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ANALYSES OF THE MANGROVE'S REHABILITATION PROCESS IN ABANDONED SALTWORK AREA, IN THE CEARÁ RIVER, NORTHEAST BRAZIL

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ABSTRACT

The mangroves are among the most productive and biologically important ecosystems in the world supplying unique conditions and services to all tropical coastal system. The vulnerability of the coastal environments is frequently emphasized to the anthropogenic impacts. In the Ceará River, Northeast Brazil, during the last century, mangrove ecosystems lost extensive areas, due the exploitation of saltworks. Right behind the decline of this economic activity, the saltwork structures have been abandoned, and mangroves recovered part of these areas. The current study is focus on the mangrove rehabilitation process in abandoned saltwork area. It was considered different spatial-temporal scales in the Ceará river estuary system, in the period of 1968, 1997 and 2009, using remote sensing techniques and the software QGIS 1.7®. These data fomented the elaboration of thematic maps, showing the evolutionary mangrove rehabilitation area and the saltwork area. In the period of 41 years analyzed the mangrove area from the Ceará river estuary increase 165%, reaching 1006.6 ha in 2009. The saltwork area have decreased from 621,9 ha to 226.9 ha. The natural mangrove rehabilitation in saltwork areas covered 395 ha of the abandoned territory in four decades, but there still are 34% of abandoned saltwork areas that need to be restored. The conceptual analysis of the mangrove dynamics show the importance of the climate, the natural recruitment of mangrove trees, the soil quality and the range and time of inundation to enhance the rehabilitation process of abandoned saltworks. The expansion zones of the mangrove forest has described the presence of the mangrove-associated plant *Beldroega marítima* and *Laguncularia racemosa*. Management mangroves areas in estuary regions depend on effective actions of monitoring the forests development and understand the different interactions with the entire environmental system.

KEYWORDS: Anthropogenic Impacts, Remote Sensing, Coastal Management, Estuarine System

INTRODUCTION

Mangroves and Saltworks

The coastal energetic fluxes converge into the estuary regions. The estuary system involves a complex web of inter-relations including the continent-ocean-atmosphere connections, and the geomorphologic and ecodinamic interactions (Meireles *et al.*, 2007). Estuary landscapes and their landforms are modeled by the continual co-adjustments of forms to water, tidal, and wave energies and associated constructive/erosive processes (Schaeffer-Novelli *et al.*, 2000). The distribution of the input energies combined with the tropical climate, made a perfect scenario providing the mangrove natural condition to well development. Mangroves are ecologically important coastal wetland systems, occupying 137,760km^2 around the globe (Giri *et al* , 2010). It is a unique coastal forests found in sheltered estuaries and along river banks and lagoons (FAO, 2007). Mangroves are ecologically important coastal wetland system, serving as a breeding ground and nursery habitat for marine life, performing a major environmental role in sheltering coastlines and estuaries

(Sathirathai; Barbier, 2001). The abundance of food and primary energies support a vast biological community and their genetic structure, representing a great value of biodiversity. Limited information on how specific mechanisms regulate the structure and function of ecosystems has restricted the development of management plans that govern can use, conservation and restoration of natural resources (Twilley *et al.*, 1998). In spite of all the research on mangroves, studies of the dynamics of mangrove ecosystems lag behind the need for new information for conserving these ecosystems, thus forcing users to act without full understanding of the risks and consequences of their actions (Lugo, 2002). The vulnerability of the coastal environmental system is frequently emphasized to the anthropogenic impacts. In reality, anthropogenic activities are often a prime cause for mangrove depletion (Duke *et al.*, 2007). The high population pressures, frequently present in coastal zones, have in some places led to the conversion of mangrove areas for urban development and industry activities. Mangroves have been fragmented and degraded through overexploitation of shrimp and fish farming, agriculture and salt production, frequently encouraged by governments in order to increase the state economy. (FAO, 2007)

In northeast Brazil some of the most important cities have started their expansion and constructions near to the old artisan saltworks that were constructed throughout the estuaries of the main rivers from the period of Portuguese colonization in the XV century (Rocha *et al.*, 2009). According to the same author, the preference to construct the saltworks in northeast Brazil estuaries systems is related to the conjuncture of environmental factors, such as semi-arid climate, high temperatures (> 28C), low precipitation (<800 mm/year) and high evaporation rates, with water availability of the estuary. Nowadays, the northeast coast of Brazil is still the major area where the solar saltworks are installed, being responsible by 95% for the produced and exported marine salt in the country (Rocha *et al.*, 2012). But due the modernization process of the salt industry and the less relevance of this economic activity in regional scale, most of the artisanal saltworks have been abandoned and mangrove forests are expanding their territory over these areas. This similar process has been reported in other areas of Brazilian northeast coast (Lacerda *et al*, 2007).

