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Mangrove shrimp farm mapping and productivity on the Brazilian Amazon coast: Environmental and economic reasons for coastal conservation

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A B S T R A C T

The present study evaluates the role of marine aquaculture in the conversion of mangrove forests into shrimp (*Litopenaeus vannamei*, Boone, 1931) farms using remote sensing and geographic information system techniques and analyzes the productivity of the installed farms in the mangroves and adjacent coastal plateau. The extension of the shrimp ponds was quantified using satellite image analysis, and the water quality of the shrimp farms was analyzed based on measurements of dissolved oxygen concentration, temperature, pH, and salinity. The productivity of the farms was measured using biometric data. The data were analyzed using ANOVA with Tukey's post-test. The results indicated that shrimp farms cover an area of ~0.8 km^2 (approximately 0.4% of Brazilian ponds), of which 29.4% are located within areas of mangroves, and 70.6% are located in the coastal plateau. Saltwater aquaculture contributed to the conversion of 0.53 km^2 of the mangroves into rearing ponds, which represents only 0.007% of the total area of the Amazonian mangroves. The installations in the mangrove presented significantly higher pH, temperature, transparency, and salinity compared with the ponds installed in the coastal plateau, although coastal plateau ponds had higher dissolved oxygen concentrations. Based on these differences, the mean sizes of the shrimp raised in the mangrove and coastal plateau ponds were 5.7 g and 4.3 g, respectively. However, the estimated value of one hectare of mangrove is much higher than its potential value in the production of shrimp. The considerable value of the ecosystem services provided by the mangroves indicates that the production of shrimp in the coastal plateau is relatively less damaging in ecological and economic terms. Thus, we can consider that the production of shrimp in the coastal plateau instead of in mangrove areas is less damaging to the long-term conservation of mangrove forests, which follows the management best practices established by international organizations. The coastal zone is considered a common resource that belongs to all citizens in Iberoamerican countries, and it is defined as a zone of non-building. Therefore, we conclude that mangroves are more valuable intact than converted into aquaculture ponds. Hence, aquaculture activities in the Amazon coastal plain are not sustainable from environmental and socioeconomic perspectives.

1. Introduction

Mangrove forests are an extremely valuable natural resource due to their high productivity and fundamental role in the maintenance of the biological diversity of coastal and marine environments (Barbier et al., 2011). The adequate conservation of mangrove habitats is fundamentally important to the ecological

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equilibrium of coastal zones and the maintenance of natural resources and ecological services. These resources sustain important socio–economic activities, such as artisanal and commercial fisheries, aquaculture, and agriculture, and they also provide firewood, building materials, and other products that are exploited for subsistence activities (Saenger et al., 1983; Nagelkerken et al., 2008; Walters et al., 2008).

Due to continuous population growth throughout the world, mangroves are becoming one of the planet's most endangered environments (Valiela et al., 2001). Mangroves have disappeared dramatically in many countries over the past four decades (Alongi, 2002; Barbier and Cox, 2003; FAO, 2007; Gilman et al., 2008). Some countries in Latin America, Asia, and Africa have lost between 30% and 70% of their mangrove forests in the last 40 years (Spalding et al., 2010). The conversion of mangroves into agriculture, aquaculture, and urban areas is the principal factor driving the loss of mangrove habitats worldwide (Barbier and Cox, 2002; Barbier and Sathirathai, 2004; Seto and Frakias, 2007; Giri et al., 2008a,b; Guimarães et al., 2010).

Saltwater shrimp farming is one of the most serious threats to the integrity of mangroves (Primavera, 1997). Shrimp farming has undergone massive expansion in recent years; global production increased from less than nine thousand tons in 1970 to 3.2 million tons in 2007 (FAO, 2008). Asia is the world leader in shrimp farming and produces nearly 80% of the world's farmed shrimp (Biao and Kaijin, 2007). Brazil is 12th in shrimp production, with 69,571 tons in 2011, occupying the 3rd position in the Western Hemisphere, behind Ecuador (260,000 tons) and Mexico (109,816 tons) (FAO, 2013).

The construction of holding ponds for the farming of fish and shrimp is an activity considered to be responsible for the loss of approximately 38% of the world's mangrove forests (Polidoro et al., 2010). In northeastern Brazil, shrimp farming has grown rapidly in recent years; it increased from a total area of 3000 ha in 1997 (an annual production of approximately 4000 tons) to 20,000 ha in 2008 (an annual production of 70,000 tons) (Rocha, 2010). This rapid expansion of shrimp farming activities, together with widespread disregard for environmental legislation, has led to the deforestation of large areas of mangrove habitats and the use of hypersaline areas, locally known as apicum (Guimarães et al., 2010; Queiroz et al., 2013).

The increase in production is related to the profitability of aquaculture systems in mangrove environments, which reflects the high value of their ecological services. The high productivity of mangroves and universal ecological illiteracy has led to the widespread underestimation of the economic value of the natural products and ecosystem services provided by mangrove forests (Rönnbäck, 1999). Therefore, intensive shrimp farming, although it is known to be an ecologically and socio–economically unsustainable activity, has been established in many countries (Dahdouh-Guebas et al., 2002; Primavera, 2006). Conversion of mangrove areas into saltwater farms has incited conflicts between shrimp farmers and the traditional communities in other Brazilian areas (Queiroz et al., 2013). However, this situation has not been observed in the Amazon region.

Geographic information systems (GISs) provide a framework for integrating remote sensing and other thematic data. Hence, satellite images with digital maps enable researchers to improve the precision of measurements of the sizes of holding ponds, monitor environmental changes caused by shrimp farming, and identify areas suitable for shrimp farming within mangrove habitats (Kapetsky et al., 1990; Meaden and Kapetsky, 1991; Populus et al., 1995). This research presents the first results of an investigation of the relationship between the environmental parameters of pond waters and shrimp productivity within mangrove and coastal plateau areas. This analysis is notably important for planning land use in the Amazonian mangrove coast. To define the role of local aquaculture practices in the degradation of the mangroves of the Amazon coastal zone (Fig. 1, A–I), the present study aims to quantify the mangroves and surrounding coastal plateau areas that have been converted into shrimp farming infrastructure using visual interpretations of high-spatial resolution remote sensing images and GIS. Additionally, data on the productivity of saltwater shrimp farms located in these two areas will be compared to determine whether shrimp farming production in mangrove ecosystems is feasible from environmental and socioeconomic perspectives.

2. Study site

2.1. Mangrove land use and specific licensing requirements

Approximately 1.5 million hectares of coastal areas have been converted to shrimp farms, mainly in Thailand, China, Indonesia, and Ecuador (Biao and Kaijin, 2007). Shrimp aquaculture has developed in these countries without regulations or laws in many cases. During the last decade, many authors have found evidence showing that the unsustainability of intensive and semi-intensive shrimp aquaculture methods is contributing to shrimp farm expansion and the degradation of mangrove forests (Barbier and Cox, 2002; Paul and Vogl, 2011; Mialhe et al., 2013). Due to this process, many countries are adopting policies to reduce environmental and socioeconomic impacts on the coastal zone. In the case of Brazil, the uncontrolled activity is mainly due to the influx of farms without environmental permits (Queiroz et al., 2013). The first legal instrument of national scope appeared in 1965, when federal law number 4,771, which instituted the Brazilian Forestry Code, considered mangroves to be an area of permanent preservation. In 1988, the Brazilian National Constitution established that mangroves could only be altered or removed with the permission of the states or municipalities. Later, in 2002, Resolution 312 of the National Environmental Council (CONAMA) reinforced the status of mangrove ecosystems as preserved areas in the Brazilian coast.

