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How remote sensing supports mangrove ecosystem service valuation: A case study in Ca Mau province, Vietnam

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ABSTRACT

This paper highlights the importance of using household survey and remote sensing data for the assessment of mangrove ecosystem services (fisheries and timber related products, carbon sequestration, storm protection) in Ca Mau Province, Vietnam. The results indicate that remote sensing plays an important role in ecosystem service valuation in the large areas where mangroves and aquaculture are mixed. We estimated the value of mangrove ecosystem services using market price and replacement cost approaches to determine an initial assessment of the overall contribution of mangroves to human well-being. The total estimated value was US$ 600 million/year for 187,533 ha (approximately US$ 3000/ha/year), which is slightly smaller than the gross domestic product (GDP) of the province (US$ 0.69 billion in 2010). However, this is only a partial estimate that does not consider other services (tourism, biodiversity, cultural and social values), due to the absence of primary data. The main contribution of this study is that it is the first to combine the approaches of remote sensing and household survey for the quantification of mangrove ecosystem services in the mangrove-shrimp integrated system. Our findings indicate that the continued expansion of aquaculture has reduced the benefits to local communities provided by the mangrove ecosystem.

1. Introduction

Mangrove forest ecosystems dominate the intertidal zone of estuaries and open shorelines along many of the World's tropical and subtropical coastlines (Alongi, 2002; Brander et al., 2012a; Giri et al., 2003; Hogarth, 2007). These ecosystems are economically valuable, providing direct livelihood benefits to local communities from fishery products (e.g., fish, shrimp, crabs, mollusks), timber products (e.g., firewood, timber, construction materials), and recreational uses such as eco-tourism (Alongi, 2008, 2002; Clough, 1998; Kuenzer et al., 2011). Mangrove forest ecosystems also provide a number of important ecosystem functions or services, including habitat and nursery functions for aquatic and non-aquatic animal species (Brander et al., 2012a; Hussain and Badola, 2010; Lewis, 2005; Rönnbäck, 1999), coastal protection (Danielsen et al., 2005; Mazda et al., 2006), carbon sequestration and storage (Bouillon et al., 2008; Donato et al., 2011; Duarte et al., 2005; Lewis et al., 2011), and management of coastal water quality (Benfield et al., 2005; Lewis et al., 2011). However, notwithstanding their significant economic and ecological benefits, mangrove forests continue to be destroyed by conversion to other land uses or degraded by over-exploitation (Alongi, 2002; Gilman et al., 2008; Kuenzer et al., 2011), in part because of the difficulty of valuing the goods and services they provide.

Many studies on the economic valuation of mangrove ecosystem services have been completed over the past 20 years (Barbier and Cox, 2002; Barbier and Strand, 1997; Hussain and Badola, 2010; Kaplowitz, 2001; Rönnbäck et al., 2007; Sathirathai and Barbier, 2001; Sathirathai, 2004; Tong et al., 2004). These studies have applied different valuation approaches for estimating the monetary value of different mangrove ecosystem services, such as avoided cost, contingent valuation, market price, production approach, replacement cost, and travel cost. The details of these methods and its advantages and disadvantages are reviewed by Vo et al. (2012).

The wide range of valuation methodologies applied to estimate the monetary values of mangrove ecosystem services has resonated in a large variability and inconsistency in terms of economic values attributed by different ecosystem valuation studies. Distinct valuation approaches are likely to result in large differences in the economic value assigned. For instance, coastal protection and sediment stabilization provided by mangroves are valued higher when a replacement cost approach is used rather than a contingent valuation method (Kuenzer and Vo, 2013; Salem and

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Mercer, 2012). Similarly, value from carbon sequestration is reported higher by a replacement cost approach in comparison to market price approaches (Salem and Mercer, 2012). In addition to the various valuation methodologies, the estimated values vary due to the specific conditions of economic activities, geographical or temporal specificity, and the culture or behavior of the local population (Brander et al., 2012a; de Groot et al., 2012; Salem and Mercer, 2012; Vo et al., 2012).

The estimated values of mangrove ecosystem services are different across study sites due to differences in the bio-physical and socio-economic characteristics of ecosystem services and are significantly affected by the prosperity of the society and its cultural characteristics (Brander et al., 2012a; de Groot et al., 2012; Gammage, 1994; Salem and Mercer, 2012; Vo et al., 2012). In addition, the price information used for cost and benefit analyses is easily distorted by distributional biases and the prosperity of the society being examined. For instance, people living in developing countries may underestimate the regulating services of mangrove ecosystems because people can have limited experience in the valuation of those services (i.e., water filtration, carbon sequestration, and pollination), which are crucial to the long-term sustainability of their livelihoods (Wegner and Pascual, 2011). Generally, ecological services are expected to have more value in countries with higher GDP per capital (Salem and Mercer, 2012). Changing perceptions and time references are also resulting in disparity of mangrove valuation (e.g. carbon sequestration only became economically valuable during the past decade) and thus leading to underestimation of mangrove ecosystem services at that time (de Groot et al., 2012). Therefore, the best solution for the assessment of mangrove ecosystem services will always be the collection and use of primary, site-specific data that reflect the characteristics and context of the study site. To be most useful for policy making, ecosystem services must be assessed within their appropriate spatial context, and economic valuation should provide estimates of value that can support decisions at the appropriate scale.

