuality   total score in term of biological
quality for the area
;
POSITIVE VARIABLES
v_HabitatQuality    score in term of biological quality per
parcel
```

```
v_TotProduction (u) total production per type of shrimp (kg)
v_Benefit(p,u)  benefit per parcel and land use type  (VNP)
;
BINARY VARIABLES
b_Dest(p,u)   land use type
;
EQUATIONS
*HABITAT MODEL STRUCTURE----------------------------------------
-----
Q_River     impeding allocation of uses on water
Q_HabitatQuality   habitat quality for parcels on river
Q_HabitatLandscapeQuality     total score in biological quality
Q_HabitatConnect1 parcels must have access to water
Q_HabitatConnect2 parcels must have access to water
Q_BHmodel   production function - linear equations that
approximate the Heverton Holt Model
Q_HabitatBenefit  monetary benefit from habitat

*AQUACULTURE MODEL STRUCTURE------------------------------------
-----
Q_AquaPondProduction    production per parcel allocated to pond
Q_AquapondCost    cost of aquaculture depending on distance from
water
Q_AquaPondBenefit net benefits from aquaculture ponds
Q_AquacultureProduction total aquaculture production
Q_AquacultureBenefit    total aquaculture benefits

Q_UseConstraint   one use for each parcel
Q_Constraint      constraining benefits from aquaculture
Q_Profits   profits
Q_Objective objective function
;

*HABITAT MODEL STRUCTURE----------------------------------------
-----
Q_River(p)$(s_Water(p))..     sum(u, B_Dest(p,u)) =L= 0;

Q_HabitatConnect1(u,p, s_s)$(s_Nature(u) and m_ROWS(p, "s2"))..
b_Dest(p,u)=G= 0;

Q_HabitatConnect2(u,p, s_s)$(s_Nature(u) and not s_Water(p) and
not m_ROWS(p, "s2"))..  b_Dest(p,u) =L=
sum(j$m_AdjacencyWater(p,j),b_Dest(j,u));

Q_HabitatQuality(u,p)$(s_Nature(u))..
v_HabitatQuality(p,u) =E= p_BioProductivity(p,u)*b_Dest(p,u);

Q_HabitatLandscapeQuality..
v_HabitatLandscapeQuality =E=
sum(u$s_Nature(u), sum(p,v_HabitatQuality(p,u)));

Q_BHmodel(u, s_CoeffBHmodel)$(s_Nature(u))..
v_TotProduction(u) =L=
p_NrOfShrimpPerKg*(P_mBHmodel(s_CoeffBHmodel)*v_HabitatLandscape
Quality+P_nBHmodel(s_CoeffBHmodel));

Q_HabitatBenefit(u)$(s_Nature(u)).. v_TotBenefit(u)
=L= v_TotProduction(u)*p_Price(u);

* AQUACULTURE MODEL STRUCTURE-----------------------------------
-----
Q_AquaPondProduction(p,u)$s_Pollut(u)..   v_Production (p,u) =E=
p_BioProductivity(p,u)*b_Dest(p,u);
```

```
Q_AquaPondCost(p,u)$s_Pollut(u)..   v_CostAqu(p) =E=
(p_CostPer100m*p_Distance(p)*b_Dest(p,u));

Q_AquaPondBenefit(p,u)$s_Pollut(u)..      v_Benefit(p,u) =E=
p_Price(u)*v_Production(p,u) - v_CostAqu(p);

Q_AquacultureProduction(u)$s_Pollut(u)..  v_TotProduction(u) =E=
sum(p, v_Production(p,u));

Q_AquacultureBenefit(u)$s_Pollut(u)..     v_TotBenefit(u) =E=
sum(p, (v_Production(p,u)*p_Price(u))-v_CostAqu(p));


* GENERAL STRUCTURE
Q_UseConstraint(p)..                             sum(u,
b_Dest(p,u)) =L= 1;
Q_Profits..                                       v_Profits =E=
sum(u, v_TotBenefit(u));
Q_Constraint(u)$s_Pollut(u)..                      sum(p,
b_Dest(p,u)) =E= 1125-p_Fixy;
Q_Objective..                                     v_Objective
=E= sum(u$s_pollut(u),v_TotProduction(u))
;



parameter
*saving results for each solve
p_CompParc(u,sol)         saving nr of parcels allocated per
land use
p_Profits(sol)            saving profits
p_Benefit(p,u,sol)       saving benefits per parcel and land use
p_TotBenefit(u,sol)      saving benefits per land use
p_TotProduction(u,sol) saving production per land use
*p_CompParcII
p_LandUse(p,sol)
p_Constraint(sol)
p_HabitatLandscapeQuality(sol)
p_Dest(p,u, sol)
;

