Forecasting effects of sea-level rise and windstorms on coastal and inland ecosystems

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We identify a continental-scale network of sites to evaluate how two aspects of climate change – sea-level rise and intensification of windstorms – will influence the structure, function, and capacity of coastal and inland forest ecosystems to deliver ecosystem services (eg carbon sequestration, storm protection, pollution control, habitat support, food). The network consists of coastal wetland and inland forest sites across the US and is representative of continental-level gradients of precipitation, temperature, vegetation, frequency of occurrence of major windstorms, value of insured properties, tidal range, watershed land use, and sediment availability. The network would provide real-time measurements of the characteristics of sea-level rise and windstorm events and would allow an assessment of the responses of wetlands, streams, and inland forests at spatial and temporal scales associated with sustainability of ecosystem services. We illustrate the potential of this approach with examples of hypotheses that could be tested across the network.

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Two components of climate change likely to have a disproportionate effect on the biosphere are rising sea level and increased frequency and intensity of windstorms (eg hurricanes, typhoons, extra-tropical storms). Within the context of ecosystem connectivity, the effects of climate change will extend from the coastal zone throughout much of the continent and will vary regionally. These regional effects will be modified by human activities, particularly those that influence the delivery of sediments and nutrients from watersheds. They will, in turn, affect the functioning of coastal wetlands and barrier islands and their capacity to buffer continental landmasses from the ravages of intense windstorms and sea-level rise (Bortone 2006; Cahoon 2006; Greening *et al.* 2006; Stanturf *et al.* 2007).

In a nutshell:

- We identify a continental-scale network of coastal and inland sites to evaluate how two aspects of climate change, sea-level rise and intensification of windstorms, will influence the structure, function, and capacity of coastal and inland forest ecosystems to deliver services
- The network is representative of continental-level gradients of precipitation, temperature, vegetation, frequency of occurrence of major windstorms, value of insured properties, tidal range, watershed land use, and sediment availability
- The precision and extended scale of this network would enhance our capacity to model climate-change scenarios in association with other landscape changes that disrupt ecosystem services for long periods, including land use, soil movements such as landslides, sediment delivery to the coast, forest fragmentation, and flooding

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Globally, sea level has risen between 10 and 25 cm over the past century, primarily because of a net input of water (ie eustatic sea-level rise or ice melt; Rahmstorf *et al.* 2007) and thermal expansion (ie steric sea-level rise or water warming). This rate of rise is an order of magnitude greater than that of the past several millennia (Douglas *et al.* 2001). Observed trends in relative sea level (level of the sea relative to local landmass) vary across the North American continent (Figure 1), however, from very large increases along the Gulf coast (exacerbated by tectonic subsidence, sediment compaction, and oil and gas extraction; eg Morgan 1970; Penland and Ramsey 1990; Morton *et al.* 2003) to decreases in parts of the Pacific Northwest (plate subduction and uplift). Changes in Alaska are thought to be the result of tectonic uplift (eg Aleutians) or crustal rebound following glacial melting. The projected sea-level rise for the mid-Atlantic is 10–31 cm by 2030 and 40–102 cm by 2095 (IPCC 2001); the rate of rise for the past 20 years (to 2006) is 25% faster than the rate in any 20-year period over the past 115 years (Rahmstorf *et al.* 2007).

Coastal wetlands and upland forests are also impacted by intense, ocean-originating storms. These are mainly hurricanes and typhoons that build on energy from the release of heat stored in seawater, but also include more

