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Mangrove Zone Ecology

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Introduction

The mangrove zone consists of the intertidal coastal area lying between the spring high tide line and the spring low tide line in protected coastal waters encompassing a wide range of plant and animal communities. These communities are capable of tolerating extremes in inundation, drying, salinity, exposure, and storm damage and occur generally in the tropical and subtropical zones between latitudes 32° N and 38° S, gradually grading into salt marshes at both of these extremes as more frequent freezing events occur. Only recently, in the late 20th century, have the ecological communities within the mangrove zone been acknowledged by scientists to have important ecological characteristics and by coastal zone managers to have important economic and social values to humans. Prior to about 1970, they were generally treated as coastal swamps of little value to ecological processes or human society. With more enlightened attitudes and careful scientific studies it has been found that the mangrove zone contains a great variety of both plants and animals of direct human benefit as medicines, food, and building materials and also provides protection from storms, water pollution abatement, and a critically important function in the global carbon cycle.

General Overviews

Macnae 1968 is the first comprehensive examination of mangrove biology for a large area of the world (Indo-West-Pacific) but was published before the ecological value of mangroves was documented. Lugo and Snedaker 1974, building on the pioneer work of Heald and Odum 1970, synthesized the then-current science about mangroves with the first ecosystem approach and cautions about destruction and loss of fisheries associated with mangroves. Chapman 1976 is considered the first published international compendium of previous discussions of the vegetation of the mangrove zone with citations going back to 325°BC. Chapman took a very broad view of vegetation types within the mangrove zone including marine algae, fungi, and herbaceous plants as well as the generally accepted forty or so species of woody vegetation as shrubs and trees. Tomlinson 1986 is a first edition emphasizing the botany of mangroves, and these constitute the major scientific publications about mangroves during that period. The Proceedings of the (First) International Symposium on Biology and Management of Mangroves (8–11 October 1974, Honolulu, Hawaii) were published in 1975 (Walsh, et al. 1975). Several similar symposia were held infrequently in subsequent years. The modern era of mangrove zone ecology began with the publication of Hogarth 1999 and Saenger 2002 and continued with Alongi 2009, emphasizing ecosystem energetics and carbon pathways.

- **Alongi, D. M. 2009. *The energetics of mangrove forests*. Dordrecht, The Netherlands: Springer Science + Business Media.**

  The most current summary of the energy flow patterns in and ecosystem functions of mangroves.

- **Chapman, V. J. 1976. *Mangrove vegetation*. Vaduz, Liechtenstein: J. Cramer.**

  The first truly international summary of mangrove biology and physiology. An essential starting point.

- **Heald, E. J., and W. E. Odum. 1970. The contribution of mangrove swamps to Florida fisheries. *Proceedings of the Gulf and Caribbean Fisheries Institute* 22:130–135.**

This was the first scientific documentation of the role of mangroves in supporting fisheries and led to many subsequent research efforts.

- **Hogarth, P. J. 1999. *The biology of mangroves*. Oxford: Oxford Univ. Press.**

  One of the first of the modern syntheses of mangrove biology that included ecological functions and proper acknowledgement of the similarities between ecological functions of Old and New World mangroves.

- **Lugo, A. E., and S. C. Snedaker. 1974. The ecology of mangroves. *Annual Review of Ecology and Systematics* 5:39–64.**

  The first peer-reviewed synthesis paper documenting the ecological importance of mangrove zone ecosystems on a worldwide basis.

- **Macnae, W. 1968. A general account of the fauna and flora of mangrove swamps and forests in the Indo-West-Pacific region.*Advances in Marine Biology* 6:73–270.**

  A very thorough review of the plants and animals using mangroves in the Old World, but with limited ecosystem functional analyses.

- **Robertson, A. I., and D. M. Alongi, eds. 1992. *Tropical mangrove ecosystems*. Coastal and Estuarine Studies 41. Washington, DC: American Geophysical Union.**

  This is the first worldwide summary of knowledge about mangrove ecology with a number of essential papers.

- **Saenger, P. 2002. *Mangrove ecology, silviculture and conservation*. Dordrecht, The Netherlands: Kluwer Academic.**

  The first modern summary of mangrove ecology including extensive data and discussion on mangrove silviculture and management of forests for conservation.