2.2. Mangroves and environmental conditions in northern Brazil

In 2009, the total area of Brazilian mangrove forests was approximately 1,071,000 ha (Magris and Barreto, 2010), almost 70% of which was located within the Amazon macrotidal coastal zone (Souza-Filho, 2005). This macrotidal zone extends from Marajó Island to São José Bay and includes 18 environmentally protected areas (Fig. 1). The mangrove flora in this zone consists of six tree species (i.e., *Rhizophora mangle*, *Rhizophora racemosa*, *Rhizophora harrisonii*, *Avicennia germinans*, *Avicennia schaueriana*, and *Laguncularia racemosa*) and many other plants (e.g., *Conocarpus erectus*, *Muellera*, *Rhabdadenia*, and *Acrostichum*) (Menezes et al., 2008).

The climate of the Amazon coast is governed by seasonal shifts in the position of the Intertropical Convergence Zone (ITCZ) and instability lines. The mean annual rainfall in the study area increases from east (2300 mm) to west (2800 mm). The rainy season (January–April) is relatively well defined and accounts for 73% of the annual precipitation. The dry season occurs between September and November when the monthly precipitation is close to zero (Moraes et al., 2005).

2.3. Saltwater shrimp aquaculture and fishery production in Brazil

The commercial cultivation of marine shrimp in Brazil began in the Northeast Region in the early 1970s. The native species initially

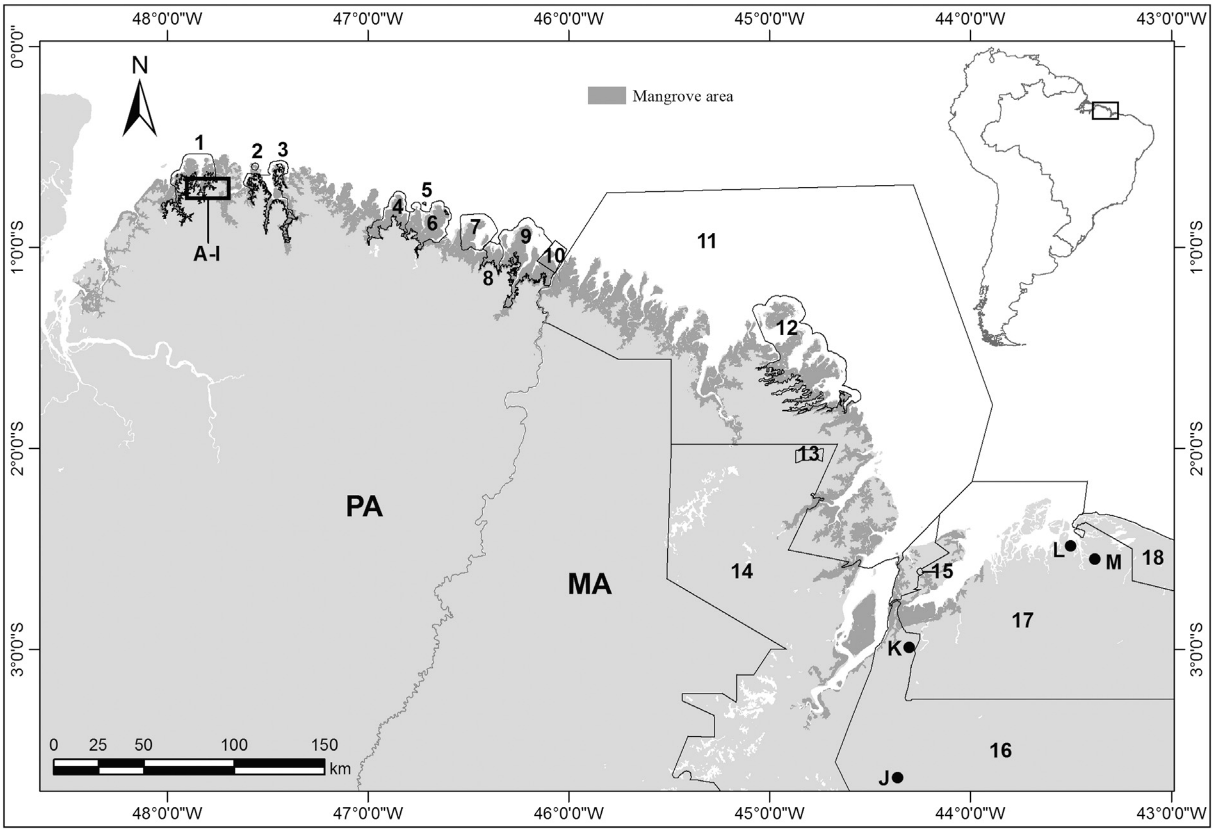

Fig. 1. Map of the coastal conservation units located to the east of the Amazon River mouth (Source: IBAMA, 2007). Numbers indicate the position of environmental protected areas, while letters show the location of the aquaculture ponds in the study site.

tested were *Farfantepenaeus brasiliensis* (Latreille, 1817), *Farfantepenaeus paulensis* (Farfante Pérez, 1967) and *Litopenaeus schmitti* (Burkenroad, 1936) (Damasceno et al., 1982; Machado, 1988). Later, cultivation developed further with the introduction of the exotic species *Marsupenaeus japonicus* (Bate, 1888) and *Penaeus monodon* (Fabricius, 1798) (Damasceno et al., 1982).

Shrimp farms in Brazil cover a total area of approximately 20,000 ha, with most located in the Northeast and Southeast Regions (Rocha, 2010). Between 1996 and 2003, shrimp farming expanded considerably in terms of the area of installations, total production, and productivity. Production increased 3132%, and productivity increased 676% during this period (Natori et al., 2011; Nunes et al., 2011). However, Brazilian operations faced two major problems in 2004. The first was related to the appearance of viruses, such as infectious myonecrosis (IMNV) in the Northeast and white spot syndrome in Santa Catarina (Southeast), which caused the death of all animals and a total loss of production. The second problem was an unfavorable exchange rate, which reduced the competiveness of the product in the international market. This led to the stagnation of the sector, which produced no more than its minimum capacity between 2005 and 2007 (Fig. 2) (IBAMA, 2007; Rocha, 2010). Fig. 2 shows the production of farmed and wild-caught shrimp between 1997 and 2007 in Brazil and in the main coastal states. In 2007, the coastal Amazonian states of Pará and Maranhão were together responsible for only ~0.8% of the farmed output, and 19.8% of the product was harvested from wild stocks. Currently, the farming of saltwater shrimp in these two states focuses on the production of a single species, the Pacific white shrimp (*Litopenaeus vannamei*, Boone, 1931).

2.4. Ecosystem services, processes and functions of mangroves

The destruction of mangroves around the world is of concern because they provide valuable ecosystems services (including raw materials, food, coastal protection, erosion control, water purification, maintenance of fisheries, and carbon sequestration) and are also a source of tourism, recreation, education, and research (Barbier et al., 2011). In Thailand, Vietnam and the northeast of Brazil, studies show a continuous increase in the area and yield of coastal aquaculture in which mangrove areas are converted to shrimp farms (Barbier and Cox, 2002; Lan, 2009; Queiroz et al., 2013). Hence, ecosystem services, such as coastal protection, erosion control, maintenance of fisheries and carbon sequestration, are lost. Due to the deforestation process necessary for the implementation or enhancement of shrimp farm activities, raw material production, such as wood exploitation, increases for a short period of time.

According to Barbier et al. (2011), three ecosystem services must receive the most attention in relation to their value to coastal populations: (i) the use by local coastal communities for a variety of products, such as fuel wood, timber, crabs, and shellfish; (ii) the role as a nursery and breeding habitat for offshore fisheries; and (iii) the propensity to serve as natural coastal storm barriers.