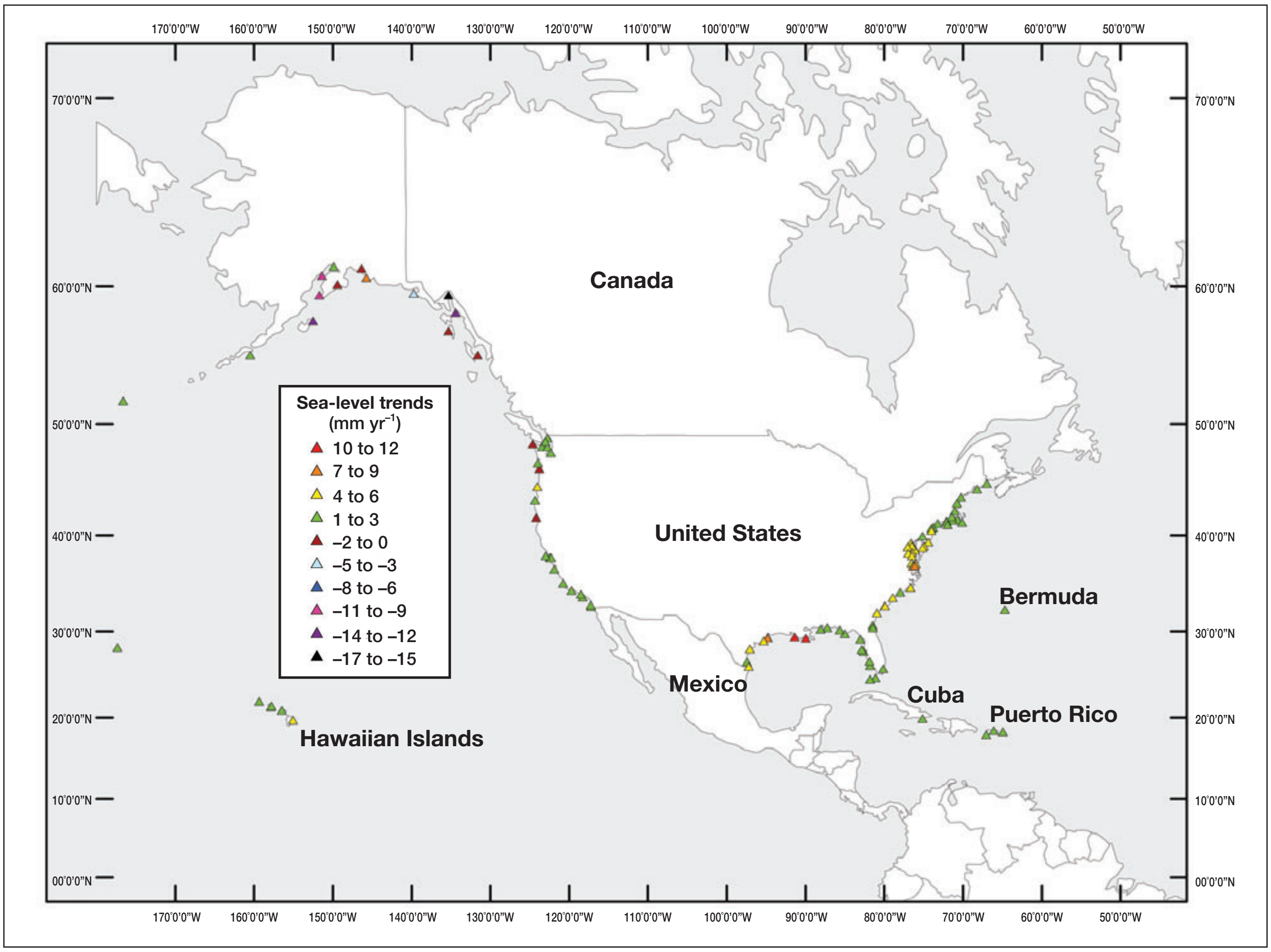

Figure 1. *Sea-level trends around portions of North America (http://tidesandcurrents.noaa.gov/sltrends/slrmap.html). Modifications courtesy of J Carpenter.*

frequent extra-tropical cyclones that affect both the east and west coasts of the US. Extra-tropical cyclones form from poleward-moving tropical systems or from strong temperature gradients between air masses (baroclinic storms, such as nor'easters). Hurricanes control climate by dissipating energy from low latitudes to high latitudes and can move enormous quantities of water from the low latitudes into the middle and high latitudes. Much is known about the characteristics and forecasting of hurricanes and extra-tropical storms (Diaz and Pulwarti 1997; Goldenberg *et al.* 2001; Webster *et al.* 2005; Holland and Webster 2007). Both types of storms, and the surf they create, are predicted to increase in intensity due to global warming (IPCC 2007). Hurricane frequency in the North Atlantic basin may also increase (Holland and Webster 2007), but a scientific consensus for this prediction has still not developed (IPCC 2007; Bengtsson *et al.* 2007 a,b; Boissonnade *et al.* 2007; Vitart and Doblas-Reyes 2007). Hurricanes change in character with geography, typically becoming weaker as they move northward or inland, but historic hurricane tracks have shown effects as far inland as the Great Lakes (Neumann *et al.* 1978). A large fraction of the US mainland, all of Puerto Rico, and the US Virgin Islands are currently exposed to 4- to 35-year return periods for hurricanes (Figure 2; Neumann *et al.* 1978), which translates to 2–16% probabilities of being in the direct path of a hurricane in any given year (Crossett *et al.* 2004). Storm events vary from year to year, with interannual and decadal oscillations associated with El Niño–Southern Oscillation (ENSO; El Niño/La Niña sea-surface warming) and other climatic oscillations.

