Climate change and sea level rise impacts on mangrove ecosystems

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Mangrove forests are tropical intertidal habitats and are extensively developed on accretionary shorelines. There are 34 species of mangrove trees, in addition to three hybrids, with the centre of diversity being in southern Papua New Guinea. There is a decline in diversity from west to east across the Pacific, reaching a limit at American Samoa, while Atlantic mangrove species diversity is relatively poor. Global distribution is controlled by the 20°C isotherm, with diversity, forest height and associated productivity declining with increasing latitude away from the equator.

Sea level rise poses a major threat to mangrove ecosystems through sediment erosion, inundation stress and increased salinity at landward zones. These problems will be exacerbated for mangrove stands that are subjected to 'coastal squeeze', ie where landward migration is restricted by topography or human developments. Increased air temperatures and atmospheric CO_2 concentrations are also likely to increase mangrove productivity, change phenological patterns, and expand the ranges of mangrove forests into higher latitudes.

Mangroves can provide important services for adjacent ecosystems, and also supply many useful products to human societies. For example, mangroves provide (1) nursery habitats for many species of fish and invertebrates that spend their adult lives on coral reefs, (2) sediment trapping to sustain offshore water quality for coral reefs, (3) protection for inland sites from storm surges and flooding, (4) building materials, (5) traditional medicines, (6) firewood and (7) food. As human populations have expanded, the shortage of productive land in many developing countries has led to the clearance of large areas of mangrove for agriculture and aquaculture production. Demands for timber (for charcoal, building etc) and coastal development space have also been highly damaging. Mangrove forests in some areas have been reduced to mere relicts of their former ranges as a result of human exploitation. In addition to these pressures, mangroves are threatened by sea level rise, projected between 0.9 and 8.8 mm/year. Although there are several factors important in determining patterns of mangrove advance or retreat, studies have shown that mangroves are closely controlled by sea level elevation at their seaward margin.

Mangrove species display a distinct zonation from low to high water, based on controls including the frequency of inundation and salinity exposure. This is controlled by the elevation of the substrate surface relative to mean sea level. Hence mangrove substrates can keep up with sea level rise through vertical accretion. Some of this accumulation will be from organic matter production, but this can be augmented by external inputs of sediment from rivers. Rates of accretion reveal that mangrove ecosystems are highly vulnerable to projected rates of sea level rise. Mangroves of low relief islands in carbonate settings that lack rivers are probably the most sensitive to sea level rise, owing to their sediment-poor environments and hence poor rates of vertical accretion. Mangrove response to sea level rise has been investigated by reconstructing Holocene analogues in the Cayman Islands, Tonga and Bermuda. Radiocarbon dating of stratigraphy determined a peat accretion rate of 1 mm/year for all locations. Recession of mangrove forests and replacement by lagoon environments are shown to occur during more rapid sea level rise. On Grand Cayman, 20 km^2 of mangroves receded between 4080 and 3230 years BP. In Tonga, a large mangrove swamp that had persisted from 7000 to 5500 years BP, retreated when rates of sea level rise exceeded 1.2 mm/year.

In Bermuda, present rates of sea level rise exceed 1.2 mm/year, and contemporary recession of the seaward margin of mangroves has been demonstrated. The extensive coastal mangrove swamps of southern New Guinea (Irian Jaya) are also retreating from rising sea level. This demonstrates that, while low island mangroves are likely to be the most sensitive to sea level rise, continental margin mangroves will also suffer disruption and retreat. Mangroves have the capacity for extensive establishment under conditions of stable sea level, but are highly prone to retreat under conditions of sea level change.

Linking temperate and arctic zones: managing the coast for migrant birds

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Arctic zones and low-lying coastal areas are amongst the regions that are most vulnerable to the impacts of climate change and associated sea level rise. Migrant bird species that move between arctic and coastal temperate regions on an annual basis may thus face dramatic changes to the habitats that they use at both ends of the migratory range. This is particularly true for the many high arctic breeding species that are almost entirely restricted to intertidal habitats in temperate zones during winter. Coastal management in temperate zones for migratory birds must therefore take account of both breeding and winter season processes, and any interactions between the two.

Changes in climate and sea level can potentially influence bird populations through a suite of direct and indirect routes in both the breeding and wintering seasons. For example, northward movement of the tree line in the arctic (Huntley *et al*., this volume) may reduce the area of tundra available for migrant birds at the same time that sea level rise and changing precipitation and temperature patterns may alter the structure or quality of temperate wintering areas. Whereas climate change and sea level rise may be the primary drivers of change in the arctic, in temperate zones policy responses to climate change are likely to have a more direct and immediate bearing on biodiversity. It is thus critical that policy decisions in the coastal zone are informed by species-level studies that address the complexity of the processes influencing population responses to climate change. Biodiversity conservation in temperate coastal zones is structured through a network of site designations, underpinned by national and international legislative frameworks (Figure 1). Decisions relating to the management and long-term sustainability of these sites are key in maintaining networks for migratory species.

Detailed studies of Icelandic black-tailed godwits, *Limosa limosa*, across the migratory range (Figure 2) have shown how site quality influences individual survival and breeding success and how these processes interact across locations thousands of kilometres apart. This information can be used to assess how changes to breeding and wintering habitats in response to climate change will influence population size and distribution. This provides a useful model for identifying the range of mechanisms by which climate change can influence migratory populations and for predicting population-level responses to climate change.

It is not, however, sufficient to consider the ecological responses of species to potential climate change in isolation. Coastal management for migratory species requires multi-disciplinary, integrated approaches in which models of structural changes to coastlines and consequent impacts on habitat structure and