- **Tomlinson, P. B. 1986. *The botany of mangroves*. 1st ed. Cambridge Tropical Biology Series. New York: Cambridge Univ. Press.**

  This book still stands as the definitive discussion of botanical aspects of the ecology of the mangrove zone. 419 pp.

- **Walsh, D., S. Snedaker, and H. Teas. 1975. *Proceedings of the International Symposium on Biology and Management of Mangroves*. 8–11 October 1974, Honolulu, HI. 2 vols. Gainesville: Univ. of Florida Press.**

  Fifty-eight peer-reviewed papers from around the world. Still a classic early summary with papers of continuing importance.

Journals

Though no longer published, the journal *Mangroves and Salt Marshes* was published in three volumes between December 1996 and December 1999. It has now been incorporated into *Wetlands Ecology and Management*, one of the main journals in which papers on mangrove zone management and restoration are currently published. Other journals where mangrove papers are commonly published are *Wetlands*, *Ecology*, *Ecological Applications*, *Restoration Ecology*, *Bulletin of Marine Science*, and *Estuarine and Coastal Shelf Science*.

- ***Bulletin of Marine Science*. 1951–.**

  An international journal devoted to marine sciences with many important papers on mangroves. Now available free online.

- ***Ecological Applications*. 1991–.**

  A more recent series of journals published by the Ecological Society of America and devoted to applied ecology.

- ***Ecology*. 1920–.**

  The premier journal on ecology of world ecosystems, published by the Ecological Society of America.

- ***Estuarine, Coastal and Shelf Science*. 1975–.**

  An international multidisciplinary journal that includes frequent papers on mangrove science.

- ***Mangroves and Salt Marshes*. 1996–1999.**

  Published in three volumes between December 1996 and December 1999. It has now been incorporated into Wetlands Ecology and Management.

- ***Restoration Ecology*. 1993–.**

The journal of the Society for Restoration Ecology, in which papers on mangrove management and restoration are published frequently.

- ***Wetlands*. 1981–.**

  The journal of the Society of Wetland Scientists. Fewer papers on mangroves, but often has papers of related interest such as tidal marsh ecology papers.

- ***Wetlands Ecology and Management*. 1991–.**

  The journal where most international papers on mangroves are published.

Databases

Online databases often supply up-to-date descriptions of projects and provide direct access to published materials as .pdf files. For example, the Mangrove Restoration website has over eighty free .pdf files of older mangrove zone ecology literature as well as more current publications. It is often difficult for mangrove zone researchers and managers in less developed countries to access large libraries where free access to such literature may be provided. The nongovernmental organization (NGO) the Mangrove Action Projectis an international organization with overseas offices and many active projects described on its website. Mangroves for the Future is also an NGO that has funded a number of projects on mangrove management and restoration and provides free access to a number of reports on these efforts. *National Geographic* published a very comprehensive and well-illustrated international summary of mangrove zone ecology, Warne 2007. Description of mangroves and mangrove habitats in the largest area of mangroves in North America including information about mangroves in the Florida Everglades can be found at the State of Florida mangrove website. Both the Ocean Portal and Radford University sites provide detailed descriptions of mangrove zone biomes around the world. It is important to note that all these sites are updated regularly and need to be revisited to look for new information on a regular basis. This is just a sample of the multitude of sites that can be found with routine searches.

- **Mangrove Action Project.**

  Website for the NGO Mangrove Action Project with extensive mangrove management and restoration project descriptions and community action project examples.

- **Mangrove Restoration.**

  Mangrove restoration information and general mangrove information. Over eighty free .pdf files to download.

- **Mangroves for the Future.**

  Website for the international NGO Mangroves for the Future. Dozens of reports on international projects on mangrove research, management, and restoration are accessible here.

- **Ocean Portal Report.**

  US Smithsonian Institute’s National Museum of Natural History Ocean Portal Team report on mangroves.

- **Radford University.**

  Radford University mangrove website with detailed, mostly New World mangrove biome descriptions and photographs.