In northern Brazil, the subsistence of rural coastal populations is based primarily on agriculture and the harvesting of mangrove crabs (*Ucides cordatus*) as well as artisanal fishing in mangrove swamps (Glaser and Grasso, 1998; Glaser et al., 2010). Some households extract timber from the mangroves for the sale of charcoal or firewood, although this is illegal under Brazilian federal

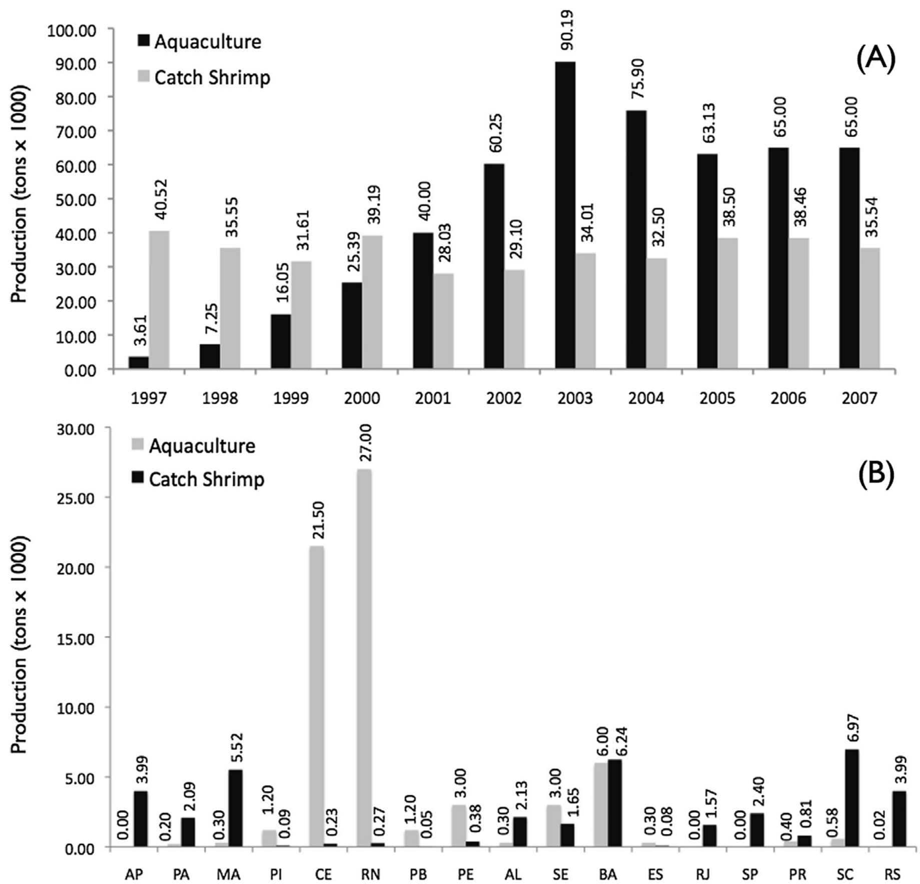

Fig. 2. A) Production of aquaculture and wild-caught shrimp in Brazil between 1997 and 2007. B) Production of shrimp in the Brazilian coastal states during the same period. AP-Amapá, PA-Pará, MA-Maranhão, PI-Piauí, CE-Ceará, RN-Rio Grande do Norte, PB-Paraíba, PE-Pernambuco, AL-Alagoas, SE-Sergipe, BA-Bahia, ES-Espírito Santo, RJ-Rio de Janeiro, SP-São Paulo, PR-Paraná, SC-Santa Catarina, RS-Rio Grande do Sul. Source: FAO, 2008; IBAMA, 2007.

legislation (Glaser, 2003). In the 1990s, approximately 83% of the region's rural households depend on the mangrove as a source of income (Grasso, 2000).

3. Methods

3.1. DGPS field measurements

Precise planialtimetric measurements were acquired via a differential global positioning system (DGPS) at the study site. Ground control points (GCPs) were used for the calculation of the shrimp farming area with sub-centimeter accuracies. One dual frequency receptor was used in the field for static DGPS measurements. One DGPS was used as a fixed station at the shrimp farms, while an other DGPS was used to collect sixteen static GCPs that were tracked over a period of 30 min.

3.2. Remote sensing dataset and digital image processing to enhance coastal features

The investigation was based on optical information obtained from a high-resolution geometric (HRG2) sensor image, with 5 m in spatial resolution from the SPOT-5 satellite, acquired on June 21, 2009. Additionally, GeoEye satellite images with a 1.6 m spatial resolution were obtained from the Google Earth PRO program for 2009.

The dataset was geometrically corrected through orthorectification process to assure corrections for terrain distortions (Toutin, 1995). The radiometric correction for the HRG2 SPOT-5 data was related to the attenuation of atmospheric effects and was based on the minimum histogram pixel approach. Image enhancements were applied based on linear stretches. Three bands for a red–green–blue color composite 2R3G1B were selected and chosen for visual interpretation.

3.3. Visual interpretation for production of thematic maps

A visual analysis of the digitally enhanced images was adequate to map shrimp farming and surrounding coastal features. Standard keys, such as tone/color, texture, pattern, form, size, context, geometry, and drainage, were used and supported by field validation. The HRG2 SPOT-5 bands provided the spectral, geometric, and textural attributes of the landforms. The landform classification followed a system of geomorphological surveying (Souza Filho and Paradella, 2002), with the structural organization of a unified geomorphological coastal classification system. The classification was based on field observations that identified coastal geomorphology, sedimentary environments and vegetation cover. Fifteen classes were recognized, including coastal plateau, mangrove, degraded mangrove, tidal creek, aquaculture farming, abandoned aquaculture farming, recolonized aquaculture farming, tailing pond, dikes, dune vegetation, sand dune, huts, residence, urban areas, and roads. Urban areas, roads and residences were mapped, but they were not considered in the classification of coastal and aquaculture systems.

