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Extreme weather impacts on tropical mangrove forests in the Eastern Brazil Marine Ecoregion

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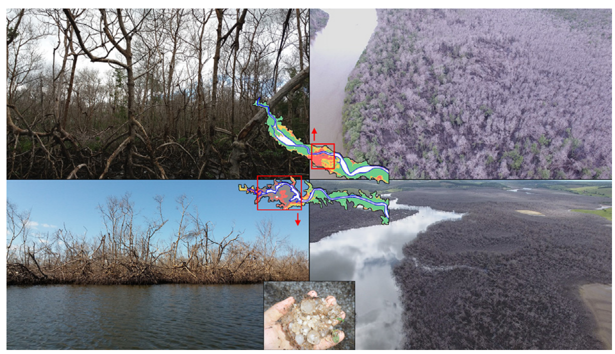
HIGHLIGHTS

- Over 24% of mangroves were suddenly lost by a hailstorm in Eastern Brazil.
- There was further degradation of impacted areas one year after the initial impact.
- *Rhizophora mangle* was the most impacted species by the hailstorm.
- Extreme weather events and long-term stress offer significant risks to wetlands.
- Significant economic social losses continue in the impacted estuary.

GRAPHICAL ABSTRACT



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ABSTRACT

Extreme weather events are likely to become more frequent in the 21st century bringing significant impacts to coastal ecosystems. However, the capacity to detect and measure those impacts are still limited, with effects largely unstudied. In June 2016, a hailstorm with wind gusts of over 100 $km \cdot h^{-1}$ caused an unprecedented mangrove dieback on Eastern Brazil. To quantify the scale of impact and short-term recovery of mangroves (15-mo), we used satellite imagery and field sampling to evaluate changes in forest structure in control and impacted areas after the hailstorm. Satellite imagery revealed mangrove dieback in over 500 ha, corresponding to 29.3% of the total forest area suddenly impacted after the hailstorm. Fifteen months after the hailstorm, some impacted areas show an initial recovery, while others continued to degrade. The El Niño years of 2014–2016 created mild drought conditions in Eastern Brazil. As observed in wetlands of semi-arid regions during the same period, mangrove recovery may have been impaired by continued physiological stress and climate change effects. Economic losses in the study site from typical mangrove ecosystem services including food provision, climate regulation, raw materials and nurseries are estimated to at least US$ 792,624 yr^{-1}. This is the first evidence of an extreme weather impact on mangroves in Brazil that typically provide unique ecological and economic subsistence to coastal populations. Our results reveal that there is a pressing need for long-term monitoring and climate change adaptation actions for coastal wetlands in Brazil, and to provide broad estimates of ecosystem values associated with these ecosystems given many areas are already experiencing chronic stress from local impacts, drought and high temperatures.

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1. Introduction

Climate change is likely to impact coastal ecosystems through changes to mean temperatures, rainfall patterns and sea level along with alterations to the frequency and intensity of extreme events (IPCC, 2001; Doney et al., 2012). Sea level rise and regional changes in precipitation are of special concern for mangrove forests, which also need to cope with a naturally harsh estuarine environment (Alongi, 2008). Recent studies show that changes in minimum winter temperature and precipitation regimes are among the major climatic factors that may expand or contract coastal wetland ecosystem extensions in the future (Gabler et al., 2017; Feher et al., 2017; Osland et al., 2017). Concerningly, a marked decrease in precipitation volume and an increase in drought periods have already been observed in a number of coastal areas during the last few decades (Dai, 2013). Prolonged drought stress has been associated with massive losses of coastal wetlands including salt marshes and mangroves (McKee et al., 2004; Duke et al., 2017). Because mangrove forests are resilient to multiple environmental changes and human impacts, it has been difficult to identify causes of sudden massive dieback of marshes and mangrove trees; these events have been associated with long-term stress on vegetation by sea level and drought (Cintrón et al., 1978; Houston, 1999; Alongi, 2008).

There are over 960,000 ha of mangrove forests along the Brazilian coast distributed from the Amazon to subtropical Marine Ecoregions with variable climatic and geomorphological settings (Giri et al., 2010; Schaeffer-Novelli et al., 2016). Climate models and decadal climate trends indicate that most Marine Ecoregions in Brazil with extensive mangrove forests are under rising temperatures and are likely experiencing drought stress (Marengo et al., 2010; Dai, 2013; Bernardino et al., 2015). Given the importance of mangroves to climate regulation, fisheries and social resources, it is imperative to identify their vulnerability to long-term changes (e.g. high temperatures, sea-level rise and prolonged drought) before subtle and large-scale ecosystem losses occur, a challenge in most coastal areas given insufficient monitoring (Kristensen et al., 2008; Donato et al., 2011; Mcleod et al., 2011; Alongi, 2012; Queiroz et al., 2017). For example, based on the increase in frequency and intensity of extreme events in the 21 century (IPCC, 2001), El Niño can intensify the reduction in rainfall rates and increase evapotranspiration, impacting mangroves and marshes through physiological stress from salinization (MacKay et al., 2010; Allen et al., 2015; Brimelow et al., 2017).