- **State of Florida, USA.**

  Description of mangroves and mangrove habitats in the largest area of mangroves in North America including information about mangroves in the Florida Everglades.

- **Warne, Kennedy. 2007. Mangroves: Forests of the tide. *National Geographic* February: 132–151.**

  A *National Geographic* article about mangroves. [class:magazineArticle]

Defining the Mangrove Zone

The definition of the mangrove zone in Macnae 1968 (cited under General Overviews) differs from the one proposed here in that it covers “. . . the level of high water of spring tides and level close to but above mean sea-level” (p. 74). The difference is that Macnae and nearly all other authors define the mangrove zone based upon the presence of one or more plant species of what are called “mangroves.” Duke 1992 lists sixty-nine species of plants that are called mangroves, sixty-five species of trees or shrubs, three species of fern, and one species of palm. Giesen, et al. 2006 lists 52 species of “true mangroves,” 42 of which are trees or shrubs, just for Southeast Asia, and an additional 216 “mangrove associates.” This latter list excludes marine algae characteristic of mangrove forests, of which Chapman 1976 (cited under General Overviews) lists about twenty species. While there is great diversity in plant species composition, the dominant plant species in all mangrove zone forests around the world are generally trees in the families Avicenniaceae (eight species) and Rhizophoraceae (nine species). Giesen, et al. 2006 also defines the mangrove zone as extending down close to lowest tidal levels similar to what is proposed here, although this may be due to the erroneous assumption that mangrove trees routinely occur at this tidal level, which they do not (see Lewis 2005). The primary difference in all of these definitions is the difference between the area occupied only by mangrove trees (the mangrove forest) and the intertidal ecological zone, which includes subtidal flats, typically unvegetated except for algae (i.e., mud or sand flats) in front of mangrove forests, and the supratidal flats lying landward of the mangrove forest and often dominated by salt marsh species mixed with areas devoid of obvious vegetation except of algae (salt flats, salt barrens, salinas). Ecologically, all of these communities are hydrologically and energetically connected to the mangrove forest proper, and in particular the large colonies of wading and sea birds that are characteristic of the mangrove zone are absolutely dependent on the feeding and roosting areas provided by the subtidal and supratidal portions of the mangrove zone, as are many fish species.

- **Duke, N. 1992. Mangrove floristics and biogeography. In *Tropical mangrove ecosystems*. Edited by A. I. Robertson and D. M. Alongi, 63–100. Washington, DC: American Geophysical Union.**

  This is generally considered to be the definitive paper on what constitutes mangrove zone plants.

- **Giesen, W., S. Wulffraat, M. Zieren, and L. Scholten. 2006. *Mangrove guidebook for Southeast Asia*. Bangkok: Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific.**

  An update to Duke 1992 with a listing of 268 species of mangroves and mangrove associates along with some keys to identification.

- **Lewis, R. R. 2005. Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering* 24.4: 403–418.**

  A review paper on all previous efforts at mangrove restoration with one hundred citations to previous work and a detailed discussion of mangrove hydrology related to measured topography at a number of sites worldwide.

Zonation and Hydrology

One of the most characteristic structural attributes of the mangrove zone is the occurrence of bands or zones of unique vegetation types (or bands of unvegetated areas) within mangrove forests and generally parallel to topographic relief or elevation changes. Much discussion has occurred in the literature about what causes this distinct zonation. Smith 1992 provides a complete review of the competing theories about the causes and generally rejects the more accepted theories such as propagule sorting and plant succession in favor of more influence by geomorphology and competition. Zonation along a topographic gradient also implies an important role of hydrology in controlling mangrove plant distribution within the intertidal zone, as lower topography is flooded more often than higher topography, and eventually no normal tidal flooding takes place at the highest topography typically behind the mangrove forest and the supratidal flats separating either terrestrial or freshwater plant communities from the mangrove zone. The author of Kjerfve 1990 provides a detailed discussion of the science behind understanding mangrove zone hydrology and recommendations for study approaches. He was also the first scientist to note that mangrove forests are flooded much less frequently that had been previously thought. His study of the flooding frequency of mangroves along the Andaman Sea in Thailand found that the mangrove zone wetland lying above the tidal creeks was flooded only 9 percent of the time. Previous characterization of flooding frequencies within mangroves by Watson 1928 was in terms of five inundation classes ranging from “inundated by all high tides” (Class 1) to “occasionally inundated by exceptional or equinoctial tides” (Class 5). In addition to tidal hydrology related to flooding, hydrological characterization of tidal creek flows and total exchange and velocities of flow related to the tidal prism are discussed by Wolanski, et al. 1992; Furukawa, et al. 1997; and Mazda, et al. 2007.

