VOLUME 8 ISSUE 4

The International Journal of

Climate Change: Impacts and Responses

Impacts of Climate and Sea-level Changes on Mangroves from Brazilian Littoral in a Millennial, Secular, and Decadal Time Scale

MARCELO CANCELA LISBOA COHEN, MARLON CARLOS FRANCA, AND LUIZ CARLOS RUIZ PESSENDA

COMMON GROUND

ON-CLIMATE.COM

The International Journal of Climate Change: Impacts and Responses

www.on-climate.com
ISSN 1835-7156 (Print)
doi:10.18848/1835-7156/CGP (Journal)

First published in 2016 in Champaign, Illinois, USA by
Common Ground Publishing
www.commongroundpublishing.com

The International Journal of Climate Change: Impacts and Responses is a peer-reviewed, scholarly journal.

Associate Editors
Articles published in *The International Journal of Climate Change: Impacts and Responses* are peer reviewed by scholars who are active participants of the Climate Change: Impacts & Responses Knowledge Community or a thematically related Knowledge Community. This engagement with the Knowledge Community, as well as Common Ground Publishing's criterion-referenced evaluation system, distinguishes our peer-review process. In recognition of the valuable feedback and publication recommendations that they provide, reviewers are acknowledged as Associate Editors in the volume that includes the article(s) they have reviewed. The Associate Editors listed in the following link have contributed significantly to the overall editorial quality and content of the journal: www.on-climate.com/journal/editors.

Article Submission
The International Journal of Climate Change: Impacts and Responses publishes quarterly (March, June, September, December). Please visit www.on-climate.com/journal/call-for-articles to find out more about the submission process.

Abstracting and Indexing
Please visit www.on-climate.com/journal to view a full list of databases in which this journal is indexed.

Knowledge Community Membership
Authors in *The International Journal of Climate Change: Impacts and Responses* are members of the Climate Change: Impacts & Responses Knowledge Community or a thematically related Knowledge Community. Members receive access to journal content. Please visit www.on-climate.com/about/become-a-member to find out more about community membership.

Our Model
We are working to change the way in which knowledge is valued. Rather than focusing solely on acceptance rates and citation counts—standards that are seriously fraught—we measure quality by a criterion-based peer-review process, assessing the intellectual excellence and accessibility of the work against clearly articulated disciplinary standards. Please visit www.on-climate.com/journal/model to find out more.

Subscriptions
The International Journal of Climate Change: Impacts and Responses is available in electronic and print formats. Subscribe to gain access to content from the current year and the entire backlist. Contact us at cg-support@commongroundpublishing.com.

Ordering
Single articles and issues are available from the journal bookstore at www.ijc.cgpublisher.com.

Hybrid Open Access
By publishing in *The International Journal of Climate Change: Impacts and Responses*, authors have made their articles available to a large number of scholars who have individual subscriptions or whose institutions subscribe. *The International Journal of Climate Change: Impacts and Responses* is Hybrid Open Access, meaning authors can also choose to make their articles open access. This allows their work to reach an even wider audience, broadening the dissemination of their research and potentially increasing the incidence of other scholars citing their work. Please visit www.on-climate.com/journal/hybrid-open-access to find out more about our Open Access option.

Crossref

Common Ground Publishing is a member of Crossref.

Impacts of Climate and Sea-level Changes on Mangroves from Brazilian Littoral in a Millennial, Secular, and Decadal Time Scale

Marcelo Cancela Lisboa Cohen, Federal University of Pará, Brazil
Marlon Carlos Franca, Federal Institute of Pará, Brazil
Luiz Carlos Ruiz Pessenda, University of São Paulo, Brazil

Abstract: The present work integrates geomorphological, sedimentological, and palynological data with radiocarbon dating, as well as δ13C, δ15N, and C/N from sedimentary organic matter previously published in order to provide models of mangrove dynamics from northern and southern Brazil. The mangrove dynamics have been analyzed within the context of millennial, secular, and decadal climatic and sea-level changes. According to these models, climatic changes and sea-level fluctuations caused by regional or global climatic change have affected significantly the Brazilian mangrove area during the Holocene. However, the impacts on mangroves, caused by those driving forces, depend on the environmental factors of each littoral such as topography, wave and current energy, coastal morphology, and mainly the input of nutrients, sediment, and freshwater. Consistent with multi-proxy analyses and the projected sea-level rise and climatic changes, mangroves will continue to migrate landward to occupy higher parts of the tidal flats. However, due to the significant topographic difference between tidal flats and coastal plain, this process may cause a decrease in mangrove area along the northern littoral. Considering the decrease in rainfall, it will cause a reduction in fluvial discharge, and consequently, the tidal water salinity will increase upriver. This dynamic of the estuarine salinity gradients will cause a replacement of várzea vegetation (freshwater wetland) by mangroves (brackish water wetland) along the fluvial flood flats. Regarding the southeastern Brazilian littoral, erosion of beach ridges, and expansion of lagoons, estuaries, and mangroves are expected according to sea-level rise and decrease of rainfall. The assessment of mangrove dynamics according to climatic and sea-level changes in a millennial, secular, and decadal time scale have been crucial for the understanding of their survival ability under future scenarios with probable accelerated SLR rates as well as intensification of extreme climatic events for this century.

Keywords: Palavras-chave: C and N Isotopes, Mangrove, Palynology, Sea-level Change, Climate Change

Introduction

Mangroves are vulnerable because they are restricted to the land-ocean interface and are strongly threatened by rising sea level and climate change. Mangrove forests are affected by several disturbances, which differ in their nature (e.g., geological, physical, biological) and which occur at different time and spatial scales. Mangroves are found at low latitudes and in hostile environments. They are subjected to daily variations in water level, tidal currents, temperature, exposure to salt, and levels of anoxia (Alongi 2008). Mangrove forests and their associated fauna are thus resistant and highly adaptable to life in saline and flooded soils and in humid tropical, humid sub-tropical, or semiarid climates.