The aim of the present study is to establish a framework for linking remotely sensed spatial data, household survey data, and geophysical data to estimate the values of mangrove ecosystem services. We calculate the overall contribution of mangrove ecosystem services to the local communities, focusing on provisioning services of fishery and timber products and two regulating services (carbon sequestration, erosion control) of mangrove ecosystems. Other services, such as cultural services or genetic biodiversity, are excluded because our goal is to demonstrate the possibility of linking earth observation data, a household survey, and geophysical results for site-specific assessment of the value of mangrove ecosystems. Moreover, genetic biodiversity and cultural services are difficult to measure because these services do not enter to the market at all, so their price is also difficult to establish. Understanding the economic value of mangrove ecosystems and the services they provide to local communities has become increasingly important for local, national, and global policy and decision making. Indeed, quantifying and integrating these services into decision making will be crucial for sustainable development, where short-term economic benefits should be balanced against longer term environmental and economic sustainability.

2. Methods

2.1. Study area

The Vietnamese Mekong Delta (MD), comprising an area of approximately 40,000 km^2 located between 8°33′–10°55′N and 104°30′–106°50′E produces approximately 50% of the nation's rice and contributes more than 30% to the Gross Domestic Product of Vietnam from agricultural and aquacultural production (Gebhardt et al., 2012). Ca Mau Province, one of the biggest delta provinces, has the largest total area of mangrove forest in the MD (Fig. 1). However, the area of mangrove forest has declined about 50% over the past few decades, primarily due to increasing population pressure and the expansion of shrimp farming (Green et al., 1998; Johnston et al., 2000a; Lam et al., 2011; Tong et al., 2004). Much of the remaining mangrove forest in Ca Mau is managed under an integrated mangrove-aquaculture farming model in which farmers are required to protect and manage mangroves on at least 60% of their land holding area. Shrimp production from the remaining 40% of the land area is the primary source of income for farmers (Christensen et al., 2008; Tong et al., 2004), but the potential profitability of shrimp farming relative to mangrove protection is a powerful incentive for farmers to gradually expand their pond area by cutting down mangroves (Vo et al., 2013).

2.2. Methodology

To establish a framework of mangrove ecosystem service evaluation based on earth observation data and a household survey, we selected services that are highly relevant to the livelihoods of local communities. The household survey involved two stages. The first was the development and pre-testing of a questionnaire to ensure that relevant questions were included and captured the most robust data. The second stage consisted of a detailed survey of 300 randomly selected households, which was eventually reduced to 285 households after data exclusion due to the absence of important information such as shrimp farming area, total area as well as income and investment of shrimp farming activities. The survey used a semi-structured questionnaire with over 150 questions on different aspects of mangrove ecosystem services. The questionnaire included measures of both discrete information (land size, mangrove area, and mangrove-related income) and general qualitative information on the awareness of mangrove ecosystems, mangrove forest utilization, and the perception of mangrove forest protection. Information from all households interviewed was analyzed using SPSS statistics software.

For fisheries and wood-based products, the market price approach was used to calculate the values of fishery products and wood-related products with different mangrove forest densities using the following equation:

$$A = \sum (P_i\, Q_i - I_i)$$

where A = the total value (US$/ha/year), P_i = the product price, Q_i = the quantity, I_i = the investment, and i = the product.

Values for A, Q, I_i and i were derived from information provided by householders during the household survey. The following product market prices, current at the time of the survey, were used: an analysis of variance (ANOVA) was used to determine whether the mean values per hectare differed among the different percentages of mangrove cover (the null hypothesis states that there is no difference among the different mangrove densities in terms of the net benefit).

Multiple comparison analyses (post-hoc test) were performed to further determine the significant differences among the mangrove covers.

In general, measuring indirect-use values require different methods than measuring direct-use values because most indirect-use values are not traded in the market (Costanza et al., 1997; van Oudenhoven et al., 2012). In the present study, the valuation of carbon sequestration is estimated by benefit transfer (BT) approach. The BT approach is a technique for calculating the value of an ecosystem by employing an existing valuation estimate

