Spatial distribution of southern brown shrimp (*Farfantepenaeus subtilis*) on the Amazon continental shelf: a fishery, marine geology and GIS integrated approach

Déborah E. G. Martins[1], Maurício Camargo-Zorro[2], Pedro Walfir M. Souza Filho[3,], Israel Hidenburgo Aniceto Cintra[4], Kátia C. A. Silva[4]*

[1] Universidade Federal do Pará, Programa de Pós-Graduação em Ecologia Aquática e Pesca. Brasil Ministério da Pesca e da Aquicultura, Superintendência do Pará.
(Belém, CEP: 66075-110. Belém, CEP: 66645-250, Brasil)
[2] Instituto Federal de Educação, Ciência e Tecnologia da Paraíba.
(Cabedelo, CEP: 58000-000, Brasil)
[3] Universidade Federal do Pará, Instituto de Geociências. Instituto Tecnológico Vale.
(Belém CEP: 66075-110, Brasil. Belém, CEP: 66055-090, Brasil).
[4] Universidade Federal Rural da Amazônia, Instituto Socioambiental e dos Recursos Hídricos.
(Belém, CEP: 66000-000, Brasil).

*Corresponding author: pedro.martins.souza@itv.org

Financial Support: CAPES through Marine Science Announcement 2009.

Abstract

The spatial distribution of the southern brown shrimp *Farfantepenaeus subtilis* (Pérez-Farfante, 1967) was studied based on industrial fishing fleet activities and is associated with geological and oceanographic characteristics of the benthonic environments on the Amazon continental shelf. Using a geographical information system (GIS) this paper sought to calculate the relative abundance of brown shrimp based on catch per unit effort (CPUE) and compare it with bathymetry, type of sedimentary structure, sedimentation rate and bottom salinity. As a result, we have concluded that the relative abundance (in terms of CPUE) is not uniformly distributed in space. Spatial analysis indicates that commercial trawling efforts were made in the (foreset) region of the subaqueous Amazon delta at depths of 40 to 60 m. In this region, prawn are responsible for the bioturbation of the sediments and the creation of a sedimentary structure called mottled mud. In the foreset region, sedimentation rates progressively increased up to 10 $cm.yr^{-1}$; re-suspension was reduced and bottom salinity was high (~ 36). It appears that all of these factors define a stable muddy area with intense bioturbation. This notable biological activity is to be explained by the occurrence of a high *F. subtilis* abundance that appears to originate in a microbial loop. We concluded that by combining fishery information with environmental data from a GIS, it was possible to identify abundance distribution patterns for southern brown shrimp and other economically important fishery resources and to understand how they change on a large spatial-scale.

Descriptors: Shrimp fishery, Spatial analysis, GIS, Oceanography.

Resumo

A distribuição espacial do camarão-rosa *Farfantepenaeus subtilis* (Pérez-Farfante, 1967) foi estudada a partir de dados oriundos da pesca industrial, os quais foram associados às características geológicas e oceanográficas dos ambientes bentônicos da plataforma continental do Amazonas. A partir do uso de um sistema de informações geográficas (SIG), este trabalho teve como objetivo calcular a abundância relativa do camarão rosa baseada na captura por unidade de esforço (CPUE) e compará-la com dados batimétricos, tipo de estrutura sedimentar, taxa de sedimentação e salinidade de fundo. Como resultado, nós podemos afirmar que a abundância relativa (em CPUE) não está uniformemente distribuída. A análise espacial indica que o esforço do arrasto da pesca industrial foi realizado na região frontal do delta submerso (foreset) do Amazonas, entre 40 e 60 m de profundidade. Nesta região, os camarões são responsáveis pela bioturbação dos sedimentos e geração de uma estrutura sedimentar chamada lama mosqueada. Na região do foreset, as taxas de sedimentação foram de até 10 cm/yr; o processo de ressuspensão foi reduzido e a salinidade de fundo mostrou-se alta (~ 36). Parece que todos estes fatores definem uma área estável de lama com intensa bioturbação. Esta notável atividade biológica é explicada pela ocorrência de alta abundância de *F. subtilis* que parece ter sido originada pela alça microbiana. A partir da combinação de dados pesqueiros com dados ambientais em um SIG, é possível identificar um padrão de distribuição de abundância do camarão rosa e outros recursos pesqueiros de importância econômica, assim como compreender como eles variam espacialmente.

Descritores: Pesca de camarão, Análise espacial, SIG, Oceanografia.

http://dx.doi.org/10.1590/S1679-87592015090106304

INTRODUCTION

During the last decade there has been an increasing interest in the development of geographical information systems (GIS) that are applied to fishery management in order to understand a variety of three-dimensional fields of knowledge (MORRIS; BALL, 2006; RIGHTON; MILLS, 2006). However, relatively few studies have been published to describe the use of GIS to map the activity of industrial fishing and its relationship with geological characteristics and oceanographic processes in continental shelf regions (WALUDA et al., 2001). Hence, this paper used the spatial ecology address to integrate geosciences and fishery engineering data in a GIS approach to jointly examine geographical science and ecological information (SAITOH et al., 2011; SKIDMORE et al., 2011; LAFFAN et al., 2012). Knowledge of the spatial distribution of fishing resources is very important for fishery planning. For fishery managers, it is essential that all the information related to a given resource is presented succinctly and precisely in an easily understood format (CADDY; GARCIA, 1986). The spatial dimension is important for both the development and the planning of fishery resource exploitation (MEADEN, CHI, 1996; GRAAF et al., 2003; RIOLO, 2006).

Approximately 3.4 million tons of shrimp are caught worldwide every year. This resource is, therefore, the most important fishery commodity sold worldwide in terms of value, accounting for 17% of fishing product trading; the market is concentrated in the United States, Japan and Europe (GILLETT, 2008; FAO, 2009). In many countries, shrimp is the most valuable fishery export product (GILLETT, 2008). In Brazil, frozen shrimp were the second most exported fishery product in 2007, totaling 17,217 t and worth US$ 74.9 million (IBAMA, 2008). The northern coast of Brazil, which is 2500 km long and located between the mouths of the Parnaiba (Brazil) and the Orinoco Rivers (Venezuela), belongs to one of the most important shrimp fishery areas in the world. The southern brown shrimp *Farfantepenaeus subtilis* (PÉREZ-FARFANTE, 1967), which is the target of both artisanal and industrial fishing fleets (ISAAC et al., 1992), is among the harvested species.