- **Furukawa, K. E., E. Wolanski, and H. Mueller. 1997. Currents and sediment transport in mangrove forests. *Estuarine, Coastal and Shelf Science* 44:301–310.**

  Important description of hydrology of mangroves primarily in the Old World.

- **Kjerfve, B. 1990. *Manual for investigation of hydrological processes in mangrove ecosystems*. UNESCO/UNDP Regional Project, Research and Its Application to the Management of the Mangroves of Asia and the Pacific (RAS/86/120).**

  The first comprehensive look at the hydrology of mangroves by a well-recognized expert on wetland hydrology.

- **Mazda, Y., E. Wolanski, and P. V. Ridd. 2007. *The role of physical processes in mangrove environments*. Tokyo: Terrapub.**

  A book with many of the previous papers on the subject reprinted along with new data.

- **Smith, T. J., III. 1992. Forest structure. In *Tropical mangrove ecosystems*. Edited by A. I. Robertson and D. M. Alongi, 101–136. Washington, DC: American Geophysical Union.**

  This is considered one of the most important papers on mangrove zone forest structure and appropriate sampling.

- **Watson, J. G. 1928. *Mangrove forests of the Malay Peninsula*. Malayan Forest. Rec. No. 6. Singapore: Fraser and Neave.**

  An early paper devoted mostly to forest inventories, silvaculture, and harvesting of mangroves for wood, but includes the earliest discussion of mangrove zonation and hydrology.

- **Wolanski, E., Y. Mazda, and P. Ridd. 1992. Mangrove hydrodynamics. In *Tropical mangrove ecosystems*. Edited by A. I. Robertson and D. M. Alongi, 43–62. Washington, DC: American Geophysical Union.**

  Next to Kjerfve 1990 this is the companion paper furthering our knowledge of mangrove zone hydrology.

General Distribution and Area

Mangrove trees are tropical-to-subtropical species and occupy the same intertidal zone generally occupied by salt marshes in more temperate portions of the protected coasts of the world. Their distribution limits are generally 32° N and 25° S in the New World and 28° N and 38° S in the Old World. These limits are generally defined by the occurrence of frost events which can damage mangroves if light, and kill them if lasting more than a few hours. Ranwell 1972 cites reports of such damage at their northern limit in Florida at 29°22′ N at Ormond Beach, Florida, and at their southern limit in New Zealand. However, the most southern of all mangrove forests in the Old World occur in southern Australia at 38°45′ S as reported by Spalding, et al. 2010. The total area of mangroves presently occurring is subject to some minor changes as more accurate mapping takes place over time, but it is generally agreed to be approximately 150,000 square kilometers (15 million hectares) as noted by Spalding, et al. 2010. Giri, et al. 2011, using the most up-to-date satellite coverage for the world available in 2000, reports a total area of 137,760 square kilometers in 118 countries. Estimates of the historical coverage of mangroves range from "greater than 200,000 square kilometers" (Spalding, et al. 2010) to twice the current coverage (Ong 2002), which would be equal to about 300,000 square kilometers. Thus, the worst-case situation is the loss of 50 percent of the historical coverage and a current loss of about 1 percent per year worldwide (Saenger 2002). Spalding, et al. 2010 contains numerous maps and calculations of area of mangroves in various countries worldwide. Also included are discussions of specific unique management opportunities and challenges.

- **Giri, C., E. Ochieng, L. L. Tieszen, et al. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography* 20.1: 154–159.**

  This paper stands as the most recent detailed attempt to measure the area of mangroves on the planet.