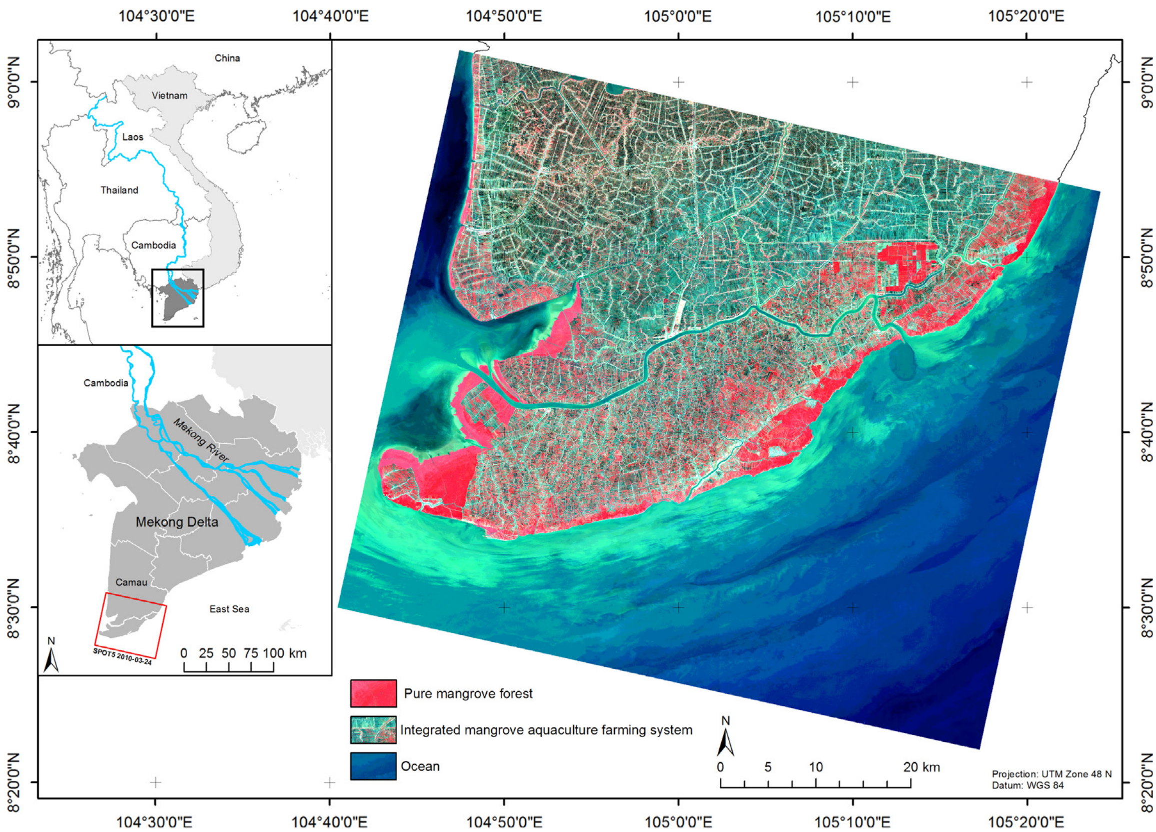

Fig. 1. Location of the study site in Ca Mau Province in the Mekong Delta (Source: Vo et al., 2013, modified).

for a similar ecosystem (Plummer, 2009). A recent study of the carbon sequestration rate of a *Rhizophora apiculata* forest plantation in Ca Mau Province was performed by McNally et al. (2011) and showed that the carbon sequestration rate depends on the age of the forest, with an average approximately 25.85 t/ha. In the present study, the value of carbon sequestration is calculated as the product of the carbon sequestration rates in the site being valued and the global price of carbon taken from a source, such as the WB reports (US$ 24/ton in 2010). The most widely used approach for assessing the economic value such as coastal protection or erosion prevention, is the replacement cost (RC) approach, which derives the value of constructing man-made alternatives with the same protective function for the shoreline (Brander et al., 2012b; Navrud and Ready, 2007; Sundberg, 2003). The present study applies the replacement cost method for the economic valuation of the protection services of mangrove using the cost from a pilot project, which was initiated to build a sea dike at one of the most eroded sites in Ca Mau Province (the same site of the current study); the total cost for constructing a 1-km dike (concrete embankment) along the coast was estimated at approximately US$470,000 (VNS, 2010). In the study, the value of coastal protection and stabilization is calculated by the replacement cost of constructing man-made alternatives that would provide the service, the value of the property that may be damaged without the service, or the value attached by the community to the service. Therefore, the economic value of carbon sequestration and erosion control of mangrove forests is calculated by using the results from previous studies (McNally et al., 2011; VNS, 2010) performed in the same location of the present study. To address the difference in time, a gross domestic product (GDP) deflator is used to convert the values from different years to the year in which the primary data (remote sensing and household survey data) were collected (i.e., 2010).

As stated above, the mangrove forests in Ca Mau Province are subject to a special integrated mangrove-shrimp farming system in which mangrove forest and shrimp farming are mixed in each pond. However, the quantification of an accurate percentage of mangrove cover in a pond is challenging when applying pixel-based approaches, even with high-resolution data. As this paper does not have a technical remote sensing focus, the interested reader is referred to remote sensing based mangrove mapping methods which can be found in Vo et al. (2013). To correspond to socio-economic household data, remote sensing results should be able to quantify the continuous percentage of mangrove cover in a pond. For this, we employed an object-based approach using the algorithms described by Vo et al. (2013), which provides more accurate estimation of mangrove forest cover in shrimp ponds than would be possible with the object-based techniques used in earlier studies with mangroves (e.g. Conchedda et al., 2008; Heumann, 2011; Myint et al., 2008). Briefly, the methodology includes several steps, including geometric and atmospheric correction, image segmentation, classification, and, finally, an accuracy assessment (Vo et al., 2013). The value of fishery-related products is estimated based on the different mangrove densities and, whereas the value of erosion control and carbon sequestration is calculated based on the existence of mangrove forest.

