

CONTINUING THE JOURNEY AMONGST MANGROVES

Barry Clough



ISME Mangrove Educational Book Series No. 1

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International Society for Mangrove Ecosystems

International Tropical Timber Organization

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Cover photographs:

Sunset at a mangrove shore in Iriomote, Japan

Stilt or prop roots of *Rhizophora apiculata*

Brightly coloured, luminescent bugs in the mangroves

Fishing boats docked in the mangroves

Contents

ISME and ITTO	iii
About the Author	iv
Preface	v
Acknowledgements	v
Note from ISME	vi
Glossary of Terms	vii
Chapter 1 INTRODUCTION	1
Chapter 2 MANGROVE DISTRIBUTION AND ENVIRONMENT	5
Global Distribution	5
Latitudinal Gradients and Limits	6
Patterns Associated with Rainfall and Aridity	8
Local Zonation Patterns	9
Environmental Settings of Mangroves	11
Chapter 3 LIVING WITH STRESS	17
Coping with Salt	17
<i>Salt exclusion</i>	18
<i>Salt secretion</i>	19
<i>Succulence</i>	20
<i>Storage in woody tissues</i>	21
<i>Cellular compartmentalisation</i>	21
<i>Coping with a lack of water</i>	21
Coping with Anaerobic Soils	24
Reproduction and Dispersal	27
Chapter 4 OTHER LIVING COMPONENTS	31
Faunal Components	31
<i>Mammals</i>	31
<i>Reptiles and amphibians</i>	32
<i>Birds</i>	33
<i>Fish</i>	33
<i>Crabs</i>	34
<i>Shrimp and other crustaceans</i>	35
<i>Gastropods and other molluscs</i>	35
<i>Insects</i>	36
<i>Small benthic invertebrates (meiofauna)</i>	37
Other Plant Components	38

Chapter 5 UTILISATION AND VALUES OF MANGROVES	39
Mangrove Goods and Services	39
Mangrove-Derived Products	40
<i>Timber products</i>	40
<i>Tannins and cloth dyes from mangrove bark</i>	43
<i>Thatching and other products from Nypa</i>	44
<i>Honey</i>	45
<i>Other human foodstuffs</i>	46
<i>Fodder</i>	46
<i>Medicines</i>	47
<i>Fisheries and other marine resources</i>	49
Other Services Provided by Mangroves	50
<i>Coastal protection</i>	50
<i>Coastal erosion</i>	50
<i>Protection from waves</i>	50
<i>Carbon storage</i>	51
<i>Coastal wastewater treatment</i>	52
Chapter 6 THREATS AND ENVIRONMENTAL IMPACTS	53
Conversion to Agriculture and Salt Ponds	53
Conversion to Aquaculture	55
Urban Expansion and Industrial Development	56
Pollution	57
Exploitation for Timber and other Wood Products	57
Climate Change	58
<i>Sea level rise</i>	59
<i>High atmospheric CO₂ concentrations</i>	61
<i>Temperature and rainfall</i>	62
<i>Storm frequency and intensity</i>	62
<i>Interactions and uncertainties</i>	63
Chapter 7 CONSERVATION AND MANAGEMENT	65
Management Frameworks	67
Conservation Strategies	68
<i>Preservation systems</i>	69
<i>Restricted-use systems</i>	69
<i>Production systems</i>	69
Afforestation and Rehabilitation	70
Concluding Remarks	71
Some Useful Links to Online Materials	71
References	75
Box 2.1 Description of geomorphic mangrove settings	12
Box 2.2 Description of the six functional types of mangrove forest	14
Box 7.1 ISME Charter for Mangroves	72

ISME and ITTO

ISME

The International Society for Mangrove Ecosystems (ISME) is an international non-profit and non-governmental scientific society established in August 1990. With its headquarters in Okinawa, Japan, ISME was certified as a Foundation in 1992 by the Japanese Law of Foundation. In 2003, under a new Japanese law of promoting specified non-profit activities, ISME was registered as a Non-Profit Organization (NPO). Revised at the Eighth General Assembly in 2012, the Statutes of ISME stipulate that 'the Society shall collect, evaluate and disseminate information on mangrove ecosystems', and 'shall promote international cooperation'. ISME has been carrying out its activities at the global level through: a) application of knowledge to particular situations, b) training and education, and c) exchange of necessary information. Activities of the society have been supported with collaboration and links by a number of other organizations, universities, research institutes and local communities. Currently, ISME's membership includes 40 institutions and over 1,150 individuals from 92 countries.

ITTO

The International Tropical Timber Organization (ITTO) is an intergovernmental organization promoting the conservation and sustainable management, and the use and trade of tropical forest resources. Its 65 members represent most of the world's tropical forests and 90% of the global tropical timber trade. ITTO develops internationally agreed policy documents to promote sustainable forest management and forest conservation, and assists tropical member countries to adapt such policies to local circumstances and to implement them in the field through projects. In addition, ITTO collects, analyses and disseminates data on the production and trade of tropical timber, and funds projects and other actions for developing industries at both community and industrial scales. All projects are funded by voluntary contributions, mostly from consumer member countries. Since it became operational in 1987, ITTO has funded more than 800 projects, pre-projects and activities valued at more than USD 350 million. The major donors are the governments of Japan, Switzerland, EU and USA.

About the Author

Barry CLOUGH

Dr. Clough obtained his Ph.D. from the University of Sydney in Australia. He worked as a research scientist (1979–1984) and senior research scientist (1985–2004) at the Australian Institute of Marine Science (AIMS). He was the Vice-President of ISME (1992–1994), Coordinator of the Australian National Mangrove Committee (1985–1990) and active participant of the UNDP/UNESCO Regional Mangrove Project. He was the Coordinator of the ISME/ITTO Project on the *Economic and Environmental Values of Mangrove Forests and their Present State of Conservation in the South-East Asia/Pacific Region*.

From 1995–2001, he was the Australian Project Leader for *Mixed Shrimp Farming – Mangrove Forestry Models in the Mekong Delta* a collaborative project between the Governments of Australia and Vietnam, supported mainly by the Australian Centre for International Agricultural Research. From 1999–2000, he was seconded to the Network of Aquaculture Centers in Asia-Pacific in Bangkok. His consultancies have included a GTZ Coastal Development Project in Bac Lieu, Vietnam, and the World Bank Coastal Wetland Protection and Development Project in Ca Mau, Vietnam. Currently, he is a part-time Volunteer in Teaching and Research at Cantho University in Vietnam, supervising post-graduate students working on mangroves and coastal biodiversity.

Preface

In 1995, the International Society for Mangrove Ecosystems (ISME) and the International Tropical Timber Organization (ITTO) published *Journey Amongst Mangroves*, authored by C.D. Field, which aimed to present the nature and importance of mangroves to as wide an audience as possible. This book, a sequel and hence its title *Continuing the Journey Amongst Mangroves*, is written with the same objectives.

This book is also the first in a trilogy to be published simultaneously. The others are *Structure, Function and Management of Mangrove Ecosystems* by Jin Eong Ong and Wooi Khoo Gong, and *Useful Products from Mangrove and other Coastal Plants* by Shigeyuki Baba, Hung Tuck Chan and Sanit Aksornkoae.

Being the first in the series, this book aims to provide a more general, not too technical introduction to mangroves for the two accompanying volumes, which will cover a number of the topics in much greater detail. In keeping with its objectives, I have attempted to limit the use of technical scientific jargon. However, some technical jargon was unavoidable, and where possible I have tried to provide simple English explanations for technical terms. Many of the references cited can be found and downloaded by searching the internet, but I have not included links in the bibliography to avoid possible copyright issues.

Finally, many of the examples used in this book come from Asia and the Western Pacific. Some readers may rightly feel that the New World mangroves of the Americas and Africa are not well covered. Any bias towards Old World examples simply reflects the abundance of information on them and my familiarity with them; it does not imply that the mangroves of the New World are less important or that they have been less widely studied.

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Many colleagues have contributed to this book, either directly or indirectly. I am indebted to all of them, but particularly to the Project Coordinator and Editor, Hung Tuck Chan, for his careful proof-reading, editing and comments, and for assistance with references and photographs, to Stefanie Gendera whose artistic flair has greatly enhanced many of the illustrations, and to Peter Saenger for comments and advice on mangrove distributions. The thorough checking of the final proof by Ryoko Miyagawa and Mio Kezuka (staff of the ISME Secretariat) is much appreciated.

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Note from ISME

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ISME is indebted to the Project Technical Committee, comprising members of the Executive Committee, for their support of the project, and critical comments and sound advice on the chapters of the books. The contributions of Prof. Sanit Aksornkoae, Ambassador Noboru Nakahira, Prof. François Blasco, Prof. Norman Duke, Prof. Salif Diop and Dr. Mami Kainuma are very much appreciated. The commendable efforts of Dr. Steve Johnson as the Project Manager from ITTO, Dr. Hung Tuck Chan as the Project Coordinator and Book Editor, and Ms. Nozomi Oshiro as the Project Administrator have enabled the smooth implementation of the project activities. Gratitude goes to the Sabah Forestry Department in Sandakan, Sabah for collaborating with ISME, and for providing the Rainforest Discovery Centre as venue for the launching of the books and seminar of the project.

Under the project, three books representing the beginning of the *ISME Mangrove Educational Book Series* are produced. They are written, published and launched in commemoration of Prof. Shigeyuki Baba, the Executive Director of ISME, who will be retiring from University of the Ryukyus in March 2013.

Glossary of Terms

Based in part on Field (1996). Not all the terms are used in this book, but all those from Field (1996) have been retained for general reference.

Abiotic: non-living.

Abscission zone: the region at the base of a leaf, flower or fruit or other part of a plant consisting of a layer of weak cells and a layer of corky cells, which protect the wound when the parts separate.

Abscission: the separation of parts.

Accretion: growth by the addition of new matter; the accumulation and extension of land and soil.

Adventitious: tissues and organs found in abnormal positions.

Aerial roots: roots that grow from the trunk or lower branches of the crown.

Afforest: to convert into forest.

Air-layering: a form of vegetative propagation. A branch is stimulated to form roots while still on the parent plant by removing part of the bark and keeping the area moist.

Alluvial: deposits formed by finely divided material laid down by running water.

Apical: at tip of growing point.

Anaerobic: lacking oxygen.

Anthropogenic: originated by man.

Benthic: living on sea bottom.