Potential impacts of storms and hurricanes on mangrove forests are known to cause acute and long-term changes (Houston, 1999; Cahoon et al., 2003; McLeod and Salm, 2006; Long et al., 2016). Although episodic storms may lead to regional losses of mangrove forests, there is limited understanding of the potential damage that extreme weather events cause in forests experiencing chronic climate change stress. On June 1st, 2016, a hailstorm with wind gusts of 100 $km \cdot h^{-1}$ hit the mangrove forests of the Piraquê Açú-Mirím (PAM) estuary in Eastern Brazil. The hail event caused housing and infrastructure damage to the nearby villages of Santa Rosa (19.927°S, 40.284°W) and Irajá (19.905°S, 40.234°W). This was the first occurrence of an extreme weather event in the PAM estuary, which has 1746 ha of preserved mangrove forests within a conservation unit in the Eastern Brazil Marine ecoregion (Bernardino et al., 2015).

Monitoring coastal landscapes is a challenge that has greatly benefited from remote sensing techniques (Ibharim et al., 2015). Initiatives such as the Landsat Program offer high spatial and temporal resolution data to monitor climate conditions for long periods (Jones, 2015). In particular, vegetation indexes derived from satellite images are largely used to assess coastal impacts over large areas (Pettorelli, 2013; Yengoh et al., 2015; Duke et al., 2017). Here we used satellite images of the PAM estuary (Supplemental Fig. S1) to quantify the initial impact of an extreme weather event on mangrove forests in Eastern Brazil. We used images from three periods (pre-impact, impact and one year after impact) to assess changes in mangrove forest canopy; we attempted to identify the spatial scales of impact and study the temporal recovery of impacted sites. We finally assessed potential economic losses based on the spatial and temporal impacts on mangrove ecosystem services in the study area. This is the first evidence of a mangrove forest dieback suddenly driven by a hailstorm in Eastern Brazil, with little evidence of recovery one year after the event.

2. Materials and methods

2.1. Study area and sample design

The study area was located in the PAM estuary (17°58′S; 40°00′W), within the Eastern Brazil Marine Ecoregion (Bernardino et al., 2015; Fig. 1). The region has two well-defined seasons, dry winter (April to September) and wet summer (October to March), with an average rainfall of 111.1 $\pm$ 25.2 $mm \cdot y^{-1}$, temperatures of 24 to 26 °C (Alvares et al., 2013; Bernardino et al., 2015) and a semi-diurnal microtidal regime (<2 m). This estuary has a Y-shape morphology with 1746 ha of mangrove forests, composed of *Rhizophora mangle, Laguncularia racemosa* and *Avicennia schaueriana* (PMA, 2013). Water salinity in the PAM estuary ranges from 15.5 to 36 psu (Supplemental Fig. S2). A polyhaline sector is typically observed within the estuary as is a euhaline sector near the sea. The most recent in-situ monitoring of water salinity within the PAM estuary in Nov 2015 recorded salinities ranging from 34.6 to 39.1 psu. The PAM estuary is part of the municipal conservation unit: the "sustainable development reserve of the mangroves of the rivers Piraquê Açú and Piraquê Mirím". Traditional communities, such as fisherman and Tupinikin and Guarani indians, live near the estuary and use the fisheries resources (e.g. fishes and crabs) for subsistence. Other ecosystems services provided by PAM estuary are raw materials, tourism, climate regulation and nursery habitats. From 2014 to 2016, the PAM estuary was under the most intense El Niño of this century (ggweather, 2017), which resulted in decreased rainfall and salinization in the area (Fig. 2; Supplemental Fig. S2). After the hailstorm (June 1st 2016), a sudden massive dieback occurred along the fringe of the mangrove, classified as predominantly "moderate impact" in both areas (Piraquê Mirím = PM and Piraquê Açú = PA).

The impacts of the sudden hailstorm on mangrove forests were studied using a BACI design (before-versus-after, Underwood, 1992) by comparing satellite images of mangroves coverage before and after the hailstorm. Initial mangrove coverage was assessed from images collected up to one year before the hailstorm (Jan 2015 to May 2016). Impacted areas were assessed from images collected 1-mo to over 1-yr after the hailstorm (Jun 2016 to Aug, 2017). As the hailstorm impacted two sites within the PAM estuary, we monitored changes in those two sites near Irajá village (site PA) and Santa Rosa village (site PM). The spatial differences between impacted and natural mangrove forests were then compared with two control sites. The structure of mangrove forests in the PAM estuary was accessed at each control and impacted site after the hailstorm (August of 2017).

2.2. Weather assessment

Changes in rainfall patterns from 1948 to 2016 were monitored from automatic meteorological stations located in the nearest areas of the PAM estuary from the Brazil National Weather Agency (total daily rainfall; ANA, 2017, stations 1940002, 1940021 and 2549007). The standardized precipitation index (SPI) quantify the rainfall deficit, being useful to identify and monitor climatic droughts by categories, which range from ≥2 SPI to ≤−2 SPI (extreme wetness to extreme dryness; Supplemental Table S1; McKee et al., 1993). SPI can be calculated in a range of temporal scales (3 to 48-months scale), where 12-months scale is useful to identify climatic drought influence on hydrologic regimes and water resources (Moreira et al., 2008). The hailstorm was identified by the change in wind field patterns considering the intensity