MODEL ParcelConfiguration /ALL/;
loop(sol,
p_Fixy =
ParcelLocationPerHab_from_10_18_EfficiencyFrontier(sol);
SOLVE ParcelConfiguration  USING mip MAXIMIZING v_Objective;
*      saving results
         p_CompParc (u,sol)= sum (p, b_Dest.l(p,u));
         p_Profits(sol)  = v_Profits.l;
         p_Benefit(p,u,sol) = v_Benefit.l(p,u);
         p_TotBenefit(u,sol) = sum(p, v_Benefit.l(p,u));
         p_TotProduction(u,sol)= v_TotProduction.l(u);
         p_HabitatLandscapeQuality(sol)=
v_HabitatLandscapeQuality.l;
         p_Dest(p,u, sol)= b_Dest.l(p,u);
* parameter used in the maps next parameter:
*         p_LandUSe=0 -> river
*         p_LandUSe=1 -> aquaculture
*         p_LandUse=2 -> mangrove
         p_LandUse(p,sol)= sum(u, b_Dest.l(p,u))
                 + sum(u$(s_Nature(u)),b_Dest.l(p,u))
;
```

```
*        p_CompParcII(u,sol) = sum (p$s_NorthSouth("north",p),
b_Dest.l(p,u));

);

file
OutputFile_10_18_EfficiencyFrontier_NoEcoServ_NoSpat_I/OutputFil
e_10_18_EfficiencyFrontier_NoEcoServ_NoSpat_I.txt/;
put OutputFile_10_18_EfficiencyFrontier_NoEcoServ_NoSpat_I;
OutputFile_10_18_EfficiencyFrontier_NoEcoServ_NoSpat_I.pc=0;
OutputFile_10_18_EfficiencyFrontier_NoEcoServ_NoSpat_I.pc=6;
put "p"; put "xcoor";put "ycoor";loop(sol, put sol.tl; ) put/;
put//;

loop(p, put p.tl;put p_xcoor(p);put p_ycoor(p); loop(sol, put
p_LandUse(p,sol););); put/);

file
OutputEconomicDataFil_10_18_NoEcoServ_NoSpat_I/OutputEconomicDat
aFil_10_18_NoEcoServ_NoSpat_I.txt/;
put OutputEconomicDataFil_10_18_NoEcoServ_NoSpat_I;
put "profits    productionAqu   productionHAB     nr. of parcel
per Aqu       nr. of parcel per HAB"; put/;

loop(sol, put sol.tl, put p_profits(sol); loop(u,put
p_TotProduction(u, sol));loop(u,put p_CompParc(u, sol));put/;);

*$offtext
DISPLAY
p_HabitatLandscapeQuality
p_BioProductivity
m_ParcelWaterTranspConn
p_CompParc
p_Ycoor
p_Xcoor
p_AbsDistBTWParcels
p_DistanceFromWater
p_DistanceMinFromWater
m_ROWS
m_Adjacency
m_AdjacencyWater
m_Catch
m_AdjacencyInWater
m_AdjacencyTower
m_RiverLenght
m_TempRiverLenght
*m_RiverWay
*m_RiverAdj
p_DistanceP4
p_LandUse
*p_PondProduct

;

*file OutputPondMap/OutputPondMap.txt/;
*put OutputPondMap;

*put"p:    xcoor:    ycoor:  p_ManhDist: p_PondProduct:"; put//;
*loop(p, put p.tl;put":"; put p_xcoor(p);put":";put
p_ycoor(p);put":"; put p_ManhDist(p)put":";; put
p_BioProductivity(p,"aqu");put":";; put/;);
parameter
```

```
p_ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpatI(p,sol)
;
p_ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpatI(p,sol)
= p_Dest(p,"aqu", sol);
Execute_Unload
'ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpat',
p_ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpatI;
```

APPENDIX IIIB – NSM SECOND STEP GAMS CODE

```
*GAMS CODE NSM - step2 SCENARIO

* maximization of wild shrimp Production s.t to a minimum level
of aquaculture productions