In the northern portion of the western South Atlantic Ocean, which includes the Amazon continental shelf, no analysis has been performed that relates this information to the physical environmental characteristics or even to the spatialization of the harvested shrimp volume or the southern brown shrimp targeting efforts (DRAGOVICH, 1981). *Farfantepenaeus subtilis* occurs at depths of up to 190 meters, often on muddy and sandy bottoms and sometimes associated with mollusks (HOLTHUIS, 1980).

Identifying areas of concentrated fishing efforts, quantifying the catch by area and assessing the relationships between captures and efforts are of interest to fishery resource managers (MEADEN, 2000). Understanding the relationships between the distribution of fishery resources and environmental factors provides information for establishing a fishery management plan that will make rational and sustainable harvesting of shrimp stocks possible.

Studies of the Amazon continental shelf have indicated that several overlapping factors, such as the location near the Equator, the great physical energy that is released by tides, ocean currents and winds and the enormous discharge of water, solutes and particulate matter by the Amazon River, play a major role in regional hydrological dynamics (NITTROUER; DEMARTER, 1996). The Amazon River discharge forms a plume of low-salinity water that extends offshore and northwestward over the north Brazilian shelf (LENTZ; LIMEBURNER, 1995). Meteorological and physical processes (e.g., discharge, precipitation, winds, currents, tides, and waves) are among the principal factors responsible for spatial and temporal variations in salinity, turbidity, nutrient concentration, phytoplankton blooms and nekton along the Amazon coast (BARTHEM, 1985; NITTROUER; DEMASTER, 1986; DEMASTER et al., 1996; SANTOS et al., 2008; SILVA et al., 2010). However, only the spatial distribution of the southern brown shrimp is considered in this study. This study applies data from a geographical information system (GIS) to industrial southern brown shrimp fisheries on the Amazon continental shelf to identify possible spatial distribution patterns of stocks in areas where industrial fishing is active and to relate them to geological and oceanographic processes.

MATERIAL AND METHODS

Three main factors were considered when designing the sampling procedures: i) fishery areas, ii) catches and fishing effort, and iii) the accessibility of geospatial information related to continental shelf morphology, and bottom-salinity.

Study area

The Amazon River exhibits the largest discharge volume (5.5x1012 m3.year^{-1}) and drainage basin size (6x106 km2) in the world (GIBBS, 1967; MEADE et al., 1979). The suspended matter transported by the Amazon is approximately 800x10^{6} tons (MARTINEZ et al., 2009). The Amazon discharge is sufficiently large for ocean waters not to penetrate the river mouth even during the lowest flow period, which means that the estuarine circulation is displaced toward the shelf (GIBBS, 1970).

The Amazon continental shelf was defined by NITTROUER and DEMASTER (1986) as the region extending from the coastline out as far as the shelf break, which corresponds to the 100-m isobath. The region extends from the Pará River estuary to the 5ºN parallel and is limited by the frontier between Brazil and French Guyana (Figure 1).

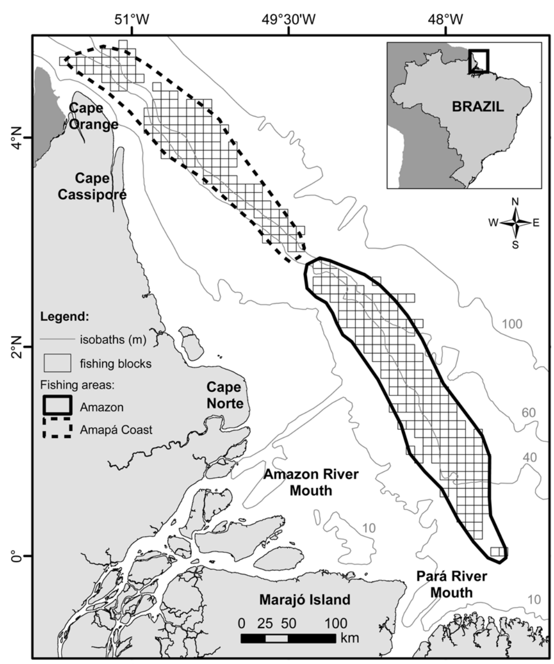

Figure 1. The Amazon continental shelf study area. The fishery sites and the representation of fishing blocks are shown.

Based on the typology of the mudbanks formed along the shelf, the region may be divided into two distinct areas: the Amazon and the Amapá coast. The Amazon coast is located southward of 2ºN latitude and is characterized by surface sand waves with heights of 3 to 6 m and wavelengths of 100 to 200 m. To the north, on the Amapá coast, the predominant features are large mudbanks with heights of 20 to 30 m and wavelengths of 6 to 8 km (NITTROUER; DEMASTER, 1996; NITTROUER et al., 1986).

Fishery data and CPUE

Data on catch and fishing efforts were extracted from the Project on Shrimp Biology and Fishing on the Northern Coast of Brazil undertaken by the Center for Research and Management of Fishery Resources of the Northern Brazilian Coast (*Projeto Biologia e Pesca de Camarões na Costa Norte do Brasil do Centro de Pesquisa e Gestão de Recursos Pesqueiros do Litoral Norte* - CEPNOR/ IBAMA) which collected monthly samples from at least two boats of the industrial fishing fleet. The data were collected from 2000 to 2004 at depths between 10 and 100 m along the Amazon continental shelf in daily fisheries.

