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The role of spatial information in the preservation of the shrimp nursery function of mangroves: A spatially explicit bio-economic model for the assessment of land use trade-offs

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ABSTRACT

Conversion to aquaculture affects the provision of important ecosystem services provided by mangrove ecosystems, and this effect depends strongly on the location of the conversion. We introduce in a bio-economic mathematical programming model relevant spatial elements that affect the provision of the nursery habitat service of mangroves: (1) direct or indirect connection of mangroves to watercourses; (2) the spatial allocation of aquaculture ponds; and (3) the presence of non-linear relations between mangrove extent and juvenile recruitment to wild shrimp populations. By tracing out the production possibilities frontier of wild and cultivated shrimp, the model assesses the role of spatial information in the trade-off between aquaculture and the nursery habitat function using spatial elements relevant to our model of a mangrove area in Ca Mau Province, Viet Nam. Results show that where mangrove forests have to coexist with shrimp aquaculture ponds, the inclusion of specific spatial information on ecosystem functions in considerations of land allocation can achieve aquaculture benefits while largely preserving the economic benefits generated by the nursery habitat function. However, if spatial criteria are ignored, ill-advised land allocation decisions can easily lead to a collapse of the mangrove's nursery function.

1. Introduction

Mangrove forests have faced major changes in recent decades worldwide, disappearing at an estimated rate of 1–2% per year (Duke et al., 2007). Mostly located in developing countries in tropical and sub-tropical coastal areas, mangrove forests are threatened by human activities, such as pollution, land conversion and resource extraction (DeFries et al., 2009; Polidoro et al., 2010). Development plans are a major driver of mangrove forest clearance, with aquaculture ponds for shrimp production accounting for an estimated 38% of global loss (Barbier and Cox, 2004; Valiela et al., 2001).

The mangrove loss rate is likely to be higher than what is socially efficient given the great variety of ecosystem services they provide (e.g. Barbier et al., 2010; Brander et al., 2012), including coastal protection from wave damage (Gedan et al., 2011), carbon sequestration (Siikamäki et al., 2012), and absorption of organic pollution (e.g. Wickramasinghe et al., 2009). Most importantly, mangroves are widely acknowledged as important nursery habitats for commercially harvested marine species (Kimirei et al., 2013; Mumby et al., 2004; Nagelkerken, 2009).

Spatial characteristics, such as the distribution and connectivity of mangrove and estuarine habitats, affect the nursery habitat function of mangrove forests, even though the ecological mechanisms determining coastal productivity in relation to connections between mangroves, seagrasses and estuarine shallow water habitats are not yet well understood (Nagelkerken, 2009). The nursery habitat function appears to be non-linearly related to spatial extent and other spatial attributes of mangrove forests. In particular the relationship between mangrove area and shrimp population abundance is likely to be characterized by diminishing returns to scale. The perimeter of the mangrove area, the forest/land–water interface, and the extent of shallow water habitats (<5 m), have stronger correlations with near-shore production of shrimp and

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fish than absolute extension of mangrove forest (Manson et al., 2005). For instance, in western peninsular Malaysia Loneragan et al. (2005) find a significant reduction in landings where the mangrove has been cleared for shrimp aquaculture. However, they observe little variation in the shrimp population in regions with a wide (100–200 m) mangrove margin along the coast compared to areas with a narrow (5–10 m) margin. The mangrove–water interface thus may be more important than total mangrove area as nurseries for commercial species (Aburto-Oropeza et al., 2008; Blaber, 2013; Loneragan et al., 2005; Meynecke et al., 2007).

The non-linear relation with areal extent is driven by a combination of three processes: (1) a density-dependent survival effect of recruits to the coastal stock; (2) a higher rate of shrimp survival in the remaining mangrove forests after partial clearance; and (3) a heterogeneous distribution of the nursery function across the mangroves. With initial loss and fragmentation of mangrove forest, the length of the interface zone first increases before declining with further habitat loss. Studies of salt marshes indicate that increased edge habitat produces higher shrimp survival rates by providing more foraging opportunities, protection from predation and lowered densities (Browder et al., 1989; Haas et al., 2004). Moreover, shrimp production of shallow open waters also contributes to the recruitment of coastal shrimp populations (Fry, 2008; Loneragan et al., 2005; Roth et al., 2008). This means that the level of recruitment of juveniles to the adult population depends on density-dependent factors arising from the configuration of mangrove forests, namely, (1) the structure of the shallow estuarine “foraging arena” (Walters and Martell, 2004), and (2) the connectivity of its various habitat elements. Only at high levels of mangrove clearance the nursery function collapses: stocks of shrimp species then depend entirely on recruitment from open shallow water (Fig. 1).

