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Invited Feature

Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change

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Abstract

This review assesses the degree of resilience of mangrove forests to large, infrequent disturbance (tsunamis) and their role in coastal protection, and to chronic disturbance events (climate change) and the future of mangroves in the face of global change. From a geological perspective, mangroves come and go at considerable speed with the current distribution of forests a legacy of the Holocene, having undergone almost chronic disturbance as a result of fluctuations in sea-level. Mangroves have demonstrated considerable resilience over timescales commensurate with shoreline evolution. This notion is supported by evidence that soil accretion rates in mangrove forests are currently keeping pace with mean sea-level rise. Further support for their resilience comes from patterns of recovery from natural disturbances (storms, hurricanes) which coupled with key life history traits, suggest pioneer-phase characteristics. Stand composition and forest structure are the result of a complex interplay of physiological tolerances and competitive interactions leading to a mosaic of interrupted or arrested succession sequences, in response to physical/chemical gradients and landform changes. The extent to which some or all of these factors come into play depends on the frequency, intensity, size, and duration of the disturbance. Mangroves may in certain circumstances offer limited protection from tsunamis; some models using realistic forest variables suggest significant reduction in tsunami wave flow pressure for forests at least 100 m in width. The magnitude of energy absorption strongly depends on tree density, stem and root diameter, shore slope, bathymetry, spectral characteristics of incident waves, and tidal stage upon entering the forest. The ultimate disturbance, climate change, may lead to a maximum global loss of 10−15% of mangrove forest, but must be considered of secondary importance compared with current average annual rates of 1−2% deforestation. A large reservoir of below-ground nutrients, rapid rates of nutrient flux and microbial decomposition, complex and highly efficient biotic controls, self-design and redundancy of keystone species, and numerous feedbacks, all contribute to mangrove resilience to various types of disturbance.

Keywords: climate change; disasters; disturbance; mangrove forest; resilience; tsunami

1. Introduction

Change is a natural attribute of Earth's ecosystems, with organisms responding and adapting to spatial and temporal patterns in climate and other physical characteristics, including tectonic events, atmospheric and oceanic circulation, and landform settings. Such biological and ecological changes are often the result of individual, population, or community attributes such as tolerance to physicochemical factors, the ability to compete for limiting resources, and functional processes (ingestion, growth, respiration rates). All of these changes occur within a milieu of natural disturbance to the ecological equilibrium or 'steady-state'. All ecosystems are subject to a variety of disturbances both natural and anthropogenic that vary in their duration, frequency, size, and intensity, and play a crucial role in facilitating adaptive change (Odum and Barrett, 2004).

Mangrove forests, like other ecosystems, are subject to various disturbances that vary in their intrinsic nature (e.g., geological, physical, chemical, biological) in time and space. Inhabiting the interface between land and sea at low latitudes, mangroves occupy a harsh environment, being daily subject to tidal changes in temperature, water and salt exposure, and varying degrees of anoxia. Mangrove forests and their inhabitants are therefore fairly robust and highly adaptable (or

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tolerant) to life in waterlogged saline soils within warm, subtropical and tropical seascapes.

Mangroves may therefore exhibit a high degree of ecological stability. The term stability has been variously used to refer to environmental constancy, community persistence, and community or ecosystem response to disturbance. Because the term stability conveys different meanings, I here use the terms persistence and resilience as defined by Boesch (1974) in reference to estuarine ecosystems. *Persistence* refers to constancy over time, regardless of environmental perturbation. *Resilience* means the ability to recover from disturbance to some more or less persistent state. This definition has more recently been termed *ecological resilience* (Gunderson et al., 2002) as opposed to *engineering resilience* which conceives of the speed of an ecosystem to return to a stable steady-state.

Mangrove forests currently occupy 14,650,000 ha of coastline globally (Wilkie and Fortuna, 2003), with an economic value on the order of 200,000−900,000 USD ha^{-1} (UNEP-WCMC, 2006). Regardless of their monetary value, mangrove ecosystems are important habitats, especially in developing countries, and play a key role in human sustainability and livelihoods (Alongi, 2002), being heavily used traditionally for food, timber, fuel, and medicine (Saenger, 2002). These tidal forests are often important nursery grounds and breeding sites for birds, mammals, fish, crustaceans, shellfish, and reptiles; a renewable resource of wood; and sites for accumulation of sediment, nutrients, and contaminants (Twilley, 1995; Kathiresan and Bingham, 2001; Manson et al., 2005). As addressed in this review, it is believed that mangroves offer protection from waves, tidal bores, and tsunamis, and can dampen shoreline erosion (Mazda et al., 2007).

