

Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events

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Regional warming associated with climate change is linked with altered range and abundance of species and ecosystems worldwide. However, the ecological impacts of changes in the frequency of extreme events have not been as well documented, especially for coastal and marine environments. We used 28 y of satellite imagery to demonstrate that the area of mangrove forests has doubled at the northern end of their historic range on the east coast of Florida. This expansion is associated with a reduction in the frequency of “extreme” cold events (days colder than -4°C), but uncorrelated with changes in mean annual temperature, mean annual precipitation, and land use. Our analyses provide evidence for a threshold response, with declining frequency of severe cold winter events allowing for poleward expansion of mangroves. Future warming may result in increases in mangrove cover beyond current latitudinal limits of mangrove forests, thereby altering the structure and function of these important coastal ecosystems.

ecological threshold | frost tolerance | Landsat | coastal wetlands

The biological impacts of climate change—temperature increases in particular—have been documented across a large number of terrestrial ecosystems (1). For example, increasing annual mean temperatures are associated with shifts in the abundance and distributions of hundreds of plant species toward higher latitudes and elevations (2). Although most investigations into the response of ecosystems to climate change have focused on the impacts of gradual increases in mean temperatures, there is growing recognition that changes in the frequency of extreme weather events can also have profound impacts (3, 4). Thresholds in the mechanisms by which individuals respond to environmental conditions can lead to ecosystem-level nonlinear responses, particularly when foundation species are already close to environmental tipping points (5, 6). Recent evidence suggests that several important ecosystems may soon cross such thresholds (7). For example, CO_2 concentrations of 450 ppm and a temperature increase of $+2^{\circ}\text{C}$ have been identified as tipping points for mass coral bleaching and mortality (8). In rocky intertidal systems, temperature-related thresholds are linked to increased mortality and reproductive failure in barnacles and mussels (9, 10).

Although an increasing number of such ecological regime shifts are predicted in future years (11), there are still surprisingly few empirical examples of climate-related thresholds in natural systems (12, 13). In practice, identifying threshold responses on regional scales is challenging because of the difficulty involved with observing ecosystems over long enough time periods and large spatial scales (13). In addition, covarying environmental variables and biotic and abiotic interactions can make it difficult to isolate the environmental factors driving threshold responses.

The “velocity” of climate-driven change appears greatest in the coastal zone (14), a region that includes more than 70% of the world’s population and some of our most biologically productive ecosystems (15). Mangrove forests are among the most

ecologically and economically important of these coastal ecosystems, providing food and habitat to a diverse array of terrestrial and marine species. Ecosystem services provided by mangroves include food, nesting, and nursery grounds for commercially important fish and invertebrates, wood production, waste processing, coastal protection, and recreation (16, 17). The value of these services has been estimated at more than \$1.6 trillion per year (18). The serious threats that mangrove forests face as a result of coastal development, aquaculture, and timber production have been well documented (19, 20). However, our understanding of how climate-induced changes in environmental conditions are impacting these systems is limited relative to that of terrestrial systems (21). This is in part because long-term observations of changes in coastal and marine systems are rare by comparison with those on land (1).

The historical northern limit of mangroves in eastern North America, believed to be set by cold temperatures, is located near 30°N , just north of St. Augustine, FL (22). Salt marshes dominate the more temperate climates to the north, whereas mangroves and salt marsh coexist in an ecotone to the south (28°N to 30°N in Florida). Distribution modeling suggests the hypothesis that mangrove–salt marsh ecotones around the world persist near climate-related thresholds (23, 24), whereby small increases in temperature could lead to large increases in the relative abundance of mangroves and therefore in the structure and function of

Significance

Coastal mangrove forests support a diverse array of associated species and provide ecosystem services to human communities. Mangroves cannot tolerate extreme freezing temperatures and so are generally limited to tropical environments. However, climate change in the form of increasing temperatures has the potential to facilitate increases in mangrove abundance near tropical–temperate transition zones. Here, we use 28 y of satellite imagery to demonstrate that increases in mangrove area have already occurred along the northeast coast of Florida. These increases correspond to decreases in the frequency of extreme cold events in this region. We also identify a temperature-related ecological threshold of -4°C . These results suggest that landscape-scale increases in mangrove area may occur in other regions where this threshold is crossed.