An environmental factor that significantly influences the geographical distribution of mangroves is the temperature of air and water, since this ecosystem is incapable of developing under conditions of low temperatures; therefore, more than half of the world’s mangroves are located mostly between latitudes of 10°N and 10°S. They are restricted to regions where the monthly mean winter temperature is above 20°C, and the thermal amplitude is smaller than 5°C (Chapman 1975; Walsh 1974). In this context, and considering the increase in mean annual temperature between 3 and 5°C in southern Brazil by 2080 (Marengo 2006), mangroves would migrate to more southerly latitudes of Brazil according to the decrease of temperature (Soares et al. 2012).

The International Journal of Climate Change: Impacts and Responses
Volume 8, Issue 4, 2016, www.on-climate.com

ISSN: 1835-7156 (Print)

Today, there is great concern about how mangroves will respond to changes in temperature, carbon dioxide, rainfall, storms and sea-level rise (Duke et al. 2007; McLeod and Salm 2006). The ecosystem products and services provided by mangrove forests are well understood and include the protection of coasts from erosion (Ewel, Twilley, and Ong 1998), sources and sinks of organic carbon (Dittmar et al. 2006), sediments (Walsh and Nittrouer 2004), and plant and animal productivity (Ewel, Twilley, and Ong 1998).

Another important aspect related to mangrove forests and global climate change is the role of these systems in the carbon capture and storage (Giri et al. 2011). Despite mangrove being present only in 0.7% of the total area of tropical forests in the world, the position of mangroves in the continent-ocean interface suggests an important role of this ecosystem in the carbon cycle (Downing and Cataldo 1992; Kristensen et al. 2008; McLeod et al. 2011). According to Estrada et al. (2013), the global carbon sequestration induced by mangroves (0,142 PgC.year-1) may compensate about 10% of greenhouse gases emissions produced by deforestation and degradation of forests and wetlands (1.5 PgC. year-1-) (Van der Werf et al. 2009).

It is important to note that this ecosystem represents 8% of the coastal areas globally and a quarter of the tropical coastal area (Spalding, Blasco, and Field 1997). The Brazilian coast contains the world's second largest unitary mangrove region, estimated to cover a total area of 1.38 million hectares along a coastline of approximately 6800 km (Kjerfve and Lacerda 1993).

However, global mangrove distributions have fluctuated throughout the geological and human history due to climatic changes and sea-level oscillations (Fromard, Vega, and Proisy 2004; Alongi 2008; Cohen et al. 2012). Regarding the Brazilian littoral, the post-glacial sea-level rise and changes in the fluvial discharges are considered the main driving forces to the mangrove expansion/contraction phases (Cohen et al. 2012; Cohen et al. 2014), although tectonics might have played a role in this geological setting (Rossetti and Valeriano 2007; Miranda et al. 2009) at least during the Holocene. The equilibrium between the fluvial sediment/water supply and the relative sea-level changes must have controlled the mangrove distribution (Cohen et al. 2012; Cohen et al. 2014). Recent works (Cohen et al. 2008; Cohen et al. 2009; Cohen et al. 2012; Cohen et al. 2013; Lara and Cohen 2009; Miranda, Rossetti, Pessenda 2009; Guimarães et al. 2012; França et al. 2012; França et al. 2013; Smith et al. 2012) based on sedimentary structures, pollen, and isotopes studies have contributed to elucidating the effects of sea-level rise/climatic changes interaction on the Brazilian mangroves during the Holocene. Therefore, in order to integrate these data to understand the mangrove survival ability under future scenarios, this work presents a synthesis of some works that discusses the mangrove development in a millennial, secular, and decadal time scale in Brazil. Few studies have been conducted, at least in the east coast of South America, under this perspective and using the combination of these tools.

Study Area

The study site is located along the northern and southeastern Brazilian littoral and reflects the mangrove dynamics along 900 and 300 km of coastline, respectively (Figures 1 and 2).

Northern Brazilian Littoral

The studied samples were collected in Macapá and Calçoene, along the Amapá littoral (Guimarães, Cohen, Franca, Pessenda, and Behling 2013; Guimarães, Cohen, Franca, Pessenda, Souza, et al. 2013; Guimarães et al. 2012); Bragança, Salinópolis, São Caetano de Odivelas (Cohen et al. 2009; Cohen, Behling, and Lara 2005); and Lake Arari-Marajó Island, along the Pará littoral (Cohen et al. 2008; França et al. 2012; Lara and Cohen 2009; Smith et al. 2012; Smith et al. 2011). These sites are part of the wetland system influenced by tidal water salinity between 30% and 0%. The coastal mangrove belt is interrupted by a *várzea* vegetation area under the Amazon River influence (Cohen et al. 2012). Lake Arari (Smith et al. 2011; Smith et al. 2012) and the town of Macapá (Guimarães et al. 2012) are located under such conditions.

The climate is a warm and humid tropical one with a mean annual temperature of 27°C and mean annual precipitation of approximately 3000 mm, concentrated between January and June (IDESP 1974). The mean Amazon River discharge is about 170,000 m3 s-1 (at Óbidos city), with maximum and minimum outflow of 270,000 and 60,000 m3 s-1 (ANA 2003). The Amazon estuary is classified as semidiurnal macrotidal (Pugh 1987), with a tidal range of 4 to 6 m (Gallo and Vinzon 2005). The structure of the plume is controlled by the North Brazilian Current, which induces a northwestern flow with speeds of 40 to 80 cm/s over the continental shelf (Fig. 1) (Lentz 1995), strong tidal currents (Beardsley et al. 1995) and trade winds (Lentz 1995). Consequently, the river discharge and hydrodynamic conditions allow a strong reduction of water salinity along the Amazon River and adjacent coast (Vinzon, Vilela, and Pereira 2008; Rosario, Bezerra, and Vinzón 2009).

The marine influenced littoral is characterized by peninsulas crossed by tidal channels that link the wetlands with the estuaries, in particular of the eastern coastal region of Pará State. The main hydrodynamic features are macrotides of ~4 m range and current velocities reaching ~1.5 m s-1 for spring tides (Cohen et al. 1999). The modern vegetation is represented by the following units: Amazon coastal forest (composed of terrestrial trees), elevated herbaceous flats, mangroves, and restinga (Cohen, Behling, and Lara 2005; Cohen et al. 2009).