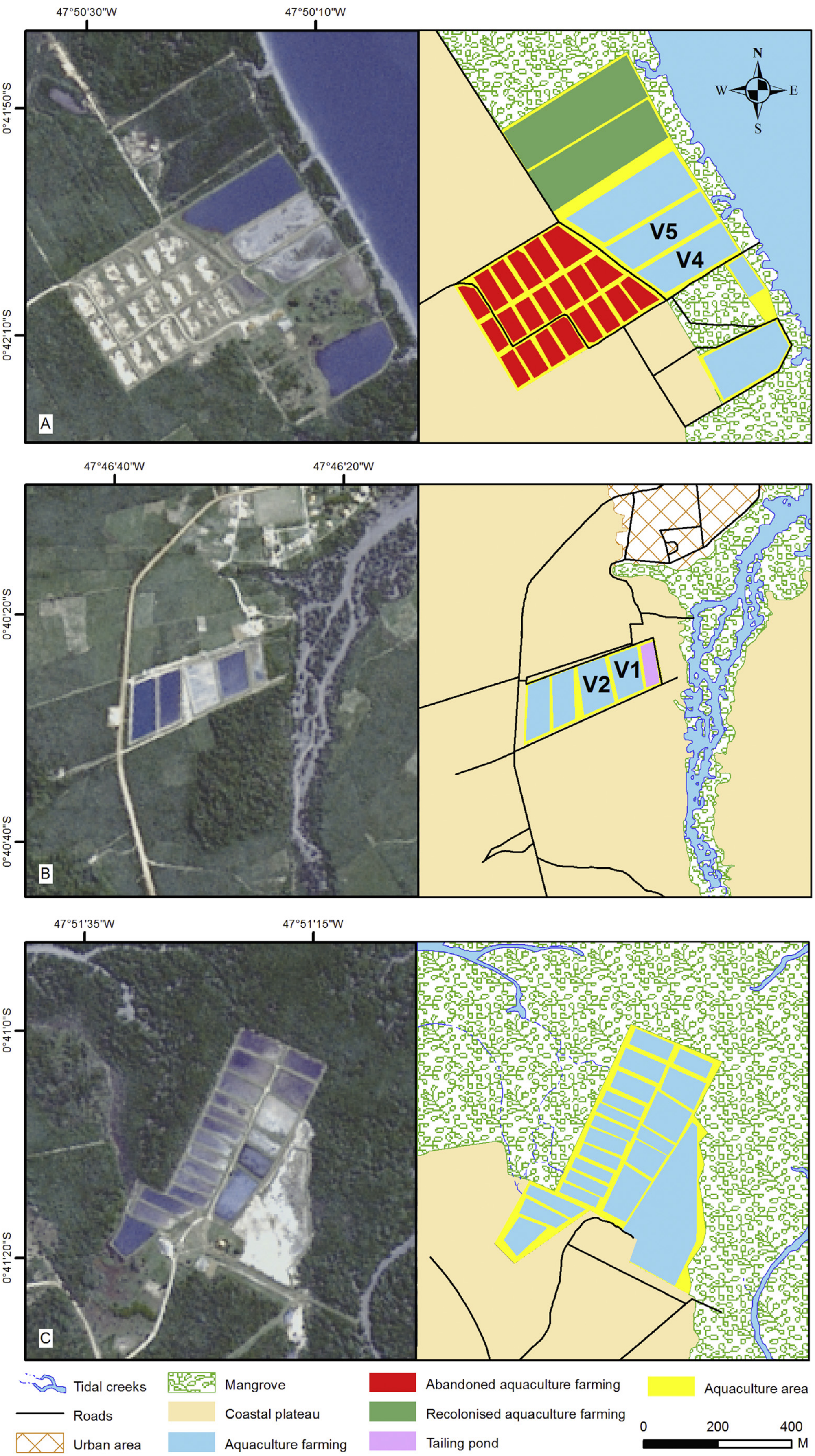

Fig. 3. Images and maps showing the area occupied by the shrimp farming ponds in relation to the distribution of mangrove habitat in the Pará State. Left side shows HRG2 sensor of the SPOT 5 satellite obtained in 2009. Right side shows maps generated from image interpretation. The positions of shrimp's farms from A to I can be observed in Fig. 1. Note the location of ponds V4 and V5 (Figure A), installed within the mangrove, and ponds V1 and V2 (Figure B) constructed over coastal plateau.

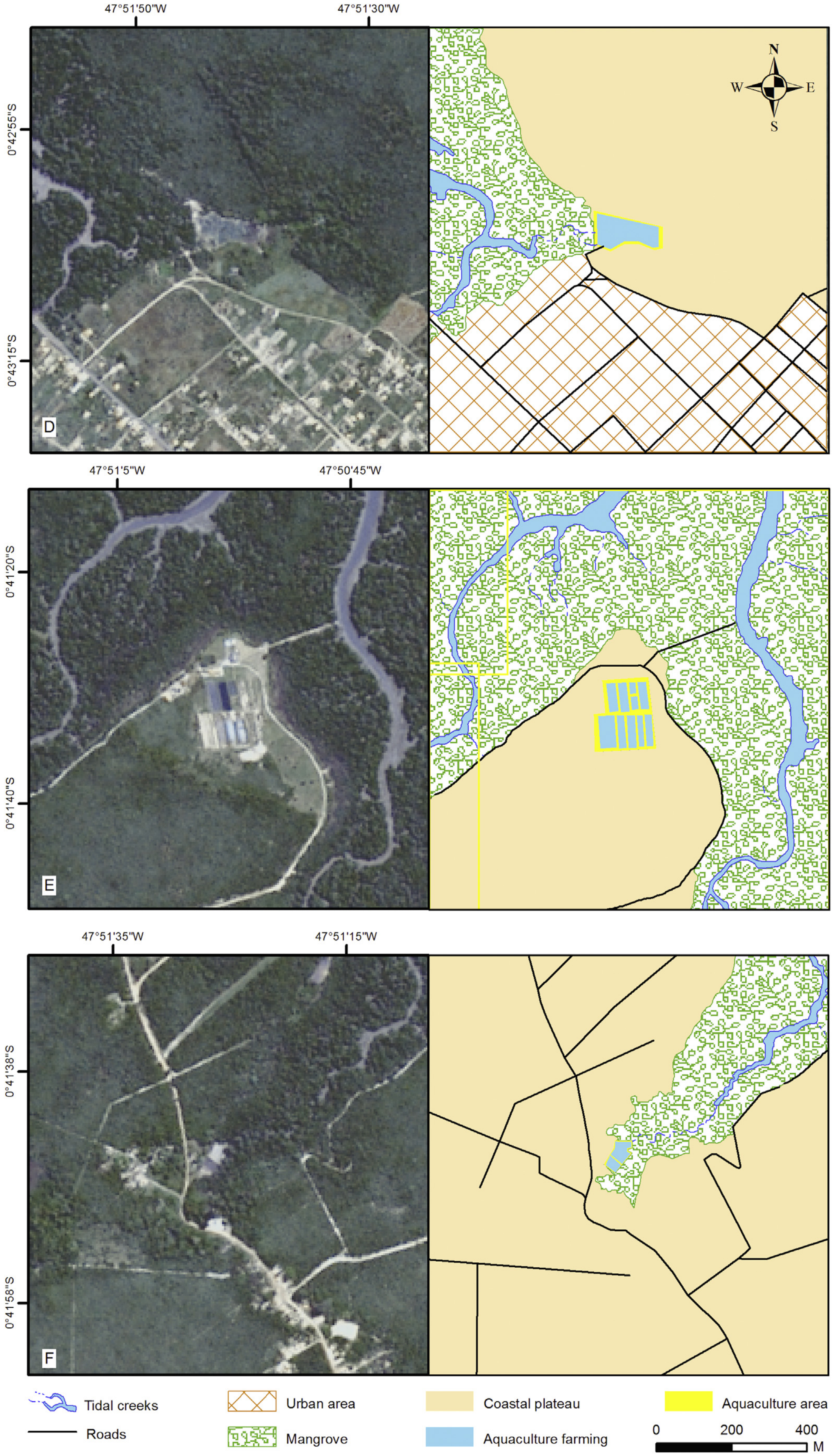

Fig. 3. (*continued*).