Biological diversity (biodiversity): the variety of all life forms: the different plants, animals and micro-organisms, the genes they contain, and the ecosystems they form. It is usually considered at three levels: genetic diversity, species diversity and ecosystem diversity.

Biomass: total weight of animals and/or plants per unit area.

Biotic: related to living things.

Calcareous: growing on soil derived from decomposition of limestone.

Canopy: topmost layer of leaves, twigs and branches of forest trees or other woody plants.

Catchment: an area that collects water (usually from rainfall) and drains into a water body such as a reservoir or river. The term 'drainage basin' is also used widely.

Cation: a positive electrically charged atom or molecule.

Chlorotic: affected by an abnormal condition characterised by the absence of green pigments in plants.

Clastic: composed of broken pieces of older rocks. Clay: sediment particles between 0.002 mm and 0.004 mm in diameter.

Communities: any group of organisms belonging to a number of different species that co-exist in the same area and interact through trophic and spatial relationships.

Compatible solute: an organic compound synthesised naturally by a plant or animal, mainly for the purpose of osmoregulation, that does not have ill-effects on cellular metabolism. Common compatible solutes include glycine-betaine and proline.

Conservation: the protection, maintenance, management, sustainable use, restoration and enhancement of the natural environment.

Coppice: small wood of undergrowth and small trees grown for periodic cutting.

Cotyledon: seed leaf; the first leaf or leaves of the embryo in seed plants.

Deforest: to clear forests and to convert land to non-forest uses.

Detritus: small pieces of dead and decomposing plants and animals.

Diameter at Breast Height [DBH]: the width of a plant stem as measured 1.4 m above the ground surface.

Disturbance: change caused by an external agent, either natural or human induced.

Diurnal: daily; of each day.

Ecology: science concerned with the interactions of organisms and their physical and biotic environment.

Ecosystem: a dynamic complex of plant, animal, fungal and, microorganism communities and the associated non-living environment.

Edaphic: influenced by conditions of soil or substratum.

Eh: redox potential, a quantitative measure of reducing power.

Evapotranspiration: loss of soil moisture by transpiration through the leaves and by direct evaporation.

Exotic: not produced naturally in a region.

Family: a group consisting of related genera of plants or animals that are so similar in structure that they are believed to have a common evolutionary origin. See genus.

Flocculation: the clumping of fine particles.

Genus (plural: genera): a group of species regarded as so closely related in their evolution that they share a common generic name.

Geogenic: a geographical or geochemical aspect of an area, which affects organisms living or growing in it.

Geomorphology: the study of the origin, evolution and configuration of the natural features on the surface of the Earth.

Germination: process of initial development in a seed from uptake of water to beginning of photosynthesis.

Ground-truthing: confirming maps derived from satellite images by ground surveys.

Habitat: the environment occupied by individuals of a particular species.

Herbivore: a plant-eating organism.

Holocene: most recent geological epoch, last 10,000 years.

Humidity: the amount of moisture in the air.

Hydrology: the science dealing with the properties, distribution and circulation of water both on the surface and under the earth.

Hydromorphic: structurally adapted to an aquatic environment.

Hypocotyl: the region of the stem derived from that part of the embryo between the cotyledons and the radicle.

Indigenous species: a species native to a region.

Insolation: exposure to the rays of the sun.

Inundation: a condition in which water from any source temporarily or permanently covers a land surface.

Lenticel: small elliptical pore in the periderm that is a means of gaseous exchange.

Littoral: of, on or near the shore. Region lying along the shore, especially land lying between the high and low tide levels.

Loam: a rich friable soil consisting of a roughly equal mixture of sand and silt and smaller proportion of clay.

Marl: soil consisting of clay and lime. Mangroves: trees, shrubs, palms or ground ferns growing in the zone between high and low tide marks.

Meristem: plant tissue containing actively dividing cells and capable of giving rise to new cells and tissues, as at growing tips.

Mitigation: avoiding the impact altogether by not taking a certain action or reducing the impact over time by preservation and maintenance operations.

Monoculture: growth of a single plant species.

Mudflats: open expanses of intertidal mud, usually at the entrance of the estuary to the sea, but may occur as accreting banks of sediment in the estuary.

Necrosis: death of cells or tissues.

Osmoregulation: the process of controlling the amount of water and solutes in cells and organs to maintain a balance between water and solutes that is needed for normal cell and organ function. (see Solute).

Osmotic potential and water potential: osmotic potential refers to the activity of water molecules in an aqueous solution of water and solutes. The concept of osmotic and water potential is based on the theory of thermodynamics. By convention the osmotic potential of pure water is zero. The presence of inorganic and inorganic solutes reduces the activity of water molecules, thereby lowering the osmotic potential, so the osmotic potential of an aqueous solution containing solutes is always negative (i.e. less than zero). For an aqueous solution directly exposed to the atmosphere the osmotic potential and water potentials are the same, so seawater, for example, has an osmotic potential and a water potential of around -2.5 MPa (pressure units). However, most plant cells and tissues are constrained by relatively rigid cell walls, which impose a positive pressure on their contents. The water potential in plant tissues is therefore the difference in pressure applied by the cell walls and the osmotic pressure (i.e. water potential = wall pressure + osmotic potential [where the osmotic potential is negative]). (see also Solute).

Pathogen: any disease-producing microorganism.

Palynology: the study of pollen and its distribution.

Pedogenic: the formation of soil.

Pericarp: the wall of a fruit, derived from the maturing ovary layer.

Percolation: oozes through, permeates.

Pest: troublesome, annoying or destructive entity.

pH: the negative logarithm (to base 10) of the hydrogen concentration. It is a measure of the acidity of water or soil in which pH 7 is neutral, values above 7 are alkaline and values below 7 are acidic.

Phenology: the study of the timing of natural phenomena; for plants this means a study of the morphological and reproductive phases that a plant passes through during its life, such as the onset of flowering.

Photoperiod: duration of daily exposure to light.

Photosynthesis: the complex process carried out by plants in which light energy absorbed by the green pigment chlorophyll breaks the water molecule to liberate free oxygen and transfer hydrogen to acceptor molecules, which drive the formation of carbohydrate from carbon dioxide.

Phytoplankton: small marine or fresh water wandering plants.

Plasticity: capacity to change under the influence of stimuli.

Plumule: the embryonic shoot. In dicotyledons, the plumule is situated between the cotyledons.

Pneumatophores: aerial roots, which develop from underground horizontal roots.

Ponded: a condition in which water stands in a closed depression. Water may be naturally removed only by percolation, evaporation or transpiration.

ppt: parts per thousand.

Pristine: original and unspoiled.

Productivity: net annual primary productivity is the amount of plant biomass that is generated per unit area per year.

Propagule: any seed, fruit, or other portion of a plant, which when being dispersed is able to produce a new plant.

Radicle: the embryonic root.

Redox potential (Eh): oxidation reduction potential, a measure of the tendency of a given system to act as an oxidising or reducing agent.

Redundancy: unused excess capacity.

Reforest: to restore a forest.

Respiration: the process by which energy of organic material is made available to drive energy-consuming reactions in a living organism or cell.

Restoration of an ecosystem: the act of bringing an ecosystem back into, as nearly as possible, its original condition, renewing it or bringing it back into use.

Rhizome: an underground stem that grows horizontally and through branching acts as an agent for vegetative propagation.

Salinity: measure of the total concentration of dissolved salts in water, often expressed as parts per thousand (ppt).

Sand: non-cohesive sediment particles measuring 2.0–0.06 mm in diameter.

Sedimentation: process of deposition of particulate matter.

Seed: a reproductive unit formed from a fertilised ovule consisting of an embryo, food store and protective coat.

Senescence: the complex of ageing processes that eventually lead to death.

Silviculture: the cultivation, growing and tending of trees.

Solute: a solute is an inorganic (not containing carbon) or organic (containing carbon) substance dissolved in water. Common inorganic solutes include sodium, magnesium, potassium, calcium, chloride and sulphate ions. Common organic solutes include sugars such as sucrose, glucose and fructose, and all dissolved metabolites.

Substrate: the base or substance on which an attached species is growing.

Succession: a geological, ecological or seasonal sequence of species; the development of plant communities leading to a climax.

Surficial: of the earth's surface.

Sustainable development: development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable mangrove forest management: utilisation of mangrove forest (including aquatic resources) without undermining their use by present and future generations.

Terrigenous: derived from land.

Testa: the protective outer covering of a seed.

Tidal: a situation in which the water level periodically fluctuates due to the action of lunar and solar forces upon the rotating earth.

Transpiration: the loss of water by evaporation from the leaves of plants. The water is lost through small pores (stomata) in the surface of the leaf.

Tree biomass: the biomass of vegetation classified as trees including foliage, stumps and roots.

Tree: a woody plant with a single main trunk bearing lateral branches. Sometimes defined as a woody plant less than 750 mm in diameter at breast height.

Tunicate: provide with a coat or tunic.

Vascular (bundle): Vascular tissue in plants is made up mainly of xylem and phloem. Xylem carries water and nutrients from the roots to the leaves, whereas phloem transports materials (mainly photosynthetic products and other organic compounds) in the opposite direction, from the leaves to other parts of the plant. Xylem and phloem are usually bundled together in a ring-like arrangement called the 'vascular bundle' (see also Xylem).

Vivipary: fruit germinating while still attached to the plant.

Water potential: Water flows from the soil to the plant, and in the plant from the roots to the leaves, along a gradient of decreasing water potential (i.e. from less negative to more negative (see Osmotic potential)).

Water table: the upper surface of groundwater or the level below which the soil is saturated with water.

Wreck: seaweed cast up or growing below high water mark.

Xylem (Xylem vessels): The xylem is the tissue in plant roots, stems and leaves that carries water from the roots to the leaves. Xylem forms part of what is called the vascular bundle. Xylem made up of many small tube-like vessels. In principle, a xylem vessel can be likened to a blood vessel in the human body, except that xylem vessels have perforated (with tiny holes) cross-walls at intervals along their length. (also see Vascular).

Zonation: arrangement or distribution in zones.

Zone: an area characterised by similar flora or fauna; a belt or area to which certain species are limited.

Chapter 1

INTRODUCTION

Mangroves are a diverse group of trees, shrubs and ground ferns that grow in a particular habitat – the intertidal area between land and sea along tropical and subtropical coastlines throughout the world. The term ‘mangrove’ is also used more generally to describe both the plant communities they form and the habitat itself. Together with the animals and other organisms that live in the same habitat, they form a unique type of ecosystem, the ‘mangrove ecosystem’.