The fluvial littoral is represented by part of the Amapá State and the Marajó Island. The vegetation consists of natural open areas dominated by Cyperaceae and Poaceae that widely colonize the eastern side of the Marajó Island. The *várzea* vegetation (a seasonally inundated floodplain and a swamp permanently inundated by freshwater, composed of wetland species [Zarin et al. 2001; Junk and Piedade 2004; McGinley 2007]) and Amazon Coastal Forest occur on the western side of the island (Cohen et al. 2008). Mangroves are restricted to a small area (100–700 m in width) along the northeastern coastal plain of the Marajó Island (França et al. 2012).

Southeastern Brazilian Littoral

The studied samples were collected in Linhares-Espírito Santo (Cohen et al. 2014; França et al. 2013) and Ilha do Cardoso-São Paulo (Pessenda et al. 2012). This littoral exhibits geomorphological features with predominance of sandy coasts formed by deltaic systems, which significantly contrast with the northern Brazil's muddy coasts mainly formed by estuaries (Cohen et al. 2014; Cohen et al. 2012; França et al. 2013).

Southeastern Brazil is characterized by a warm and humid tropical climate, with annual precipitation averaging 1400 mm (Peixoto and Gentry 1990). Seasonal climate is controlled by the position of the South Atlantic Convergence Zone (SACZ), which controls moisture at this latitude and Inter Tropical Convergence Zone (ITCZ), or meteorological equator, that divides the year into a rainy (austral summer) and a dry season (austral winter) (Carvalho, Jones, and Liebmann 2004). The SACZ is evident throughout the year, but more intense during the summer when it is connected with the area of convection over the central part of the continent, causing episodes of intense rainfall over much of southeastern South America (Liebmann et al. 1999). The ITCZ corresponds to the belt of minimum pressure and intense low-level convergence of the trade winds over the equatorial oceans, producing the rainy season of northern State of Espírito Santo—Brazil (Garreaud et al. 2009). The rainy season occurs between November and January, with a drier period between May and September. The average temperature ranges between 20°C and 26°C (Carvalho, Jones, and Liebmann 2004).

The vegetation is characterized by tropical rainforest (Peixoto and Gentry 1990). A herbaceous plain, mainly represented by Cyperaceae and Poaceae with some trees and shrubs, occurs at the edges of delta plain. The transition from the distal deltaic plain to the shoreline is dominated by restinga vegetation with tolerance against the stresses of sand mobility and salt spray (Moreno-Casasola 1986), represented by shrub vegetation and coastal herbs over sand plains and dunes without tidal influence. Palm trees, as well as orchids and bromeliads growing on the trunks and the branches of larger trees, are also present along the shoreline. The vegetation inside the lakes and at their margins comprises emergent, submerged, floating-leaved, and floating plants. The marine and fluvial marine areas are colonized by mangroves.

Methods

A three-color band composition (RGB 543) LANDSAT image was created and processed using the SPRING 3.6.03 image processing system to individualize geobotanical units (Cohen and Lara 2003; Cohen et al. 2009). Aerial photography, visual observation, photographic documentation, and GPS measurements were used to determine typical plant species and characterize the main geobotanical units. Forty-four sediment cores were sampled from lakes and mud tidal flats colonized by mangroves and herbaceous vegetations. The sediment cores were collected using a "Russian" sampler and a Percussion Drilling (Hammer Cobra TT). The cores were submitted to X-ray to identify internal structures. The sediment color was described using a Munsell soil chart and a spectrophotometer. The sediment grain size distribution was analyzed by laser diffraction in a Laser Particle Size. The pollen analyses followed standard pollen analytical techniques (Faegri and Iversen 1989). Ninety-eight subsamples were taken for Accelerator Mass Spectrometer (AMS) radiocarbon dating, performed at the Leibniz Laboratory of Isotopic Research at the Christian Albrechts University in Kiel (Germany), Physikalisches Institut at the University of Erlangen-Nürnberg (Germany), Van der Graaff Laboratory at the Utrecht University (Netherlands), Center for Applied Isotope Studies at the University of Georgia (USA), C-14 Laboratory of CENA/USP, and Brazilian AMS Radiocarbon Laboratory-Fluminense Federal University. The δ13C, δ15N and elementar C and N (C/N) analysis were carried out at the Stable Isotopes Laboratory of Center for Nuclear Energy in Agriculture (CENA), University of São Paulo (USP), using a Continuous Flow Isotopic Ratio Mass Spectrometer (CF-IRMS).

Results

Mangrove Dynamic from Northern Brazil in a Millennial Time Scale

The Marajó Island and Macapá town present a regional low water salinity produced by the larger fresh water discharge from the Amazonas river as compared to the rivers from southeastern Pará and northwestern Amapá littoral (Kjerfve et al. 2002; Santos et al. 2008). This produced a fluvial sector and a marine-influenced littoral (Figure 1a).

The marine littoral is mainly dominated by mangrove and herbaceous flats, typical of brackish waters, while the fluvial littoral is mainly characterized by *várzea* and herbaceous vegetation, typical of freshwaters. Mangroves are more tolerant to soil salinity than the *várzea* forest (Cohen et al. 2008; Gonçalves-Alvim, Santos, Fernandas 2001), and, considering the Amazon River, the salinity is basically controlled by position along the estuarine gradient (Lara and Cohen 2006).

Marine Littoral

The multi-proxy analyses, obtained from the northern Brazilian littoral, indicate the establishment of a continuous marine influenced littoral during the early and middle Holocene as a consequence of the post-glacial sea-level rise that was favored by tectonic subsidence. This event produced a marine incursion along this littoral where the relative sea-level stabilized at its current level between 7000 and 5000 yr BP (Cohen, Behling, and Lara 2005). The tidal water salinity should have increased due to low river discharge resulting from increased aridity during the early and middle Holocene. During the early Holocene, the mangrove establishment was marked by dominance of *Avicennia* trees in the Bragança littoral, while the *Rhizophora* expanded relative to *Avicennia* during the middle and late Holocene (Vedel et al. 2006). The mangroves along the marine littoral have remained continually during the Holocene (Cohen et al. 2012).