*HABITAT FEATURES:
* - connectivity/access to the water way
* - suitability index (nr of shimp per parcel)
* - BH model that links the suitability index to the total
production of the landscape in term of wild shrimp

* AQUACULTURE FEATURE:
* - Productivity depending on the distance from the waterways
* - Distance (along the waterways) to the "exit of the
landscape"
*----------------------------------------------------------

SETS
p     parcels
s_water(p)  parcels defined as water
;
PARAMETER
p_Xcoor     parcels x coordinates
p_Ycoor     parcels y coordinates
p_ShrimpDensity   shrimp density per parcels (nr. Of shrimps per
squared meters)
p_ShrimpDensityAverage
p_ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpatI
;
* call external file GDX
$Gdxin mangrolfSD
$Load p
$Load s_Water
$Load p_Xcoor
$load p_Ycoor
*$load p_ShrimpDensity
$Gdxin

$Gdxin MZdensity
$load p_ShrimpDensity
$Gdxin

p_ShrimpDensityAverage=sum(p,p_ShrimpDensity(p))/1125;

*---------------------------------------------
* CODE PER BEVERTON HOLT MODEL
* computing parameters for the piecewise linear approximation of
the (non-linear) model
*1. the model computes for each 11 points how many shrimps there
are, according to the Beverton Holt Model
*2. the model then takes some points and it computes the line
parameters. It computes 11 lines

SET
s_CoeffBHmodel nr of lines /c1*c11/
;
PARAMETER
p_K carrying capacity /1125/
p_Juveniles(s_CoeffBHmodel) shrimps juveniles present in the
area - BevertonHoldModel(kg)
```

```
;
*y= mx + n
PARAMETER
p_MaxMangrov / 1125 /
P_mBHmodel(s_CoeffBHmodel)
P_nBHmodel(s_CoeffBHmodel)
x1
x2
y1
y2
yy1
yy2
xx(s_CoeffBHmodel)
;
xx(s_CoeffBHmodel) =
p_MaxMangrov*(ord(s_CoeffBHmodel)/card(s_CoeffBHmodel));
p_Juveniles(s_CoeffBHmodel)=p_ShrimpDensityAverage*(xx(s_CoeffBH
model))/(1+(p_ShrimpDensityAverage*xx(s_CoeffBHmodel)/p_k))
;
VARIABLE
dummy
m
n
;
EQUATION
* system of equations to find the parameter for the linear
approximation
q_retta1
q_retta2
q_Dummy
;
q_retta1..        x1*m+n=E=y1;
q_retta2..        x2*m+n=E=y2;
q_dummy..        dummy=E=0;
model lineareqfinder /all/;
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) eq 1),
x1=0;
y1=0;
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next model (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
loop(s_CoeffBHmodel$(ord(s_CoeffBHmodel) ne 1),
x1=xx(s_CoeffBHmodel-1);
y1=p_Juveniles(s_CoeffBHmodel-1);
x2=xx(s_CoeffBHmodel);
y2=p_Juveniles(s_CoeffBHmodel);
solve lineareqfinder using lp minimizing dummy;
* saving parameter for the next mdoel (m and n)
P_mBHmodel(s_CoeffBHmodel)= m.l;
P_nBHmodel(s_CoeffBHmodel)= n.l
             );
display
P_mBHmodel
P_nBHmodel
p_Juveniles
p_ShrimpDensityAverage
;
* END CODE PER BEVERTON HOLT MODEL
*---------------------------------------------------------
```

```
*CALL GDX FILE

*CALL GDX FILE

$Gdxin ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpat
$Load p_ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpatI
$Gdxin
*-----------------------------------------------------------------
--------------------------------------
SETS
sol   solves  /solve1*solve34/
U     land use                      /aqu, hab/
s_Nature(u) Nature land uses    / hab /
s_Pollut(u) Polluting land uses / aqu /
s_s   strips along watercourses/s1*s4/
;
ALIAS (u,v)
ALIAS (j,p)
ALIAS (q,j)
ALIAS (i,q)
ALIAS (z,i)
ALIAS (k,z)
;
SETS
*---MAPS OF SETS
m_ROWS(p, s_s)    mapping strips
m_Adjacency(p,j)  mapping adjacency 360 degrees
*---MAPPING CONNECTIVITY TO WATER------------
m_AdjacencyWater(p,j) mapping parcels adjacent to water
m_Catch(p) mapping parcels next to water - progressively
increases in a loop statement
m_TempCatch(p) saving result in the loop for m_Catch