- **Ong, J. E. 2002. *The hidden costs of mangrove services: Use of mangroves for shrimp aquaculture*. International Science Roundtable for the Media, 4 June 2002, Bali, Indonesia.**

  A short summary paper noting the likelihood that half of all the world's mangroves have been lost.

- **Ranwell, D. S. 1972. *Ecology of salt marshes and sand dunes*. London: Chapman and Hall.**

  An older book primarily devoted to marsh zone ecology, but with some important insights into mangroves.

- **Saenger, P. 2002. *Mangrove ecology, silviculture and conservation*. Dordrecht, The Netherlands: Kluwer Academic.**

  The first modern summary of mangrove ecology including extensive data and discussion on mangrove silviculture and management of forests for conservation. 360 pp.

- **Spalding, M., M. Kainuma, and L. Collins. 2010. *World atlas of mangroves*. Washington, DC: Earthscan.**

This second edition is considered the definitive mapping by country with many detailed color maps of mangrove zone areas for the world. 319 pp.

Ecological Functions

Among the most important ecological functions of mangrove zone forests are primary production and secondary production. Primary production is the direct result of photosynthesis and includes the production of carbohydrates which are consumed through respiration and produce the energy that mangrove plants need to survive and grow, but also the complex structural carbohydrates like cellulose that represent the structural elements of wood and other portions of the structure of these plants. Secondary production is the biotic elements of the mangrove zone community that depend either directly on herbivory of structural elements like leaves, or indirectly through detrital pathways resulting from decomposition of structural elements, or carnivory through predation on animals that are part of the mangrove zone food web.

PRIMARY PRODUCTION

Alongi 2009 provides detailed discussions of the energetics of mangrove forests and generalizes for mangroves in general, based upon six studies worldwide that show that gross primary production and net ecosystem production average 232 and 89 mol C m^{-2} yr^{-1}, respectively. There is also a positive relationship between tidal range at a particular mangrove forest site and net ecosystem production.

- **Alongi, D. M. 2009. *The energetics of mangrove forests*. Dordrecht, The Netherlands: Springer Science + Business Media.**

  The most current summary of the ecosystem functions of and energy flow patterns in mangroves.

SECONDARY PRODUCTION

Alongi 2009 notes that models of pristine and human-influenced mangroves have shown that herbivorous and detritivorous carbon pathways are equally important, with human-influenced systems generally producing an increase in the relative importance of algal primary production, herbivorous zooplankton, and meiofauna. As documented by Heald and Odum 1970 (cited under General Overviews), and confirmed by Alongi 2009, the detritus-based food web is typical of more pristine forests, and is responsible for a great diversity and abundance of fish and invertebrates, which often use the forests for protection and as a food source as juveniles which may migrate to offshore locations as they mature. A recent single issue of the journal *Bulletin of Marine Science* (Serafy and Araujo 2007) contains the Proceedings of the First International Symposium on Mangroves as Fish Habitat and contains twenty-five papers and numerous abstracts on the subject of secondary production in mangrove forests. Previous summary documents on the subject include Macnae 1968; Odum, et al. 1982; Field 1995; Mastaller 1997; and Kathiresan and Bingham 2001. Fish and invertebrate production in inshore waters has historically been quantitatively linked with the associated area of adjacent mangroves, but the recent work Saenger, et al. 2013 questions the strength of those assumptions and suggests that much more research needs to be done. Many of these also document the use of mangrove trees as nesting sites for many wading birds and seabirds, and as a major source of nutrition via fish and invertebrates in the mangrove zone for adult birds and their young.

- **Alongi, D. M. 2009. *The energetics of mangrove forests*. Dordrecht, The Netherlands: Springer Science + Business Media.**

  Current summary of the ecosystem functions of and energy flow patterns in mangroves.

- **Field, C. D. 1995. *Journey amongst mangroves*. Okinawa, Japan: International Society for Mangrove Ecosystems.**

  A tabletop summary of human use issues and life forms in mangroves. 140 pp.

- **Kathiresan, K., and B. L. Bingham. 2001. Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology* 40:81–251.**

  An updated summary of plant and animal interactions in mangroves. Some of the fish data and assumptions have recently been replaced by the Serafy and Araujo 2007 symposium volume.