Not surprisingly, there are differing opinions about which plant species should be recognised as mangroves and which should not. Broadly speaking, a mangrove is ‘a tree, shrub, palm or ground fern, generally of more than 50 cm in height, that normally grows above mean sea level in the intertidal zone of marine coastal environments or along the margins of estuaries’ (Duke, 1992). But perhaps the best operational definition is that by Saenger (2002), ‘*A mangrove is a higher plant (tree, shrub, palm, herb or fern) which (1) predominantly grows in the intertidal areas of tropical and subtropical shorelines, which (2) exhibits a marked degree of tolerance to high salt concentrations and soil anoxia, and which (3) has propagules able to survive dispersal by seawater.*’

Approximately 73 species of plants belonging to over 20 unrelated plant families fit these criteria and show fidelity to the mangrove habitat (Spalding et al., 2010). What they all have in common are a range of adaptations that enable them to cope with regular tidal flooding, strong winds, waves and water currents, unstable muddy soils, high levels of salt in the water, and oxygen deficient soils. Given the diversity of their origin, it is clear that mangroves are an ecological assemblage of very different species with many attributes in common, rather than a taxonomic group.

In addition to the so-called ‘true mangroves’, which by the definitions above are naturally restricted to mangrove habitats, many other plant species that occur in coastal areas are also sometimes found in mangrove habitats. The *Mangrove Guidebook for Southeast Asia*, for example, lists 268 plant species that are found in intertidal mangrove areas in Southeast Asia, of which only 52 are regarded as ‘true mangroves’ (Giesen et al., 2007). These include a wide range of ground-dwelling trees, palms, vines, herbs, grasses and ferns, as well as epiphytic ferns, orchids and mistletoes that grow on the trees. They are more common in back mangrove areas near the upper tidal limit and in upstream regions of tidal rivers. Although they contribute to floristic diversity in mangrove habitats, they seldom form dominant plant communities.

Because they occur at the boundary between land and sea, mangroves are part of the ecosystem continuum from terrestrial to fully marine. While mangroves tend to recycle nutrients and organic materials very efficiently, they are nevertheless open systems in the sense that water, sediment, nutrients and organic materials are imported from and exported to adjacent ecosystems by incoming and outgoing tides, and by river flows from upstream catchments. Interactions between these and other hydrological factors determine whether there is a net import or a net export of materials from a particular area of mangroves.

Although mangroves are predominantly tropical and subtropical they are also occasionally found along some cooler temperate coastlines, notably in Australia and on the east coasts of South America and Africa in the southern hemisphere, and China and southern Japan in the northern hemisphere. In estuaries and estuarine deltas in humid equatorial climates, mangroves can form extensive and imposing tidal forests of up to about 40–60 m in height. Mangroves are also found along protected sandy and rocky shorelines, on coral islands and sometimes even along

coastlines exposed to waves and strong sea currents. In these situations they are often limited to a narrow band of up to several hundred metres in width, often less. There are also cases of natural mangroves growing inland, apparently cut off from any oceanic or tidal influences in north-western Australia, Senegal, Madagascar and the Caribbean, and even at elevations of about 75 m above sea level in Papua New Guinea and on terraces on Christmas Island ranging in elevation from about 30–300 m above present sea level (Saenger, 2002). These are thought to be relic mangrove communities that have survived for thousands of years since they were raised above sea level. The trees in these atypical settings presumably have the capacity to reproduce, for otherwise it is unlikely that they could have persisted for so long.

There are no reliable records on the area of mangroves at the beginning of the 20th Century, but it was probably more than 200,000 km². Today, mangroves cover an area of just 152,360 km² (Spalding et al., 2010), less than 0.4% of the world's forests and woodlands (Field, 1995). However, as we shall see later, their importance ecologically and benefits to people far outweigh their relatively small area.

Traditional coastal dwellers and communities have long understood the value and benefits of the mangroves on which they depend for food, shelter, fuel and other necessities of life. Late 19th Century accounts of mangroves by French, German, Dutch and British naturalists described many of the traditional uses of mangroves by those who had made mangroves their home. Around this time, British, Dutch and French foresters were beginning to practise mangrove silviculture to provide sustainable supplies of timber and other forest products, mainly in Bangladesh and Malaysia. In 1928, for example, J.G. Watson published a classic and comprehensive account of the *Mangrove Forests of the Malay Peninsula*, complete with a management plan for sustainable timber production. A revised version of that management plan is still being used today in the Matang mangrove in Perak, West Malaysia.

Unfortunately, modern urbanised and industrialised societies have not been so kind to mangroves, which until relatively recently were often regarded as marginal wastelands better used for other purposes. Large areas of mangroves have been converted to oil palm plantations in Malaysia and Indonesia, and to rice fields in the Philippines and West Africa. However, the most dramatic loss of mangroves has probably occurred from their conversion to shrimp ponds, particularly in Asia and Latin America.

It is now clear that mangroves provide a range of goods and services to humankind. These can be of material value such as timber, fisheries, coastal protection, biofiltration, medicine and livelihoods for coastal people, or they can also be of non-use or existence values like cultural or religious, and their value as part of the biodiversity on earth. However, in only a few cases has it been possible to put a reliable monetary value on the goods and services provided by mangroves. Consequently, they are still being destroyed at an alarming rate to make way for urban expansion, ports, and particularly the construction of shrimp ponds for short-term benefits to a few at the expense of long term-benefits to society as a whole.

The Mangrove Species

Notwithstanding what seem to be reasonable criteria for determining what is and what is not a mangrove, there is still no universal agreement on the number of mangrove species worldwide. For example, Saenger (2002) listed 84 mangrove species globally, Duke et al. (1998b) 70 species and Spalding et al. (2010) 73 species. In all cases these include hybrids, which are formed by cross-fertilisation between two closely related species to produce offspring that share some of the characteristics of both parent species.

There are also still some taxonomic uncertainties with some groups of mangroves, notably the family Rhizophoraceae, and particularly the genus *Rhizophora*, where the East African *Rhizophora mucronata* appears to be similar to the Asian-Pacific species *Rhizophora stylosa* in its morphological characteristics and its ecological preferences. The origin and classification of the hybrid *Rhizophora x harrisonii* in the Atlantic-East Pacific region also remains to be clarified (Saenger, 2002).

Plant taxonomists have traditionally distinguished between plant species using differences in visual morphological characteristics such as the shape and structure of flowers, fruits, leaves and stems, and sometimes on ecological affinities. However, modern molecular genetic techniques are increasingly being used for taxonomic purposes. These have been used to clarify the taxonomic status and distribution of some species, for example, the genus *Ceriops* (Ballment et al., 1988; Sheue et al., 2009b), the genus *Kandelia* (Sheue et al., 2003), and an apparently new species, *Ceriops zippelliana* (Sheue et al., 2009a). These examples illustrate some of the taxonomic uncertainties that still remain with the identification of mangrove species. While important, they do not influence discussions of the broader structure and function of mangrove ecosystems significantly, and here we will adopt the shorter species listing of Spalding et al. (2010), for no other reason than it is simpler and covers the main mangrove species (Tables 1.1 and 1.2). Furthermore, we will not be concerned with detailed descriptions of individual species of mangrove. For these, readers should consult the excellent books by Tomlinson (1986), Saenger (2002) and, for Southeast Asian mangroves by Giesen et al. (2007).

Table 1.1 The 62 mangrove species and hybrids of the Indo-West Pacific region. One species, *Acrostichum aureum*, is also found in the Atlantic-East Pacific. Families and species in blue are considered to be core mangrove species. From Spalding et al. (2010).

Family	Species	Family	Species
Acanthaceae	<i>Acanthus ebracteatus</i>	Rhizophoraceae	<i>Bruguiera cylindrica</i>
	<i>Acanthus ilicifolius</i>		<i>Bruguiera exaristata</i>
Arecaceae	<i>Nypa fruticans</i>		<i>Bruguiera gymnorhiza</i>
Avicenniaceae	<i>Avicennia alba</i>		<i>Bruguiera hainesii</i>
	<i>Avicennia integra</i>		<i>Bruguiera parviflora</i>
	<i>Avicennia marina</i>		<i>Bruguiera sexangula</i>
	<i>Avicennia officinalis</i>		<i>Bruguiera x rhynchopetala</i>
	<i>Avicennia rumphiana</i>		<i>Ceriops australis</i>
Bignonaceae	<i>Dolichandrone spathacea</i>		<i>Ceriops decandra</i>
Bombaceae	<i>Camptostemon philippinensis</i>		<i>Ceriops tagal</i>
	<i>Camptostemon schultzei</i>		<i>Kandelia candel</i>
Caesalpiniaceae	<i>Cynometra iripa</i>		<i>Kandelia obovata</i>
Combretaceae	<i>Lumnitzera littorea</i>		<i>Rhizophora apiculata</i>
	<i>Lumnitzera racemosa</i>		<i>Rhizophora mucronata</i>
	<i>Lumnitzera x rosea</i>		<i>Rhizophora samoensis</i>
Ebenaceae	<i>Diospyros littorea</i>		<i>Rhizophora stylosa</i>
Euphorbiaceae	<i>Excoecaria agallocha</i>		<i>Rhizophora x lamarckii</i>
	<i>Excoecaria indica</i>		<i>Rhizophora x neocaledonica</i>
Lythraceae	<i>Pemphis acidula</i>		<i>Rhizophora x selala</i>
Meliaceae	<i>Aglaia cucullata</i>	Rubiaceae	<i>Scyphiphora hydrophyllacea</i>
	<i>Xylocarpus granatum</i>	Sonneratiaceae	<i>Sonneratia alba</i>
	<i>Xylocarpus moluccensis</i>		<i>Sonneratia apetala</i>
Myrsinaceae	<i>Aegiceras corniculatum</i>		<i>Sonneratia caseolaris</i>
	<i>Aegiceras floridum</i>		<i>Sonneratia griffithii</i>
Myrtaceae	<i>Osbornia octodonta</i>		<i>Sonneratia lanceolata</i>
Plumbaginaceae	<i>Aegialitis annulata</i>		<i>Sonneratia ovata</i>
	<i>Aegialitis rotundifolia</i>		<i>Sonneratia x gulngai</i>
Pteridaceae	<i>Acrostichum aureum</i>		<i>Sonneratia x hainanensis</i>
	<i>Acrostichum danaeifolium</i>		<i>Sonneratia x urama</i>
	<i>Acrostichum speciosum</i>	Sterculiaceae	<i>Heritiera fomes</i>
			<i>Heritiera globosa</i>
			<i>Heritiera littoralis</i>

Table 1.2 The 12 mangrove species and hybrids found in the Atlantic-East Pacific region. One species, *Acrostichum aureum*, is also found in the Indo-West Pacific. Families and species in blue are considered to be core mangrove species. From Spalding et al. (2010).