*---MAPPING ADJACENCY WITH NO DIRECTION
m_AdjacencyInWaterNoDirection mapping adjacency for parcel in
river with downstream direction
m_AdjacencyTower(p,j)   adjacency not considering the diagonals
*---MAPPING adjacency WITH DIRECTION
m_AdjacencyInWater(p,j) mapping adjacency for parcel in river
m_RiverLenght(p)   mapping the river to compute the distance of
each river parcel to the end of the river
m_TempRiverLenght(p)    saving result for m_RiverLength
*---COMPUTING RIVER LENGTH
m_River(p)  landscape exit/p133/
m_RiverWay(p,j)
m_TempRiver(p)
m_TempAdj(p)
m_AdjNo
m_TempAdjNo
m_Route
m_TempRoute
m_RiverAdj
;
SCALAR
sc_SomeBigNr      big number /1000000000/
;
PARAMETER
p_Fixy to fix aquaculture production - it changes in the loop
statement
p_Constraint(sol) takes the value in the loop statement and it
give it to p_Fixy
p_CostPer100m cost per 100 m (VND per 100 m) /1/
p_Price(u)  price of activities (VND -1000- per kg)
```

```
        /
        aqu 110
        hab  35
        /
;
PARAMETERS
p_AbsDistBtwParcels     computing distances between parcels (100
m)
p_DistanceFromWater(p,j)      computing distances of each parcel
to each parcel that are water
p_DistanceMinFromWater(p)     computing the minimum distance to
water
p_TransportCost          computing transportation costs    (VNP
per 100 m)
p_DistanceP4
p_TempDistanceP4
;
p_AbsDistBTWParcels(p,j)= sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j)))))/100;

p_DistanceFromWater(p,j)$s_Water(j)= sqrt(sqr((p_Xcoor(p)-
p_Xcoor(j)))
+sqr((p_Ycoor(p)-p_Ycoor(j)))))/100;

p_DistanceMinFromWater(p)= smin(j$s_Water(j),
sqrt(sqr((p_Xcoor(p)-p_Xcoor(j)))+sqr((p_Ycoor(p)-
p_Ycoor(j)))))/100);

*COMPUTING MAP SETS --------------------------------------------
-----

*ASSIGNING PARCELS TO STRIPS------------------------------------
-----
m_ROWS(p, "s1")= yes$(s_Water(p));

m_ROWS(p, "s2")= yes$((p_DistanceMinFromWater(p) GT  0) and
(p_DistanceMinFromWater(p) LE 1.5 ));

m_ROWS(p, "s3")= yes$((p_DistanceMinFromWater(p) GT  1.5) and
(p_DistanceMinFromWater(p) LE 2.9));

m_ROWS(p, "s4")= yes$((p_DistanceMinFromWater(p) GT  2.9))
*          and (p_DistanceMinFromWater(p) LE 3.606))
;
m_Adjacency(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1.5) and
(p_AbsDistBTWParcels(p,j)GT 0));

m_AdjacencyTower(p,j)= yes$((p_AbsDistBTWParcels(p,j)LE 1) and
(p_AbsDistBTWParcels(p,j)GT 0));

* MAPPING CONNECTIVITY TO WATER---------------------------------
-----
*1. assigning parcels to set – It increasingly acquires the
parcels. start from the river, then the next strips, etc etc
m_Catch(p)= yes$(s_Water(p));
while(card(m_Catch) lt card(p),
*2. loop over the parcels that are catchment
        loop(p$m_Catch(p),
*3. defining the parcels that are adjacent to the catchment
parcels
                 loop(j$(m_Adjacency(p,j) and (not m_catch(j))),
                  m_AdjacencyWater(j,p) = yes;
*4. temporarily assiging these parcels to the catch
```

```
                         m_TempCatch(j)=yes;
                         );
                 );
         m_Catch(p)$m_TempCatch(p) = yes;
);
* end of the loop-----------------------------------------------
-----