3. Results

3.1. Results of remote sensing classification

Remote sensing data were reclassified into areas with three different percentages of mangrove cover ("$\leq 30\%$ of mangrove"; mixed mangrove, "31–69% of mangrove"; and pure mangrove, "$\geq 70\%$ of mangrove") corresponding to the socio-economic household data (Fig. 2). More than ninety five thousand hectares

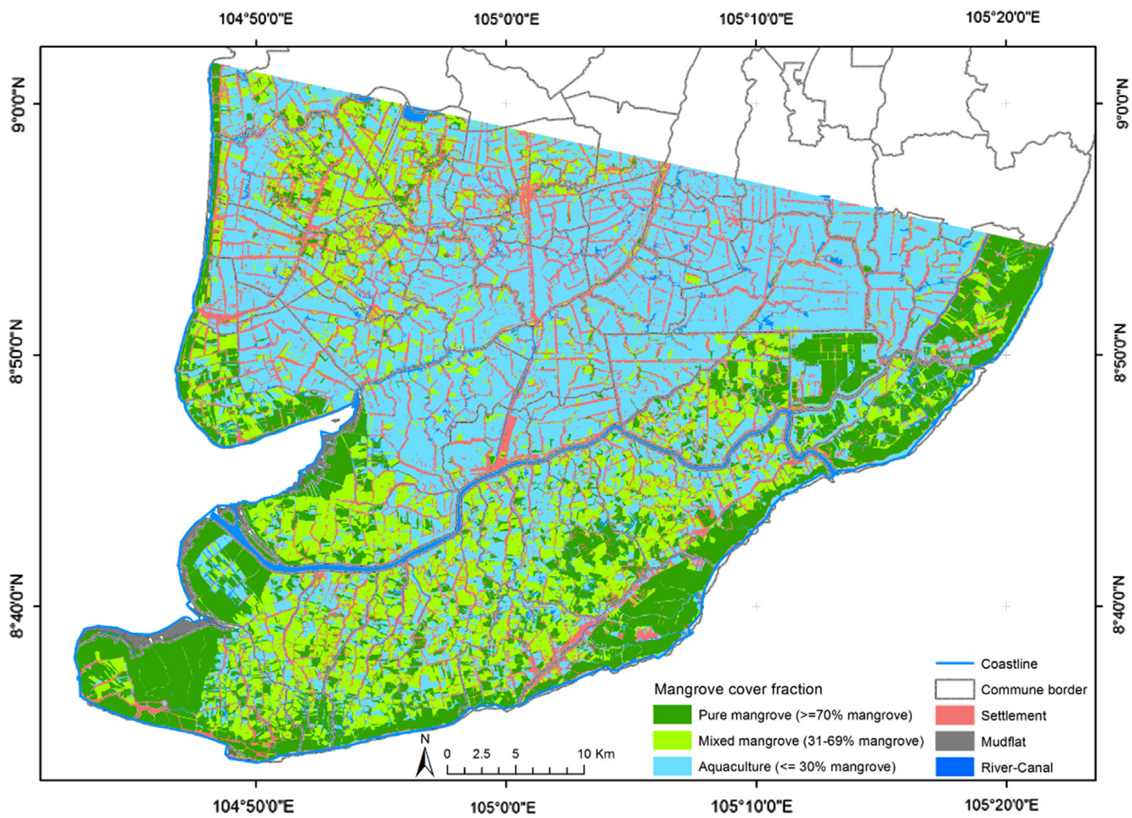

Fig. 2. Results of mangrove cover fractions from remote sensing.

Table 1
General characteristics of the household survey.

Variable		**No. of interviewees**	**Percentage**
Age (year)	≤ 30	22	7.7
	31–50	157	55.1
	> 50	106	37.2
Sex	Male	264	92.6
	Female	21	7.4
Education Level	Primary school	121	42.6
	Intermediate school	107	37.7
	Secondary school	45	15.8
	College of university	0	0.0
	Illiterate	11	3.9
Experience in mangrove management (year)	1–10	130	50.6
	11–20	102	39.7
	21–30	23	8.9
	> 30	2	0.8
Major occupation	Shrimp farmer	272	96.8
	Government officer	2	0.7
	Trader	2	0.7
	Hired laborer	1	0.4
	Unemployed	4	1.4

has mangrove cover of less than 30%, 48961 ha has mangrove cover between 30% and 70%, and only 22% has mangrove cover $> 70\%$. Because the farmers tend to stretch the limits set by the local authorities. Indeed, the farmers engage in different shrimp farming practices depending on the percentage of mangrove cover on a farm. With the traditional method ($\geq 70\%$ of mangrove cover), shrimp farming in Ca Mau Province has been extensive and is based on the tidal recruitment and harvest of wild shrimp from local waterways, with little or no supplementary feeding, aeration, water pumping, or soil treatment. In contrast, industrial shrimp farming ($\leq 30\%$ of mangrove cover) requires a high investment for land preparation or shrimp seed. Therefore, the cost and benefit of the different shrimp farming methods were analyzed. The farmers were asked about their total income and investment to determine the net benefit per hectare per year.

3.2. Results of household survey analysis

More than 90% of the interviewees were male, and the majority of respondents were within the age range of 31–50 years (55%), followed by those over 50 years old (37%) (Table 1). The main occupation in the area was shrimp farming (96%), either in an integrated mangrove-aquaculture farming system (extensive or semi-intensive aquaculture) or catching natural fishery resources in tide-operated sluice gates. Although most of the interviewees had finished primary school (42%) or intermediate school (37%), nearly 4% of the households had not received school education because the area is very remote. With regard to experience in mangrove management, more than 50% stated that they had been involved in the shrimp-mangrove integrated system from 1 to 10 years, with approximately 40% of the interviewees having 11–20 years of experience (Table 1).

Table 2 shows that the mean value of net benefit per hectare is highest at a mangrove cover of $\geq 70\%$ (US$ 3248, $n=55$), whereas the lowest is found at $\leq 30\%$ (US$ 990, $n=59$). The reason for this difference is that farmers tend to invest more money in aquaculture (land preparation, labor, and shrimp seeds). However, there are also risks, such as outbreaks of diseases that affect shrimp, which could adversely affect the livelihoods of shrimp farmers in Ca Mau Province (Johnston et al., 2000b).