Family	Species	Family	Species
Avicenniaceae	<i>Avicennia bicolor</i> <i>Avicennia germinans</i> <i>Avicennia schaueriana</i> <i>Tabebuia palustris</i>	Pellicieraceae	<i>Pelliciera rhizophorae</i>
		Pteridaceae	<i>Acrostichum aureum</i>
		Rhizophoraceae	<i>Rhizophora mangle</i> <i>Rhizophora racemosa</i>

At the global and regional level, the modern day distribution of mangroves shows three major patterns – marked differences in species, both taxonomically and numerically, between Africa, Asia and the Americas – a decline in the number of species with increasing latitude, mostly associated with temperature – and a reduction in species diversity with decreasing rainfall and increasing aridity. At the local level, the floristic composition of mangrove forests is determined by spatial variability in elevation and topography relative to sea level, by the tidal range, by proximity to the sea or position upstream in a river, and by local site drainage.

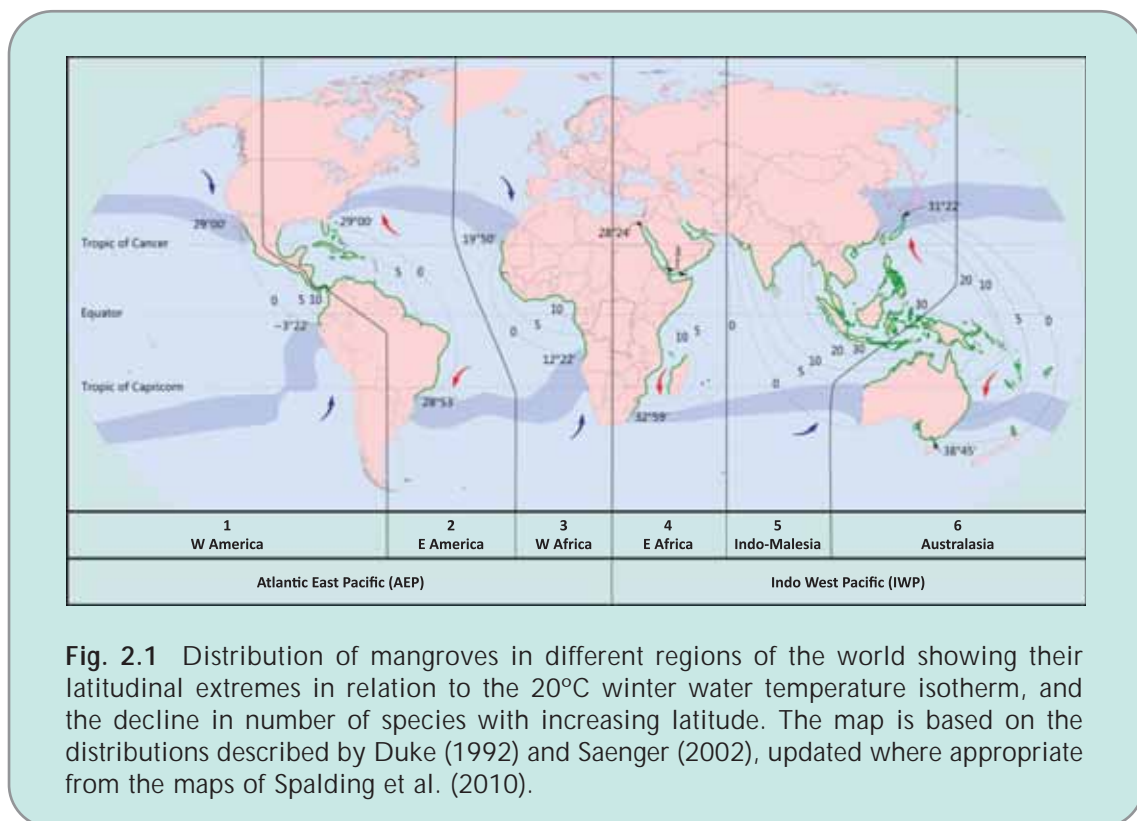
In the following chapters, we will first explore the evolution of mangroves and some of the factors that have led to their present distribution patterns globally, regionally and locally (Chapter 2), and then examine some of the strategies they use to cope with their inhospitable habitat (Chapter 3). Later chapters will briefly cover the faunal components of mangroves (Chapter 4), the goods and services they provide to human society (Chapter 5), land use activities and other threats that one day could lead to their disappearance (Chapter 6), and sustainable management (Chapter 7).

Chapter 2

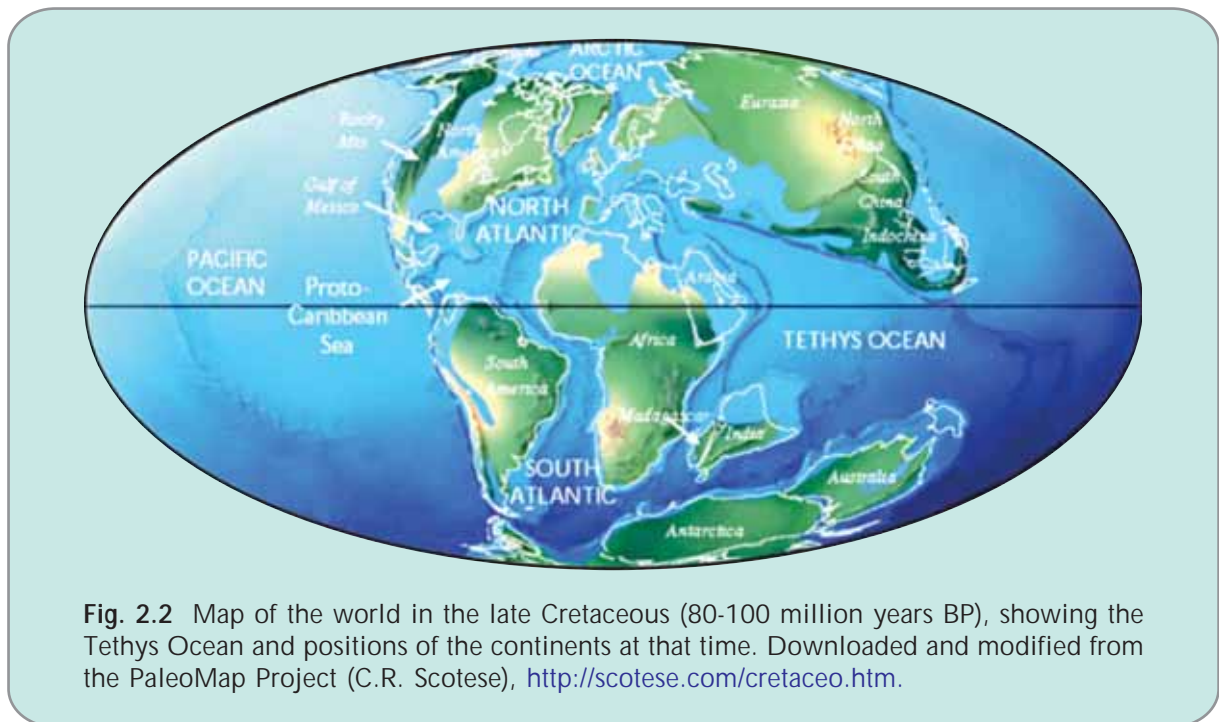
MANGROVE DISTRIBUTION AND ENVIRONMENT

Global Distribution

The present day distribution of mangroves can be divided in six distinct zones from east to west, each separated by land or oceanic barriers that prevent migration from one zone to another (Fig. 2.1). Although the propagules of some mangrove species can remain viable in seawater for a period of months, the present extent of the Atlantic and eastern Pacific Oceans appear to be significant barriers to trans-ocean migration between tropical continental coastlines of Africa, the Americas and Asia. Mangrove migration between the east Pacific and west Atlantic coastlines of the Americas is prevented by the Isthmus of Panama between North and South America and the extension of the southern tip of South America into colder sub-Antarctic waters, effectively isolating these two floras. Likewise, in Africa the mangrove flora on west Indian Ocean coastline are isolated from those on the eastern Atlantic coastline by cold, rough seas at the southern tip of South Africa and in the north by the present day closure of the oceanic link between the Indian Ocean and the Mediterranean Sea.



As many authors have pointed out, the present day distribution of mangrove species, with its clear distinction between the old world (Indo-West Pacific and East African) and new world (Atlantic coasts of West Africa and eastern Americas) mangrove floras, and the differentiation between the mangrove floras of the east and west coasts of Africa and the Americas, can only be explained by historical processes. It is beyond the scope of this book to discuss in detail the ongoing debate about various theories on the origin and distribution of present day mangroves. However, most evidence (see Ellison et al., 1999 and Saenger, 2002) suggests



that modern day mangrove genera, or their closely related ancestors, originated in the late Cretaceous (ca. 80 to 100 million years BP) along the shores of the Tethys Sea (Fig. 2.2).

It is likely that there was more than one centre of origin, *Rhizophora* and *Avicennia* in the eastern Tethys, *Nypa* and perhaps *Laguncularia* and *Conocarpus* in the western Tethys, and *Sonneratia*, *Heritiera*, *Pelliciera* and *Aegiceras* in the central Tethys (Ellison et al., 1999; Saenger, 2002). From the Late Cretaceous (100 million years BP) through to the mid Eocene (ca. 45 million years BP), the world was warm, much of it was covered by forest and there were no polar ice caps, ideal conditions for the evolution and development of mangroves. During this time mangroves became widely dispersed along the shores of the Tethys, Atlantic and Pacific Oceans. Fossil pollen records indicate they extended northwards throughout the Mediterranean into what are now the United Kingdom, France and perhaps elsewhere in Europe. As the world began to cool in the late Eocene about 40 million years BP, mangroves gradually contracted southwards from Europe, and presumably northwards from some higher latitude coasts in the southern hemisphere. Then about 18 million years BP continental drift brought Africa into contact with western Asia, closing off the sea route from the Tethys Sea (now the Indian Ocean) to the Atlantic and separating the 'Old World' and 'New World' mangrove floras. Finally, around 3 million years BP, the closure of the Panama Isthmus between North and South America effectively separated the mangrove flora on the East Pacific coast from that on the West Atlantic coast. There is likely to have been further contraction of mangroves towards equatorial regions associated with global cooling through to at least the last glacial maximum 10,000 to 20,000 years BP, and rising sea levels and other climatic changes since then are likely to have led to further contraction and changes in the structure and floristic composition of mangroves along a number of coastlines. A more extensive discussion of the evolution of mangroves can be found in Saenger (2002).