* MAPPIGN ADJACENCY WITH NO DIRECTION---------------------------
----
m_AdjacencyInWaterNoDirection(p,j)=yes$(
                         (s_Water(p))
                         and (s_Water(j))
                         and  m_AdjacencyTower(p,j)
                                 );
*------------
* MAPPING adjacency in river from parcels in the river to
parcels in the river WITH DIRECTION downstream
*1. start of the river:
m_RiverLenght(p)=
yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2. loop over parcels in river
WHILE(card(m_RiverLenght) lt card(s_water),
*3. loop over parcels in river and not already assigned in the
river at 1.
loop(p$( (s_Water(p)) and not(m_RiverLenght(p))),
*4. loop over parcels that are in river and are adjacent to each
other
         loop(j$(m_RiverLenght(j) and m_AdjacencyTower(p,j)),
*5. mapping the adjacency
                 m_AdjacencyInWater(p,j)=yes$m_RiverLenght(j) ;
*6. temporarily assigning the parcels to the river
                 m_TempRiverLenght(p) = yes;
         );
      );
*7. adding these parcels to the m_TempRiverLenght, so that are
not used for the loop at point 4.
  m_riverlenght(p)= m_riverlenght(p)+ m_TempRiverLenght(p);
*8. end of the loop------------
);
*);
*------------
*COMPUTING DISTANCES ALONG THE RIVER----------------------------
-----
*1.
m_route(p)= yes$((p_Xcoor(p)=509150)and(p_Ycoor(p)=957350));
*2.
p_DistanceP4("p133")=0.5;
WHILE(card(m_route) lt card(s_water),
loop(i$m_route(i),
         loop(j$(m_AdjacencyInWater(j,i) and (not m_Route(j))),
                 p_DistanceP4(j)=
p_DistanceP4(i)+p_AbsDistBTWParcels(j,i);
                 m_TempRoute(j)= yes;
                 );
         m_route(p)$m_TempRoute(p) = YES;
);
);
*---------------------------------------------------------------
-----
SETS
m_ParcelWaterTranspConn(p,j)   defining the closest parcel in
water for each parcel that is not in water
```

```
;
parameter
p_Distance(p)  distance per aquaculture pond (100 m)
p_BioProductivity(p,u) biological productivity in term of shrimp
per land use (10.000 nr of shrimp per ha)
p_PondProductivity pond productivity /600/
p_NrOfShrimpPerKg /65/
p_PondProductReductionCoeff(s_s) the biological procuctivity per
aquaculutre pond depends on the distance from the water (
         /
         s1 = 0
         s2 = 0
         s3 = 0.01
         s4 = 0.05
         /
;
* MAPPING M_PARCELWATERTRANSPCONN-------------------------------
-----
*1 checking all the parcels that are inland
loop(p$(not s_Water(p)),
*2 cheking all the parcels that are in water
         loop(j$s_Water(j),
*3 assigning m_ParcelWaterTranspConn if the absolute distance
between the p and j is equal to the minimum distance from water
(previously computed)
*4 warning, the code finds multiple parcels that comply with the
requirements
                 m_ParcelWaterTranspConn(p,j) =yes$(
p_AbsDistBTWParcels(p,j) eq p_DistanceMinFromWater(p));
                         );
         );
* COMPUTING THE DISTANCE-----------------------------------------
-----
*because of 4, among m_ParcelWaterTranspConn the code chooses
the minimum among p_DistanceP4 (previously computed, it's the
distance for each parcel
* in the water to a given parcel(p133))
p_Distance(p)= smin(j$m_ParcelWaterTranspConn(p,j),
p_DistanceP4(j))+ p_DistanceMinFromWater(p)
         ;
* COMPUTING THE BIOLOGICAL PRODUCTIVITY PER AQUACULTURE
PRODUCTION
* the productivity gets lower the further away from water ways
loop(m_Rows(p, s_s),
*loop(s_s,
*         loop(p$(m_Rows(p, s_s)),
         p_BioProductivity(p,u)$(s_Pollut(u))=
p_PondProductivity* (1-p_PondProductReductionCoeff(s_s))
);
* ASSIGNING THE BIOLOGICAL PRODUCITIVITY PER WILD SHRIMP--------
----
p_BioProductivity(p,u)$(s_Nature(u))= p_ShrimpDensity(p);
VARIABLES
v_Profits  profits (VND)
v_CostAqu  cost of aquaculture ponds (VND per pond)
v_Production (p,u)   production for parcel and land use type
(kg)
v_Objective   the variable that is maximized (habitat from
benefit)
v_TotBenefit  tot benefit per land use (VND)
v_HabitatLandscapeQuality   total score in term of biological
quality for the area
;
```