The aim of this paper is to underline the importance of the rehabilitation process of mangrove ecosystem in abandoned saltworks and contribute to the comprehension of the natural mangrove forest dynamics in anthropogenic impacted areas.

STUDY AREA

Brazil´s coastline stretches out for approximately 8,500 km (Jablonki and Filet, 2008), and according to Schaeffer-Novelli et al. (2000) 6,786 km contain mangrove forests, which cover an estimated area of 25,000 km^2. The Ceará river is located in the Metropolitan Region of Fortaleza, Ceará State, NE, Brazil, between latitudes 03°45´0´´ S; 03°41´0´´ S and longitude 038°39´0´´ W; 038°36´0´´ W. Climate is tropical, semi-arid, with average annual rainfall of about 1,200 mm/year (Guedes *et al.*, 2007) influenced by the intense convective activity of the Intertropical Convergence Zone. The precipitations are distributed in a rainy summer from February to June and dry season from July to January (Lacerda, *et al.*, 2007). Most of the estuary comprises the “APA do Rio Ceará”, an Environment Protected Area (EPA), which prevents damage to the environment and predicts a sustainable use of the land. Before this law, in the 1960´s, important artisanal saltworks were constructed over original mangroves areas. The solar evaporation of marine salt was an important economic activity until the latest XX century. When the artisanal salt exploration has lost its economic relevance in regional markets, the salt ponds were abandoned and new environmental conditions arise. The mangrove rehabilitation process in the Ceará river happened over saltworks and wetlands (Meireles *et al.*, 2007). It is evident in the “Margarida Saltwork”, downstream the Ceará river, in the left bank, where it is still possible to see the abandoned structure of the old saltwork structure and the growing vegetation.

METHOD

The methodology was based on mapping the saltworks and the mangrove area from the Ceará River Estuary. Three digitalized images were mapped using Quantum GIS (1.7.3) software, with 1:50.000 resolution, resulting into three maps, relative to the panchromatic aerial photograph, year of 1968, over flight Atlântico Sul Company, from the collection of the Geography Department of Federal University of Ceará (Brazil) (1:70.000), the second was the satellite image made available by INPE, National Institute for Space Research-Brazil, year of 1997, LANDSAT-5 RGB image (1:50.000) and the third, a satellite image, from 2009, comprehend of data such as Quick Bird and IKONOS (available within the enhance version of Google Earth®). It was analyzed the growth pattern and measure the extension of the mangrove area and the saltworks area for each year. The images were visually analyzed using forms and size of polygons, colors and texture. Detailed inspecting of the area was carried on during several field trips performed between 2009 and 2012 for ground truth purposes and better knowledge of local communities.

It was also important for correcting inherent errors due the satellite images resolution. These field trips also allowed investigating the distribution and general structural characteristic of mangrove stands. The field works were fundamental to allow the contact with the traditional population that lives in the vicinities of the Ceará River estuary for many years long, in order to determine some fundamental aspects about the saltworks history, the interactions between mangrove rehabilitation and abandoned saltworks, and the human relationship with that environment.

To provide a systemic analysis of the landscape in the Ceará river´s estuarine system it was considered the hierarchical organization levels proposed by Schaeffer-Novelli et al. (2000), and the application of different geotechnological tools in different spatial-temporal scales, proposed by Cunha-Lignon et al. (2009). The conceptual approach about the evolutionary mangrove rehabilitation process was based on Twilley *et. al.* (1998), being possible the prediction of mangrove forest development process scenario, describing conditions and tensors of the rehabilitation process. The ecological type of the mangrove forest is based on the physiographic characteristics of mangroves, taking into account the suggestions offered by Schaeffer-Novelli *et al.* (2000). This classification may recognize two major types (fringe and basin) and three subtypes (over wash, scrub and dwarf).