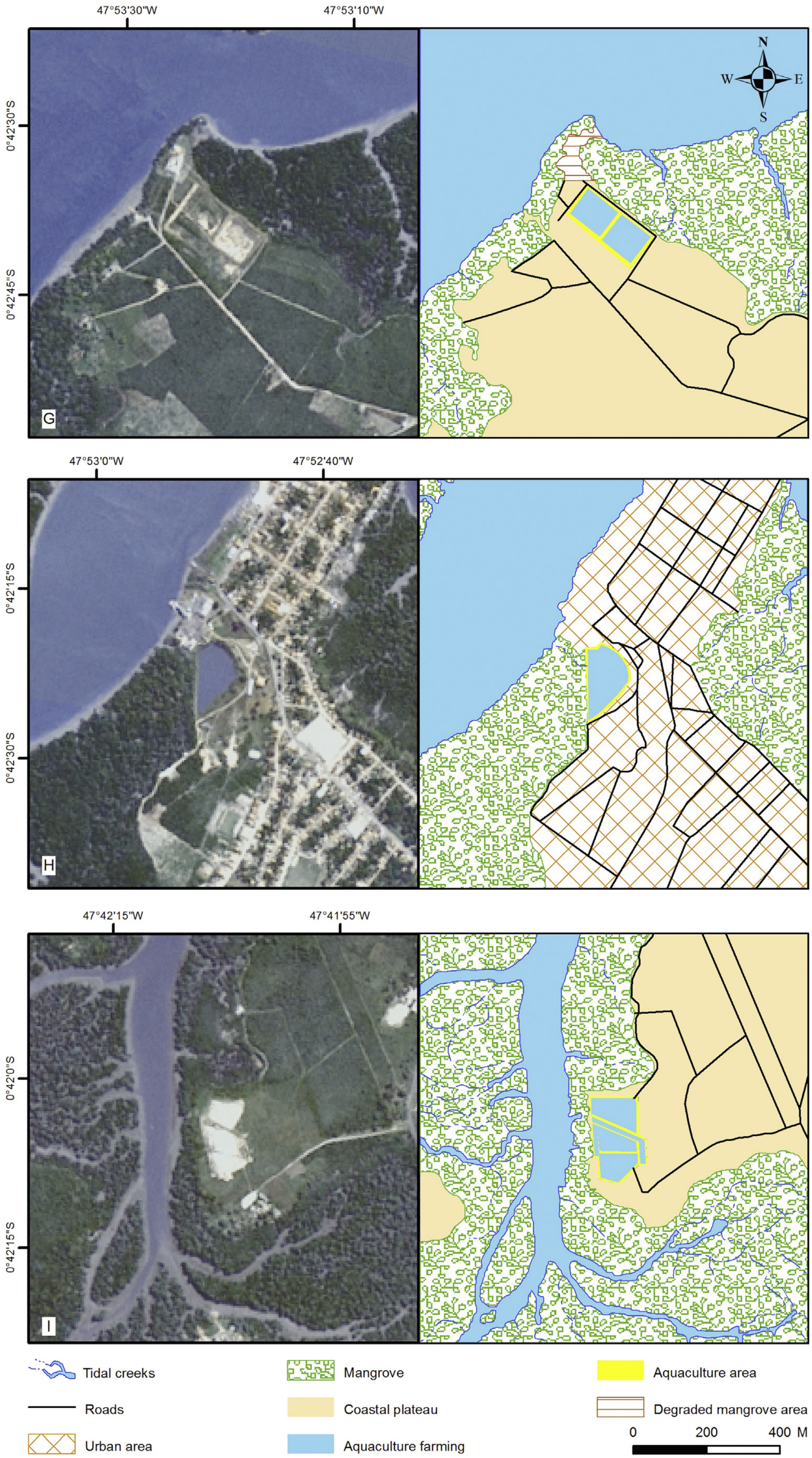

Fig. 3. (*continued*).

3.4. Measurement of environmental parameters and selection of shrimp farms for the analysis of productivity

Of the thirteen shrimp farms that were identified within the study area, two were selected for data collection on the water environmental parameters and shrimp productivity. These two shrimp farms represent the largest farms in terms of activity and the general environmental conditions that were observed along the Amazon coast, where ponds were built in mangroves and adjacent coastal plateaus. Furthermore, we had permission to access this private area, which was conducive for simultaneously monitoring the water parameters and biometric measurements of these two types of shrimp farms. The first type is located over the coastal plateau, and it is represented by ponds V1 and V2, which have 1.80 m and 1.50 m depths, respectively (Fig. 3B). The second type of shrimp farm is situated over the mangrove intertidal flat, and it is represented by ponds V4 and V5, which have 2.0 m and 3.5 m depths, respectively (Fig. 3A).

The water quality and productivity of the ponds were monitored daily and weekly, respectively, between July 1 and October 23, 2003. The minimum growth rate of 0.7 g per week was estimated based on the shrimp reaching market weight (10–12.5 g) within 90–120 days of cultivation. The selected density was 50 shrimp/m^2 due to the lack of laboratories in the region. The post-larvae (PL10) were acquired in Northeast Brazil and transported by truck (travel time was 25 h). During the preparation of the ponds, twelve surface samples of soils were collected in each pond. They were chemically analyzed in the laboratory to determine the necessity of liming. Liming was performed using limestone ($CaCO_3$) in dosages of 920 kg/ha (V1 and V2) and 1840 kg/ha (V4 and V5) (Vinatea et al., 2004). During this process, limestone was homogeneously distributed in all ponds, and the pond bottoms were manually plowed. After these steps, we applied urea (40 kg/ha) and superphosphate (04 kg/ha). At the conclusion of these processes, we began filling and fertilizing the ponds. pH values of 6.5 and 5.0 were obtained in ponds V1 and V2 (coastal plateau) and V4 and V5 (mangrove), respectively. During acclimation, water was added from the ponds to the plastic bags containing the post-larvae to induce a maximum temperature variation of 1 °C and 0.3 units of pH/h (Nunes et al., 2002).

Each pond location was chosen for its farming potential. Aerators were operated throughout the experiment at 4.0 hp/ha/pond. Initially, the pond was supplied with 40% crude protein (CP) during the first 28 days of cultivation (for ponds V4 and V5, the proportion was a 1 kg ration to 100,000 PLs) four times per day at 07 h, 10 h, 13 h and 15 h feeding schedules. After this period, all of the ponds were rationed with 35% CP, which was exclusively distributed in the feed trays three times per day (7 h, 10 h and 13 h). For ponds V1 and V2 (1.0 ha) 100 trays/ha were used, whereas for ponds V4 (2.8 ha) and V5 (3.0 ha) 53 trays/ha were used. These proceedings followed the methodological approach proposed by Barbieri and Ostrensky (2002).

Dissolved oxygen (DO in mg/l), temperature (T in °C), salinity (SAL), pH and transparency (TRANS in cm) were measured daily at 13 h (SAL/TRANS), 17 h (pH/OD/T), 24 h (OD/T), 02 h (OD/T), and 05 h (OD/T/pH). All of the parameters were measured using a multiparameter probe system, except for transparency, which was measured using a Secchi disk. This experiment considered the following parameters and ranges to be optimal for the cultivation of *L. vannamei*: 6–10 mg/l of OD, 23–30 °C, a salinity of 15–27, a pH of 8.1–9.0 and 35–45 cm of transparency (Hermandéz, 2000; Peixoto et al., 2003; Nakayama et al., 2009).

To determine the productivity of shrimp farming as measured in grams (g), weekly biometric measurements were recorded from the 28th day of the settlement of the ponds to the end of the electronic precision balance, with a precision of 0.01 g. The shrimp were captured with a casting net, and after their measurements were taken, the shrimp were returned to their pond.

3.5. Statistical analysis of the farm infrastructure and productivity data

All statistical analyses were conducted within the Minitab 14 program. Standard parameters, such as the means, standard deviations, and variation coefficients (indices of dispersal), were calculated for the environmental and biometric data (Kutner et al., 2004). To evaluate the differences among the sites, a one-way analysis of variance (ANOVA) was run for each dataset, where d.f. $= n-1$ and $\alpha = 0.05$ (Ivo and Fonteles-Filho, 1997). Tukey's post-test was run to determine the significance of the differences between the pairs of sites (Montgomery et al., 2011).