Climate exerts broad-scale control on coastal intertidal wetlands (marshes and mangroves) that varies through interactions with local-scale processes (Michener *et al.* 1997; Figure 3). Sea level sets the minimum elevation for an emergent wetland, but land use and ocean use, as well as storm disturbance, can affect the physical and biological processes that deliver sediment to the coasts and allow material to accumulate. Although inland forests are not directly affected by sea-level rise (SLR), there is a connection in that coastal wetland loss increases the vulnerability of inland ecosystems (and humans) to storm disturbance. It is therefore critical to develop a predictive understanding of the ability of coastal wetlands to persist in the future, particularly in light of the continental-scale processes and feedbacks that control this response.

The wind and rain generated by ocean-originating storms affect upland forests in multiple ways. The immediate effects of hurricanes on forest structure and nutrient cycling have been described (eg Everham and Brokaw 1996). However, the ecological, hydrological, geomorphological, and geochemical effects of hurricanes, intense rainfall, and related windstorms are not well understood (Walker *et al.* 1991, 1996). There is even less knowledge about inland impacts and long-term continental effects of hurricane passage, particularly under a regime of increased storm intensity (eg Gerald *et al.* 2006; Slutzman and Smith 2006; Knight and Davis 2007; Stanturf *et al.* 2007).

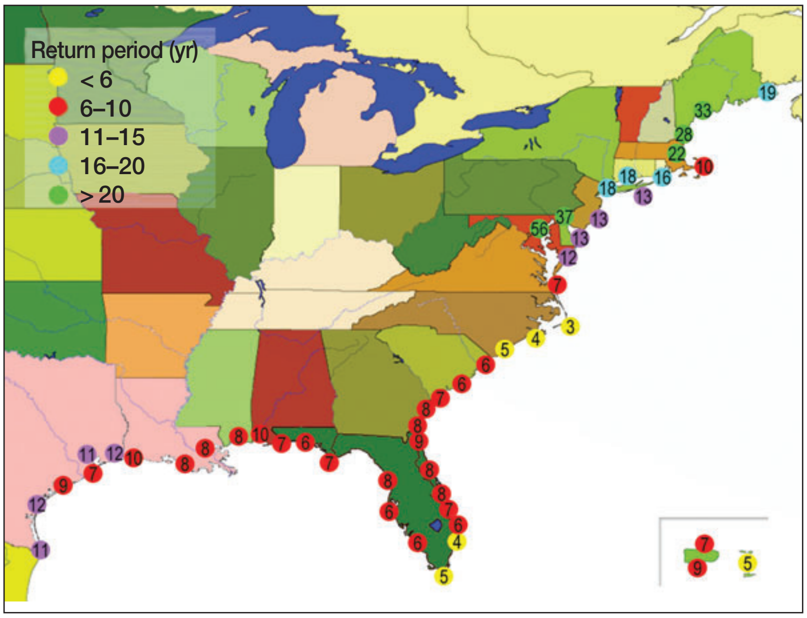

Figure 2. *Return period for a Category 1 or stronger hurricane on the US east coast and the Caribbean (Blake* et al. *2006, with data for Puerto Rico and US Virgin Islands courtesy of C McAdie, National Hurricane Center).*

Predicted alterations to coastal wetlands and inland forests will affect their ability to provide ecosystem services in the future. Coastal intertidal wetlands provide services unrivaled among natural environments, including waste assimilation, food-web support for fish and shellfish, and wildlife habitat. Ecosystem services derived from inland forest habitats, such as carbon sequestration, nutrient retention, maintenance of water quality, and prevention of sediment erosion, can be severely affected by storm events. Addressing questions of climate effects is important because, over the long term, these events shape the structure, function, and species composition of coastal ecosystems at local to regional scales. These changes will also affect the habitability of the coastal zone, which is one of the most developed areas on Earth; more than 53% of the US population now lives in coastal counties, which comprise only 17% of the total land area of the US (Crossett *et al.* 2004). In addition, we do not have a good understanding of the connection that exists between storm events and disease vectors (not limited to human diseases), in terms of the numbers of individuals transported, changes in strains, transmission rates, virulence, and the possibility of spread of invasive non-native species.

Here, we provide a conceptual framework and guidelines for development of a network of coastal observatories to understand and predict the effects of SLR and major storms on coastal wetlands and forests. Monitoring programs have been proposed previously to explore the relation between SLR and barrier island erosion (Leatherman *et al.* 2003). A predictive understanding can be reached through a comparative analysis, across major continental gradients, of climate, topography, geology, pollution, land use, latitude, biogeographic province, tidal range, human habitation, SLR, and hurricane frequency. By combining observations from across a continental network of sites with experimentation and modeling, we would be able to address the following types of scientific questions:

Status and trends: What are the continental-scale trends and predictions for SLR and coastal wetland persistence? What are the transcontinental effects of, and responses to, hurricanes and other intense storms? How will the vulnerability of human property and institutions to wetland loss and intense storms in the coastal zone compare and change across gradients in population density, geology, and topography?