RESULTS AND DISCUSSIONS

Diagnostic of the Satellite Images

Table 1: Areas Measure in Hectares (ha): Mangrove Area, Saltwork Area and Mangrove Growth, in the Years 1968, 1997 and 2009

Ano	1968	1997	2009
Mangrove	380.4	859.8	1006.6
Saltwork	621.9	373.7	213.8
Mangrove Growth	380.4	479.4	626.2
%	**0**	**126%**	**165%**
Saltwork Rehabilitate	0	248.2	408.1
%	**0**	**40%**	**66%**

The remote images were analyzed, in a temporal scale of 41 years, considering two periods, representing by different classification zones (mangroves, saltworks) the rehabilitation process of mangrove vegetation in the Ceará river estuary system. The thematic classification provides the quantification of each area in hectares, making possible different associations (Table 1). The first approach was to synthesize data into the hierarchical classification level of study, considering the Ceará river estuary system (figure 1). The level *Setting* (10-100 km) was used to the analyses the temporal-spatial dynamic of the mangrove vegetation.

First Period (1968 – 1997)

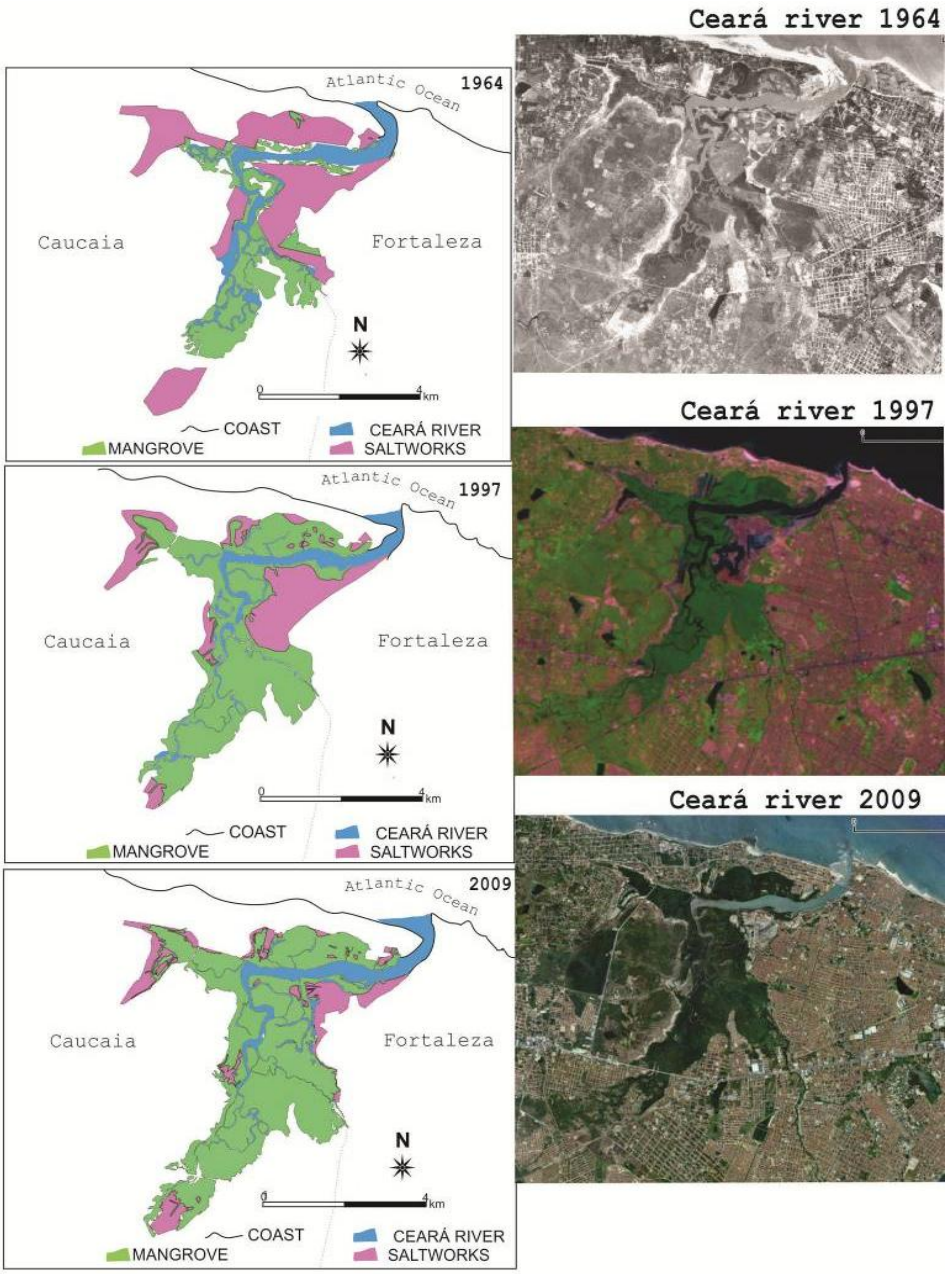

Figure 1: Original Images and QuantumGIS® Maps of Landcover Features along the Ceará River Estuary, Ceará, Brazil, in 1968, 1997 and 2009. Mangrove (in Green), Saltwork (in Pink)

Major changes in mangrove area occurred between 1968 and 1997 mostly due the cessation of salt production, the abandon of the saltworks and river damming. Saltworks were reported to have converted mangroves during their construction and accounted for 621.9 ha in 1968.

The mangrove original area at the Ceará river estuary in 1968 reached 380.4 ha. In 1997, mangroves have recomposed a vast area of abandoned saltworks, increasing in area about 126% or 248.2 ha of abandoned saltworks. In terms of urban occupation and human pressure in the estuary region, many things have changed in these 29 years time lapse. The traditional land use of artisanal saltworks, in the 1960´s, changed into a scenario of mangrove forests recomposing area in the 1990´s. The vicinities of the estuary, in 1968, were unoccupied, except from small houses from the saltworks´ workers. According to the ancient villagers, the saltworks were the main economic activity at that time.

Second Period (1997 – 2009)

The second period analyzed between 1997 and 2009, of exact 12 years, the mangrove cover increased 146.8 ha, representing a growth of 66% in abandoned saltworks. In this same period the vegetation grew 133,25 ha in 10 years.