4. Results

4.1. Mangrove areas converted to shrimp farms

Thirteen shrimp farms were identified in the study area (Fig. 1). Of these, nine were located in Pará State, including five in mangroves and four in coastal plateau sites (Fig. 3). The other four farms were in Maranhão State and installed on the coastal plateau (Fig. 4). The total area of the ponds was 77 ha, 69% (53 ha) of which was constructed within the mangrove, whereas the remainder (24 ha) was located in adjacent areas of coastal plateau. Mangrove trees naturally recolonized a mangrove area of approximately 9 ha, which had been converted into shrimp ponds in the 1980s (Fig. 3A/B). Hence, saltwater aquaculture contributed to the conversion of 44 ha of the mangrove into rearing ponds, which represents almost nothing (only 0.007%) of the total area of the Amazonian mangroves.

4.2. Analysis of the quality of the water in the ponds and the biometric characteristics of the farmed shrimp

All of the analyzed parameters exhibited highly significant differences among the ponds, based on the results of ANOVA (Table 1). The mean dissolved oxygen (DO) concentration (mg/l) was highest in Pond V2, lowest in pond V4 and most variable in pond V5 (standard error). The results of the Tukey test indicate that ponds V1, V4, and V5 all have significant DO concentrations compared with pond V2.

For temperature, pH, transparency, and salinity, significant differences were predominantly found between ponds located in the mangrove and coastal plateau. The temperature in all of the ponds was within the recommended values (23°–30 °C). The highest values were recorded in ponds V5 (28.90 °C) and V4 (28.70 °C), while the lowest values were observed in ponds V1 (28.06 °C) and V2 (28.09 °C). Similarly, the pH was highest in pond V5 (7.66) and lowest in pond V2 (7.27); these ponds also presented the lowest variation (standard error). Once again, the values recorded in the coastal plateau ponds (V1 and V2) were significantly lower than those recorded in the mangrove ponds (V4 and V5).

The values of transparency in all ponds remained close to the optimal level (40 cm), but minimum values were only recorded for ponds V2 (36.87 cm) and V1 (36.83 cm), both located in the coastal plateau, while ponds V4 (45.65 cm) and V5 (44.57 cm) showed the highest values of transparency. Salinity was also lower in the coastal plateau ponds than in the mangroves. The mean salinity was highest in pond V5 (28.39), lowest in pond V2 (25.50), and the least variable in ponds V4 and V5. However, even though the *coastal plateau* pond V2 was significantly different from both mangrove

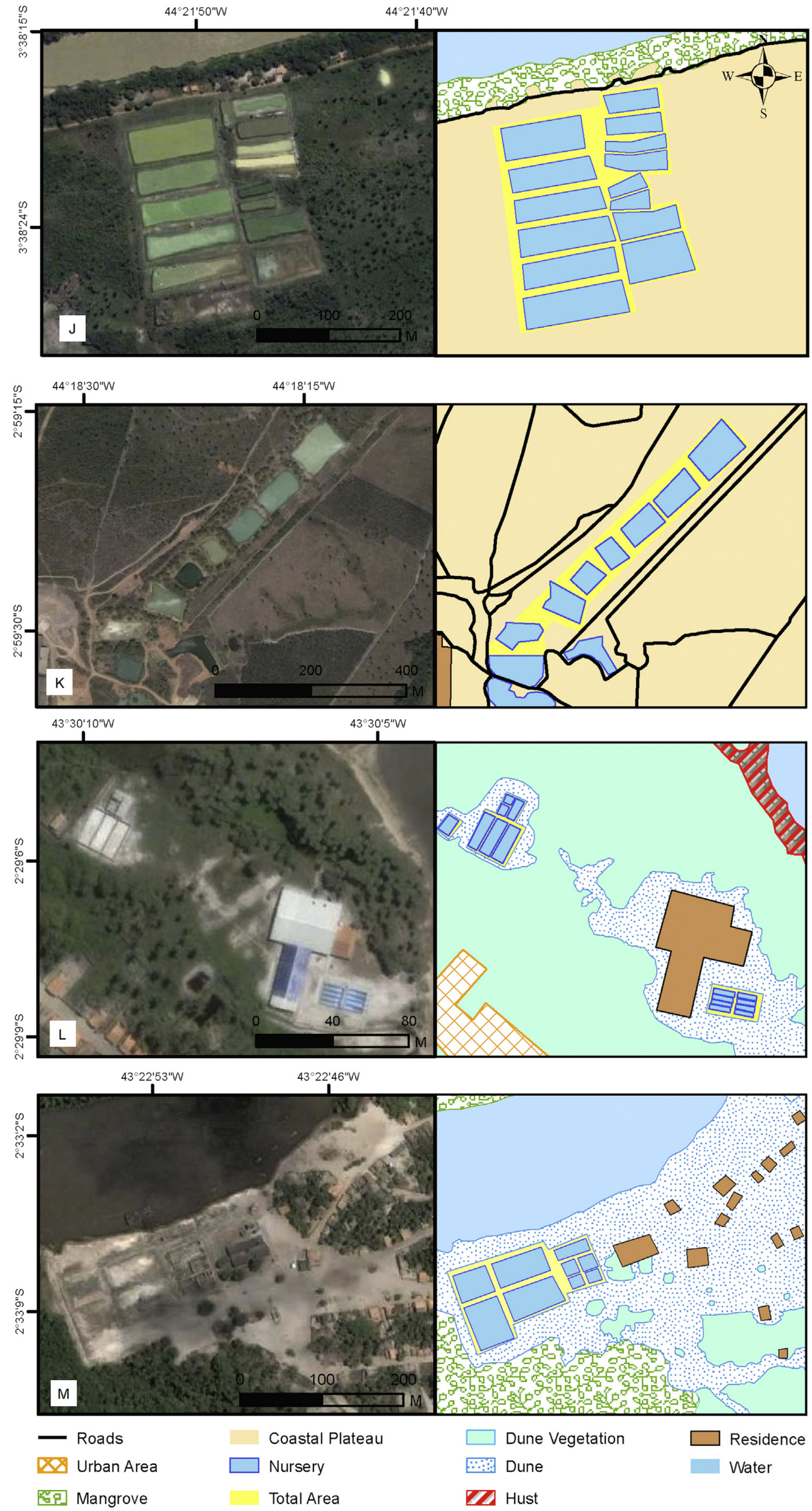

Fig. 4. Images and maps showing the area occupied by the shrimp farming ponds in relation to the distribution of mangrove habitat in the Maranhão State. Left side shows GeoEye images obtained in 2009. Right side shows maps generated from image interpretation. The positions of shrimp's farms from J to M can be observed in Fig. 1. Note that all the ponds are located outside the area of mangrove.

Table 1
Mean values for the dissolved oxygen concentrations, temperature, pH, transparency, and salinity that were recorded in the monitored shrimp ponds (the *p* values are from ANOVA). Ponds marked with different letters for the same variable are significantly different ($p < 0.05$) based on the Tukey test.

Variable	Range of values	Pond	Mean	Standard error	*p*
Dissolved oxygen (mg/l)	6.0–10.0	V1	4.19^{a}	0.0677	<0.001
		V2	4.63^{b}	0.0781	
		V4	4.03^{a}	0.0646	
		V5	4.22^{a}	0.0583	
Temperature (°C)	23.0–30.0	V1	28.06^{a}	0.0613	<0.001
		V2	28.09^{a}	0.0557	
		V4	28.70^{b}	0.0902	
		V5	28.90^{b}	0.0844	
pH	7.1–9.0	V1	7.31^{a}	0.0356	<0.001
		V2	7.27^{a}	0.0345	
		V4	7.62^{b}	0.0349	
		V5	7.66^{b}	0.0345	
Transparency (cm)		V1	36.83^{a}	0.5430	<0.001
		V2	36.87^{a}	0.5470	
		V4	45.65^{b}	1.0100	
		V5	44.57^{b}	1.0100	
Salinity	15.0–27.0	V1	26.89^{ab}	0.4970	<0.001
		V2	25.90^{a}	0.4890	
		V4	28.37^{b}	0.4660	
		V5	28.39^{b}	0.4660	

ponds (Tukey's test), the difference between these ponds and pond V1 was not significant.