The boats involved had steel hulls and an average total length of 22 meters. On average, these vessels performed 4 daily trawls with approximate durations of 5 to 6 hours using a double-rig system (ARAGÃO; SILVA, 1999). For each haul, onboard observers recorded a variety of information, such as the date, starting time, duration (h), initial latitude and longitude, depth (m), fishing site and amount of southern brown shrimp that were caught (kg). In addition to shrimp, catches on the Amazon continental shelf are typically composed of many other species that are generally discarded. Generally, part of this by-catch is retained depending on the species' economic value and the available on-board space. In the study area, the by-catch ratio was estimated as 7:1 (ARAGÃO; SILVA, 1999). However, for this paper, only the retained brown shrimp catch was registered and no estimates were made of the discarded by-catch.

The CPUE (capture per unit of effort) was adopted as the index of relative abundance and calculated for each haul. The CPUE is defined as the ratio between production (in kilograms) of southern brown shrimp and the haul duration (in hours), expressed in kg.h^{-1} (KING, 1995).

Geospatial information acquisition and analysis

Bottom salinity data for high water discharge at the Amazon River mouth (May) were spatialized based on LENTZ and LIMEBURNER (1995). The water discharge on May was chosen because the strongest seaward near-bottom salinity front occurs near the 20-m isobath at this time. Moreover, this tide-induced mixing influences the position and structure of the bottom salinity front that separates the well-mixed near-shore region from the stratified plume (GEYER et al., 1996).

Isobaths were obtained by digitizing nautical charts that were drawn by the Hydrography and Navigation Directorate (DHN) and the bathymetric chart that was prepared for the GEBCO Project (General Bathymetric Chart of the Oceans) (IOC et al., 2003).

The morphological classification of the Amazon continental shelf was determined in accordance with the characteristics proposed by NITTROUER et al. (1986), who divided the shelf into three distinct portions based on seismic stratigraphic data: (a) 10 to 40 m: wide and gently dipping inner shelf (< 1:3000), called the *topset*; (b) 40 to 60 m: middle shelf, with a relatively more abrupt inclination, known as the *foreset*, in which the inclination is 1:1000 on the Amazon, that is gentler than on the Amapá coast where the downward slope reaches 1:100; and (c) 60 to 100 m: outer slope, with a gentle downward slope (1:2000), called the *bottomset*.

The characterization of the Amazon continental shelf substrate was based on the descriptions of KUEHL et al. (1982); KUEHL et al. (1986b), who described the following regions according to the sedimentary structure: (a) interbedded mud and sand; (b) faintly laminated mud, and (c) mottled mud, characterized by sediments that had been considerably reworked by benthic macrofauna - and also according to the description of KUEHL et al. (1986a), who determined the annual sedimentation rate.

Shrimp fishery data analysis

By means of a GIS, the data that were organized in layers were integrated using the ArcGIS 9.3 program (ESRI, 2008). The bases for environmental factors (bathymetry, substrate and salinity) were digitized using the WGS-84 projection. The layers were integrated in pairs by applying the *Identity* command. Fishery data for the study period were analyzed simultaneously.

To identify areas with the highest CPUE values for southern brown shrimp, the fishing area was divided into 9-km x 9-km blocks with at least three hauls per block (Figure 1). The number of hauls and the median CPUE were calculated for each block and these results were then spatialized.

The CPUE spatial distribution patterns were based on 3,543 records of fishing operations (hauls) that had an average duration of 4.55 ± 1.3 hours, which represented 16,117.840 hours of total trawling. Descriptive CPUE statistical parameters were calculated for each depth interval and substrate type. Due to the bathymetric differences of each fishing area, the effect of depth on the CPUE was determined for each area. After negative normality tests had been performed on the CPUE data, the Kruskal-Wallis test was applied to the depth strata classification proposed by NITTROUER et al. (1986): 10 to 40 m and 40 to 60 m for the Amazon fishing area and 40 to 60 and 60 to 100 m for the Amapá Coast. To assess a possible correlation between depth and CPUE, the Spearman rank order correlation was applied (p = 0.05) for each fishing area.

RESULTS AND DISCUSSION

The boats of the industrial fishing fleet surveyed operated in a zone along the Amazon continental shelf that extended from the Amazon River mouth to Cape Orange. Figure 2a shows the spatial distribution of the hauls that were surveyed during the study period.

The median CPUE for the fishing blocks varied from 2 to 20 $kg.h^{-1}$. Four areas presented the highest CPUEs for southern brown shrimp and these represent important fishing sites known by the local fishermen as Cabo Orange and Cascalho on the Amapá coast and Praia Grande and Lixeira in the Amazon region (Figure 2b).

CPUE distribution in relation to bathymetry

At the Amazon River mouth, the hauls were concentrated at depths of 40 to 60 m (67.83%), while on the Amapá coast, the largest haul frequency was at depths of 60 to 100 m (64.85%). The CPUE remained greater than 5.00 $kg.h^{-1}$ except for the depth stratum of 60 to 100 m, where the median CPUE was 3.54 $kg.h^{-1}$ (Table 1).

On the Amapá Coast, the CPUE was significantly higher at depths of 40 to 60 m ($H(1, N = 1098) = 87.64$; $p < 0.05$). Moreover, for the Amazon, no significant differences were found between the different depth strata ($H(1,N = 2313) = 0.36$; $p = 0.55$) (Figure 3).

A low negative correlation was observed between the depth and CPUE on the Amapá Coast ($r_s = - 0.32$; $p < 0.05$), while no correlation was found for the Amazon ($r_s = 0.03$; $p = 0.13$) (Figure 4).

Even though catches of *Farfantepenaeus subtilis* occurred at depths from 12 to 100 m, there was clearly a higher incidence of hauls in the 40- to 60-m bathymetric stratum. Another common pattern on the Amapá coast was an evident reduction in the CPUE with increasing depth.