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(Table 1). We examined changes in land cover to determine whether eutrophication from agricultural or urban runoff could be linked to increases in mangrove area. This analysis would also capture large-scale revegetation of abandoned agricultural lands by mangroves if it were occurring. It is unlikely that regional-scale increases in mangrove area would arise from local scale changes in nutrient inputs, sedimentation, or hydrology, as these local drivers typically have local scale impacts (37, 38). Another alternative is that sea level rise has contributed to inland expansion of mangroves across our study area (30). However, this mechanism does not create the positive relationship between latitude and increase in mangrove area we observed. No significant latitudinal variability in sea-level changes along the east coast of Florida has been recorded over the past 50 y. According to National Oceanic and Atmospheric Administration (NOAA) data, mean sea level trends for tidal stations in Miami Beach, FL (25.8°N), Daytona Beach, FL (29.2°N), and Mayport, FL (30.4°N), have been 2.39 ± 0.43 mm/y, 2.32 ± 0.63 mm/y, and 2.40 ± 0.31 mm/y, respectively (39). In addition, there was no latitudinal trend in the amount of low-elevation habitat vulnerable to inland expansion by mangroves (*Methods* and Fig. S1A) and no significant relationship between change in mangrove area and the amount of this low-elevation habitat ($r = 0.19$; $P = 0.44$; Fig. S1B). In fact, the coast of southern Florida is expected to experience particularly large increases in mangrove area as a result of sea level rise (40). However, we found the opposite pattern: over the past 30 y, mangrove area has decreased marginally in southeast Florida and increased dramatically in northeast Florida.

Although reductions in the frequency of extreme cold events are facilitating an expansion of mangrove forests poleward, these forests face a number of other local- and regional-scale threats such that the net change in global mangrove area may be negative in the near term. Coastal development, aquaculture, and timber production are driving mangrove deforestation losses of 1% to 2% per year (19, 20). Other aspects of climate change are expected to cause reductions in mangrove area. For example, decreases in precipitation and increases in temperature may decrease mangrove survival in some arid regions, and rising sea levels may threaten 10–20% of mangroves by 2100 (41). To the extent that inland habitat is suitable, these losses may be offset by landward migration of mangroves. However, accelerating coastal development may eliminate the potential for landward migration in many areas. Replacement of coastal wetland foundation species, whether salt marsh or mangrove, will dramatically alter the structural complexity, community composition, food web dynamics, nutrient cycling, carbon sequestration, water filtration, and stability of these sensitive coastal environments.

Methods

Our study area included the entire east coast of Florida from 25°N to 30°N (Fig. 1A). Most of this area lies within the Indian River Lagoon, a drowned river valley where subtropical and temperate climatic zones converge. Coastal wetlands in this region receive large nutrient inputs from runoff, canals, and rivers draining agricultural and urban development. Salt marsh wetlands in the region are vegetated by short-statured herbaceous plants, including *Spartina alterniflora* (smooth cordgrass) and *Spartina bakeri* (sand cordgrass) in the low intertidal and *Distichlis spicata* (saltgrass), *Salicornia virginica* (glasswort), *Batis maritima* (saltwort) and *Suaeda* spp. (seablite) in the high intertidal. Meadows of *Juncus roemerianus* (needlegrass rush) and *Borrchia frutescens* (bushy sea ox-eye) are also common in the high intertidal. Mangrove wetlands in this area are dominated by one to three species of short to medium-sized trees, including *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove).