- **Macnae, W. 1968. A general account of the fauna and flora of mangrove swamps and forests in the Indo-West-Pacific region.*Advances in Marine Biology* 6:73–270.**

  Very thorough review of the plants and animals using mangroves in the Old World, but with limited ecosystem functional analyses.

- **Mastaller, M. 1997. *Mangroves: The forgotten forest between land and sea*. Kuala Lumpur, Malaysia: Tropical Press SDN, BHD.**

  Another good summary of human uses and mangrove zone biology in a glossy tabletop format, but peer reviewed for accuracy. 200 pp.

- **Odum, W. E., C. C. McIvor, and T. J. Smith III. 1982. The ecology of the mangroves of south Florida: A community profile. U.S. Fish and Wildlife Service, Washington, D. C. FWS/OBS/-81/24.**

  The most complete summary of the biology and ecology of one of the larger and better-studied areas of mangroves in the world (144 pp.).

- **Saenger, P., D. Gartside, and S. Funge-Smith. 2013. *A review of mangrove and seagrass ecosystems and their linkage to fisheries and fisheries management*. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, RAP Publication 2013/09.**

  A recent detailed summary of the evidence for and against fishery production being dependent on the area of mangroves or seagrasses associated with that fishery. The authors point out that such associations are site specific and much additional work needs to be done to accurately quantify the real associations (82 pp.).

- **Serafy, J. E., and R. J. Araujo, eds. 2007. *Special issue: Proceedings of the first international symposium on mangroves as fish habitat*, *April 19–21, 2006, Miami, Florida*. *Bulletin of Marine Science* 80.3.**

  The only comprehensive look at fish and invertebrate use of mangroves worldwide. A free download at the Bulletin of Marine Science website.

Value of Mangroves to Humans

Saenger 2002 describes the direct benefits that mangrove forests contribute to human welfare including harvestable timber and fiber, bark for tanning, charcoal, firewood, fish and invertebrates like crabs and shrimp for human consumption, honey production, harvestable wildlife for consumption, salt production, and aquaculture. Mangrove foliage is also collected for food for herbivores like cattle, goats, and camels. Direct shoreline protection and storm protection are also provided, as is erosion control. In some parts of the world mangroves represent a major pharmaceutical resource. Mangrove forests also filter runoff from industrial and residential areas and process water to remove pollutants and sediments and therefore protect inshore water quality and such light-sensitive plant and animal communities as seagrass meadows and coral reefs. More recently, the recreational value of mangroves for ecotourism, fishing, and bird watching has become a major source of income for many local indigenous populations. Finally, with global increases in greenhouse gases (GHGs) and the possible impacts to global climate change, mangroves have been identified as one of the most important sinks for stored carbon, and for further storage of carbon over time. Donato, et al. 2011 characterized mangrove forests as being “among the most carbon-rich forests in the tropics” and encouraged their preservation and restoration to store carbon and in the future remove more GHGs from the atmosphere. Although they constitute only about 0.7 percent of global tropical forests, they may store up to ten times the carbon of similar temperate and tropical forests. Most of this storage is in the soil.Siikamaki, et al. 2012 notes that the release of this vast GHG source can result from destruction of mangrove forests, and thus the topic of avoided emissions has become the subject of efforts to preserve these forests.

- **Donato, D. C., J. B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kannineri. 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience Letters* 4:293–297.**

  Considered the most up-to-date discussion of the data in support of carbon storage in mangrove zone forests.

- **Saenger, P. 2002. *Mangrove ecology, silviculture and conservation*. Dordrecht, The Netherlands: Kluwer Academic.**

  First modern summary of mangrove ecology including extensive data and discussion on mangrove silvaculture and management of forests for conservation (360 pp.).

- **Siikamaki, J., J. N. Sanchirico, and S. L. Jardine. 2012. Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proceedings of the National Academy of Sciences of the United States of America* 109.36: 14369–14374.**

A careful examination of the issue of mangrove zone forest loss as a contributor to GHG emissions.