Ecosystem processes: What ecosystem attributes affect the ability of an area to withstand changes in storms or sea level, and how do these feed back into climate cycles? What factors control the limits to vertical accretion of coastal wetlands and the rate and type of regeneration in forests? How do changes in intensity, spatial distribution, and frequency of intense windstorms affect ecosystem attributes? How do changes in sea level and storm dynamics interact with the spread of invasive species?

Ecosystem services: How will changes in sea level and storms alter the capacity of coastal wetlands and inland forests to deliver ecosystem services to humans and contribute to sustainability? What are the continental-scale implications of coastal wetland loss for carbon sequestration, commercial fisheries production, and wildlife habitat? How will storm damage in inland forests (soil erosion, water retention, nutrient export) affect coastal systems?

Human interactions: How will regional changes in the export of water, nutrients, and sediments interact with climate change to affect the ability of

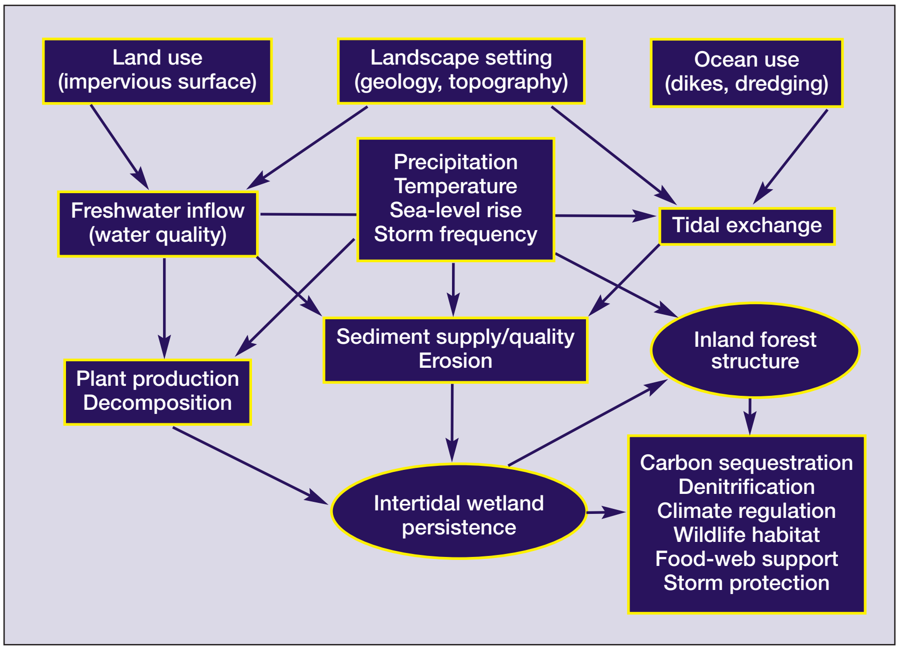

Figure 3. *Conceptual model of factors influencing the persistence of coastal wetlands, the ecosystem services they provide, and their link to inland forests.*

intertidal wetlands to maintain areal extent and elevation relative to SLR? How will wetland loss, increased frequency of intense windstorms, and increased destruction of human property affect the displacement of people and their settlement patterns at the continental scale? Will SLR and storm dynamics render currently settled coastal areas uninhabitable or uninsurable?

Why a continental-scale analysis is required

At present, we lack the knowledge needed to predictively map responses of coastal and upland systems to SLR and intense windstorms. The controlling factors do not vary linearly along the coast or across the country; rather, most factors vary at regional and even local scales. In addition to variations in the rate of SLR, there are also strong spatial variations in other drivers, including tidal range, marsh flooding frequency, and sediment delivery. While the frequency of storm occurrence follows a relatively smooth gradient, forest stature and structural complexity differ greatly across the continent. Thus, we can expect tremendous variability in ecosystem response at all spatial scales. It is not enough to study one site and thereby understand outcomes across the country: a doubling of the hurricane probability in Massachusetts would equal the current probability in Puerto Rico, but there is no reason to expect that New England temperate forests would respond in the future in the same way that subtropical moist forests respond at present.