In the 41 years analyzed in the present study the mangrove area of the Ceará River estuary increase from 380,4 ha to 1006,6 ha, representing a growth of 165% . The saltworks, in the other hand, have decreased the area from 621.9 ha to 226.9 ha, resultant from the colonization of about 395 ha of mangrove natural rehabilitation process. However there still are 34% of abandoned saltwork areas that need to be rehabilitated by mangrove forests.

Conceptual Model of Ecological Succession in the Mangrove Rehabilitation Area in Saltworks

Analyzing the recomposing process of the mangrove vegetation on the abandoned saltwork area, using remote sensing techniques and data about mangrove's functions and structure, is possible to produce a conceptual model of mangrove forests dynamics. We considered the methodology proposed by Twilley, *et al.* (1998), to discuss the application of a classification scheme and a modeling approach to describe the rehabilitation of mangrove forest on saltworks territory in the Ceará River Estuary. Coastal and marine research and conservation needs to be holistic and dynamic because of the embedding matrix and the multiplicity of cross scale linkages between the objects embedded in it (Dahdouh-Guebas and Koedam, 2008). The hierarchical classification system proposed, considered four mains system levels that compose the estuary environment: Global Distribution; Geomorphological type; Ecological type; Mangrove structure.

Global Distribution

Globally the Ceará River Estuary (3°45´S) is located near the Equad or tropic, ensuring high solar radiation inputs, and integrated in the Brazilian semi-arid territory. This climatic zone is characterized by low frequency of rains and its concentration in the first semester of the year. This disturbance condition interferes in the fresh water availability and nutrient support, resulting in medium development mangrove forests (Schaeffer-Novelli et al., 2000).

Geomorphological Type

To determine the geomorphological classification it was necessary consider the analysis scale (Setting, 10-100 km) and the environmental settings. In this study case, it is situated in an estuarine region, an open environment system, transitional zone between marine, river and terrestrial territory. The mangrove occupies the river margins until the influence of the tide upstream the river. The transitional zones inside land, occurs the salt flats, salt marshes or "apicuns". Periodic flushing by rain drainage may be important in controlling the transport of materials from the saltwork to the main channel of the estuary. In the other hand, the tidal and fluvial energy, are in charge of controlling the reverse process, transporting materials from the estuary complex to the wetlands, including mangroves and the abandoned saltworks.