Fluvial Littoral

However, during the late Holocene, the littoral near the Amazon River underwent a significant increase in fluvial influence that fragmented this mangrove belt. As a consequence, the mangroves were replaced by *várzea* vegetation, and the marine organic matter in the sediment changed to freshwater organic matter (Figure 1). Most likely, it was caused by the increase of river freshwater discharge during the late Holocene, which caused a significant decrease of tidal water salinity in the Marajó Island and part of the Amapá coastline. These changes in the Amazon discharge were likely caused by dry and wet periods recorded in the Amazonia region during the Holocene (Cohen et al. 2012, 2014).

Mangrove Dynamic from Northern Brazil in a Secular and Decadal Time Scale

Considering the last 400 years, the mangrove area along the tidal mud flats of the marine littoral migrated to lower surface. It was followed by the transition of brackish water organic matter to terrestrial C3 plants in upper surface. In addition, the geochemical data indicate a decrease in sea water influence during this time interval. Likely, mangrove migration was caused by a relative sea-level fall that may be associated to eustatic sea-level influenced by the Little Ice Age or local drier conditions with less rainfall during the second part of the last millennium (Cohen, Behling, and Lara 2005; Cohen et al. 2015).

In a decadal time scale, time series analyses suggest retraction of the mangrove vegetation along the coastline, mainly due to landward sand migration, which covers the mudflat and asphyxiates the vegetation. Image analyses suggest that loss of mangrove vegetation coverage has been the dominating process along the northern Brazilian coastline. On the other hand, the mangroves have invaded the elevated herbaceous flats in the highest surface. This vegetation coverage change seems to be compatible with a long-term trend related to the predicted rates of sea-level rise (Cohen and Lara 2003; Cohen et al. 2009).

Mangrove Dynamic from Southeastern Brazil in a Millennial Time Scale

The post-glacial sea-level rise produced erosion of the continental sedimentary deposits, and the marine transgression during the early and middle Holocene caused reactivation of paleo-estuaries, formed during the penultimate marine transgression. Probably, it has been intensified by decreased fluvial sediment supply to the coast due to a dry period. It was followed by a drop in sea-level during the late Holocene, which produced coastal progradation (Figure 2). This event was combined with wetter climatic conditions, which increased sediment input to coastal system and enhanced the continentality. Probably, the relative sea-level fall and increase of sediment supply to coastal system during the late Holocene contributed to delta development. Consequently, the marine influence decreased, causing the loss of mangrove areas and the expansion of freshwater organic matter and freshwater diatoms. According to sea-level fall during the late Holocene, the mangroves have migrated to lower surface (Castro et al. 2013; Cohen et al. 2014; França et al. 2013; Pessenda et al. 2012).

Mangrove Dynamic from Southeastern Brazil in a Secular and Decadal Time Scale

Regarding the last centuries, sediment cores have recorded the transition from a herbaceous tidal flat to a mangrove tidal flat, suggesting a recent relative sea-level rise. The last phase of mangrove establishment and the increased contribution of estuarine organic matter recorded in the last centuries may be associated to the modern global sea-level rise. Under this condition, erosion of beach ridges and expansion of lagoons and mangroves as recorded in the time series analyses are expected (França et al. in press).

Conclusion

Climatic changes and sea-level fluctuations caused by regional or global climatic change have significantly affected the Brazilian mangrove area during the Holocene. However, the impacts on mangroves caused by those driving forces depend on the environmental factors of each littoral, including topography, wave and current energy, coastal morphology, and mainly the input of nutrients, sediment, and freshwater. According to multi-proxy analyses and the projected sea-level rise and climatic changes, mangroves will continue to migrate landward to occupy higher parts of the tidal flats. However, due to the significant topographic difference between tidal flats and coastal plain, this process may cause a decrease in mangrove area along the northern littoral. Considering the droughts, it will cause a reduction in fluvial discharge, and consequently, the tidal water salinity will increase upriver. This dynamic of the estuarine salinity gradients will cause a replacement of *várzea* vegetation (freshwater wetland) by mangroves (brackish water wetland) along the fluvial flood flats. Considering the southeastern Brazilian littoral, the combined action of sea-level rise and lower rainfall rates, probably, will contribute to the expansion of estuaries and lagoons. These sedimentary environments are suitable to establishment and development of mangroves.

The assessment of mangrove dynamics according to climatic and sea-level changes along a ~3500 km of coastline in a millennial, secular, and decadal time scale has been crucial for the understanding of their establishment, expansion, and contraction under future scenarios with probable accelerated SLR rates, droughts, and heat waves for this century.