Regarding productivity, the largest shrimp (mean body weight = 6.17 g) were raised in pond V4, and the smallest shrimp (mean = 4.26 g) were raised in pond V1. Pond V1 also exhibited the smallest standard error (0.3250 g). Significantly larger shrimp were raised in pond V4 than in the coastal plateau ponds, although the difference in relation to pond V5 was not significant (Fig. 5). In 105 days, pond V4 had a productivity of 4445 kg/cycle, a survival of approximately 66%, a final weight of 13.5 g and a feed conversion factor (FCF) of 1.1. Pond V5 had a productivity of 3822 kg/cycle, a survival of 65%, a final weight of 12 g, and an FCF of 1.2. However, the ponds located in the coastal plateau (ponds V1 and V2) had productivity between 3009 and 3060 kg/cycle, a survival between 59% and 60%, a final weight of 10.2 g and an FCF of 1.5.

Therefore, we observe that the most productive ponds (V4 and V5) presented the highest values of temperature, dissolved oxygen, pH, transparency, and salinity; while the less productive ponds (V1 and V2) showed the lowest values for the environmental parameters. Table 2 synthesizes the values of the environmental parameters and productivity for each analyzed pond.

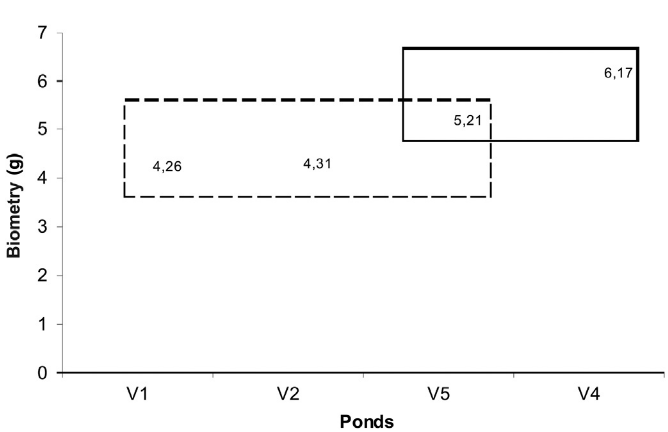

Fig. 5. Graphic representation of the results of the Tukey' post-test for the comparison of the biometric measurements obtained for each pond.

Table 2
Environmental parameters and shrimp production per pond. Ponds V1 and V2: coastal plateau. Ponds V4 and V5: mangrove.

Ponds	Dissolved oxygen (mg/l)	Temperature (°C)	pH	Transparency (cm)	Salinity	Productivity (kg/ha/yr)
V1	4.19^{a}	28.06^{a}	7.31^{a}	36.83^{a}	26.89^{ab}	3341
V2	4.63^{b}	28.09^{a}	7.27^{a}	36.87^{a}	25.90^{a}	3315
V4	4.03^{a}	28.70^{b}	7.62^{b}	45.65^{b}	28.37^{b}	4387
V5	4.22^{a}	28.90^{b}	7.66^{b}	44.57^{b}	28.39^{b}	3826

Means followed by different letters in the column differ from each otherby the Turkey test (p<0.05).

5. Discussion

5.1. Conversion of mangroves for shrimp farming

This study does not condone the worldwide trend of the use of mangroves to develop aquaculture activities, as observed in northeastern Brazil (Guimarães et al., 2010; Santos et al., 2014) and other parts of the world. It is important to mention that aquaculture is responsible for the reduction (over 45%) of the mangrove areas in Thailand, Indonesia, and Ecuador (Parks and Bonifaz, 1994; Barbier and Sathirathai, 2004; Giri et al., 2008a,b), and significant impacts have also been recorded for the mangroves of the Sundarbans in Bangladesh and India (Rajitha et al., 2007; Giri et al., 2007, 2008a,b).

Our data does not confirm the worldwide trend of the conversion of mangroves into large-scale shrimp farms. Although aquaculture activity began to expand to the Amazon coast in the early 1980s, when the first marine shrimp farms were established in Pará and Maranhão due to the decrease in the main fishery stocks in the region, its expansion was mainly limited by four socioeconomic factors: i) artisanal fisheries were still well-established, and many families were still living strictly from resources provided by mangrove services; ii) the cost of the installation and production of saltwater shrimp farms in the Amazon region is very high due to the nonexistence of a basic infrastructure, such as electricity, paved roads, research laboratories for larvae production and fish feed plants; shrimp farming aquaculture infrastructure is costly and requires logistical support; iii) the environmental laws prohibited the establishment of this activity in permanently preserved areas, making it very difficult to obtain licenses to implement this type of activity in mangrove areas; and iv) the absence of government subsidies to develop saltwater aquaculture in the Amazon region. Together, these factors guarantee the conservation of the mangroves of the Amazon coast, which have increased in area by almost 10% (718 km^2) over the past two decades (Nascimento et al., 2013).

Therefore, from this local case study, we can extract several global lessons for the conservation of mangroves in developing countries, where populations have increased over the last four decades. To reach this goal, aquaculture must be developed only in the areas already modified by human action located in the coastal plateaus. Hence, traditional populations can continue to exploit mangrove natural resources in a sustainable way. Furthermore, it is important that the traditional population socioeconomically benefits from any implementation of future economic activity (e.g., port and oil exploration in near- and off-shore zones) in the coastal zone. This simple attitude is a potential path to the worldwide conservation of mangroves.

5.2. Water quality and shrimp farming productivity

In general, the conditions in the ponds located within the mangrove (ponds V4 and V5) were quite distinct from those found in the coastal plateau (ponds V1 and V2) in terms of dissolved oxygen concentrations, temperature, pH, salinity, and transparency.

The variations observed in these parameters over the course of a day were similar to those recorded by Boyd (1982), Hernández (2000), and Krummenauer et al. (2011). The DO concentrations follow a diurnal cycle. The lowest levels of DO occur at dawn and the highest in the afternoon, as observed by Krummenauer et al. (2011). The water temperature remained within an established pattern of temperature fluctuations for tropical areas throughout the year (Boyd, 1989). In all of the ponds, thermal stratification was observed. Overnight, there was a change in stratification but only in the shallower upland ponds (V1 and V2). Because all the ponds are located in fluvio-estuarine areas, the water pH ranged between 7 and 9. The average temperature observed during the study can be considered normal for species grown in tropical waters (23 °C a 30 °C). Higher salinity values and low transparency were recorded for the mangrove ponds V4 and V5. This most likely occurred because the ponds were supplied by water from the adjacent tidal creek and estuarine channel, while the upland ponds V1 and V2 were stocked by a fluvial channel with a higher concentration of freshwater and a lower suspended sediment inflow. According to Barbieri and Ostrensky (2002), *L. vannamei* is a species that tolerates a wide range of salinity and temperature. Although, this does not mean that it can achieve maximum growth and survival in these conditions (Laramore et al., 2001). However, according to Boyd (1989), salinities between 15 and 25 and temperatures from 25 °C to 32 °C are considered ideal for the cultivation of *L. vannamei*, but these parameters were only observed in the upland ponds (V1 and V2).

The ponds located within the mangroves (ponds V4 and V5) exhibited higher temperatures and salinities than those within the coastal plateau (ponds V1 and V2), which indicates that Pacific white shrimp (*L. vannamei*) may be raised successfully in a wider range of temperatures and salinities than has been suggested by the available literature (Peixoto et al., 2003; Nakayama et al., 2009).