Management and Restoration

As a result of the great direct and indirect economic value of mangroves to humans, and the record of large losses estimated as high as 50 percent over the last fifty years according to Ong 2002, there have developed a large interest and research programs in managing mangrove forests through protection from loss, and restoration of areas of damaged or completely lost mangrove forests (Field 1996; Brockmeyer, et al. 1997; Stevenson, et al. 1999; Lewis 2005). Most authors (see, e.g., Lewis 2005 and Lewis 2009) now support a more comprehensive ecological approach to restoration, with considerations of the past history of a proposed restoration site and more careful measurements of existing hydrology of both reference and impact sites. The historical approach of just planting mangroves on mudflats has proven to be largely unsuccessful in establishing diverse and sustainable mangrove forest cover as reported by Samson and Rollon 2008 over a twenty-year period in the Philippines. More successful efforts to successfully restore large areas of impounded mangroves and their associated fish populations have been reported by Brockmeyer, et al. 1997. Due to the perception that mangroves were not of any value to human society, other than perhaps firewood, mangrove forests were not generally protected from human impacts until the mid-1980s, and then only in specific countries like the United States and Australia, where research had shown their value to both commercial and recreational fisheries. More recently, there have been efforts to develop organized programs of mangrove forest management on the state and federal levels in many countries, utilizing educational programs for local officials and user groups, such as the local subsidence-based fishing community (fisherfolk) (Walters 2000; Van Lavieren, et al. 2012). It is still too early to know how successful these programs are at really protecting and successfully restoring mangrove forests, but monitoring of these efforts is occurring (Van Lavieren, et al. 2012).

- **Brockmeyer, R. E., Jr., J. R. Rey, R. W. Virnstein, R. G. Gilmore, and L. Ernest. 1997. Rehabilitation of impounded estuarine wetlands by hydrologic reconnection to the Indian River Lagoon, Florida (USA). *Wetlands Ecology and Management* 4.2: 93–109.**

  Describes one of the largest worldwide efforts to successfully restore the ecological functions of impounded mangroves.

- **Field, C. D., ed. 1996. *Restoration of mangrove ecosystems*. Okinawa, Japan: International Society for Mangrove Ecosystems.**

  An older summary of mangrove restoration efforts, primarily in southeast Asia. 250 pp.

- **Lewis, R. R. 2005. Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering* 24.4: 403–418.**

  A review paper on all previous efforts at mangrove restoration with one hundred citations to previous work. This is the first real international synthesis of these data.

- **Lewis, R. R. 2009. Methods and criteria for successful mangrove forest restoration. Edited by G. M. E. Perillo, E. Wolanski, D. R. Cahoon, and M. M. Brinson, 787–800. *Coastal wetlands: An integrated ecosystem approach*. Amsterdam and Boston: Elsevier.**

  An updated approach to mangrove restoration emphasizing Ecological Mangrove Restoration (EMR).

- **Ong, J. E. 2002. The hidden costs of mangrove services: Use of mangroves for shrimp aquaculture. International Science Roundtable for the Media, 4 June 2002, Bali, Indonesia.**

  Short summary paper noting the likelihood that half of all the world’s mangroves have been lost.

- **Samson, M. S., and R. N. Rollon. 2008. Growth performance of planted red mangroves in the Philippines: Revisiting forest management strategies. *Ambio* 37.4: 234–240.**

  A thorough documentation of twenty years of mostly unsuccessful efforts to restore mangroves in the Philippines, with recommendations to make such efforts more likely to succeed.

- **Stevenson, N. J., R. R. Lewis, and P. R. Burbridge. 1999. Disused shrimp ponds and mangrove rehabilitation. In *An international perspective on wetland rehabilitation*. Edited by W. J. Streever, 277–297. Dordrecht, The Netherlands: Kluwer Academic.**

  The first worldwide look at the problem of shrimp aquaculture damage to mangroves with recommendations and data on successful restoration of abandoned ponds back to mangroves.

- **Van Lavieren, V., M. Spalding, D. Alongi, M. Kainuma, M. Clusner-Godt, and Z. Adeel. 2012. Securing the future of mangroves: A policy brief. UNESCO-MAB.**

The latest worldwide summary of efforts to manage existing mangroves within a community-based context. 53 pp.