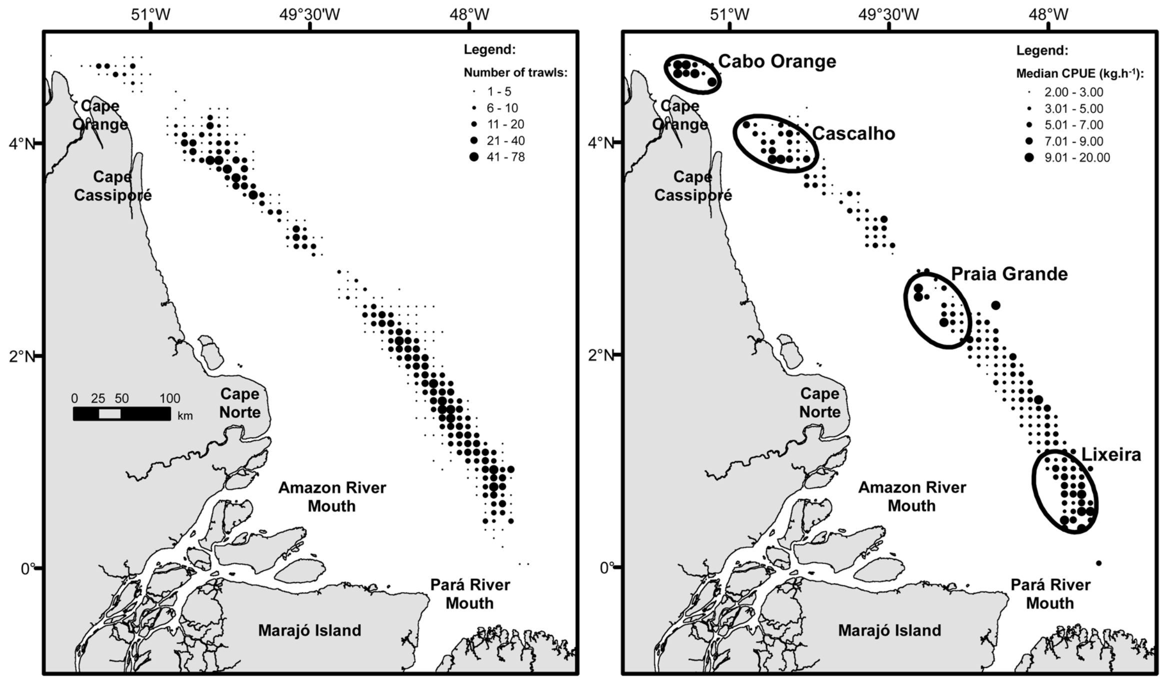

Figure 2. Number of hauls per fishing block (a) and spatial distribution of CPUE, which highlights the fishing sites for southern brown shrimp with the highest CPUE values (b).

Table 1. Number of hauls (%) and CPUE (kg.h^{-1}) of southern brown shrimp on the Amazon continental shelf according to the bathymetric and strata form data.

Area	Bathymetric and strata form data*	Number of hauls (%)	Median CPUE	Minimum CPUE	Maximum CPUE
Amazon River Mouth	10-40 m, *topset*	32.2	5.00	0.03	53.33
	40-60 m, *foreset*	68.0	5.09	0.07	44.67
Amapá Coast	40-60 m, *foreset*	35.0	5.25	0.40	25.00
	60-100 m, *bottomset*	65.0	3.54	0.86	29.85

* The depth strata data were obtained from Nittrouer et al. (1986).

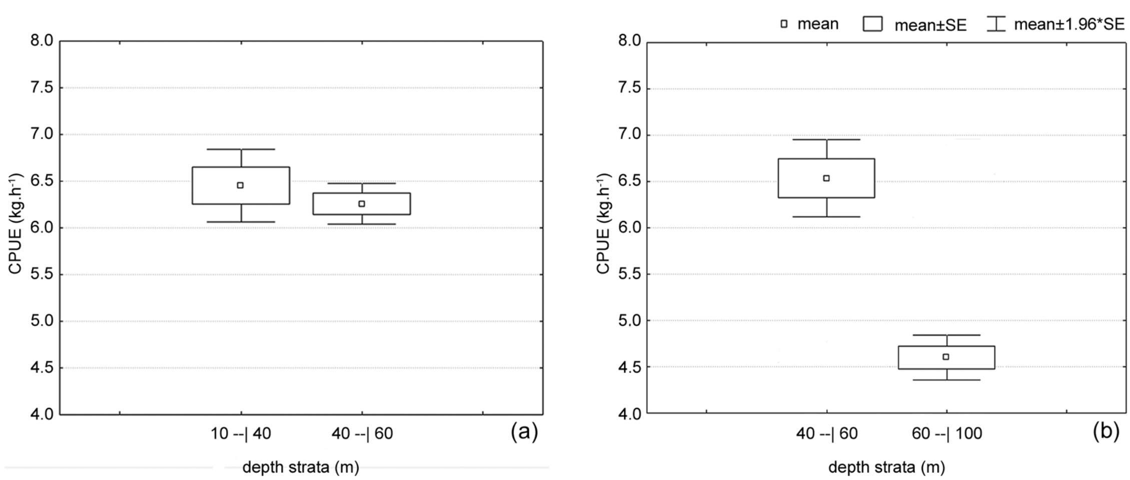

Figure 3. CPUE (kg.h^{-1}) for southern brown shrimp for depth strata in the Amazon (a) and the Amapá coast (b) sites (SE: standard error).

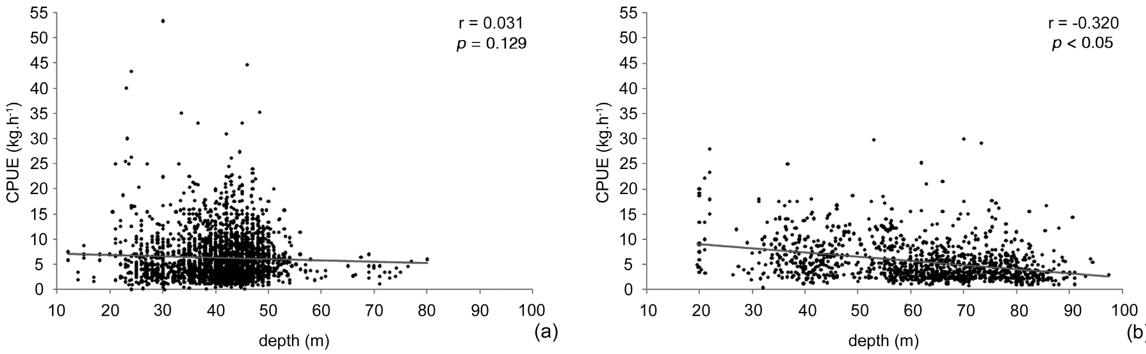

Figure 4. Relationship between the CPUE and depth for the mouth of the Amazon River (a) and the Amapá coast (b).