Latitudinal Gradients and Limits

In general, latitudinal limits seem to be correlated with water temperature, the latitudinal limits matching reasonably well with the 20°C winter water temperature isotherm (Fig. 2.1). The

extension of mangroves further poleward on continental east coasts is associated with warmer poleward flowing currents, and on continental west coasts with cooler currents flowing towards the equator. There are exceptions, however, especially in Region 6, where *Avicennia marina* extends well south of the isotherm in New Zealand and on the south-east coast of Australia (Fig. 2.1).

At any given location, daily and seasonal extremes of air temperature are far greater, and more variable, than for water temperature. Average air temperatures of mangrove habitats vary from an average monthly winter minimum of about 8°C (with extremes well below this) near their temperate latitudinal extremes, up to an average monthly summer maximum of over 40°C in places like the arid Pilbara coastline of Western Australia, north Africa, western Pakistan and coastlines along the Red Sea and Persian Gulf.

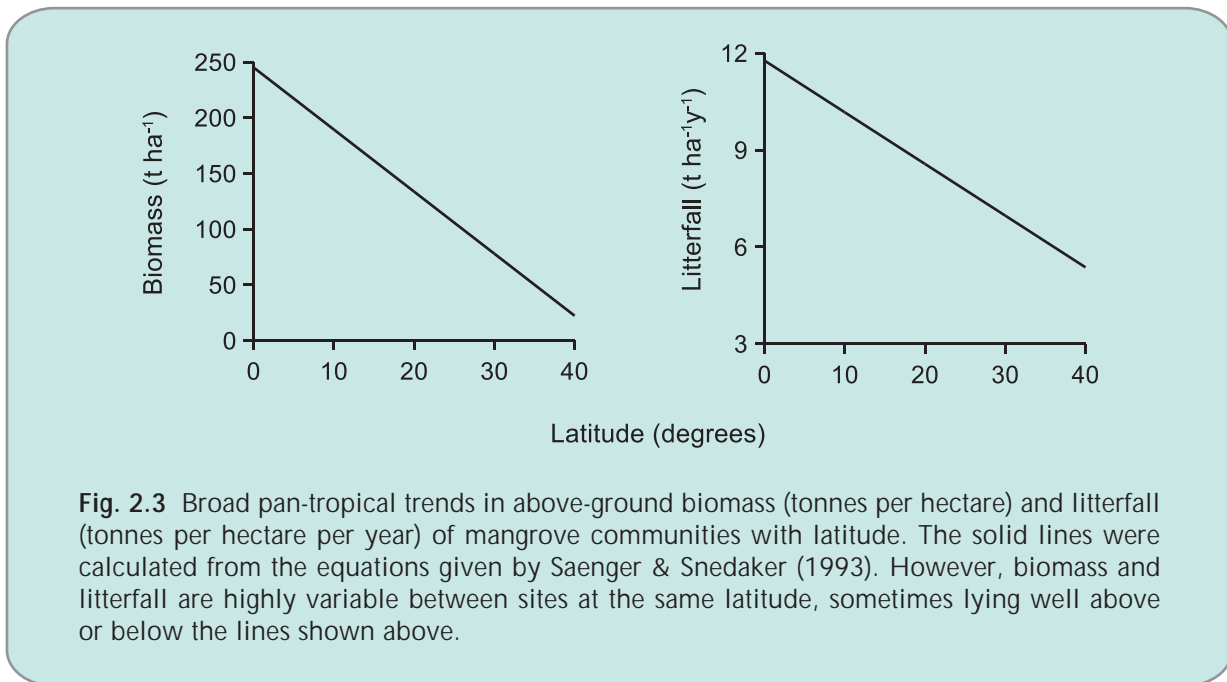
From a physiological perspective, water temperature is most likely to affect the roots and other parts of mangrove trees that are flooded regularly by the tide. Air temperature, on the other hand, mainly affects those parts of the tree that are above water, particularly the leaves which are responsible for the photosynthetic carbon fixation needed for survival and growth. Some physiological effects of air temperature on water loss and salt uptake will be discussed in Chapter 3; here we will consider more general effects of air temperature that are relevant to the latitudinal distribution of mangroves.

Frosts are rare in mangrove habitats, but they do occur occasionally in temperate climates close to the latitudinal extremes of mangroves. At least two species show some degree of frost tolerance, *Avicennia marina* (McMillan, 1975) and *Avicennia germinans* (McMillan, 1975; Markley et al., 1982). Tolerance to very low temperatures in both these species seems to depend on their origin – those from cold localities having a greater degree of tolerance to low temperatures than those from warm or hot localities (McMillan, 1975). It is also likely that *Kandelia obovata* has some degree of frost tolerance because the minimum temperate drops to as low as -3.6°C at its northernmost extent at Kiire on the island of Kyushu in southern Japan (Japan Meteorological Agency).

So what attributes or characteristics are important for low temperature tolerance in mangroves? The answer to this question is not understood well. Differences in the size of xylem vessels between species may affect their response to low temperatures. Species such as *Avicennia marina* and *Aegiceras corniculatum* have very small xylem vessel diameters (Tomlinson, 1986), which helps to prevent the formation of air bubbles (cavitation) in the xylem at freezing temperatures (Stuart et al., 2007). Cavitation leads to disruption of water transport to the leaves which, in turn, can lead to water stress and death. Other species of mangrove tend to have larger xylem vessels, and are thus more likely to be affected by temperatures below 0°C (Stuart et al., 2007). But other processes are also important. For example, one study with 27 species of mangroves found differences in the activity of chlorophyll at low temperatures between species, which appeared to correlate well with their southernmost limit of distribution along the eastern Australian coastline (Smillie, 1984; cited by Saenger, 2002).

It is clear from the foregoing discussion that, while there is a good correlation between minimum winter water temperatures and the latitudinal extremes for mangroves, air temperature can play a critical role in determining both the latitudinal limits for mangroves and the latitudinal range for particular species (Saenger & Moverley, 1985). However, there is still much to be learned about the mechanisms involved in the response of different species to low temperatures.

In addition to having greater floristic diversity and areal extent, mangrove forests close to the equator along the tropical coastlines of Africa, Asia and the Americas generally have taller trees, greater stand biomass and higher productivity than their counterparts at subtropical and temperate latitudes. Although variable because of site-specific differences in rainfall, river flows and other physical or chemical factors, there is a more or less linear decline in height, biomass and productivity with increasing latitude (Saenger & Snedaker, 1993), illustrated in Fig. 2.3. For a given coastline, this is likely to be mainly an effect of temperature, although in some cases rainfall or other factors also play a role.



Patterns Associated with Rainfall and Aridity

The third main regional pattern is a decrease in species number, tree height and growth rate along sections of coastline with low rainfall and high evaporation, that is, along arid coastlines. In addition to low rainfall, such coastlines often lack large rivers, and where there are rivers, freshwater flows from upstream catchments to estuarine deltas may be limited. Lack of freshwater inputs, together with high rates of evaporation results in higher soil salinities and, in more elevated areas near to the upper tidal limit, complete drying out of the soil surface. As we shall see in Chapter 3, high soil salinity presents mangroves with problems in managing salt and water uptake, and these problems become more severe in cloudless, hot and dry conditions which increase the rate of water loss from leaves and put greater demands on water uptake from the soil.

Mangroves are found along arid coastlines in West Africa, the Middle East, Pakistan, India, both North and South America, and Australia. The decrease in species number (Fig. 2.1) and changes in forest structure with aridity along the Australian coastline has been well documented (e.g. Semeniuk 1985; Smith & Duke, 1987; Duke, 1992). For example, there are about 35 species on the high rainfall eastern side of northern Cape York Peninsula, whereas 200 km west at the same latitude on the lower rainfall western side the number drops to 20. Further west, the number of species varies depending on a number of factors. These include temperature (higher temperature = more species), rainfall variability (greater inter-annual rainfall variability = fewer species), size of the estuary and its catchment (longer estuaries with large catchments = more species) and freshwater runoff (more runoff = more species) (Smith & Duke, 1987).

Local Zonation Patterns

For river dominated systems in the species-rich Indo-West Pacific, there is usually a clear species distribution pattern from the river mouth to the upstream limit of tidal influence (e.g. Bunt et al., 1982; Duke et al., 1998a), one example of which is shown in Fig. 2.4. These patterns can differ between rivers depending on their geographic location, catchment size, seasonal rainfall patterns, and differences between species in their response to seasonal changes in salinity (Ball, 1988a; Duke et al. 1998a).