In the present study, the shrimp raised in the mangrove ponds exhibited better growth rates than those in the coastal plateau ponds. However, though the farms located in the mangrove may technically be more productive than those in the coastal plateau, they appear to be much less sustainable, when considering the environmental, social, and/or economic factors. It is important to emphasize that the productivity of the ponds built in the mangrove area has less value than one hectare of conserved mangrove forest. Furthermore, the aquaculture activity can be developed in adjacent upland areas.

In recent years, important advances have been achieved in mapping mangrove changes in response to aquaculture development (Hossain et al., 2009; Guimarães et al., 2010). The construction of shrimp farms within the mangroves of the Amazon coast is partly the result of a lack of adequate monitoring by competent environmental and governmental organizations. Furthermore, a lack of knowledge of the importance of the mangrove ecosystem, the value of adjacent land, and the proximity to tidal waters reduce the needs for an elaborate pumping system to feed the ponds. Determining the social, economic, and environmental value of a mangrove is complex, especially when assigning numerical values to the goods and services provided by this ecosystem (Guimarães et al., 2010). Despite the difficulty in producing an accurate value, a number of authors (e.g., Costanza et al., 1998; Aburto-Oropeza et al., 2008) have provided estimates of the monetary value of mangroves in terms of the goods and services they provide. Aburto-Oropeza et al. (2008) assigned a mean global value for fringe mangrove of approximately US$ 37,500 ha^{-1} yr^{-1}; and Barbier et al. (2011) estimated a global value of approximately US$ 16,100 ha^{-1} yr^{-1}. Based on these values, the difference in the productivity between ponds located in the mangrove and coastal plateau indicates that the ultimate cause of minor damage to the environment is located in private areas. As the coastal zone is considered a common resource that belongs to all citizens in Iberoamerican countries, and it is defined as a zone of non-building (Dias et al., 2013), aquaculture activities should not be developed in mangrove areas and should only be developed on private lands that have already been modified by human activities, outside of the mangrove ecosystem and following the best management practices for aquaculture. New exploitation of mangrove resources must be prohibited to conserve mangroves for many generations without significantly impacting one of the most well preserved mangrove forests in the world.

5.3. Recommendations for the sustainable use of mangroves on the Amazon coast

At the Amazon River mouth, we have the largest and most well conserved mangrove system in world. This contradicts worldwide trends, where agriculture, aquaculture, and urban expansion are the biggest threats to mangrove areas, in addition to their conversion to other private uses. In our opinion, this is related to the absence of a basic infrastructure along the Amazon coastal plain, such as paved roads and power lines for electricity. Furthermore, for survival, traditional communities still depend on the exploitation of the natural resources provided by mangroves.

To maintain the status of mangrove conservation, the Brazilian government through the Brazilian Institute for the Environment (IBAMA) and the Chico Mendes Institute for Biodiversity Conservation (ICMBio) are establishing the Marine Extractive Reserves (RESEX), a conservation unit of sustainable use in Brazil that aims to engage the traditional knowledge system based on the idea that local people need to be partners at all stages of research and coastal management in the Amazon region (Gerhardinger et al., 2009).

Regarding mangrove conservation in the Amazon region, we recommend some guidelines for the sustainable use of this wetland forest, as stated below:

- The Brazilian government must continue devolving powers to local communities to manage mangrove resources because the participation of local communities is critical to the development of an effective coastal management system, as described by Di Ciommo (2007). Currently, this process has been carried out through the establishment of RESEX;
- The Brazilian government needs to establish a monitoring system based on satellite imaging in different spatial scales to observe the dynamic natural and anthropogenic changes in the mangrove ecosystem;
- The result of this monitoring must be shared with traditional communities and environmental agencies, such as IBAMA and ICMBio. Thus, decision makers can manage remote mangrove areas based on technical information from satellite and scientific data and supported by traditional communities.
- Decision making processes must consider that, until now, the Amazon mangrove coast has been almost entirely free of aquaculture activity, and the environmental services provided by mangroves must be preserved.

Because mangroves in the Amazon region represent over 70% of the mangroves in Brazil, and in response to the excellent state of mangrove conservation in the Amazon region, IBAMA considers the continued biodiversity conservation of this region to be of the utmost importance. Therefore, as aquaculture is one of the most damaging economic activities in mangrove ecosystems around the world, decision makers in Brazil, especially in the Amazon region, must manage mangroves to conserve this ecosystem for future

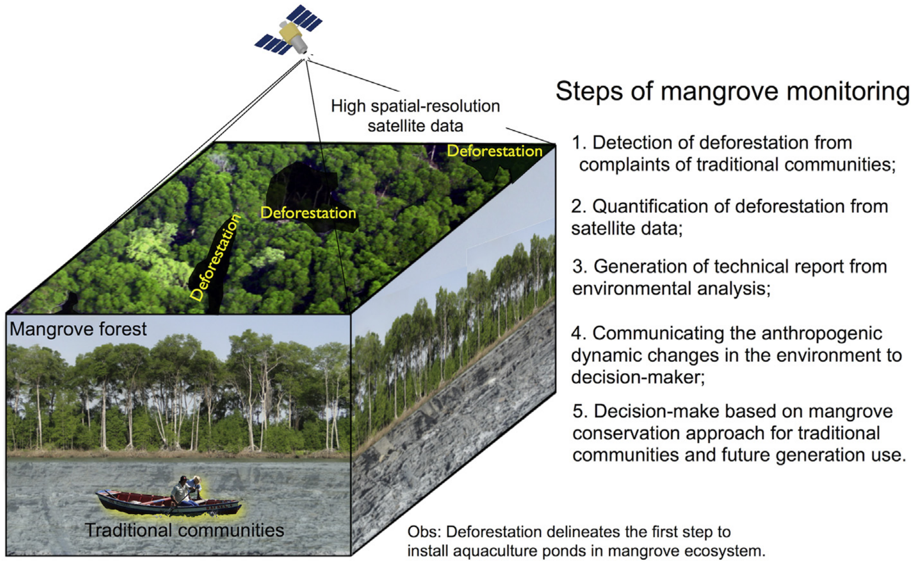

Fig. 6. A proposal of mangrove monitoring system based on satellites imagery and traditional communities reports. This proposal delineates how to deal with uncertainties related to anthropogenic changes in mangroves and to communicate these uncertainties to decision-makers to manage based on mangrove conservation approach for traditional communities and future generation use.

generations. Fig. 6 synthesizes our recommendations for maintaining Amazon mangroves in contradiction to worldwide trends of conversion to aquaculture lands.

6. Conclusions

Effective monitoring of mangroves and the rapid and precise evaluation of impacts caused by shrimp farming depend on the application of effective mapping techniques, particularly the use of remote sensing technology for obtaining information in the coastal ecosystem.

Saltwater aquaculture is a source of income and employment for rural populations in Thailand, Indonesia, India, Ecuador, and northeastern Brazil. However, in the Amazon region, the subsistence of traditional coastal communities is based on artisanal fisheries and crabbing as well as harvesting other natural resources. Hence, while these traditional lifestyles persist, they will help to maintain the nearly pristine condition of the mangroves and impede the conversion of forests for the establishment of shrimp farming operations. Thus, these traditions will ultimately contribute to the conservation of the Amazonian mangroves.

The coastal zone is considered a common resource that belongs to all citizens, and it is considered to be of extreme importance to biodiversity conservation in Brazil. Therefore, we concluded that aquaculture activities in the Amazon coastal plain, where the largest continuous and one of the most well-preserved mangrove ecosystems in the world exists, are unfeasible from economic and social standpoints.

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