Most fishery efforts occur on the foreset of the Amazon delta, which overlaps the mottled mud sedimentary structure where the prawns form a dense population. We are convinced that the prawns are responsible for the bioturbation of the sediments and the creation of a sedimentary structure called mottled mud. Furthermore, the CPUE distribution on the Amazon shelf, with the largest CPUE areas adjacent to the mouths of the Amazon and the Pará Rivers, seems to be associated with the river discharges.

CPUE distribution in relation to substrate and bottom salinity

The hauls were concentrated in the mottled mud region (66.38%) (Figure 5b), which was followed by regions with faintly laminated mud (4.83%) and interbedded mud and sand (1.33%) in the region adjacent to the mouth of the Amazon River.

The largest median CPUEs were recorded in the bands of faintly laminated mud (6.86 $kg.h^{-1}$) and interbedded mud and sand (6.00 $kg.h^{-1}$); while in the mottled mud region the lowest median CPUE (4.42 $kg.h^{-1}$) was observed. However, the number of hauls recorded for the latter region (2,352) was approximately ten times higher than the number of hauls that were recorded in the other two sediment bands (Table 2).

The regions that exhibited the highest sedimentation rates (> 5 $cm.year^{-1}$) related to the fishing blocks in which the CPUE was less than 5 $kg.h^{-1}$ (Figure 5c). Some fishing blocks at the southern tip of the study area and as far north as 4oN latitude, close to Cape Cassiporé, occurred outside the boundaries of the study area of KUEHL et al. (1986a). A comparison between the sedimentation rate and the CPUE was not therefore viable.

According to the isohalines established by LENTZ and LIMEBURNER (1995), the majority of hauls were conducted in locations where the bottom salinity was always greater than 35 (Figure 5d).

What processes determine the patterns observed for *Farfantepenaeus subtilis* on the Amazon continental shelf? The Amazon River discharge forms a surface plume that advances 200 km into the ocean and 1000 km toward the northwest (GIBBS, 1970; LENTZ; LIMEBURNER, 1995). The river plume is a route for sediment deposits and determines an intense cycling of biologically relevant materials and the production of carbon that is exported to the sea as particulate organic carbon (POC), dissolved organic carbon (DOC) and nutrients (MCKEE et al., 2004). The Amazon continental shelf and the adjacent oceanic region are also directly affected by the North Brazil Current, which flows along and over the slope of the shelf break (RICHARDSON et al., 1994). Moreover,

Table 2. Number of hauls (%) and CPUE ($kg.h^{-1}$) for southern brown shrimp on the Amazon shelf for individual sediment bands.

Sedimentary structure*	Number of hauls (%)	Median CPUE	Minimum CPUE	Maximum CPUE
Mottled mud	66.38	4.42	0.03	44.67
Interbedded mud and sand	1.33	6.00	1.00	43.33
Faintly laminated mud	4.83	6.86	1.25	28.00
Indeterminate	27.46	5.60	0.40	53.33

* The sedimentary structure data were obtained from Kuehl et al. (1982, 1986b).