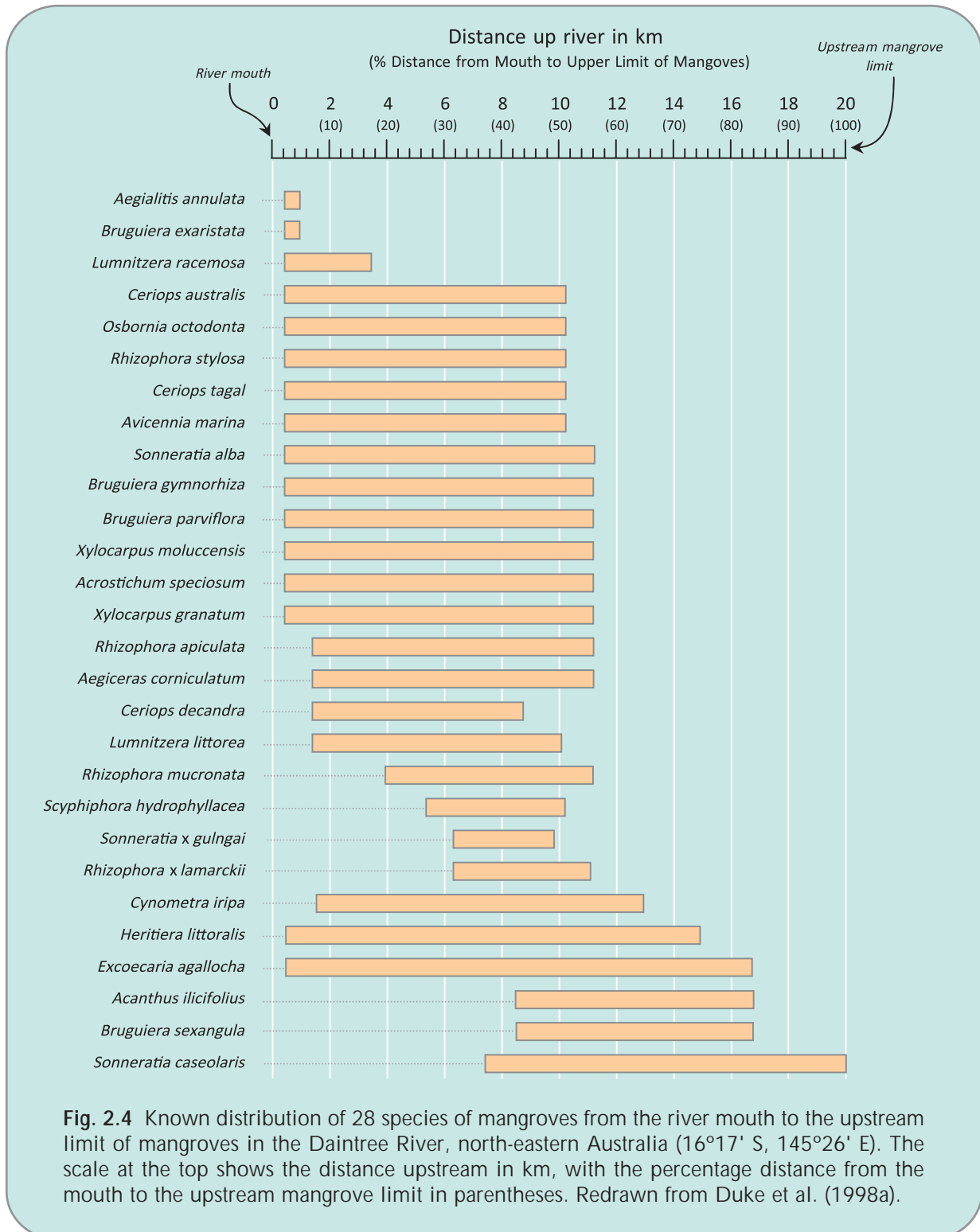
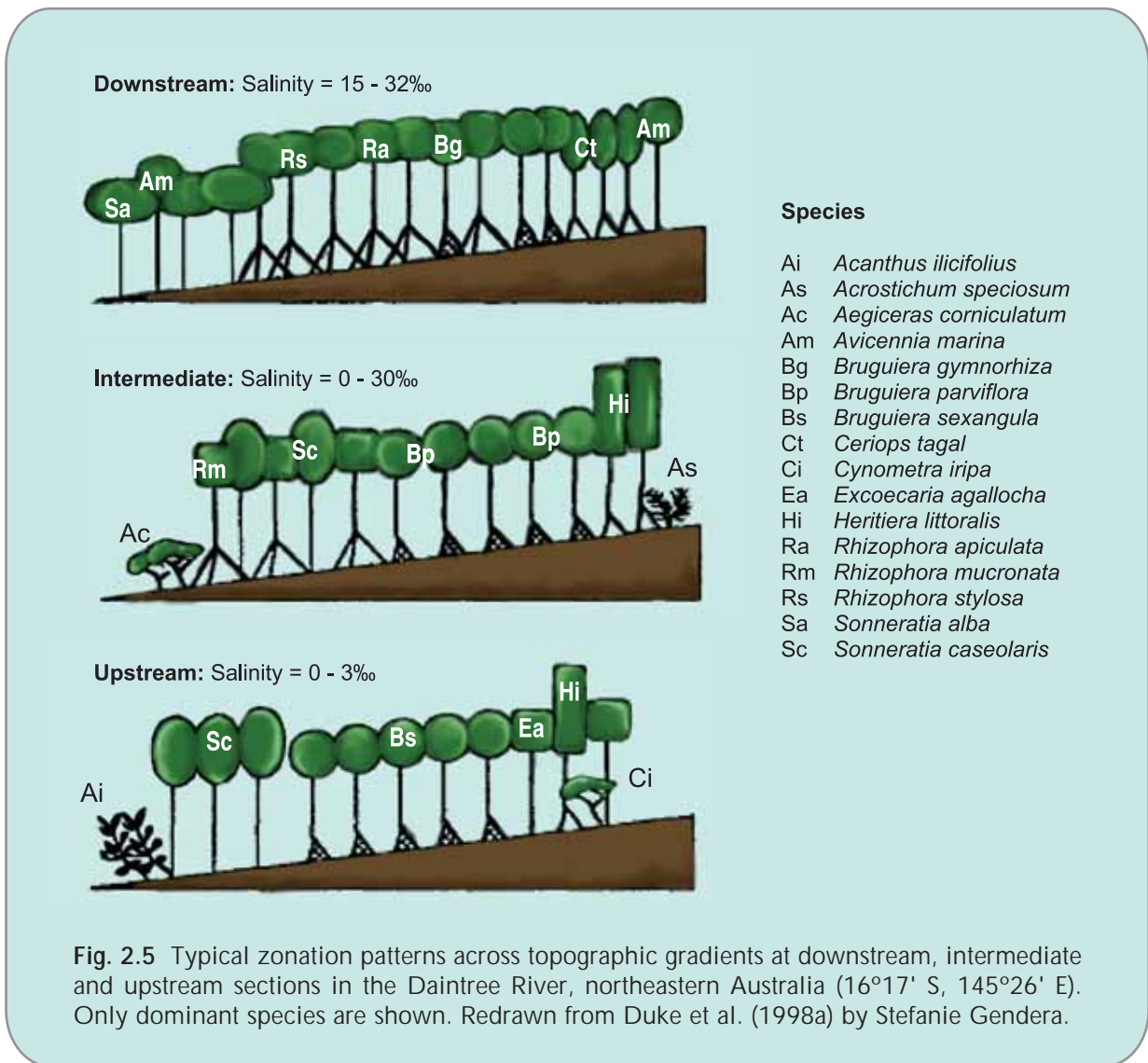


Fig. 2.4 Known distribution of 28 species of mangroves from the river mouth to the upstream limit of mangroves in the Daintree River, north-eastern Australia (16°17' S, 145°26' E). The scale at the top shows the distance upstream in km, with the percentage distance from the mouth to the upstream mangrove limit in parentheses. Redrawn from Duke et al. (1998a).



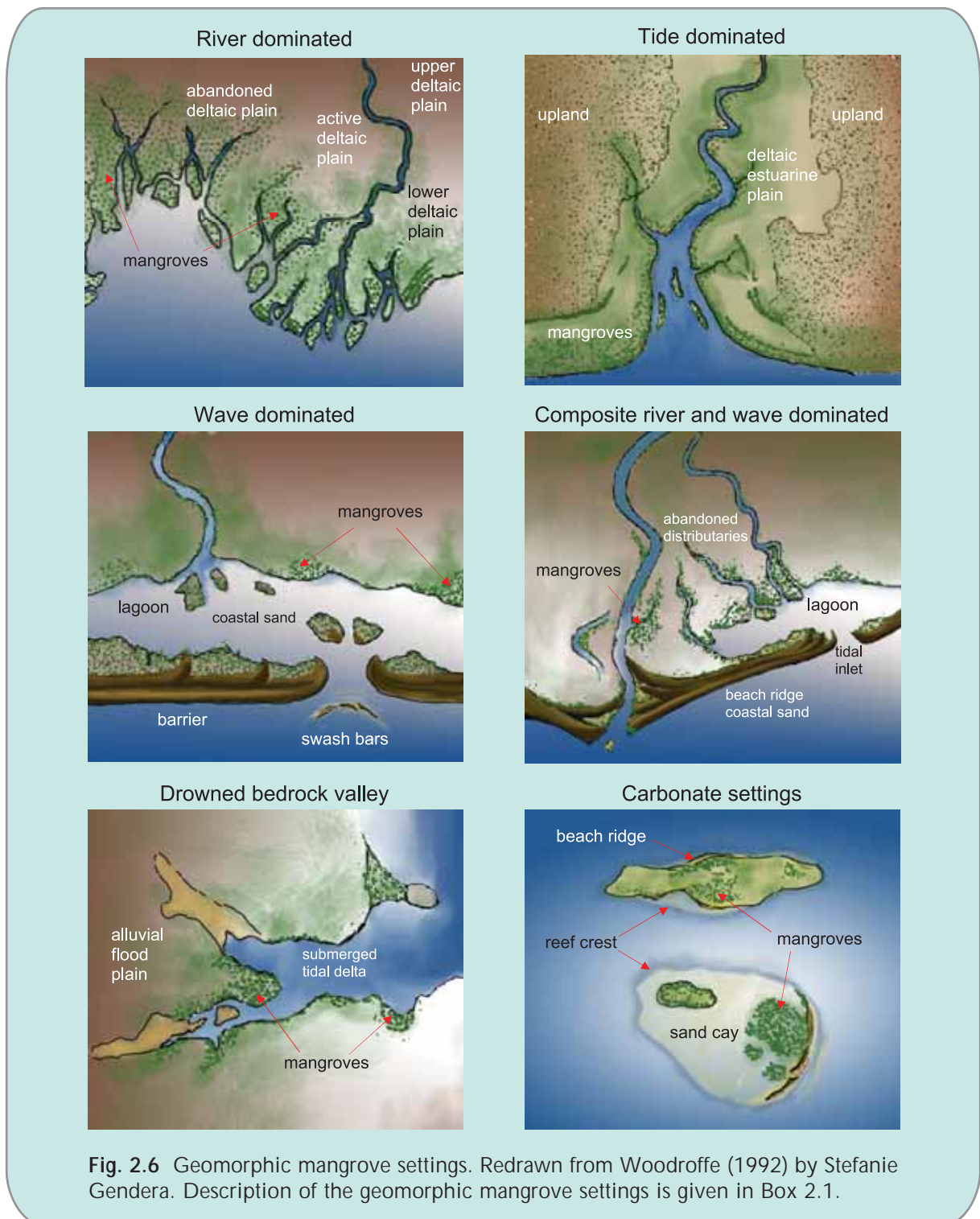
There are also clear intertidal gradients transversely from the river margin at different positions in the river (Duke et al., 1998a), which presumably reflect the tolerance of particular species to water logging and drainage (in addition to salinity). In north-eastern Australia, *Avicennia marina* often shows a bimodal distribution pattern, being present in both low and high intertidal elevations at downstream sites (Fig. 2.5).