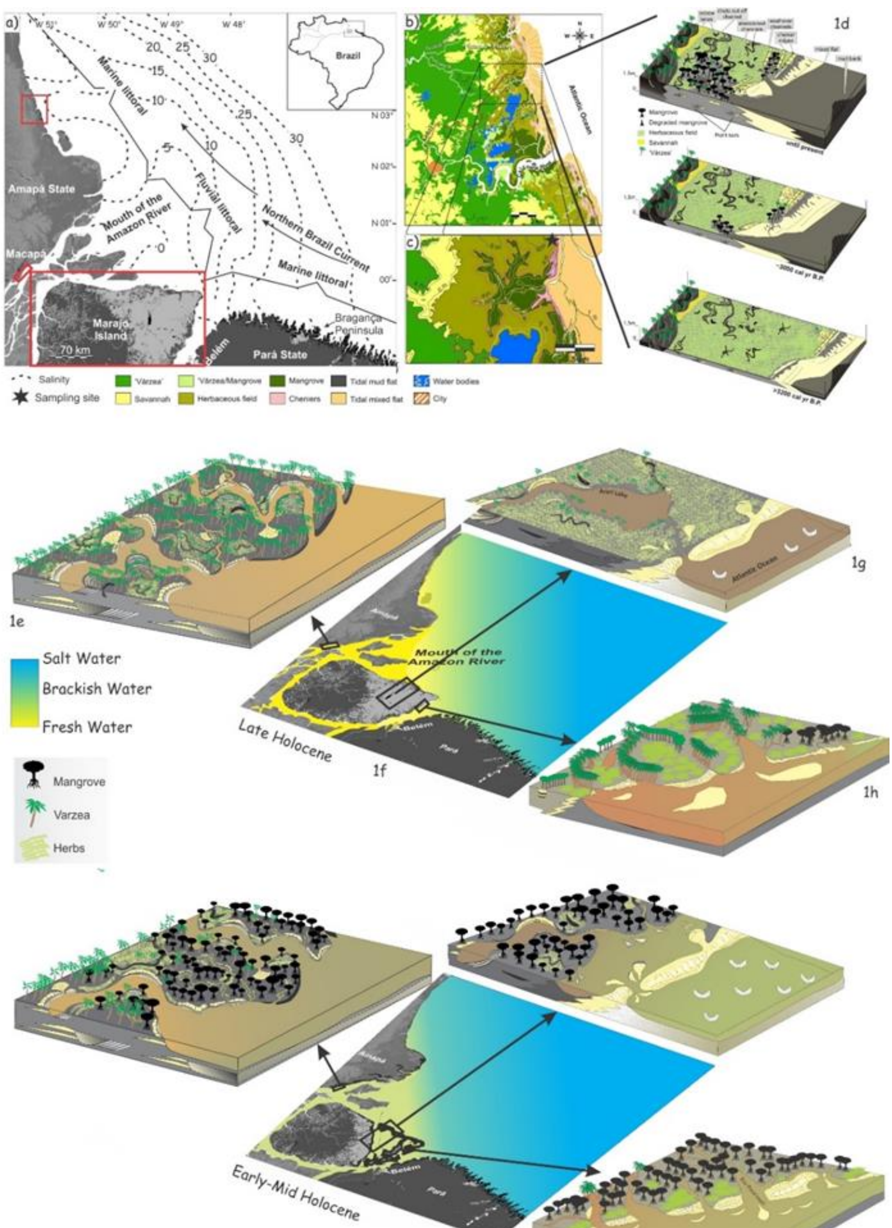

Figure 1: a) Location of the Study Area in Northern Brazilian Littoral; b) and c) Vegetation Maps of Calçoene-Amapá; Model of the Mangrove Development during the Holocene in d) Calçoene, e) Macapá, f) and g) Northern Marajó Island, and h) Eastern Marajó Island.
Sources: França et al. 2012; Smith et al. 2012; Guimarães, Cohen, Franca, Pessenda, and Behling 2013; Cohen et al. 2014

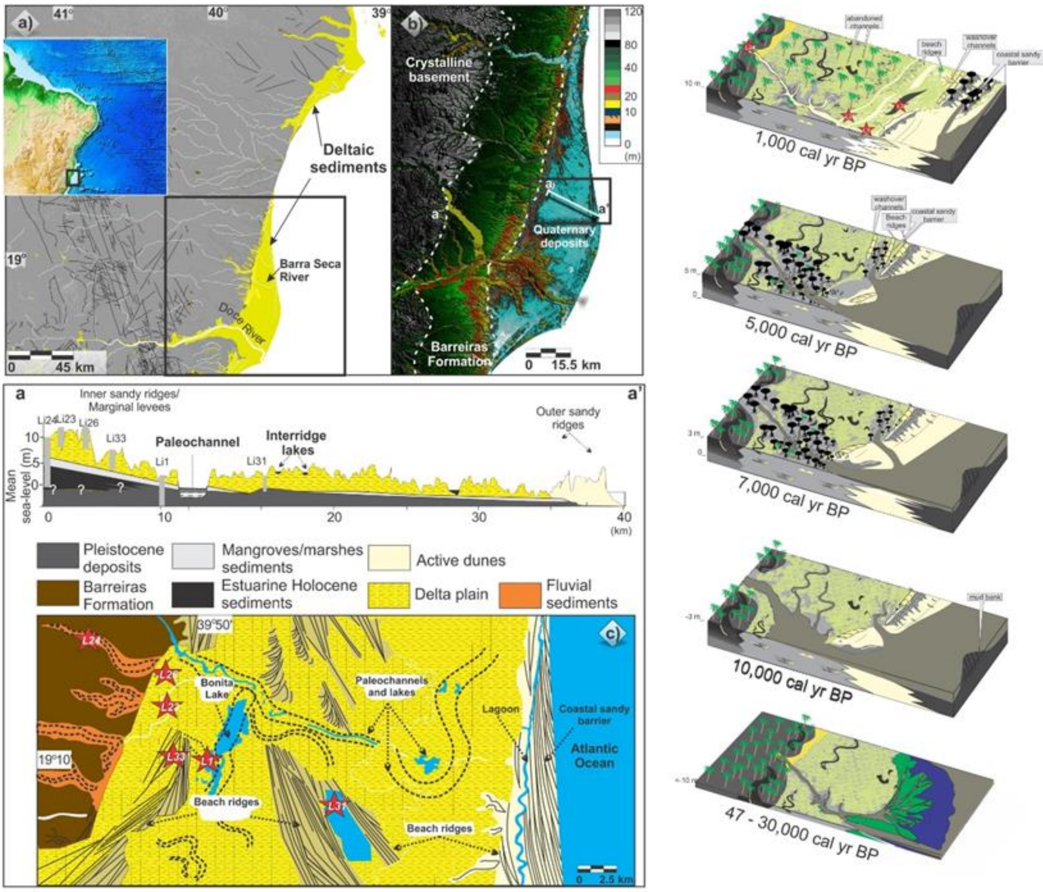

Figure 2: a) Location of the Study Area and Its Geological Context in Southeastern Brazilian Littoral; b) SRTM-DEM Topography of the Study Site and Lithostratigraphic Profiles; c) Location of Studied Sediment Cores and the Spatial Distribution of Main Geomorphological Features; d) Schematic Representation of Successive Phases of Sediment Accumulation and Vegetation Change According to Relative Sea-level Changes and Sediment Supply
Source: Cohen et al. 2014

Acknowledgement

This study was financed by FAPESP (03615-5/2007 and 00995-7/11), CNPq (Projects 473635/2012-7) and by National Institute on Science and Technology in Tropical Marine Environments - INCT-AmbTropic (CNPq Process 565054/2010-4).