Patterns at broad scales can be driven by fine- to broad-scale processes, so that understanding and predicting continental-scale dynamics requires analysis across a range of scales. For example, the deltaic wetlands of the Mississippi River are influenced by broad-scale patterns of climate (including hurricanes), topography, geology, and land use that control sediment erosion and transport to the coastal zone. They are also influenced by a combination of small-scale patterns, such as channelization and levee construction along the river and through wetlands, which control the distribution and deposition of sediments. The present and future condition of Louisiana's wetlands at the mouth of the Mississippi will reflect the interaction of these broad- and fine-scale processes. We can develop this example further from the perspective of hurricanes, where the spatial extent of coastal wetlands and their condition will directly influence the potential storm damage to inland regions. There are feedbacks as well: the greater the disruption of this coupled human–natural system along the Gulf coast, the greater the disruption at broader scales (eg as people are evacuated and oil refineries shut down). Thus, to fully understand the effects of SLR and intense storms on coastal systems, we must examine patterns and processes across a range of spatial scales.

Approach to developing a continental-scale network

Here, we apply a new strategy for experimental design (Peters *et al.* [2008] in this issue) to address the effects of SLR and storm disturbance. The design strategy consists of three steps.

Step 1: Identify continental-scale gradients

We advocate establishing a network of sites across four gradients within 200 km of the continental margin of North America. The four gradients include two latitudinal gradients (one along the east coast and another along the west coast) anchored by tropical and Arctic regions, and two coast-to-inland gradients (one on the east coast and one on the Gulf of Mexico coast; Figure 4). For coastal wetlands, these gradients subsume the standard coastal biogeographic provinces of the US.

Step 2: Define gradients for key ecosystem drivers and identify sites spanning these gradients

Coastal gradients

A combination of several gradients dictates coastal wetland characteristics and their likely response to SLR. The coastal sites network must therefore include the full range of conti-