In rivers with high discharge rates, these distribution patterns tend to move downstream towards the sea. For example, in the Hau River, the southernmost tributary of the Mekong River in Vietnam, *Sonneratia caseolaris* extends for about 60 km, from the upstream limits of mangroves down to the mouth where it forms a seaward fringe facing the open sea. Much of this seaward fringe is natural, although there has been supplemental planting to enhance coastal protection. Apart from scattered trees of *Rhizophora apiculata*, some of which have been planted, other species are rare or absent.

Intertidal zonation patterns are also observed in fringe mangrove stands. The intertidal zonation pattern shown by (Duke et al., 1998a) for the downstream section of the Daintree River on the north-eastern Australian coast is similar to the classical zonation pattern (but with fewer species) described by Macnae (1966) for coastal fringe mangroves in a lower rainfall area some 400 km south of the Daintree River.

Environmental Settings of Mangroves

There are many ways to characterise mangrove habitats. At a broad level, they can be characterised by their geomorphology – the geological and physical factors (river flows, tides and waves) that have led to their formation and maintain their overall structure and zonation patterns (e.g. Thom, 1982; Semeniuk, 1985; Woodroffe, 1992). This approach helps to understand how mangroves have developed in a particular area over historical time frames and to explain the physical factors that shape them. Some examples from Woodroffe (1992) are shown in Fig. 2.6.



Box 2.1 Description of geomorphic mangrove settings

River dominated

River-dominated settings are typically large deltas that receive large amounts of sediment from upstream catchments. They are usually highly dynamic. Examples include the Ganges and Brahmaputra Rivers which together form the vast Sundarbans mangrove forest of India and Bangladesh, and the mangrove delta of the Gulf of Papua, which extends from eastwards from the Fly River to the Purari River.

Tide dominated

Tide-dominated settings are often found along exposed coasts where there is very little freshwater input from rivers. They are common along coasts where the tidal range is greater than about 4 m (macrotidal). Such settings are typical of mangroves along the north-western coast of Australia where the tidal amplitude ranges from about 6 m up to about 10 m.

Wave dominated

Wave-dominated settings are most commonly found on exposed sandy coasts with high wave energy. Mangroves are usually restricted to lagoons and protected areas inside large sand dunes. Extensive mangrove peat deposits are common where the system has been stable for a long time.

Composite river and wave dominated

Composite river- and wave-dominated settings most often occur where rivers carry large amounts of sediment to a wave-dominated coast. Like wave-dominated settings, mangroves are commonly found in protected lagoons behind a sandy beach ridge. The main difference between this setting and wave-dominated setting is the input of substantial amounts of riverine sediment.

Drowned bedrock valley

Drowned bedrock valley settings occur in large coastal embayments that have been drowned by post-glacial sea rise. This setting is common in south-eastern Australia and is also found in the Kimberley region of north-western Australia.

Carbonate settings

Carbonate settings are typically found on oceanic islands and coral reefs, where the sediment is of calcareous origin and there is very little input of muddy sediment from the landward. Mangroves in this setting often grow over an extensive layer of mangrove peat.

Another common approach to describing mangrove habitats, developed and used most widely in New World (the neotropics or the West Atlantic-East Pacific region), is to use physiognomy (the outward visible appearance) to infer functional relationships between mangroves with particular structural characteristics, and flooding with tidal water or freshwater. In this approach, mangrove habitats are divided into six functional types – fringe, riverine, basin, scrub, hammock and overwash (Lugo & Snedaker, 1974; Woodroffe, 1992) (see Fig. 2.7). This approach helps to understand how forest structure and productivity at a local scale is influenced by elevation, tides, freshwater flow and water quality. However, as Woodroffe (1992) has pointed out, these six functional types of mangroves are not always so easily recognised in the more diverse, species rich mangrove systems of the Old World (Indo-West Pacific region).

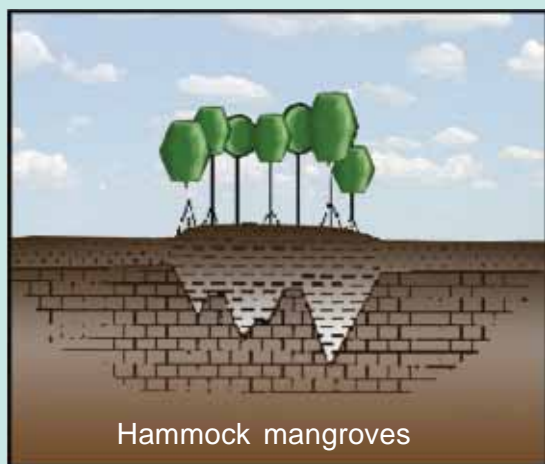
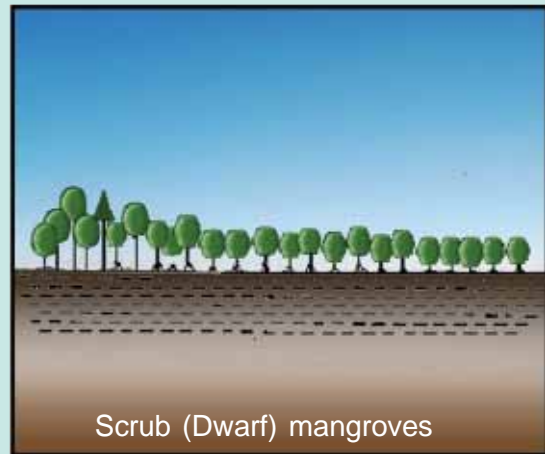
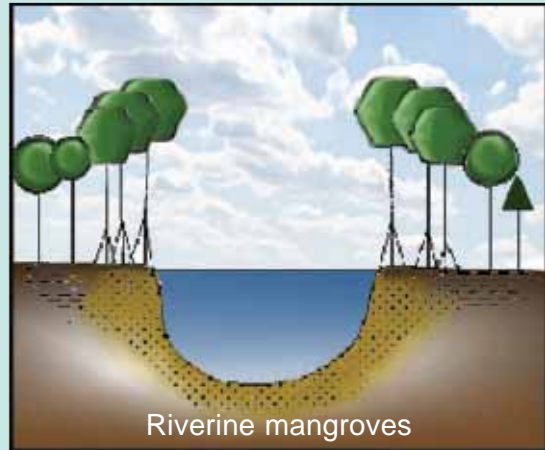
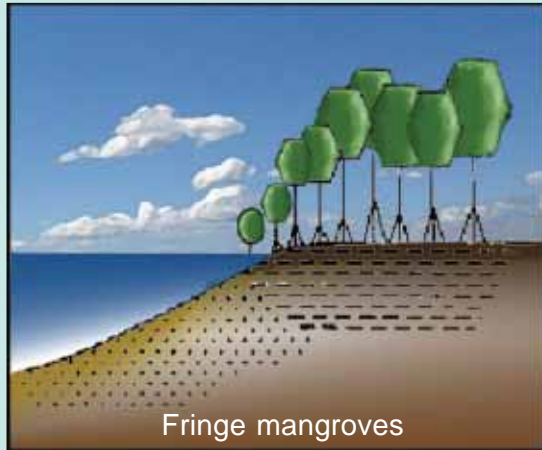


Fig. 2.7 Six functional types of mangrove forest described by Lugo & Snedaker (1974) and Woodroffe (1992). Redrawn from Woodroffe (1992) by Stefanie Gendera. Description of the functional types is given in Box 2.2.

Box 2.2 Description of the six functional types of mangrove forest

Fringe mangroves

Fringe mangrove forest is found mainly along protected open coastlines, and occasionally along more exposed coastlines. It often forms a narrow band with a distinct zonation pattern from seaward to landward. The species composition varies with geographic region, the seaward margin often being dominated by *Rhizophora mangle* in the New World, and *Avicennia marina*, *Rhizophora stylosa* or *Sonneratia alba* in the Old World Tropics (e.g. Figs. 2.6 and 2.7). Other species may also be present along the seaward margin, but are seldom dominant.

Riverine mangroves

Riverine forests are generally tall, productive forests along the margins of rivers and creeks that are flooded daily or almost daily. They can extend some distance inland from the river margins depending on elevation and local topography. The species composition varies with geographic region (that shown here is for New World mangroves – for an eastern Australian perspective see Fig. 2.5). For large rivers with significant salinity gradients, the species composition often varies with position upstream (see Fig. 2.5)

Basin mangroves

The basin forest type is found inland along drainage depressions, often but not always receiving terrestrial water runoff or drainage. In the New World, *Rhizophora mangle* tends to dominate in more tidally influenced areas, with *Avicennia germinans* and *Laguncularia racemosa* increasingly sharing dominance in less tidally influenced areas. This forest type is often difficult to define in more diverse and extensive mangrove formations in the Indo-West Pacific.

Scrub or dwarf mangroves

In the Atlantic-East Pacific region, scrub or dwarf mangroves are small (< 1.5 m tall) shrubs in areas that are usually nutrient deficient. In Australia, a similar forest type is found on elevated saline salt pans that are tidally flooded less than 1-2 days per month, where the vegetation consists mainly of small, shrubby *Avicennia marina*, *Ceriops australis* or both.

Overwash mangroves

Overwash mangroves are found on small low islands and narrow extensions to larger land masses that are overwashed at high tide. Although they are generally higher than the tide, the tidal velocity is sufficient to push tidal water over them. Overwash mangrove forest is dominated by *Rhizophora mangle* in the New World. In the Old World, other species of *Rhizophora* specific to the locality tend to dominate the mangrove community.

Hammock mangroves

The hammock mangrove type was not part of the original classification of Lugo & Snedaker (1974), but was included by Woodroffe (1992). This is a special form of basin mangrove growing on a raised layer of peat; it appears to be restricted to the Everglades of Florida.