```
POSITIVE VARIABLES
v_HabitatQuality    score in term of biological quality per
parcel
v_TotProduction (u) total production per type of shrimp (kg)
v_Benefit(p,u)  benefit per parcel and land use type  (VNP)
;
BINARY VARIABLES
b_Dest(p,u)   land use type
;
EQUATIONS
*HABITAT MODEL STRUCTURE---------------------------------------
-----
Q_River     impeding allocation of uses on water
Q_HabitatQuality   habitat quality for parcels on river
Q_HabitatLandscapeQuality     total score in biological quality
Q_HabitatConnect1 parcels must have access to water
Q_HabitatConnect2 parcels must have access to water
Q_BHmodel   production function - linear equations that
approximate the Heverton Holt Model
Q_HabitatBenefit  monetary benefit from habitat

*AQUACULTURE MODEL STRUCTURE-----------------------------------
-----
Q_AquaPondProduction    production per parcel allocated to pond
Q_AquapondCost    cost of aquaculture depending on distance from
water
Q_AquaPondBenefit net benefits from aquaculture ponds
Q_AquacultureProduction total aquaculture production
Q_AquacultureBenefit    total aquaculture benefits

Q_UseConstraint   one use for each parcel
Q_Constraint      constraining benefits from aquaculture
Q_Profits   profits
Q_Objective objective function
;

*HABITAT MODEL STRUCTURE---------------------------------------
-----
Q_River(p)$(s_Water(p))..     sum(u, B_Dest(p,u)) =L= 0;

Q_HabitatConnect1(u,p, s_s)$(s_Nature(u) and m_ROWS(p, "s2"))..
b_Dest(p,u)=G= 0;

Q_HabitatConnect2(u,p, s_s)$(s_Nature(u) and not s_Water(p) and
not m_ROWS(p, "s2"))..  b_Dest(p,u) =L=
sum(j$m_AdjacencyWater(p,j),b_Dest(j,u));

Q_HabitatQuality(u,p)$(s_Nature(u))..
v_HabitatQuality(p,u) =E= p_BioProductivity(p,u)*b_Dest(p,u);

Q_HabitatLandscapeQuality..
v_HabitatLandscapeQuality =E=
sum(u$s_Nature(u), sum(p,v_HabitatQuality(p,u)));

Q_BHmodel(u, s_CoeffBHmodel)$(s_Nature(u))..
v_TotProduction(u) =L=
p_NrOfShrimpPerKg*(P_mBHmodel(s_CoeffBHmodel)*v_HabitatLandscape
Quality+P_nBHmodel(s_CoeffBHmodel));

Q_HabitatBenefit(u)$(s_Nature(u)).. v_TotBenefit(u)
=L= v_TotProduction(u)*p_Price(u);
```

```
* AQUACULTURE MODEL STRUCTURE----------------------------------
-----
Q_AquaPondProduction(p,u)$s_Pollut(u)..   v_Production (p,u) =E=
p_BioProductivity(p,u)*b_Dest(p,u);

Q_AquaPondCost(p,u)$s_Pollut(u)..   v_CostAqu(p) =E=
(p_CostPer100m*p_Distance(p)*b_Dest(p,u));

Q_AquaPondBenefit(p,u)$s_Pollut(u)..      v_Benefit(p,u) =E=
p_Price(u)*v_Production(p,u) - v_CostAqu(p);

Q_AquacultureProduction(u)$s_Pollut(u)..  v_TotProduction(u) =E=
sum(p, v_Production(p,u));

Q_AquacultureBenefit(u)$s_Pollut(u)..     v_TotBenefit(u) =E=
sum(p, (v_Production(p,u)*p_Price(u))-v_CostAqu(p));


* GENERAL STRUCTURE
Q_UseConstraint(p)..                                sum(u,
b_Dest(p,u)) =L= 1;
Q_Profits..                                          v_Profits =E=
sum(u, v_TotBenefit(u));
Q_Constraint(p,u)$s_Pollut(u)..
b_Dest(p,"aqu") =E= p_Fixy(p);
Q_Objective..                                        v_Objective
=E= sum(u$s_Nature(u),v_TotProduction(u))
;



parameter
*saving results for each solve
p_CompParc(u,sol)         saving nr of parcels allocated per
land use
p_Profits(sol)            saving profits
p_Benefit(p,u,sol)       saving benefits per parcel and land use
p_TotBenefit(u,sol)      saving benefits per land use
p_TotProduction(u,sol) saving production per land use
*p_CompParcII
p_LandUse(p,sol)
p_Constraint(sol)
p_HabitatLandscapeQuality(sol)
p_Dest(p,u, sol)
;