Ecological Type

To the mangrove rehabilitation process on saltworks was considered these three types (figure 2): the fringe (X), as the mangrove stands near the river margins, where the lower salinities and high nutrients level prevail are the main settings attributes. The basin forest (Y) is defined where the forest stands occupy terrains where flushing is sometimes restricted to the highest tides, and the freshwater inputs play a major role in the structural settings. It was also considered a basin sub-type scrubs (Z), to define the expansion zone of mangroves, where the structural attributes are derived from particular settings as higher salinities and lower tides influence.

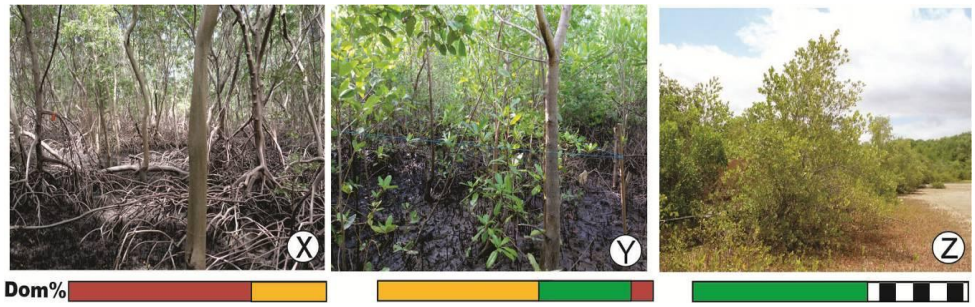

Figure 2: The Hierarchical Classification of the Ceará River Estuary System and Specie Dominance (Dom %): X –Fringe: *Rhizophora mangle* (in Red) and *Avicennia sp,* (in Yellow) *Y – Basin: Avicennia sp* and *Laguncularia racemosa,* (in Green) *Z - scrub: Laguncularia racemosa and Batis maritime* (in Stripes B&W)

In the Margarida saltwork the vegetation structure and distribution were investigated by Reis-Neto (2013) and it has been associated with these different ecological type classifications: the Fringe forest was compound of an advanced development zone, 10 m. high, diameter > 10 cm and 1333.33 tree/ha density, dominated by high *Rhizophora mangle* trees, and presence of *Avicennia sp*. The Basin forest were rated as medium development zone, 2.1 m high, < 2.5 cm diameter and 44,440.00 tree/ha density, mixed *Avicennia sp* and *Laguncularia racemosa* trees. The Scrub forest was defined as primary succession zone, with presence of the mangrove-associated vegetation *Batis maritima* and *Portulaca oleracea,* and young individuals and seedlings of *Laguncularia racemosa*. The most developed forest were found in fringe forests, where the proximity of large water masses allow greater nutrient and gas inputs, the best conditions of mangrove growth. These are the first areas where the natural forces prevail over the abandoned saltwork structure. The zonation in monospecific bands parallel to the shore is frequently visible, generally dictated by local topography, soil composition, tidal ranges and salinity (FAO, 2007).

Mangrove Structure

The mangrove structure is based on demographic data, edaphic conditions and stressors vectors (Twilley *et al.*, 1998). The demographic data has been investigated by Reis-Neto (2013), the edaphic conditions were analyzed by visual identification at fieldwork and the stressed vectors were summarized by the saltworks interventions in the wetland environment. It was used an ecological model proposed by Twilley *et al.* (1998), but modified to represent the mangrove rehabilitation process on the saltworks region (Figure 3).