REFERENCES

Alongi, D. M. 2008. "Mangrove Forests: Resilience, Protection from Tsunamis, and Responses to Global Climate Change." *Estuarine, Coastal, and Shelf Science* 76 (1): 1–13.

Carvalho, L. M. V., C. Jones, and B. Liebmann. 2004. "The South Atlantic Convergence Zone: Intensity, Form, Persistence, and Relationships with Intraseasonal to Interannual Activity and Extreme Rainfall." *American Meteorological Society*. doi:10.1175/1520-0442(2004)017<0088:TSACZI>2.0.CO;2.

Castro, D. F., D. F. Rossetti, M. C. L. Cohen, L. C. R. Pessenda, and F. L. Lorente. 2013. "The Growth of the Doce River Delta in Northeastern Brazil Indicated by Sedimentary Facies and Diatoms." *Diatom Research* 28: 455–66.

Chapman, V. J. 1975. "Mangrove Biogeography." In *International Symposium on Biology and Management of Mangroves*, edited by G. E. Walsh, S. C. Snedaker, and H. J. Teas, 179–212. Miami: University of Florida Press.

Cohen, M. C. L., I. C. C. Alves, M. C. França, L. C. R. Pessenda, and D. de F. Rossetti. 2015. "Relative Sea-level and Climatic Changes in the Amazon Littoral During the Last 500 Years." *CATENA* 133: 441–51.

Cohen, M. C. L., H. Behling, and R. J. Lara. 2005. "Amazonian Mangrove Dynamics during the Last Millennium: The Relative Sea-level and the Little Ice Age." *Review of Palaeobotany and Palynology* 136: 93–108.

Cohen, M. C. L., H. Behling, R. J. Lara, C. B. Smith, H. R. S. Matos, and V. Vedel. 2009. "Impact of Sea-level and Climatic Changes on the Amazon Coastal Wetlands during the Late Holocene." *Vegetation History and Archaeobotany* 18: 425–39.

Cohen, M. C. L., M. C. França, D. F. Rossetti, L. C. R. Pessenda, P. C. F. Giannini, F. L. Lorente, Junior A. Buso, D. Castro, and K. Macario. 2014. "Landscape Evolution during the Late Quaternary at the Doce River Mouth, Espírito Santo State, Southeastern Brazil." *Palaeogeography, Palaeoclimatology, Palaeoecology* 415: 48–58.

Cohen, M. C. L., and J. Lara. 2003. "Temporal Changes of Mangrove Vegetation Boundaries in Amazônia: Application of GIS and Remote Sensing Techniques." *Wetlands Ecology and Management* 11: 223–31.

Cohen, M. C. L., R. J. Lara, J. F. F. Ramos, and T. Dittmar. 1999. "Factors Influencing the Variability of Mg, Ca and K in Waters of a Mangrove Creek in Bragança, North Brazil." *Mangroves and Salt Marshes* 3: 9–15.

Cohen, M. C. L., R. J. Lara, C. B. Smith, R. S. Angélica, B. S. Dias, and T. Pequeno. 2008. "Wetland Dynamics of Marajó Island, Northern Brazil, During the Last 1000 Years." *CATENA* 76: 70–77.

Cohen, M. C. L., L. C. R. Pessenda, H. Behling, D. de Fátima Rossetti, M. C. França, J. T. F. Guimarães, Y. Friaes, and C. B. Smith. 2012. "Holocene Palaeoenvironmental History of the Amazonian Mangrove Belt." *Quaternary Science Reviews* 55: 50–58.

Cohen, M. C. L., P. W. M. Souza Filho, R. J. Lara, H. Behling, and R. J. Angulo. 2005. "A Model of Holocene Mangrove Development and Relative Sea-level Changes on the Bragança Peninsula (Northern Brazil)." *Wetlands Ecology and Management* 13: 433–43.

Da Cruz Miranda, M. C., D. de Fátima Rossetti, and L. Carlos Ruiz Pessenda. 2009. "Quaternary Paleoenvironments and Relative Sea-level Changes in Marajó Island (Northern Brazil): Facies, δ13C, δ15N and C/N." *Palaeogeography, Palaeoclimatology, Palaeoecology* 282: 19–31.

Dittmar, T., N. Hertkorn, G. Kattner, and R. J. Lara. 2006. "Mangroves, A Major Source of Dissolved Organic Carbon to the Oceans." *Global Biogeochemical Cycles* 20 (1). doi:10.1029/2005GB002570.

Downing, J. P., and D. A. Cataldo. 1992. "Natural Sinks of CO2: Technical Synthesis from the Palmas Del Mar Workshop." *Water, Air, and Soil Pollution* 64: 439–53.

Duke, N. C., J. O. Meynecke, S. Dittmann, A. M. Ellison, K. Anger, U. Berger, S. Cannicci, K. Diele, K. C. Ewel, C. D. Field, N. Koedam, S. Y. Lee, C. Marchand, I. Nordhaus, and F. Dahdouh-Guebas. 2007. "A World without Mangroves?" *Science* 317 (5834): 41–42.

Estrada, G. C. D., M. L. G. Soares, F. de O. Chaves, and V. F. Cavalcanti. 2013. "Analysis of the Structural Variability of Mangrove Forests through the Physiographic Types Approach." *Aquatic Botany* 111: 135–43.

Ewel, K. C., R. R. Twilley, and J. E. Ong. 1998. "Different Kinds of Mangrove Forests Provide Different Goods and Services." *Global Ecology and Biogeography Letters* 7: 83–94.