The results showed that the mean value of net benefit differed significantly among the groups, although the difference between $\leq 30\%$ and 31–69% mangrove cover was not significant (sig > 0.05). Thus, the net benefit of a group of households with a low mangrove cover ($\leq 30\%$) on their land is not different from a group with an average mangrove cover (31–69%). The reason for this observation may be that the farmers invest the same amount of money for shrimp farming if they have $< 70\%$ mangrove cover on their land. Table 3 shows a detailed comparison of the different mangrove densities.

For the purpose of utilizing mangrove forest (multiple choices possible), the results from the household survey indicated that the mangrove forests were mainly used for fuel (firewood) and construction purposes (houses, fences, and furniture), with over 60% of households indicating these as primary uses. For the economic valuation, the utilization of these timber mangrove products could be calculated in monetary value if the farmers do not have mangrove forest on their lands. Approximately 30% of the households considered mangrove forest as a place for aquacultural activity (shrimp farming) (Fig. 3).

The results of the household survey showed that more than 90% of the residents in Ca Mau Province utilized mangrove timber products for cooking and construction purposes. However, many of these individuals do not consider the mangrove forests to have economical value. Fig. 3 shows the results of combined questions between the economic value of mangrove forests and utilization of mangrove, indicating that even though more than 40% of the local people do not think mangrove forests have economic value, even though 88% used mangroves for cooking and 90% used mangroves for house construction. The economic value of these services can be estimated by asking the farmer how much money per year he or she would have to spend for those purposes (surrogate price method). The results showed that the average amount a household would have to spend is approximately US$ 300/year for firewood and approximately US$ 800/year for construction purposes.

A multiple response analysis was used to investigate which services are important to the local communities. The results indicated that most of the interviewees agreed that mangroves provide barriers for storm protection (95%) and prevent coastal erosion (59%). Accordingly, we expected a negative relationship between the distance to the coast and erosion control service. A clear trend showed that the farmers who live close to the coastline (≤ 1 km) assign greater value to the erosion prevention function of mangroves in comparison to those located farther way

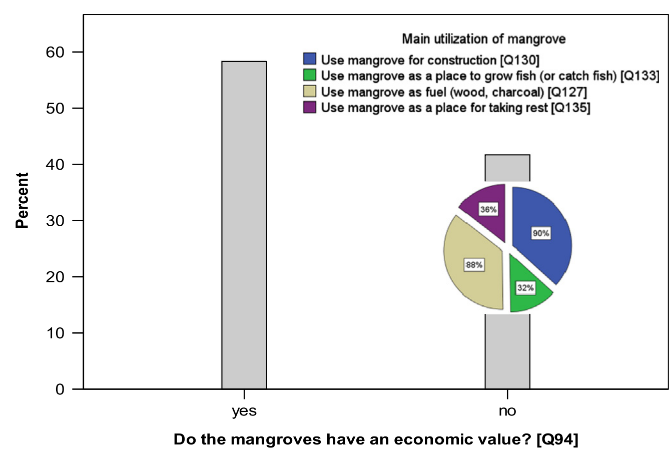

Fig. 3. Mangrove utilization and economic value.

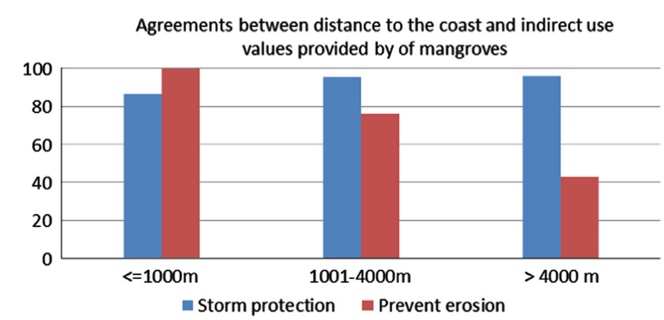

Fig. 4. Agreement between the distance to the coast and protection functions of mangroves.

Table 2
Total benefit from direct fishery products per hectare of aquaculture in US$.

Mangrove percent cover	N	Mean	Std	Std. error	Minimum	Maximum
≤30% mangrove cover	59	990.96	1392.11	181.23	−1184	6965
31–69% mangrove cover	162	1289.00	1299.11	102.06	−1435	10290
≥70% mangrove cover	55	3248.14	9539.85	1286.35	−239	72101

N: number of households; Std: standard deviation.

Table 3
Multiple comparisons between different mangrove densities.

(*I*) Mangrove density	(*J*) Mangrove fraction in percentage	Mean difference (*I*–*J*)	Std. error	*p*-Value
≤30% Mangrove cover	31–69% mangrove cover	−298.042	669.903	0.906
	≥70% mangrove cover	−2257.188*	825.741	**0.025**
31–69% Mangrove cover	≤30% mangrove cover	298.042	669.903	0.906
	≥70% mangrove cover	−1959.146*	687.527	**0.018**
≥70% Mangrove cover	≤30% mangrove cover	2257.188*	825.741	**0.025**
	31–69% mangrove cover	1959.146*	687.527	**0.018**

* The mean difference is significant at the 0.05 level.