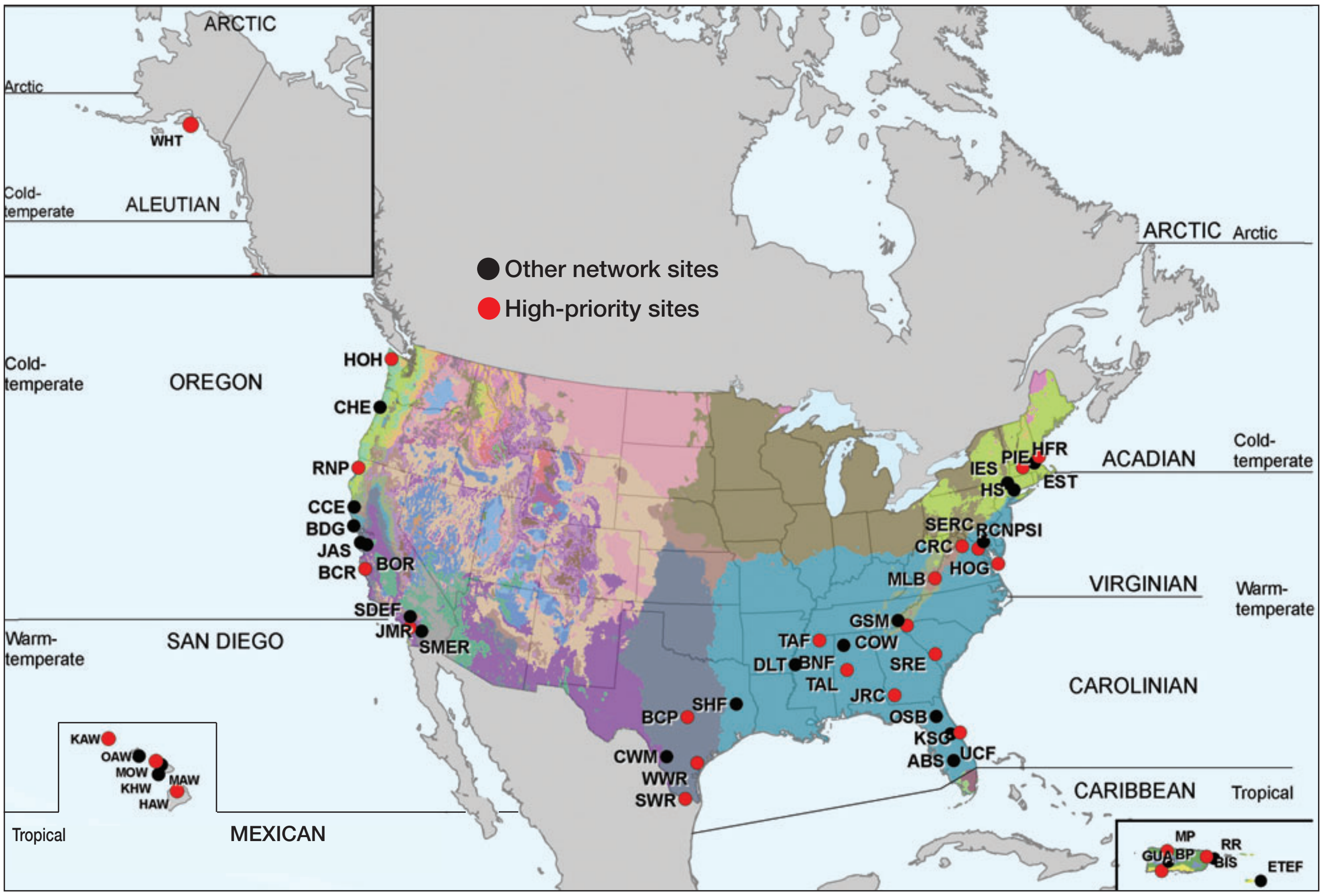

Figure 4. *The distribution of continental ecoregions and coastal biogeographic provinces and climates of North America, showing several of the major gradients that must be included in a continental-scale network. Potential inland forest sites are shown as red dots, along with other sites from several existing networks, which are shown as black dots. Potential coastal wetland sites are not shown here but would extend across all coastal biogeographic provinces and climate zones. Biogeographic provinces and climates from Briggs (1974) and Hayden and Dolan (1976).*

nental gradients in sediment export and supply (reflecting continental patterns in geology, topography, climate, and land use/land cover), tidal range (0.3–8 m), precipitation (20–182 cm yr^{-1}), temperature (4–26°C), and salinity (20–90 practical salinity units). These gradients result in wetlands dominated by marsh grasses in temperate areas (eg *Spartina patens* in the northeast and *Spartina alterniflora* in the southeast) and by mangrove trees (eg *Rhizophora, Avicennia*, and *Laguncularia*) in the tropics. This broad coverage will allow a rigorous assessment of the status and trends of wetland response to SLR across the full spectrum of factors that control wetland accretion or erosion. Data from these observatories will be critical for developing and testing predictive simulation models of the effects of SLR on coastal wetlands.

Inland forest gradients

To study the effects of windstorms, one must be in the right place at the right time. A network of inland forest sites should be arrayed across regions where the passage of windstorms is likely to occur. The network must address local and regional gradients in climate, topography, geology, and land use (eg rural to urban and wild to managed). Given the probabilities of storm occurrence computed from return periods shown in Figure 2, a network of 25 sites spread over the eastern US will likely experience 75 storm and 23 hurricane events over a 30-year lifespan. This sample size will permit development of a database capable of addressing a wide range of questions about hurricane effects, which can then be used in predictive models. We expect a similar probability for severe windstorms on the west coast.

Step 3: Observational infrastructure and spatial configuration

We envision a network of sites monitored with a combination of in-situ sensors, discrete samplings, and remote sensing. We suggest a "catchment" layout of instrumentation, to facilitate examination of both vertical and horizontal biogeochemical flowpaths.

■ Coastal wetlands

The basic geographic unit of study for coastal wetlands should be a tidal marsh "creekshed", which includes a first- or second-order tidal creek and the marsh platform flooded

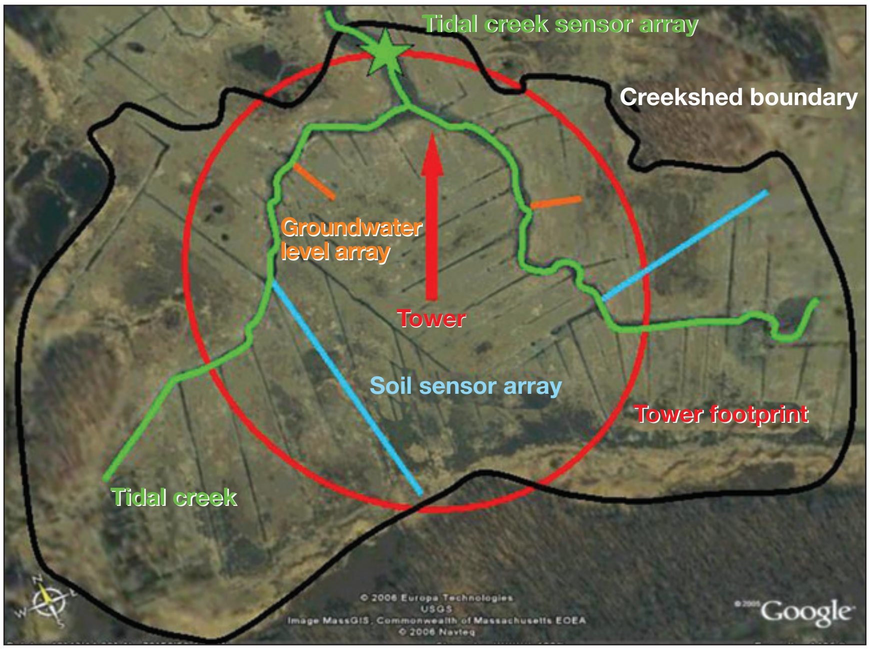

Figure 5. *Physical layout of infrastructure in a generic tidal creekshed. Such a layout, including remote sensors based on a tower, can provide the framework for developing a predictive understanding of the factors contributing to coastal wetland condition over time.*