- **Walters, B. B. 2000. Local mangrove planting and the Philippines: Are fisherfolk and fishpond owners effective restorationists?*Restoration Ecology* 8.3: 237–246.**

  Another discussion of the community-based approach to managing and restoring mangroves.

Sea Level Rise

The authors of Barth and Titus 1984 were some of the first scientists to identify sea level rise as a result of climate change and in particular global warming and thermal expansion of seawater and melting of land-based ice as a threat to the continued existence of coastal wetlands. Since then, the Intergovernmental Panel on Climate Change (IPCC) has issued a number of reports, includingIntergovernmental Panel on Climate Change 1995, which stated that "[B]y the end of the century, a 3- to 5-fold increase in rates of global sea level rise could lead to inundation of low-lying coastal regions, including wetlands." Snedaker 1993 was the most thorough early review of the issues facing mangroves exposed to sea level rise, followed by Gilman, et al. 2007 in American Samoa and more recently McKee 2011 in the Caribbean. Numerous handbooks and summaries of assessment methods and recommended adaptation approaches have been prepared, including McLeod and Salm 2006 and Ellison 2012. All generally agree that mangroves in areas with room in the uplands behind mangroves on higher ground will be able to migrate inland depending on the slope of the adjacent uplands. Less steep slopes will allow for more accommodation of migrating mangroves as they are flooded and likely die on the seaward edge and gradually colonize adjacent uplands. Without such room to expand, coastal squeeze will destroy them over time unless they can keep up with sea level rise. McKee notes that in certain locations mangroves have kept up with sea level rise but the precise biotic and physical mechanisms may differ at different sites, and much more work needs to be done in order to predict the fate of individual mangrove areas as sea level rises.

- **Barth, M. C., and J. G. Titus, eds. 1984. *Greenhouse effect and sea level rise: A challenge for this generation*. New York: Van Nostrand Reinhold.**

  The first paper on the potential role of climate change in sea level rise acceleration and loss of coastal wetlands.

- **Ellison, J. C. 2012. *Climate change vulnerability assessment and adaptation planning for mangrove systems*. Washington, DC: World Wildlife Fund.**

  A detailed handbook of applied methodologies tested at sites worldwide to assess sea level rise impacts on mangroves and what a suggested response program should be.

- **Gilman, E., J. Ellison, and R. Coleman. 2007. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. *Environmental Monitoring and Assessment* 124.1–3: 105–130.**

  One of a series of papers based upon field research in American Samoa and mapping of historical distribution of mangroves in different watersheds that describes the coastal squeeze concept, which may impact mangroves as they try to migrate landward with sea level rise.

- **Intergovernmental Panel on Climate Change. 1995. *Climate change 1995: Impacts, adaptations, and vulnerability, contribution of Working Group II on the third assessment report of the IPCC*. Cambridge, UK: Cambridge Univ. Press.**

  Part of a series of reports projecting rates of sea level rise and potential impacts to natural and manmade communities along our coasts.

- **McKee, K. L. 2011. Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. *Estuarine, Coastal and Shelf Science* 91:475–483.**

  One of a series of scientific papers documenting rates of mangrove elevation change over time in the face of sea level rise at different locations in the Caribbean. Increased growth of mangrove roots and algal mat accumulations are documented as contributing to the ability of some mangroves to keep up with sea level rise.

- **McLeod, E., and R. V. Salm. 2006. *Managing mangroves for resilience to climate change*. IUCN Resilience Science Group Working Paper Series No. 2. Gland, Switzerland: IUCN.**

  General summary of potential impacts to mangroves of sea level rise and vulnerability analyses for various mangrove forests in different parts of the globe.

- **Snedaker, S. C. 1993. Impact on mangroves. In *Climatic change in the intra-American seas: Implications of future climate change on the ecosystems and socio-economic structure of the marine and coastal regimes of***

***the Caribbean Sea, Gulf of Mexico, Bahamas and N.E. Coast of S. America*. Edited by G. A. Maul, 282–305. London: Edward Arnold.**

The definitive paper on the role of hydrology and sea level rise on the biochemistry of mangrove soils that leads to some areas keeping up with sea level rise, and other mangrove areas dying off.

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