(> 4 km). Storm protection is important to the majority of the local communities (> 80% agreement) and appeared to be independent of distance to the coastline (Fig. 4). Based on the household survey analysis, weighting factors are applied according to the agreement between the distance to the coastline and agreement on erosion control by mangrove forest (Table 4).

Three zones are generated according to the Department of Agriculture and Rural Development of Ca Mau Province (DARD). The first zone is called the "Full Protection Zone" for coastal protection purposes along the coast; it covers a band approximately 1000 m wide along the coastline. The other zone is called the "Buffer Zone" for controlled economic activities and forest protection (60% forestry and 40% shrimp farming), ranging from 1000 m to approximately 4000 m from the coastline and the inland zone, where the land is mostly used for aquaculture (Fig. 5).

3.3. Final value map of mangrove ecosystem services

A summary of the estimates of the total economic value of mangrove ecosystem services in Ca Mau is shown in Table 5. The total economic value of four selected ecosystem services provided by mangrove forests in this area is estimated at approximately US$ 600 million for 2010, approximately US$ 3000/ha/year. The value of mangrove timber is estimated at US$ 400 million, comprising 68% of the total value of Ca Mau's ecosystem service. The value of erosion control contributed to the area, at more than US$ 136 million/year, accounts for 22% of the total value of Ca Mau's ecosystem service. Carbon sequestration was assigned a value of US$ 46 million/year, amounting to 7.3% of the total value of the ecosystem services in Ca Mau, and the value of fishery-related products is estimated at approximately US$ 17 million, contributing to 2.8% of the total value of the region.

Fig. 6 shows the spatial distribution of the total economic value of mangrove ecosystem services in Ca Mau Province. There is a considerable variability in the ecosystem service values delivered by the different mangrove densities and distance to the coast. On a per hectare basis, the mangroves located close to the coast are estimated to provide the highest value (US$ 4001–10,000/ha/year), followed by the less dense mangroves (US$ 2001–4000/ha/year). The area with the lowest value is located inland, sites where mangrove coverage is low and that have a small value for erosion control and carbon sequestration (US$ < 1000/ha/year).

Table 4
Weighting factor and total economic value of erosion control.

Distance to the coast	Weighting[a]	Length (km)	Value/km (US $)	Total value (US $)
≤ 1000 m	1	171	470,000	80,370,000
> 1000–4000 m	0.5	171	470,000	40,185,000
> 4000 m	0.2	171	470,000	16,074,000

[a] The weighting factor is assigned based on the results of the household survey analyses.

4. Discussion

The household survey gives clear indicication that mangroves are the main source of timber for house construction and other buildings (small bridges and fences) to the local communities. Mangroves are also the major source of fuel, providing local communities with both firewood and charcoal for cooking. If mangrove forests did not exist on a farmer's land, he or she would have to buy these materials in the market (or use alternative fuels, such as gas or oil) to meet his or her daily needs.

However, the profits from mangrove timber after a 20-year waiting period do not appear to be very attractive compared to the annual profit from a shrimp farming harvest. Furthermore, the

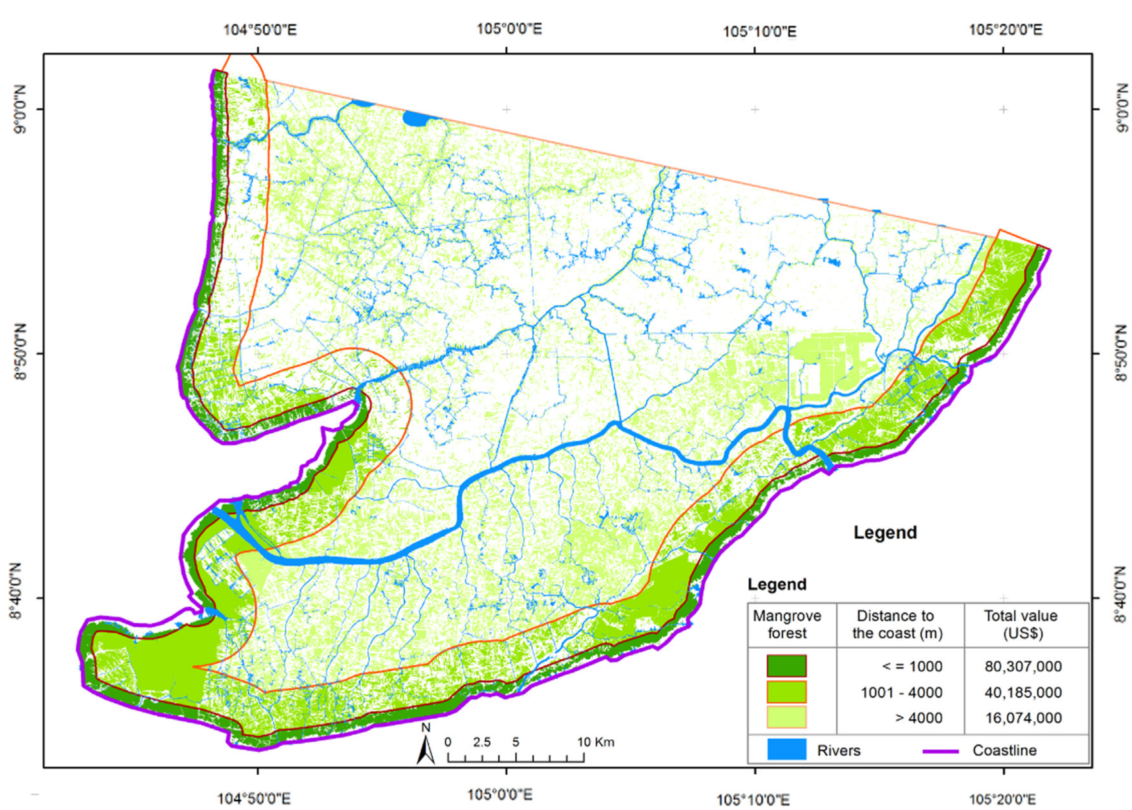

Fig. 5. Distance to the coast and value of erosion control of mangrove forests.