MODEL ParcelConfiguration /ALL/;
loop(sol,
p_Fixy(p) =
p_ParcelPerHab_from_10_18_EfficiencyFrontierNoEco_NoSpatI(p,sol)
;
SOLVE ParcelConfiguration  USING mip MAXIMIZING v_Objective;
*      saving results
         p_CompParc (u,sol)= sum (p, b_Dest.l(p,u));
         p_Profits(sol)  = v_Profits.l;
         p_Benefit(p,u,sol) = v_Benefit.l(p,u);
         p_TotBenefit(u,sol) = sum(p, v_Benefit.l(p,u));
         p_TotProduction(u,sol)= v_TotProduction.l(u);
         p_HabitatLandscapeQuality(sol)=
v_HabitatLandscapeQuality.l;
         p_Dest(p,u, sol)= b_Dest.l(p,u);
* parameter used in the maps next parameter:
*         p_LandUSe=0 -> river
```

```
*         p_LandUSe=1 -> aquaculture
*         p_LandUse=2 -> mangrove
         p_LandUse(p,sol)= sum(u, b_Dest.l(p,u))
                 + sum(u$(s_Nature(u)),b_Dest.l(p,u))
;
*        p_CompParcII(u,sol) = sum (p$s_NorthSouth("north",p),
b_Dest.l(p,u));
*p_Constraint(sol+1)=p_Fixy+100;
);

file OutputFileNSMMap/OutputFileNSMMap.txt/;
put OutputFileNSMMap;
OutputFileNSMMap.pc=0;
OutputFileNSMMap.pc=6;
put "p"; put "xcoor";put "ycoor";loop(sol, put sol.tl; ) put/;
put//;
loop(p, put p.tl;put p_xcoor(p);put p_ycoor(p); loop(sol, put
p_LandUse(p,sol);); put/);

file OutputFileNSMPPF/ OutputFileNSMPPF.txt/;
put OutputFileNSMPPF;
put "profits    productionAqu   productionHAB     nr. of parcel
per Aqu       nr. of parcel per HAB"; put/;

loop(sol, put sol.tl, put p_profits(sol); loop(u,put
p_TotProduction(u, sol));loop(u,put p_CompParc(u, sol));put/;);