Faegri, K., and J. Iversen. 1989. *Textbook of Pollen Analyses*. New York: John Wiley and Sons.

França, M., I. C. C. Alves, M. C. L. Cohen, D. F. Rossetti, L. C. R. Pessenda, P. C. F. Giannini, F. L. Lorente, A. A. Buso, J. A. Bendassolli, and K. Macario, in press. "Millennial to Secular Time Scale Impacts of Climate and Sea-level Changes on Mangroves from the Doce River Delta, Southeastern Brazil." *The Holocene*.

França, M. C., M. C. L. Cohen, L. C. R. Pessenda, D. F. Rossetti, F. L. Lorente, A. Á Junior Buso, J. T. F. Guimarães, Y. Friaes, and K. Macario. 2013. "Mangrove Vegetation Changes on Holocene Terraces of the Doce River, Southeastern Brazil." *CATENA* 110: 59–69.

França, M. C., M. I. Francisquini, M. C. L. Cohen, L. C. R. Pessenda, D. F. Rossetti, J. T. F. Guimarães, and C. B. Smith. 2012. "The Last Mangroves of Marajó Island—Eastern Amazon: Impact of Climate and/or Relative Sea-level Changes." *Review of Paleobotany and Palynology* 187: 50–65.

Fromard, F., C. Vega, and C. Proisy. 2004. "Half a Century of Dynamic Coastal Change Affecting Mangrove Shorelines of French Guiana. A Case Study Based on Remote Sensing Data Analyses and Field Surveys." *Marine Geology* 208: 265–80.

Gallo, M. N., and S. Vinzon. 2005. "Generation of over Tides and Compound Tides in Amazon Estuary." *Ocean Dynamics* 55: 441–448.

Garreaud, R. D., M. Vuille, R. Compagnucci, and J. Marengo. 2009. "Present-day South American Climate." *Palaeogeography, Palaeoclimatology, Palaeoecology* 281: 180–95.

Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. "Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data." *Global Ecology and Biogeography* 20: 154–59.

Goncalves-Alvlm, S. J., M. C. F. V. dos Santos, and G. W. Fernandas. 2001. "Leaf Gall Abundance on Avicennia germinans (Avicenniaceae) along an Interstitial Salinity Gradient." *Biotropica* 33: 69–77.

Guimarães, J. T. F., M. C. L. Cohen, M. C. Franca, L. C. R. Pessenda, and H. Behling. 2013. "Morphological and Vegetation Changes on Tidal Flats of the Amazon Coast During the Last 5000 Cal. Yr BP." *The Holocene* 23: 528–43.

Guimarães, J. T. F., M. C. L. Cohen, M. C. França, L. C. R. Pessenda, E. Souza, A. C. R. Nogueira, and R. Alves. 2013. "Recent Effects of Tidal and Hydro-meteorological Changes on Coastal Plains near the Mouth of the Amazon River." *Earth Surface Process and Landforms* 38: 1535–49.

Guimarães, J. T. F., M. C. L. Cohen, L. C. R. Pessenda, M. C. Franca, C. B. Smith, and A. C. R. Nogueira. 2012. "Mid- and Late-holocene Sedimentary Process and Palaeovegetation Changes near the Mouth of the Amazon River." *The Holocene* 22: 359–70.

IDESP (Institute of Social and Economic development of the Pará). 1974. *Integrated Studies of Marajó Island*. Belém.

Junk, W. J., and M. T. F. Piedade. 2004. "Status of Knowledge, Ongoing Research, and Research Needs in Amazonian Wetlands." *Wetlands Ecology and Management* 12: 597–609.

Kjerfve, B., G. M. E. Perillo, L. R. Gardner, J. M. Rine, G. T. M. Dias, and F. R. Mochel. 2002. “Morphodynamics of Muddy Environments along the Atlantic Coasts of North and South America.” In *Muddy Coasts of the World: Processes Deposits and Functions*, edited by T. Healy, Y. Wang, and J. A. Healy, 479–532. Amsterdam: Elsevier.

Kjerfve, B., and L. D. Lacerda. 1993. “Mangroves of Brazil.” In *Conservation and Sustainable Utilization of Mangrove Forest in Latin America and Africa Regions*, edited by L. D. Lacerda, 245–72. Okinawa: Mangrove Ecosystem Technical Report No. 2. ITTO/ISME.

Kristensen, E., M. Flindt, S. Ulomi, A. Borges, G. Abril, and S. Bouillon. 2008. “Emission of CO2 and CH4 to the Atmosphere by Sediments and Open Waters in Two Tanzanian Mangrove Forests.” *Marine Ecology Progress Series* 370: 53–67.

Lara, R. J., and M. C. L. Cohen. 2006. “Sediment Porewater Salinity, Inundation Frequency and Mangrove Vegetation Height in Bragança, North Brazil: An Ecohydrology-based Empirical Model.” *Wetlands Ecology and Management* 14: 349–58.

———. 2009. “Palaeolimnological Studies and Ancient Maps Confirm Secular Climate Fluctuations in Amazonia.” *Climatic Change* 94: 399–408.

Liebmann, B., G. N. Kiladis, J. Marengo, T. Ambrizzi, and J. D. Glick. 1999. “Submonthly Convective Variability over South America and the South Atlantic Convergence Zone.” *Journal of Climate* 12: 1877–91.

Lentz, S. J. 1995. “The Amazon River Plume during AMASSEDS: Subtidal Current Variability and the Importance of Wind Forcing.” *Journal of Geophysical Research* 100: 2377–90.

Marengo, J. A. 2006. *Mudanças climáticas globais e seus efeitos sobre a biodiversidade: caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do século XXI*. Brasilia: Ministério do Meio Ambiente.

McGinley, M. 2007. “Marajó varzea.” In *Encyclopedia of Earth*, edited by C. J. Cleveland. Washington, DC: Environmental Information Coalition, National Council for Science and the Environment. Last revised August 31, 2007. http://www.eoearth.org/article/Marajó_varzea.