Table 5
Summary of the total economic value of mangrove ecosystem services in Ca Mau Province in 2010.

Ecosystem service	Based on		Mean value (US$/ha/yr)	Value	**Sum**
Fisheries	Mangrove cover in ponds (%)	≤ 30%	991	5913,297	17,720,222
		31–69%	1289	3,966,253	
		≥ 70%	3248	7,840,672	
Erosion control	Distance to the coastline (m)	1000	7904	80,307,000	136,566,000
		3000	1651	40,185,000	
		4000	450	16,074,000	
Carbon sequestration	Mangrove area (ha)	73,994	620	45,876,280	45,876,280
Timber	Mangrove area (ha)	73,994	5700	421,770,246	421,770,246
Total value of Ca Mau in 2010 (US$)					**621,932,748**
Total area (ha)					**187,533**
Mean value/US$/ha/year					**3316**

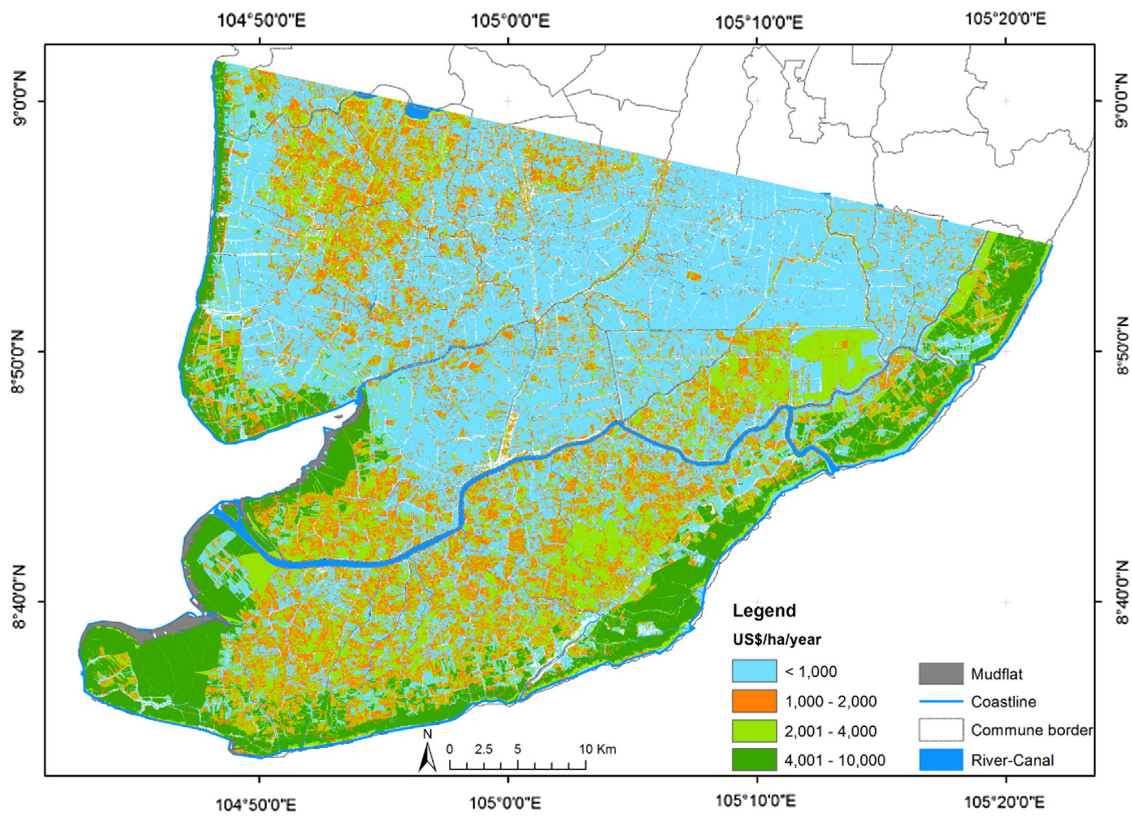

Fig. 6. Ecosystem service values in Ca Mau Province; an overview of direct-use values and indirect-use values.

farmers are unsure about the profits from mangroves, as the cost outlay is unclear to them, even though they may know the market price of mangrove wood. There is, therefore, a general distrust toward the forest management authority and profit sharing schemes, in particular. As a result, the farmers view mangroves more as a liability than a future income source (Johnston et al., 2000b).