We measured mangrove area along the east coast of Florida (25°N to 30°N) each summer from 1984 to 2011 by using 30-m resolution multispectral Landsat 5 Thematic Mapper satellite imagery. All three species of mangroves found in Florida (*A. germinans*, *L. racemosa*, and *R. mangle*) were grouped together in our analysis. We were unable to obtain imagery of the entire

coastline in 1985, 1992, 2009, and 2010 because of excessive cloud cover during the Landsat acquisitions. After atmospherically correcting the Landsat images (42), we identified potential mangrove habitat from a 2010 mangrove atlas (43). We then used spectral mixture analysis to determine how much potential habitat was covered by mangrove forest in each image (44). Each pixel of potential mangrove habitat was modeled as a linear combination of three endmembers: photosynthetic vegetation (which we assume to be mangrove), water, and bare soil. These endmembers were represented by pure pixels of each of the three land cover types. The result of this process was a measure of the fraction of each pixel that was covered by mangrove forest. To validate our Landsat based estimates of mangrove area, we identified nine distinct contiguous stands of mangroves and compared our Landsat estimates of the area of each stand to area estimates made from high-resolution (1 m) IKONOS imagery. Mangrove canopy area was identified manually on the IKONOS image; mangrove trees were easily distinguished at this resolution. We also conducted a field survey in March 2013 to validate our interpretation of the IKONOS image. During the survey, we used GPS to identify locations of pure mangrove and salt marsh stands. The GPS points matched our manual interpretation of the IKONOS image, and the Landsat estimates of the area of nine distinct mangrove stands aligned closely with the high-resolution IKONOS estimates (Fig. S2). In addition, a number of previous studies in mangroves have demonstrated strong relationships between satellite-based vegetation indices, canopy closure estimates, and other estimates of canopy cover (45–48).

Mangrove area (as estimated by Landsat) was summed into 0.25° latitudinal bins (~30 km) to examine latitudinal changes in mangrove extent. To determine long-term changes in mangrove area, we calculated the percent change in the 5-y mean of mangrove area from 1984–1988 to 2007–2011 for each latitudinal bin. We used 5-y means to average out short-term variability in mangrove area. We compared changes in mangrove area to latitude by using piecewise linear regression (49) in the R package “segmented” (50).

We obtained direct observations of daily temperature from 1984 to 2011 from 9 coastal National Weather Service stations that ranged in latitude from 25°46'N to 30°20'N (Table S2). We calculated three temperature metrics for each year of the time series: mean annual (July to June) temperature, mean winter (December to February) temperature, and the number of extreme cold events each year (July to June). Extreme cold events were defined as days when the temperature decreased below some threshold. We created 15 different extreme cold event variables by varying this threshold from -1 to -8 °C in 0.5° increments. We then compared changes in these temperature variables to changes in mangrove area by using linear regression and correlation analyses (Figs. S3 and S4). We also compared annual changes in mangrove area to the minimum winter temperature experienced during the intervening winter.

To test hypotheses other than temperature that may explain variation in mangrove area changes, we also compared changes in mangrove area to changes in precipitation and land use (Fig. S4). We obtained mean annual precipitation data from the same weather stations from which we acquired temperature data. We used Landsat-based land cover products developed by the Florida Fish and Wildlife Conservation Commission for the years 1985 and 2003 to examine land use change across our study area (51). Although the temporal coverage of our land use change data did not precisely match that of our mangrove data (1984–2011), most of the increases in mangrove area in the northern latitudes of our study area occurred before 2003 (Fig. 2). As a result, if land use change was a driver of mangrove change, its impact would likely be apparent by 2003. For each 0.25° coastal latitudinal bin, we calculated the change in area of urban and agricultural land cover from 1985 to 2003 for the watershed (52) that contained that 0.25° of coastline. Changes in urban and agricultural land cover were normalized by watershed area. Changes in the number of extreme cold events were not significantly correlated with changes in mean annual temperature, mean winter temperature, annual precipitation, urban land cover, or agricultural land cover ($P > 0.10$ for all pairwise comparisons). To test for a latitudinal trend in the amount of coastline vulnerable to inland mangrove expansion as a result of sea-level rise, we estimated the amount of coastal habitat with an elevation between -0.1 and 1 m above sea level for each 0.25° latitudinal bin. We obtained digital elevation data from the NOAA National Geophysical Data Center's US Coastal Relief Model (53).

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