by that creek's tidal water at mean high tide (Figure 5). The study unit should include adjacent uplands, if present locally. Detailed observations and experiments at these sites can facilitate examination of land–water linkages and land–atmosphere and internal fluxes. Thus, instrumentation and sampling should be laid out to capture mass fluxes of water, sediment, nitrogen, and carbon between marsh/water and the atmosphere, between the creek bank and inland marsh, between the marsh platform and its tidal creek, and between the marsh surface and buried sediments. A mass balance augmented with remote sensing will enable us to fully characterize the net accretion of a marsh and the processes contributing to its gain or loss. Real-time hyperspectral remote sensing from a tower at the site can provide temporal information on plant species composition, plant condition, and plant biomass. Aerial remote sensing can be used to extend the results to broader regions, to define the change in extent of intertidal wetlands and estuaries, to examine boundary conditions (eg human infrastructure and coastal armoring, coastal distribution of sediment), and to test predictions spatially.

Coastal inland forests

Because the passage of a windstorm is a probability event, we need sufficient instrumentation capacity to assess expected changes in forest structure and functioning over large land areas and long time periods. Measurements should include a complete suite of environmental characteristics, gas exchange, hydroecology, and telemetry of organisms before, during, and after events. Key processes and systems to examine include: plant and soil respiration, plant photosynthetic rates, primary productivity, whole ecosystem gas exchange, and alterations to the water budget and dry deposition. Rapidly deployable instruments would be placed in the likely path of oncoming storms to obtain real-time and site-specific measurements of storm intensity at a landscape scale. High-resolution remote sensing data for the whole path of the storm (coast to upland forests) collected at intervals of weeks to months to years after the storm will complete the assessment of effects and recovery patterns, and extend the understanding gained from site-level measurements. From these sources, we can develop landscape change maps to assess recovery after each major event.

Hypotheses

We offer examples of the types of hypotheses that could be addressed with a continental-scale network as described here.

Hypothesis 1: Areas with limited ability for wetland migration will see marked reductions in the provision of ecosystem services and will be increasingly vulnerable to intense storm damage in the future. By extension, human communities that have the most limited potential for migration will incur the greatest structural, cultural, and economic losses from SLR and storms.

In the absence of humans and their engineering works, it might be relatively straightforward to predict future shorelines and wetland distribution, but the ability of humans to modify coastal topography greatly complicates predictions. We expect that coastal regions with steep topography (eg west coast) or with high population densities (eg urban centers such as Charleston, South Carolina), will see a marked decrease in both estuarine and wetland areal extent as sea level rises, because transgression will be restricted. This will reduce the storm buffering service provided by coastal wetlands and thereby increase the vulnerability of human systems, which will, in turn, have continental-scale ramifications, as resources are expended to protect, repair, and distribute people and their infrastructure following storms.

Hypothesis 2: The capacity of coastal wetlands to maintain elevation relative to sea level will decrease as the rate of SLR increases, as climate warms and droughts become more severe and frequent, and as continental sediment and nutrient inputs change.

Primary factors controlling wetland accretion are vegetative sediment trapping, sediment availability, and peat accumulation. These factors, in turn, are controlled primarily by climate, continental land use, and SLR. We expect that areas likely to experience the most severe wetland degradation and loss are situated where sediment supply is reduced as a result of reforestation and erosion control management in the continental interior and where the wetland balance between gross primary production and respiration is shifted toward respiration due to climate, nitrogen deposition, and runoff (ie less root and peat production). Drought will greatly contribute to wetland loss, as it can kill wetland vegetation (peat production), while only temporarily slowing decomposition (peat decomposition and negative accretion). Shifts in vegetation structure induced by climate change (eg northward expansion of mangrove trees) have the potential to decrease wetland sediment trapping ability. Regional differences in the levels of change expected for factors controlling wetland accretion will result in varying rates of wetland loss at continental scales.

Hypothesis 3: Windstorm strength, duration, and capacity to impose ecosystem change will diminish with latitude, but windstorm effects will increase.