Our initial estimates of the value of mangrove ecosystem services using a combined approach of remote sensing and household survey analyses have shown that these benefits are a significant contributor to the local communities in Ca Mau Province. A higher percentage of mangrove cover (equal to or greater than 70%) in an integrated mangrove-shrimp farming system represents by far the most valuable factor contributing to a famer's net benefits. Mangrove forests located near the coast are more valuable in terms of erosion control and storm protection compared to inland mangroves. Other services, such as biodiversity and tourism, are not considered in this study due to the absence of primary data. Utilizing remote sensing and spatial analyses allows us to determine the specific locations of the most valuable mangrove densities in addition to the value of the mangrove ecosystem services as a whole. Fig. 6 illustrates that dense mangrove forests, mostly located in coastal areas, are very valuable. Such knowledge plays an important role in the decision-making process. The total value of mangrove ecosystem services is estimated at US$ 600 million/year, significantly smaller than the GDP of the province (US$ 0.69 billion in 2010).

The estimate for the value of mangrove environmental services in Ca Mau (US$ 3000/ha/year) is well within the range reported by Brander et al. (2012) for mangroves in Southeast Asia, even though our analysis was limited to only four ecosystem services (fisheries, timber-related products, carbon sequestration and coastal protection) owing to the absence of primary data for other ecosystem services. The total value of all ecosystem services provided by mangrove forest in Ca Mau is likely to be somewhat higher than our conservative estimate of US$ 600 million annually, and it is clear that they make a significant but often unappreciated contribution to the livelihoods and well-being of local communities.

Whereas the value of timber-based products and fisheries from mangrove forests can be estimated with reasonable confidence from catch or harvest statistics and market prices, estimating the value of coastal protection and carbon sequestration is more problematic. The capacity of mangrove forests help to reduce coastal erosion and provide protection against storm surges depends mainly on the width and integrity of the coastal mangrove fringe. This probably explains the decreasing perception of the importance of mangroves for erosion control between householders living further from the coast (Fig. 4). Protection from strong winds associated with storms, however, is a more general issue across the whole province, hence the consistently high perception amongst all householders of the importance of mangrove forests for storm protection.

Our estimate of the value of carbon sequestration by mangrove forest in Ca Mau is based on carbon accumulation in above-ground woody biomass. Rates of below-ground carbon accumulation in Ca Mau are unkown, but the limited data available from elsewhere suggest that for some mangrove forests, fine root production could account for 30–40% of total primary production (Bouillon et al., 2008). How much of this below root carbon remains more or less permanently stored in the ecosystem is uncertain, but the substantial peat deposits and high organic carbon contents reported for mangrove soils in the Western Pacific and Sundarbans (Donato et al., 2011) suggest that undecomposed or partly decomposed dead roots contribute significantly to carbon storage in relatively undisturbed mangrove forests over time scales of centuries to millennia. However, there is very little pristine, natural mangrove forest left in Ca Mau; most is disturbed by human activities to varying degrees. Arguably, the most serious disturbance is caused by the construction of shrimp ponds, the excavated spoil from which is used to build surrounding dikes or deposited in the nearest mangrove area, most likely leading to release of some previously stored carbon (Donato et al., 2011). In view of these uncertainties and the lack of specific data for Ca Mau, it would be unwise to speculate further on the value of below-ground carbon sequestration and storage.

The lack of critical primary data on the effect of current land use and management practices on carbon sequestration in mixed shrimp mangrove farming systems of Ca Mau is a major obstacle to the implementation of REDD schemes proposed by McNally et al. (2011). Future research directions on the valuation of mangrove ecosystem services should include more primary data from original research (mangrove species, mangrove ages, and populations), and other areas should be tested to determine whether this approach is transferable and consistent. Although this study used the most accurate data from remote sensing classification, the value of carbon sequestration may be different if the mangrove species and age of trees are taken into account. It will also be necessary to determine the condition of the trees and changes over time, which also affects to the total value of mangrove ecosystems.

The approach followed in this study represents a first attempt to estimate the economic value of mangrove ecosystem services using a combined approach of remote sensing and household survey data. Remote sensing data are used for the quantification of the mangrove cover in a highly structured environment, such as the integrated aquaculture-mangrove farming system of Ca Mau Province, using an object-based approach; the result of the household investigation is based on different mangrove covers to determine the direct-use value of mangrove. Spatial analysis is used to generate the final value map of mangrove ecosystems as a whole and is useful for assigning weighting factors of some of the indirect uses provided by the mangrove ecosystem. For example, we found that the value of erosion control is more valuable if the mangroves are located near the coastline and vice versa.

As noted earlier, the results of the valuation of ecosystem services depend on the context-specific, socio-economic circumstances of the study area. The estimated value of mangrove ecosystem services is meaningful to raise awareness of the benefits provided by mangroves to local authorities in their decision-making processes. In addition, the results showed that the mean value of fishery-related products is much higher when the mangrove cover in ponds increases. This information could be used to increase the understanding of the local farmers to the mangrove ecosystem, many of whom (40%) believe that mangrove forests have no economic value at all.

The importance of mangrove ecosystem services to local communities has cultural and ecological dimensions in addition to economic aspects. Revealing the importance of such aspects in monetary terms is an important way to raise awareness of mangrove ecosystems among local communities and policy makers. Information on the monetary valuation of mangrove ecosystems can be used as a communication tool to ensure better informed, more balanced decisions concerning trade-offs in land-use planning. Finally, our particular case study provides knowledge on the monetary value of different mangrove densities in an integrated mangrove-shrimp farming system in Ca Mau Province, contributing to the Ecosystem Service Value Database established in 2010 (van der Ploeg et al., 2010).

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