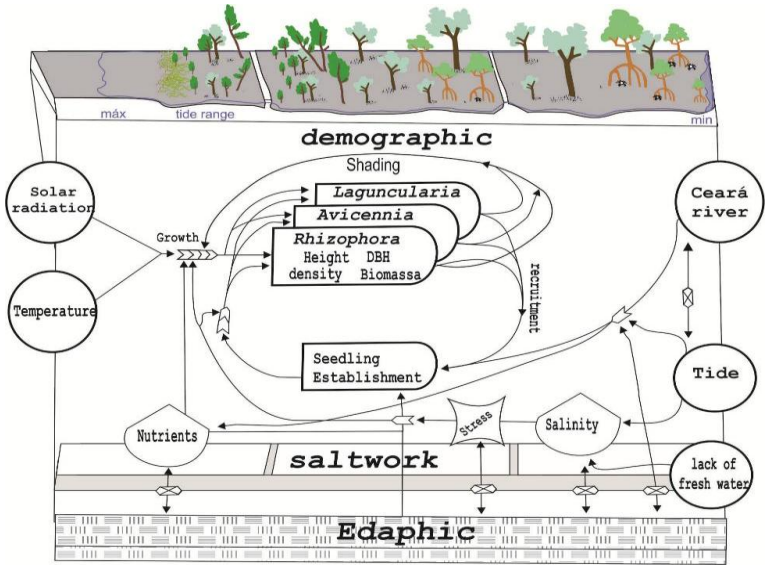

Figure 3: Conceptual Model of Mangrove Rehabilitation Process in Saltworks Areas, Including Edaphic Constrains and Forcing Functions. (Modified from Twilley, 1998)

Therefore, the Ceará River mangroves play a major role in modifying the geomorphic settings occupying instable landforms. Their spatial arrangements appear to be a response to underlying topographic and edaphic conditions (high salinity imposed by the saltwork remaining soil) and the constraints imposed by climatic (semi-arid) and hydrologic factors (estuarine system). Moreover, the magnitude of human impacts on ecosystems and landscapes has forced the ecological sciences to include humans as a fundamental constraint on ecological process and acknowledge land use as a decisive factor of habitat change (Twilley *et al.*, 1998). The saltworks structures near the main channel of the river are the first ones degraded by the potential tidal and river energies. In the directions of inside land, these forces are controlled by the basin forests combined with the edaphic conditions, influencing the mangrove inputs as hydrology, topography, tidal flushing, and organic material accumulation. These input settings are deficient because of a stress factor: the salt work structure, the concrete walls affect the energy and mass fluxes between inside land and the estuary complex.

The small size of trees in mangrove margins, the scrub type, may reflect reduced nutrient concentration and sporadic hydrological deficit. The hydrological deficit may lower available energy in a nutrient-limited environment, this affect directly the trees development, cause partial defoliation and can bring trees to death (Schaeffer-Novelli *et al*., 2000). The hydrological deficit and the recruitment disturbance are considered the main stress to the mangrove rehabilitation process on the abandoned saltwork, considering that the pond structure represents a barrier to the fluvial-marine flux into the wetland.

The walls from the salt ponds act blocking the exchanges between the tide/fresh water discharge, the salinity control, the availability of nutrients and organic matter. The last ponds are frequently the final ones to be recomposed by the mangrove. The topographic conditions and the hyper-salinity soil are results of the stress vectors influencing the mangrove forest growth on the abandoned pond. Accumulating, interpreting and applying information on rehabilitated landscapes at diverse scales can be accomplished through the construction of ecological models. These models can help us to understand the relative significance of the trajectories of natural resource response to rehabilitation process. (Twilley *et al.*, 1998).

CONCLUSIONS

The present study based on a detailed analysis of remote sensing data, shows the significant increase in mangrove areas along the Ceará river estuary. In 41 years the mangrove covered 395 ha of abandoned saltworks, but it still lack 34% of this area to be rehabilitate. The best opportunities of mangrove conservation in the Ceará river are in monitoring and management the natural rehabilitation process of the environmental systems and connect them into different scenarios of human-environment interactions, for example the mangrove rehabilitation process in abandoned saltworks areas.

To a better understanding of the environmental dynamics it is necessary a holistic and systemic overview, considering the major energy inputs for a better development conditions. The Ceará river mangrove suffers by the climate conditions, such as the Brazilian semi-arid, with low freshwater inputs. In the other hand, the proximity of the Equador tropic ensures high solar radiation rates.

The mangrove forest in this area present medium development structure and it is influenced by the anthropogenic tensors, in this case the ancient conversion of mangroves into saltworks. The hydrological deficit and the recruitment disturbance are considered the main stress to the mangrove rehabilitation process on the abandoned saltwork. The contributions to understand the mangrove rehabilitation process in stressed zones are the basis of a new kind of orientation about how human development should interact with nature processes in anthropogenic impacted areas.

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