DISPLAY
p_HabitatLandscapeQuality
p_BioProductivity
m_ParcelWaterTranspConn
p_CompParc
p_Ycoor
p_Xcoor
p_AbsDistBTWParcels
p_DistanceFromWater
p_DistanceMinFromWater
m_ROWS
m_Adjacency
m_AdjacencyWater
m_Catch
m_AdjacencyInWater
m_AdjacencyTower
m_RiverLenght
m_TempRiverLenght
*m_RiverWay
*m_RiverAdj
p_DistanceP4
p_LandUse
*p_PondProduct
;
parameter
p_LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ_Nospat(p,sol);
p_LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ_Nospat(p,sol)=p
_LandUse(p,sol);
Execute_Unload
'LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ_Nospat',
p_LandUseFrom_10_18_EfficiencyFrontier_NoEcoServ_Nospat;
```

APPENDIX IV – RESULTS

APPENDIX IV

BENCHMARK scenario					
	Profits	**Production**		**Area** (nr. of parcels)	
Solves		aquaculture	habitat	aquaculture	habitat
solve1	3494643	0	99847	0	1125
solve2	5739841	20520	99531	35	1090
solve3	7906915	40428	98892	69	1056
solve4	10143234	61026	98067	104	1020
solve5	12237996	80328	97268	137	988
solve6	14414941	100392	96430	171	954
solve7	16549139	120108	95482	204	921
solve8	18729895	140280	94420	238	887
solve9	20868212	160068	93343	271	854
solve10	23066333	180468	92069	305	820
solve11	25422167	202506	90170	342	770
solve12	27346863	220236	89482	373	752
solve13	29531585	240540	88143	408	717
solve14	31657417	260322	86744	441	684
solve15	33825108	280614	84939	475	642
solve16	36260503	303318	83197	513	602
solve17	38096442	320280	82373	542	583
solve18	40220238	340086	80844	576	548
solve19	43186948	368280	77043	625	461
solve20	44497022	380196	77043	646	461
solve21	46944962	403104	75037	686	415
solve22	48828037	420336	74724	716	408
solve23	50972537	440346	73151	750	375
solve24	53085801	460104	71481	783	342
solve25	55258862	480444	69693	817	308
solve26	57366586	500226	67795	850	275
solve27	59535257	520584	65833	884	241
solve28	61679147	540810	63576	918	202
solve29	63712435	560214	60745	951	154
solve30	65884251	581058	57343	987	114
solve31	67860428	600054	54164	1020	90
solve32	69944241	620220	50390	1055	70
solve33	71766740	640794	37865	1091	34
solve34	72582844	660282	0	1125	0

LSI scenario					
	Profits	**Production**		**Area** (nr. of parcels)	
Solves		aquaculture	habitat	aquaculture	habitat
solve1	3494643	0	99847	0,00	1125
solve2	5751898	21000	98377	35,00	1090
solve3	7948483	41400	97057	69,00	1056
solve4	10276314	63000	95717	105,00	1020
solve5	12347194	82200	94569	137,00	988
solve6	14551128	102600	93455	171,00	954
solve7	16677225	122400	92008	204,00	921
solve8	18874875	142800	90710	238,00	887
solve9	20991400	162600	89002	271,00	854
solve10	23178239	183000	87416	305,00	820
solve11	26390460	212952	85124	355,00	770
solve12	27211800	220710	84226	368,00	752
solve13	29723334	243966	82934	407,00	717
solve14	31699676	262422	81437	438,00	684
solve15	32104677	266496	80208	445,00	642
solve16	37006943	311778	78058	521,00	602
solve17	37957513	320664	77306	536,00	583
solve18	40577976	344970	75832	577,00	548
solve19	44305343	380034	72209	638,00	461
solve20	44305343	380034	72209	638,00	461
solve21	46727011	402690	70230	677,00	415
solve22	47537492	410178	69872	690,00	408
solve23	48735951	421614	68210	710,00	375
solve24	51041546	443016	66863	748,00	342
solve25	52044684	452562	65544	764,00	308
solve26	53978464	470670	63918	795,00	275
solve27	54929102	479970	61865	812,00	241
solve28	56950736	498888	60216	845,00	202
solve29	61290638	539448	56842	915,00	154
solve30	64942161	574080	52413	975,00	114
solve31	66742368	591366	49551	1005,00	90
solve32	67067800	595530	45773	1012,00	70
solve33	70274947	628764	33043	1070,00	34
solve34	72582844	660282	0	1125,00	0

NSM scenario					
	Profits	**Production**		**Area** (nr. of parcels)	
Solves		aquaculture	habitat	aquaculture	habitat
solve01	3494642,73	0	99846,94	0	1125
solve02	5711103,56	21000	97174,82	35	1069
solve03	7625798,53	41400	87766,56	69	876
solve04	9885524,79	63000	84444,91	105	807
solve05	11920085,51	82200	82232,61	137	724
solve06	14078890,53	102600	79798,78	171	656
solve07	16173725,51	122400	77422,94	204	598
solve08	18310684,62	142800	74364,96	238	528
solve09	20316997,14	162600	69459,97	271	423
solve10	22435825,62	183000	65884,03	305	329
solve11	25542695,04	213000	60366,64	355	207
solve12	26651311,25	223800	58098,7	373	169
solve13	28698159,96	244800	50580,52	408	100
solve14	29099888,72	264546	0	441	0
solve15	31844147,99	289494	0	483	0
solve16	34457732,14	313254	0	523	0
solve17	35699185,64	324540	0	542	0
solve18	37986071,31	345330	0	577	0
solve19	43670613,15	397008	0	664	0
solve20	43670613,15	397008	0	664	0
solve21	46610232,32	423732	0	710	0
solve22	47049128,33	427722	0	717	0
solve23	49118211,7	446532	0	750	0
solve24	51187296,1	465342	0	783	0
solve25	53319077,81	484722	0	817	0
solve26	55388161,68	503532	0	850	0
solve27	57519945,51	522912	0	884	0
solve28	59965226,15	545142	0	923	0
solve29	62974802,91	572502	0	971	0
solve30	65482785,93	595302	0	1011	0
solve31	66987575,34	608982	0	1035	0
solve32	68241566,37	620382	0	1055	0
solve33	70498752,8	640902	0	1091	0
solve34	72630538,24	660282	0	1125	0