McLeod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger, and B. R. Silliman. 2011. “A Blueprint for Blue Carbon: Toward an Improved Understanding of the Role of Vegetated Coastal Habitats in Sequestering CO2.” *Frontiers in Ecology and the Environment* 9: 552–60.

McLeod, E., and R. V. Salm. 2006. *Managing Mangroves for Resilience to Climate Change*. Gland: IUCN.

Miranda, M. C., D. F. Rossetti, and L. C. R. Pessenda. 2009. “Quaternary Paleoenvironments and Relative Sea-level Changes in Marajó Island (Northern Brazil): Facies, δ13C, δ15N and C/N.” *Palaeogeography, Palaeoclimatology, Palaeoecology* 282: 19–31.

Moreno-Casasola, P. 1986. “Sand Movement as a Factor in the Distribution of Plant Communities in a Coastal Dune System.” *Vegetatio* 65: 67–76.

Peixoto, A. L., and A. Gentry. 1990. “Diversidade e composição florística da mata de tabuleiros na Reserva Florestal de Linhares (Espírito Santo, Brasil).” *Revista Brasileira de Botânica* 13: 19–25.

Pessenda, L. C. R., E. Vidotto, P. E. De Oliveira, A. A. Buso, M. C. L. Cohen, D. De F. Rossetti, F. Ricardi-Branco, and J. A. Bendassolli. 2012. “Late Quaternary Vegetation and Coastal Environmental Changes at Ilha do Cardoso Mangrove, Southeastern Brazil.” *Palaeogeography, Palaeoclimatology, Palaeoecology* 363: 57–68.

Pugh, D. T. 1987. *Tides, Surges and Mean Sea-level: A Handbook for Engineers and Scientists*. London: Wiley.

Rosário, R. P., M. O. Bezerra, and S. B. Vinzón. 2009. “Dynamics of the Saline Front in the Northern Channel of the Amazon River - Influence of Fluvial Flow and Tidal Range (Brazil).” *Journal of Coastal Research* 2: 1414–18.

Rossetti, D. F., and M. M. Valeriano. 2007. "Evolution of the Lowest Amazon Basin Modeled from the Integration of Geological and SRTM Topographic Data." *CATENA* 70: 253–65.

Santos, M. L. S., C. Medeiros, K. Muniz, F. a. N. Feitosa, R. Schwamborn, and S. J. Macêdo. 2008. "Influence of the Amazon and Pará Rivers on Water Composition and Phytoplankton Biomass on the Adjacent Shelf." *Journal of Coastal Research* 243: 585–93.

Smith, C. B., M. C. L. Cohen, L. C. R. Pessenda, M. C. França, and J. T. F. Guimarães. 2012. "Holocenic Proxies of Sedimentary Organic Matter and the Evolution of Lake Arari-Amazon Region." *CATENA* 90: 26–38.

Smith, C. B., M. C. L. Cohen, L. C. R. Pessenda, M. C. França, J. T. F. Guimarães, D. De F. Rossetti, and R. J. Lara. 2011. "Holocene Coastal Vegetation Changes at the Mouth of the Amazon River." *Review of Palaeobotany and Palynology* 168: 21–30.

Soares, M. L. G., G. C. D. Estrada, V. Fernandez, and M. M. P. Tognella. 2012. "Southern Limit of the Western South Atlantic Mangroves: Assessment of the Potential Effects of Global Warming from a Biogeographical Perspective." *Estuarine, Coastal, and Shelf Life* 101: 44–53.

Spalding, M., F. Blasco, and C. Field. 1997. *World Mangrove Atlas*. Okinawa: International Society for Mangrove Ecosystems.

Van der Werf, G. R., D. C. Morton, R. S. DeFries, J. G. J. Olivier, P. S. Kasibhatla, R. B. Jackson, G. J. Collatz, and J. T. Randerson. 2009. "CO2 Emissions from Forest Loss." *Nature Geoscience* 2: 737–38.

Vedel, V., H. Behling, M. Cohen, and R. Lara. 2006. "Holocene Mangrove Dynamics and Sea-level Changes in Northern Brazil, Inferences from the Taperebal Core in Northeastern Pará State." *Vegetation History and Archaeobotany* 15: 115–23.

Vinzon, B. S., C. P. X. Vilela, and L. C. C. Pereira. 2008. *Processos físicos na Plataforma Continental Amazônica. Relatório-Técnico, Potenciais Impactos Ambientais do Transporte de Petróleo e Derivados na Zona Costeira Amazônico*. Rio de Janeiro: Petrobrás.

Walsh, G. E. 1974. "Mangroves: A Review." In *Ecology of Halophytes*, edited by R. J. Reinold and W. H. Queen, 51–174. New York: Academic Press.

Walsh, J., and C. Nittrouer. 2004. "Mangrove-bank Sedimentation in a Mesotidal Environment with Large Sediment Supply, Gulf of Papua." *Marine Geology* 208: 225–48.

Zarin, D. J., V. F. G. Pereira, H. Raffles, F. G. Rabelo, M. Pinedo-Vasquez, and R. G. Congalton. 2001. "Landscape Changes in Tidal Floodplains Near the Mouth of the Amazon River." *Forest Ecology and Management* 154: 383–93.

ABOUT THE AUTHORS

Prof. Marcelo Cancela Lisboa Cohen: Professor, Institute of Geoscience, Federal University of Pará, Belem, Pará, Brazil

Dr. Marlon Carlos França: Professor, Department of Natural Resources, Federal Institute of Pará, Belém, Pará, Brazil

Dr. Luiz Carlos Ruiz Pessenda: Professor, Center for Nuclear Energy in Agriculture, University of São Paulo, Brazil

The International Journal of Climate Change: Impacts and Responses seeks to create an interdisciplinary forum for discussion of evidence of climate change, its causes, its ecosystemic impacts and its human impacts. The journal also explores technological, policy, strategic, and social responses to climate change.

The International Journal of Climate Change: Impacts and Responses is a peer-reviewed, scholarly journal.

ISSN 1835-7156