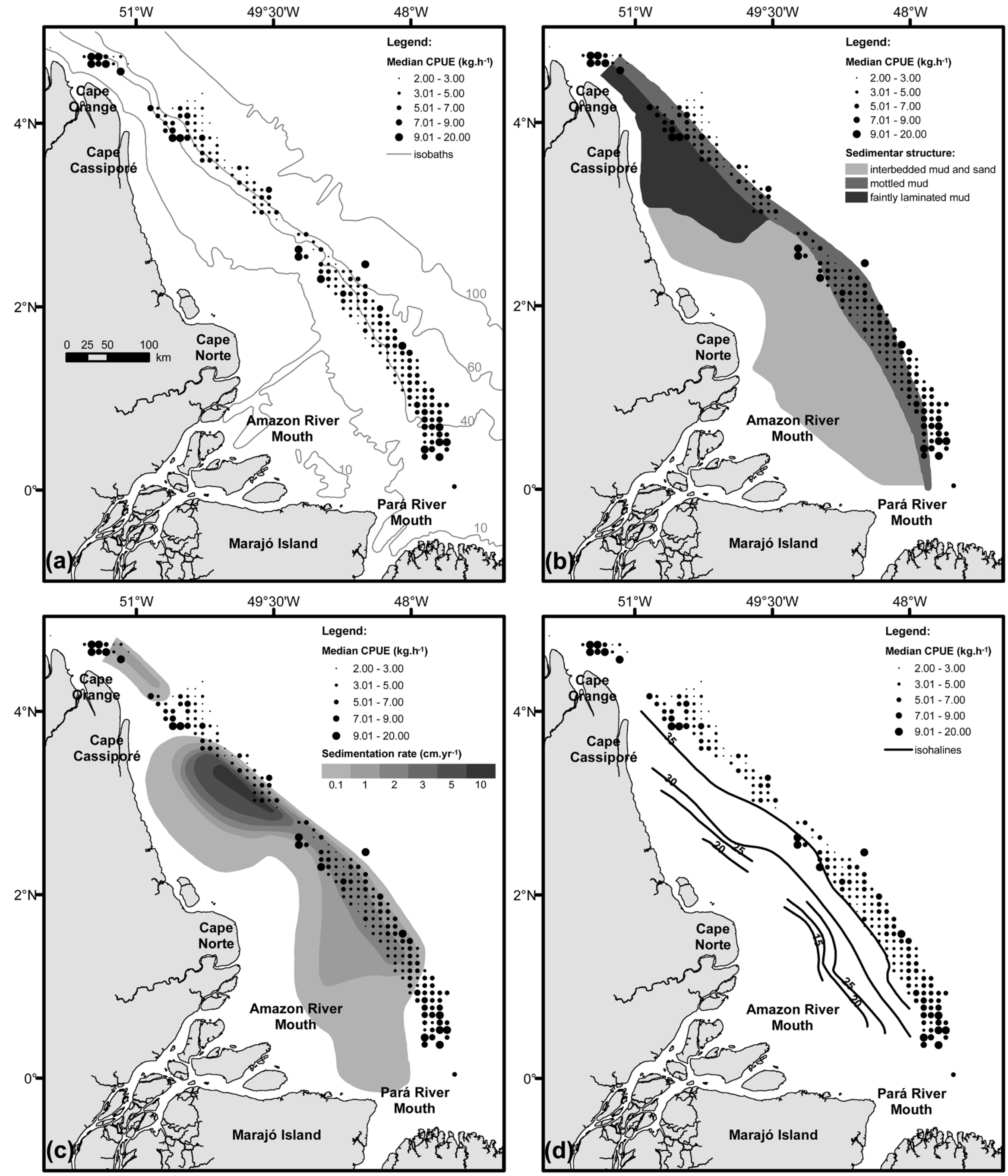

Figure 5. CPUE spatial distribution (kg.h^{-1}) in relation to environmental characteristics: a) bathymetric chart (IOC et al., 2003); b) sedimentary structure (Nittrouer et al., 1986); c) sedimentation rate (Kuehl et al., 1986a); and d) bottom salinity (Lentz and Limeburner, 1995).

this current also drives the transport of sediment toward the northwest, outside the boundaries of the Brazilian shelf (KUEHL et al., 1986a).

The low salinity waters of the Amazon plume that extend along the coast have a surface effect, exhibiting average depths of 7.3 m and a transition boundary between river and oceanic waters at the 20-m isobath. Beyond that boundary, no significant seasonal variations occur in the 35 isohaline adjacent to the substrate (LENTZ; LIMEBURNER, 1995). This phenomenon means that the joint effect of the Amazon plume and the North Brazil Current causes a deposition and salinity gradient to form in deep waters, which may subsequently determine an environmental pattern for *Farfantepenaeus subtilis*. Given that the isohaline is displaced furthest seaward in May and the captures of *Farfantepenaeus subtilis* were concentrated at the 35 isohaline boundary, one may expect that the seasonal water discharge from the Amazon should not exhibit a straightforward relationship with the bottom spatial distribution of this species (MCKEE et al., 2004).

CPUE distribution in relation to sediment accumulation rates and bioturbation

It is likely that an intrinsic association between sediment accumulation rates and the spatial distribution of *Farfantepenaeus subtilis* has occurred. KUEHL et al. (1986a) found that on the inner shelf (< 15 m depth), a dense layer of sediment is present, which is continuously reworked by surface waves and by the strong tidal currents that limit the sedimentation rates. In the outer regions, known as the topset and foreset, and at approximately 80-100 kilometers from the coastline, the sedimentation rates increase progressively due to reduced sediment re-suspension. Finally, in the most oceanic areas, which correspond to the bottomset region, the sedimentation rates are generally < 1 $cm.yr^{-1}$ in response to the reduced sediment contribution (Figure 6). These sediment stability categories, which were proposed by KUEHL et al. (1986a), may be controlling the *Farfantepenaeus subtilis* population gradients.

What factor might also explain the density of *F. subtilis* in the foreset region? Analyses of the diet of several Penaeidae have shown that complex communities of bacteria, protozoa, fungi and algae encrusted in a matrix of extracellular polysaccharides secreted by bacteria (COSTERTON; IRVIN, 1981) or microbial material and detritus, plant debris and small animals are important sources of energy for these predators (DALL et al., 1990). In turn, more than 95% of the organic material in marine ecosystems consists of polymers and high molecular weight (HMW) compounds, such as proteins, polysaccharides and lipids, which are not assimilated by many of the marine organisms at the higher trophic levels (FENCHEL, 2008). It is possible that the bioturbation process that is conducted by various organisms in the foreset region is closely related to these rich and stable sources of energy that are stored in the substrate where the microbial loop process occurs (Figure 6). This microbial process proposed by POMEROY et al. (2007) can explain why industrial fishing of *Farfantepenaeus subtilis* is concentrated in the foreset region, corresponding to the location where the benthonic organisms revolve the muddy substrate and create the mottled pattern.

Furthermore, to understand exactly where the fishery resources are utilized is essential to fishery management (MEADEN; CHI, 1996). Therefore, this information will make it possible to determine areas that should be prohibited for southern brown shrimp capture and that require habitat recovery.

These results indicate that fishery data can also be obtained from commercial fishery sources. A GIS, such as the one developed in this study, can use information available in logbooks and vessel monitoring systems. However, this is only true if participation in these programs is an obligatory condition for an annual fishery license for the industrial shrimp fishing fleets that operate along the

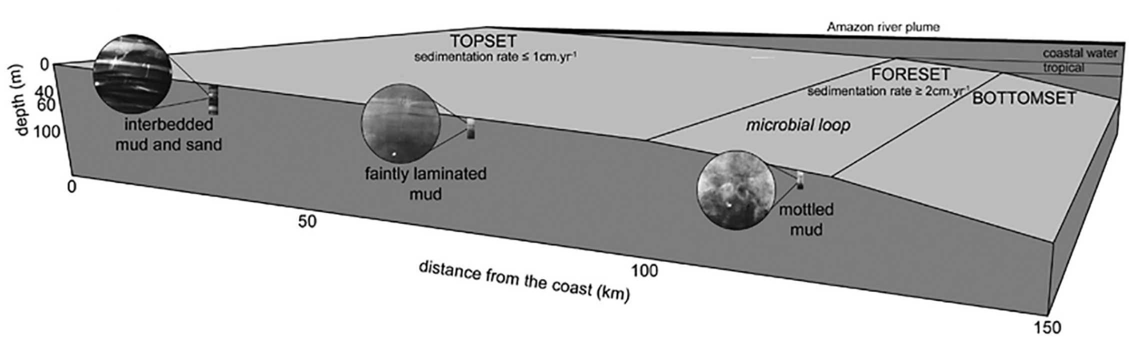

Figure 6. Cross-shelf transect showing the relationships between deltaic stratigraphy, sediment accumulation rates and the microbial loop activity hypothesis in relation to the *F. subtilis* spatial distribution and abundance.