Potentially this means that the benefits of development in coastal areas could be balanced with the benefits of mangrove preservation by taking into account the productive roles and connectivity of the different elements of a mangrove-estuarine ecosystem. Trade-offs between development and nature conservation need to be assessed in order to efficiently manage mangrove areas and to evaluate any given policy objective. This is particularly important in developing countries, where the opportunity costs of conservation are high and ecosystem conversion yields short-term benefits and long-term costs. Both spatial dimension and presence of nonlinearities should be taken into account when land use trade-offs concerning mangroves are assessed. In this context the availability of spatial details on ecosystem functions becomes crucial for a proper assessment of the trade-offs.

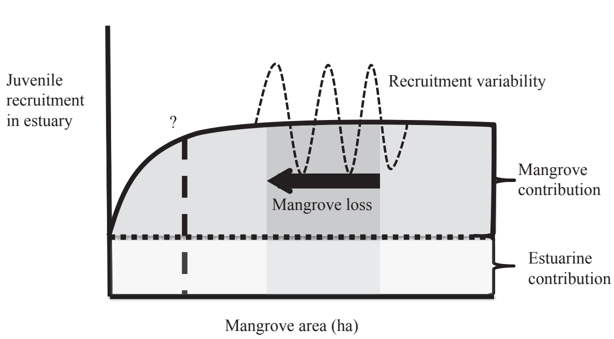

Fig. 1. Proposed Beverton-Holt type recruitment of mangrove juveniles to the coastal waters. Loss of mangrove area initially does not reduce average recruitment levels of the coastal adult shrimp stocks.

In the last decades, interdisciplinary collaborations have highlighted the importance of the spatial dimension of biodiversity conservation (e.g. Williams et al., 2005), ecosystem service protection (e.g. Cong et al., 2014; Kremen, 2005), and land allocation trade-offs between economic objectives and ecological conservation targets (e.g. Mönkkönen et al., 2014). In addition, an increasing number of studies focus on the value of spatial information for nature conservation (e.g. Costello et al., 2010; Polasky and Solow, 2001; Runting et al., 2013).

The economic literature on mangrove forests has so far largely focused on monetary evaluation of the nursery habitat service (Barbier, 2007; McNally et al., 2011; Sathirathai and Barbier, 2001), and of the storm buffer service (e.g. Barbier, 2012). Optimal land allocation of mangrove forests has been studied theoretically (Parks and Bonifaz, 1994; Sanchirico and Springborn, 2011), but few studies take a spatial approach. Barbier (2012) assumes the biological productivity of an ecosystem service is reduced by moving further inland, whereas Sanchirico and Springborn (2011) take into account the role of different habitats in the life-cycle of the species. No attention, however, is paid to (1) the micro-determinants of the spatial dimension of the problem, i.e. adjacency and connectivity of habitat patches; (2) the spatial relation of mangroves with aquaculture ponds; and (3) the spatial preferences of the aquaculture sector.

The objective of this paper is to develop a methodology to analyse land allocation trade-offs for mangrove areas in a spatially explicit manner. More specifically, we analyse (1) the spatial trade-off between different uses of a mangrove forest and (2) how the assessment of the trade-off is affected by the availability of information regarding (a) the spatial distribution of productivity, and (b) the spatial mechanisms of the ecosystem service. To stress the methodological approach taken, we consider in a simplification only two uses of a mangrove area: (1) shrimp production from aquaculture ponds; and (2) the mangrove ecosystem's nursery function for wild shrimp, taking explicitly into account the spatial dimension and the presence of diminishing returns to scale. We address these issues by formulating a mathematical model to solve a spatially explicit land allocation optimization problem. We design three scenarios that are differentiated by the level of spatial information that enters the land allocation decision problem. We apply the model to a landscape structure (watercourses, shoreline, and dry land) of a mangrove area in Ca Mau Province, Viet Nam.

Our paper adds two elements to the literature. First, our model includes spatial details on the determinants of the production levels resulting from the land allocation between the two land uses considered here, including the effect of the relative location of ponds and mangrove patches, the spatial preferences of the aquaculture sector, and the spatial distribution of the shrimp nursery service. Second, including these elements in the model enables us to assess the role of considering the spatial dimension in the management of mangrove forests. To focus on the spatial dimension of the problem, we do not attempt to assess whether mangroves should be preserved. This question has been clearly, and positively, answered elsewhere. Nor do we consider the intertemporal trade-offs, which surely are important, and that ideally are to be incorporated in future work. Lastly, we concentrate on one ecosystem function only, shrimp nurseries, whereas other ecosystem functions should be added to obtain more comprehensive evaluations of the trade-offs.

The paper is organized as follows. Section 2 introduces the model and the scenarios. Section 3 describes the landscape structure and the data we employ in the model. Section 4 presents the main results followed by the discussion and conclusion in Sections 5 and 6, respectively.