Little attention has been paid to the adaptive responses of mangrove biota to disturbance (Smith, 1992; Ellison and Farnsworth, 2000). The lack of attention to disturbance-induced impacts likely reflects the perception that mangrove forests are in steady-state (Lugo, 1980) and are of generally low diversity. Mangroves have a variety of key features that contribute to their resilience to disturbance, whether they are acute disasters such as a tsunami or millennial change in climate. These characteristics are: (1) a large reservoir of below-ground nutrients that serve to replenish nutrient losses; (2) rapid rates of nutrient flux and microbial decomposition that facilitate rapid biotic turnover; (3) complex and highly efficient biotic controls (e.g., high rates of water-use and nutrient-use efficiency) that allow predominantly internal reuse of resources to augment recovery; (4) self-design and simple architecture that lead to rapid reconstruction and rehabilitation post-disturbance, despite different species composition; (5) redundancy of keystone species, or species legacies, which can lead to restoration and recovery of key forest functions and structure; and (6) positive and negative feedback pathways that provide malleability to help dampen oscillations during recovery to a more stable, persistent state. These tidal forests can attain immense biomass and height, rivalling the size of tropical rainforests; their standing crop is ordinarily greater than other aquatic ecosystems as equatorial forests often reach an above-ground weight of 300−500 t DW ha^{-1} (Alongi, 2002).

The objective of this review is to critically examine the resilience of mangrove forests to large-scale acute and chronic disturbance, especially climate change and, as illustrated by the events of 26 December 2004, to disasters such as tsunamis. Such disparate events are, of course, not causatively linked, but both are forms of disturbance that cause physical damage and may provide clues as to how mangroves will respond to disturbances in future. The review also addresses the related themes of the role of mangroves in protecting hinterland and future losses of forest in the face of these disparate disturbances.

2. Clues from the past: sea-level reconstruction and forest development

Most of today's mangroves rests upon the remains of their past—a reflection of the ebb and flow of Earth's history. The current position of the world's mangrove forests is a legacy of the Holocene (Woodruffe, 1992, 2002; Lessa and Masselink, 2006). When viewed across geological time scales, mangroves come and go at considerable speed. Ancestral mangroves can be traced back 65 million years (Duke, 1992), and vast tracts of forest have waxed and waned since then. Because of their location, mangrove forests are—like their environment—highly dynamic. They must not be viewed as static entities.

Over the last few thousand years, mangroves have undergone almost continual disturbance as a result of fluctuations in sea-level (Woodruffe, 1990, 1992; Yulianto et al., 2005). The general pattern for the last interglacial−glacial cycle is one of overall sea-level fall through a series of oscillations related to ice-sheet accumulation, reaching the last glacial maximum at ≈18,000 yr B.P. Since then, the ice has melted and sea-level has risen rapidly, at average rates of 5−15 mm yr^{-1} (Woodruffe, 1990).

Evidence for dynamic change in mangroves over geologic time is provided by the existence of fossils and mangrove peat deposits in various parts of the world (Ellison and Stoddart, 1991; Plaziat, 1995; Kim et al., 2005). For example, on the Great Barrier Reef, relict mangrove deposits are commonly found within palaeo-channels of river beds that traversed the shelf out to the edge of the continental margin when sea-level was lower 7000 years ago. Sediment cores taken within these ancient river beds support the notion that sea-level change was abrupt (Hull, 2005). Further, as discovered at other locations, the deposits contain intact pieces of wood, bark, leaves, and roots and preserved well enough to identify to what family the trees belonged (mostly Rhizophoraceae). The persistence of these deposits indicates remarkably slow microbial decay, but it also signifies that local extinction of these forests was sudden (Hull, 2005). This interpretation supports the chronological record from cores taken further north off Indonesia on the Sunda Shelf, which indicate a rapid rise of sea-level, as much as 16 m within 300 yr (Hanebuth et al., 2000). The pattern of late Quaternary sea-level change consisted of two phases: (1) an early-Holocene phase of rapid sea-level rise (the post-glacial transgression) and (2) a mid- to late-Holocene phase of comparative stability of sea-level (Woodruffe, 2002). The broad pattern is what is reflected