North Brazilian coast. Hence, new information would be generated based on integrated fishery, environmental and geographical data.

CONCLUSION

The concentration of industrial fishing fleet hauls for southern brown shrimp in the mottled mud band of the Amazon continental shelf suggests that the overlapping of environmental factors determines the greater occurrence of *F. subtilis* in the foreset region at depths of 40 to 60 m. In this region, bottom morphology, substrate type (mud), sedimentation rate (≥ 2 cm.y^{-1}), and salinity (> 35) constitute the ideal habitat for adults of the species.

The abundance distribution patterns for southern brown shrimp and their spatial variability were determined using geo-referenced fishery information that was provided by commercial fishing fleets and combined with environmental data in a GIS framework. Therefore, in having depth, bottom-morphology and salinity data and the locations of higher and lower capture per unit effort values, it is possible to use this information to propose a more efficient fishery strategy along the Amazon continental shelf.

ACKNOWLEDGMENTS

The present research was supported by CAPES through Marine Science Announcement 2009. We would like to thank the Aquatic Ecology and Fishery postgraduate program of the Universidade Federal do Pará. PWM Souza Filho is grateful to CNPq for the research grant during this study. The authors also thank Stephen Ferrari for comments and the English review, and the anonymous reviewers for their inestimable contributions.

REFERENCES

ARAGÃO, J. A. N.; SILVA, K. C. A. National report of Brazil. In: National reports presented and stock assessment reports prepared at the CFRAMP/FAO/DANIDA. Stock Assessment Workshop on the Shrimp and Groundfish Fisheries on the Guiana-Brazil Shelf. Rome: FAO, 1999. p. 1-16.

BARTHEM, R. B. Ocorrência, distribuição e biologia dos peixes da baía de Marajó, estuário amazônico. Bol. Mus. Para. Emílio Goeldi, Ser. Zool., v. 2, n. 1, p. 49-69, 1985.

CADDY, J. F.; GARCIA, S. Fisheries thematic mapping: A prerequisite for intelligent management and development of fisheries. Oceanogr. Trop., v. 21, n. 1, p. 31-52, 1986.

COSTERTON, J. W.; IRVIN, R.T.; CHENG, K. J. The bacterial glycocalyx in nature and disease. Annu. Rev. Microbiol., v. 35, p. 299-324, 1981.

DALL, W.; HILL, B. J.; ROTHLISBERG, P. C.; STAPLES, D. J. The biology of the Penaeidae. In: BLAXTER, J. H. S.; SOUTHWARD, A. J. (Eds.). Advanced Marine Biology, San Diego, Academic press. London: Academic Press, 1990. 489 p.

DEMASTER, D. J.; SMITH JR. W. O.; NELSON, D. M.; ALLER, J. Y. Biogeochemical processes in Amazon shelf waters: chemical distributions and uptake rates of silicon, carbon and nitrogen. Cont. Shelf. Res., v. 16, n. 5/6, p. 617-643, 1996.

DRAGOVICH, A. Guianas-Brazil shrimp fishery and related U. S. research activity. Mar. Fish. Rev., v. 43, n. 2, p. 9-18, 1981.

ESRI. What is ArcGIS? Redlands: Environmental Systems Research Institute, ESRI Software 9.3 Library, 2008. 130 p.

FAO. The state of world fisheries and aquaculture 2008. Rome: FAO Fisheries and Aquaculture Department, 2009. 176 p.

FENCHEL, T. The microbial loop - 25 years later. J. Exp. Mar. Biol. Ecol., v. 366, n. 1/2, p. 99-103, 2008.

GEYER, W.R., BEARDSLEY, R.C., LENTZ, S.J., CANDELA, J., LIMEBURNER, R., JOHNS, W.E., CASTRO, B.M., SOARES, I.D., 1996. Physical oceanography of the Amazon shelf. Cont. Shelf Res. 16, 575-616.

GIBBS, R. J. The Geochemistry of the Amazon River System: Part I. The factors that control the salinity and the composition and concentration of the suspended solids. Geol. Soc. Am. Bull., v. 78, n. 10, p. 1203-1232, 1967.

GIBBS, R. J. Circulation in the Amazon River estuary and adjacent Atlantic ocean. Mar. Fish. Rev., v. 28, n. 2, p. 113-123, 1970.

GILLET, R. Global study of shrimp fisheries. Rome: FAO, 2008. 331 p.

GRAAF, G.; MARTTIN, F.; AGUILAR-MANJARREZ, J.; JENNESS, J. Geographic Information Systems in Fisheries Management and Planning: Technical manual. FAO Fisheries Technical Paper No. 449. Rome: FAO, 2003. 162 p.

HOLTHUIS, L. B. Shrimps and prawns of the world: An annotated catalogue of species of interest to fisheries. FAO species catalogue. Vol.1. FAO Fisheries Synopsis. 125. Rome: FAO, 1980. 271 p.

IBAMA. Estatística da pesca 2007 Brasil: grandes regiões e unidades da federação. Brasília: IBAMA, 2008. 151 p.

IOC; IHO; BODC. Centenary Edition of the GEBCO Digital Atlas, General Bathymetric Chart of the Oceans. Liverpool: British Oceanographic Data Centre. 2003. <http://www.gebco.net/>

ISAAC, V. J.; DIAS-NETO, J.; DAMASCENO, F. G. Camarão-rosa da Costa Norte: biologia, dinâmica e administração pesqueira. Série de Estudos de Pesca, Coleção Meio Ambiente. Brasília: IBAMA, 1992. 187 p.