Energy dissipation per unit area and time will be less at high latitudes than at low latitudes. Therefore, given the same storm frequency and forest structure, we would expect forests at higher latitudes to incur less damage. However, we know that ecosystem structure is at least partially determined in response to disturbance regimes. Increased intensity and/or frequency of windstorms may therefore result in increased damage at higher latitudes, given a lack of adaptation to high winds among most native species, a greater time since last occurrence of high-wind disturbance, and greater dominance by non-sprouting conifer species. In contrast, resilience may be greater at lower latitudes, due to the greater capacity of native species to recover rapidly and adapt to avoid long-term damage.

Hypothesis 4: The capacity of forest ecosystems to support human activities will change with increasing windstorm frequency and magnitude, and rainfall intensity, because of directional changes in species composition and ecosystem structure. Increasing storm frequency will also accelerate the rate of ecosystem change.

Long-term changes in storm frequency and intensity represent fundamental changes in the conditions that shaped modern forests. Rainfall from tropical hurricanes has increased over much of the Southeast, while non-tropical hurricane rainfall has remained largely unchanged (Knight and Davis 2007). Forest responses to gradual change in these major drivers will involve shifts in species composition and vegetation structure, which will cascade downward to phenological patterns, biogeochemical characteristics, and watershed dynamics (Batista and Platt 2003; Boutet and Weishampel 2003; Zhao *et al.* 2006). Such changes will probably affect the rates and types of services that humans derive from modern forests, rivers, coastal wetlands, and riparian ecosystems. For example, the economic costs associated with these recent cumulative disturbances can exceed $3 billion in diminished supplies of timber, lost protection of watersheds that provide essential water resources to society, reduced sequestration of carbon by old-growth forests, and extensive loss of property and human lives (Sturdevant-Rees *et al.* 2001; McNulty 2002; Stanturf *et al.* 2007).

Cyberinfrastructure and modeling for synthesis and outreach

The observational network advocated here will result in the collection of large amounts of data; this will require building capacity for data acquisition, management, and curation. We can look to several existing or proposed large-scale programs for guidance along these lines, including the Long Term Ecological Research network (LTER), the National Center for Ecological Analysis (NCEAS), and the National Ecological Observatory Network (NEON).

Modeling should play an integral role in evaluating the effects of SLR and intense windstorms on ecosystems. There are already numerous coastal models, ranging from fine-scale plant growth to coarse-scale geomorphology models (eg Morris 1982; Sklar *et al.* 1985; Gardner 1990; Konisky *et al.* 2003; van de Koppel *et al.* 2005; Lightbody and Nepf 2006) and models that describe hurricane winds, wind interactions, and forest community and population dynamics (eg EXPOS and HURRECON, Boose 2004; JABOWA, Botkin 1993; or SORTIE, Pacala *et al.* 1993). The challenge will be to link these models with newer, continental-scale models (eg land-use change and landscape models) and ocean and atmospheric models. The combined models should make use of data from the continental network to synthesize the various data sources into a single, internally consistent representation of the monitored ecosystems and to project the results in both space and time (Rastetter 1996). New visualization techniques will help to convey long-term forecasts and display landscape-change scenarios that are normally challenging to communicate to the general public.

At the national level, climate change was recently identified as a major research priority by the National Science and Technology Council Joint Subcommittee on Ocean Science and Technology. The scientific knowledge to be gained through data analysis and predictive modeling will be of value for analyzing ecosystem properties and determining risk and response to sea-level rise, marsh degradation, and storm events. What makes this network initiative unique is its emphasis on ecological feedbacks and its continental-scale scope, which will allow observations in coastal wetlands and inland forests to be evaluated in the context of broad-scale drivers, such as global climate cycles and upstream land-use decisions.

Useful products will include real-time data on the inland extent of storm damage, remote sensing imagery that can be used to visualize the effects of SLR on coastal wetlands, risk-assessment models, and simulations that explore the linkages between upstream management decisions and coastal wetland processes.

Conclusions

Inland forests and coastal wetlands provide important ecosystem services, which will be compromised given the predicted increases in sea level and the severity and frequency of intense windstorms. The development of a continental-scale network of sites is necessary to document trends and better understand the mechanisms whereby SLR and intensification of windstorms alter the structure, function, and capacity of these systems to deliver services. New models and visualization techniques will be required to transfer scientific knowledge gained from the network of observatories to the public at large, resource managers, and policy makers. The network's strength and promise lies in its focus on ecological and land-use feedbacks and its continental-scale scope, which will allow observations in coastal wetlands and inland forests to be evaluated in the context of broad-scale drivers, such as global climate cycles and upstream land-use decisions.

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