KING, M. Fisheries biology, assessment and management. Oxford: Fishing New Books, 1995. 342 p.

KUEHL, S. A.; NITTROUER, C. A; DEMASTER, D. J. Modern sediment accumulation and strata formation on the Amazon continental shelf. Mar. Geol., v. 49, p. 279-300, 1982.

KUEHL, S. A.; DEMASTER, D. J.; NITTROUER, C. A. Nature of sediment accumulation on the Amazon continental shelf. Cont. Shelf Res., v. 6, p. 209-225, 1986a.

KUEHL, S. A.; NITTROUER, C. A; DEMASTER, D. J. Distribution of sedimentary structures in the Amazon subaqueous delta. Cont. Shelf Res., v. 6, p. 311-336, 1986b.

LAFFAN, S. W.; SKIDMORE, A. K.; FRANKLIN, J. Geospatial analysis of species, biodiversity and landscapes: introduction to the second special issue on spatial ecology. Int. J. Geogr. Inf. Sci., v. 26, p. 2003-2007, 2012.

LENTZ, S. J.; LIMEBURNER, R. The Amazon river plume during AMASSEDS: spatial characteristics and salinity variability. J. Geophys. Res., v. 100, n. 2, p. 2355-2375, 1995.

MARTINEZ, J. M.; GUYOT, J. L.; FILIZOLA, N.; SONDAG, F. Increase in suspended sediment discharge of the Amazon River assessed by monitoring network and satellite data. Catena, v. 79, p. 257-264, 2009.

MEADE, R. H.; NORDIN, C. F.; CURTIS, W. F.; RODRIGUES, F. M. C.; VALE, C. M.; EDMOND, J. M. Sediment loads in the Amazon River. Nature, v. 278, p. 161-163, 1979.

MEADEN, G. GIS in Fisheries Management. GeoCoast, v. 1, n. 1, p. 82-101. 2000.

MEADEN, G. J.; CHI, T. Geographical Information Systems. Applications to Marine Fisheries. FAO Fisheries Technical Paper. Rome: FAO, 1996. 335 p.

MCKEE, B. A.; ALLER, R. C.; ALLISON, M. A.; BIANCHI, T. S.; KINEKE, G. C. Transport and transformation of dissolved and particulate materials on continental margins influenced by major rivers: benthic boundary layer and seabed processes. Cont. Shelf Res., v. 24, n. 7, p. 899-926, 2004.

MORRIS, L., BALL, D., 2006. Habitat suitability modelling of economically important fish species with commercial fisheries data. ICES J. Mar. Sci. 63, 1590-1603.

NITTROUER, C. A.; DEMASTER, D. J. Sedimentary Process on the Amazon Continental Shelf: Past, Present and Future Research. Cont. Shelf Res., v. 6, p. 5-30, 1986.

NITTROUER, C. A.; DEMASTER, D. J., The Amazon shelf setting: tropical, energetic, and influenced by a large river. Cont. Shelf Res., v. 16, p. 553-573, 1996.

NITTROUER, C. A.; KUEHL, S. A.; DEMASTER, D. J.; KOWSMANN, R. O. The deltaic nature of Amazon shelf sedimentation. Geol. Soc. Am. Bull., v. 97, n. 4, p. 444-458, 1986.

PEREZ-FARFANTE, I. 1967. A new species and two new subspecies of shrimp of the genus Penaeus form western Atlantic. Proc. Biol. Soc. Wash. 80, 83-100.

POMEROY, L. R.; WILLIAMS, P. J. L.; AZAM, F.; HOBBIE, J. E. The microbial loop. Oceanography, v. 20, n. 2, p. 28-33, 2007.

RICHARDSON, P. L.; HUFFORD, G. E.; LIMEBURNER, R.; BROWN, W. S. North Brazil Current retroflection eddies. J. Geophys. Res., v. 99, n. 3, p. 5081-5093, 1994.

RIGHTON, D.; MILLS, C. Application of GIS to investigate the use of space in coral reef fish: a comparison of territorial behaviour in two Red Sea butterflyfishes. Int. J. Geogr. Inf. Sci., v. 20, n. 2, p. 215-232, 2006.

RIOLO, F. A geographic information system for fisheries management in American Samoa. Environ. Model. Softw., v. 21, n. 7, p. 1025-1041, 2006.

SAITOH, S-I.; MUGO, R.; RADIARTA, I. N.; ASAGA, S.; TAKAHASHI, F.; HIRAWAKE, T.; ISHIKAWA, Y.; AWAJI, T. In, T.; SHIMA, S. Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. ICES J. Mar. Sci., v. 68, n. 4, p. 687-695, 2011.

SANTOS, M. L. S.; MEDEIROS, C.; MUNIZ, K.; FEITOSA, F. A. N.; SCHWAMBORN, R.; MACEDO, S. J. Influence of the Amazon and Pará rivers on water composition and phytoplankton biomass on the adjacent Shelf. J. Coast. Res., v. 24, p. 585-593, 2008.

SKIDMORE, A. K.; FRANKLIN, J.; DAWSON, T. P.; PILESJÖ, P. Geospatial tools address emerging issues in spatial ecology: a review and commentary on the Special Issue. Int. J. Geogr. Inf. Sci., v. 25, n. 3, p. 337-365, 2011.

SILVA, A. C.; ARAUJO, M.; BOURLÈS, B. Seasonal variability of the Amazon River plume during REVIZEE program. Trop. Oceanogr., v. 38, n. 1, p. 76-87, 2010.

WALUDA, C.M., RODHOUSE, P.G., TRATHAN, P.N., PIERCE, G.J., 2001. Remotely sensed mesoscale oceanography and the distribution of Illex argentinus in the South Atlantic. Fish. Oceanogr. 10, 207-216.