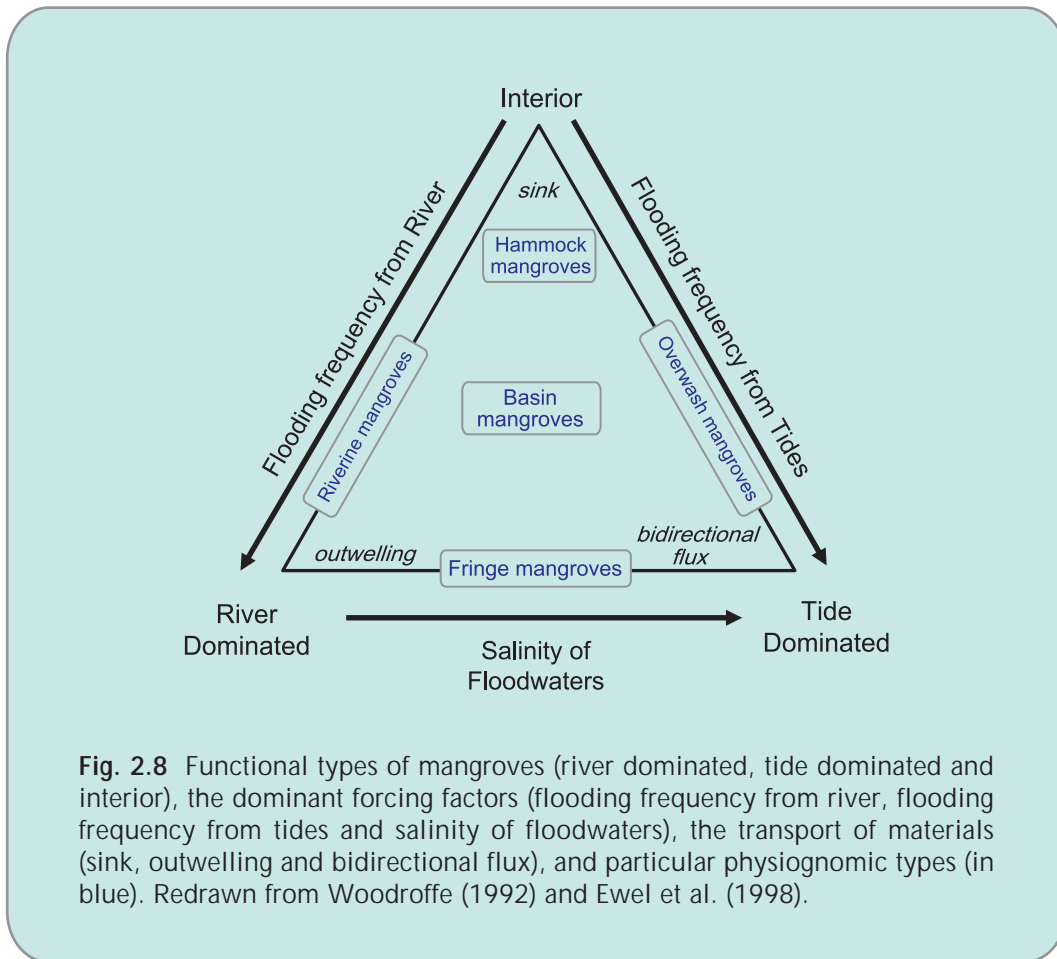


Fig. 2.8 Functional types of mangroves (river dominated, tide dominated and interior), the dominant forcing factors (flooding frequency from river, flooding frequency from tides and salinity of floodwaters), the transport of materials (sink, outwelling and bidirectional flux), and particular physiognomic types (in blue). Redrawn from Woodroffe (1992) and Ewel et al. (1998).

Both these approaches, 'geomorphic' and 'functional habitat', are valid and useful tools. However, being at the interface between land and sea, the mangrove ecosystem interacts with ecosystems and processes to both the landward and the seaward. The flow (or flux) of materials such as sediment, organic materials and nutrients between mangroves and adjacent ecosystems is a significant part of this interaction. The direction of flow and the amount of material exchanged depends on the type of mangrove habitat, its productivity, and its exposure to river flows, tidal flooding and wave action (Lugo & Snedaker, 1974; Woodroffe, 1992; Wolanski et al., 1992), the activity of fauna that process detritus (Robertson et al., 1992), and probably other factors. A generalised concept of the main direction of material fluxes in relation to tidal and river influences, and the main functional types of mangroves is shown in Fig. 2.8. While this is undoubtedly an oversimplification of a complex set of relationships, it provides a useful overview of some of the functional links between different types of mangrove ecosystems and adjacent ecosystems to the landward and the seaward.

In this chapter, we have explored the evolution of mangroves, their present day global biogeography, and some of the factors that influence their regional and local distribution patterns. We also outlined various approaches describing mangrove habitats at a broad level. In the next chapter, we will consider the strategies that mangroves have developed to cope with the dynamic and inhospitable habitat in which they live.



Photo: S. Baba

Chapter 3

LIVING WITH STRESS

The mangrove environment is indeed a harsh and difficult place for plants to live. As we have seen already, it is characterised by soft, unstable soils that are usually highly saline, more or less permanently flooded and generally anaerobic (anoxic or lacking in oxygen). No other trees can survive in such conditions, although as was noted in Chapter 2, some other trees can occasionally be found in less saline, more landward areas where the soil conditions are less severe.

In addition, since they are located at the extreme edge of coastlines and along the estuarine margins of rivers, they are often exposed to high winds and strong waves or near-shore ocean currents. They must therefore have root systems that of the right architecture and strength to keep them upright and stable in soft, unstable soils when exposed to these physical phenomena.

In this chapter, we will consider three aspects of life in the inhospitable mangrove habit – coping with excess salt and a lack of water – root structures that enable mangroves to survive in soft, unstable, anaerobic soils – and reproductive and dispersal mechanisms which give mangroves the ability to rapidly colonise suitable habitats. Other characteristics that help mangroves to survive in an inhospitable environment, such as efficient recycling of nutrients, will be discussed in the second volume of this trilogy and will not be considered here.

Coping with Salt

Seawater has a salinity of about 35 parts per thousand (35‰), so every litre of seawater contains around 35 grams of salt, mainly sodium (10.7‰) and chloride (19.3‰). Other important ions include potassium, calcium, magnesium and sulphate. The relative proportions of these ions are more or less constant. All are necessary in varying amounts for plant growth, but both sodium and chloride are necessary only in very small (trace) quantities for normal plant metabolism.

The soil salinity of mangrove habitats varies depending on the relative influences of freshwater and tidal saltwater, the frequency and duration of tidal flooding, rainfall, site elevation and slope, and the drainage characteristics of the mud or soil. Soil salinities are often around 35‰ in tidally dominated and wave dominated mangrove systems that are flooded daily by the tide, but they can be lower during periods of heavy rain and higher in compacted clayey soils with poor drainage. In extreme cases, soil salinity at landward, seasonally dry or rarely flooded sites can reach salinities of over 85‰ (Gordon, 1993). Conversely, soil salinities are often somewhat less than 35‰ in high rainfall areas, in upstream sections of tidal rivers with significant freshwater flows, and in areas where there is a flow of drainage water from landward. Soil salinity is also influenced by the burrowing activity of crabs and some other crustaceans, which increases water exchange between tidal waters and the soil (Ridd, 1996; Stieglitz et al., 2000) and helps to aerate the soil.

Most mangroves of course are tolerant of a reasonably wide range of salinities, some species, notably *Avicennia marina* and to a lesser degree *Ceriops australis*, being able to survive at salinities of 80‰ or higher on landward salt flats that are flooded only by the highest lunar tides. Short-term studies of salinity tolerance in seedlings have shown that a number of species grow best at salinities in the range of 10–20‰ (e.g. Clough, 1984; Ball, 1988b; Khan & Aziz, 2001; Paliyavuth et al., 2004). All have demonstrated that seedling growth is poor in freshwater. However, studies with seedlings under relatively uniform or controlled conditions may or may not be indicative of the salinity responses of adult trees in natural field conditions. What is

clear, however, is that different species show characteristic local patterns of distribution that are related to salinity and other hydrological factors (see Figs. 2.4 and 2.5 in Chapter 2).

High soil and water salinities pose two main problems for mangroves and other plants that grow in similar saline habitats. Firstly, the accumulation of high levels of sodium and chloride in plant tissues can have severe effects on cell metabolism (Flowers et al., 1977; Flowers et al., 1986). These effects have been studied more widely in other halophytes, but they are likely to be similar in mangroves, which share many of the attributes found in other halophytes growing in comparable habitats. For example, high salt concentrations have been reported to affect photosynthetic biochemistry (Ball & Anderson, 1986; Ball et al., 1987) and protein synthesis (Mizrachi et al., 1980), and increase respiration rates (Burchett et al., 1989).

Secondly, high salinities make it difficult for a mangrove tree to extract water from the soil owing to the low osmotic potential of the soil water. But as we will also see later, some salt uptake is necessary for the leaves to generate a low enough water potential to drive water uptake from a saline soil. Thus, avoiding salt toxicity on the one hand, while on the other, extracting sufficient water from the soil to replace that lost each day by transpiration from the tree canopy, are interrelated aspects of the capacity of mangroves to cope with high soil salinities.

There are three general strategies that a mangrove tree can use to manage salt – avoid it by excluding it from the water taken in by the roots, eliminate or dispose of it once it gets inside the plant, or store it somewhere where it can do no harm. In fact, mangroves as a group make use of all these strategies, but only two seem to be shared by all mangroves – exclusion at the root, and storage in cell organelles or tissues where it can do no harm and does not affect normal metabolism. All of them require metabolic energy and may therefore be relatively costly in terms of energetics, as implied by a higher respiration rates at high salinities (Burchett et al., 1989). A good review of salt tolerance mechanisms in mangroves can be found in Parida & Jha (2010).

Salt exclusion

The roots of all plants have the capacity to take up certain salts, while excluding others, but mangroves seem to possess an enhanced capacity to exclude sodium chloride. In a sense, this is a mangrove tree's first line of defence. The pioneering work of Scholander and colleagues in the 1960s (Scholander et al., 1962, 1964, 1965, 1966; Scholander 1968) and Atkinson et al. (1967), as well as more recent studies (e.g. Moon et al., 1986; Werner & Stelzer, 1990; Paliyavuth et al., 2004) have shown that all species of mangrove tested thus far can exclude at least 80% of the external salt during water uptake, with even greater efficiency (> 95%) in species without salt glands (see below). The mechanisms involved in salt exclusion are still not fully understood, but most recent evidence (e.g. Moon et al., 1986; Werner & Stelzer, 1990; Popp et al., 1993; Weiper, 1995 [cited by Saenger, 2002]) suggests it takes place in the outer exodermis or hypodermis (a layer cells just beneath the epidermis) where secondary thickening of the radial cell walls prevents water transport across the cell wall (water transport in cell walls external to a cell membrane is termed apoplastic transport). Apoplastic transport through cell walls seems to be limited mainly to regions near primordial root tips that have not developed secondary thickening. If this is the case, then discrimination against sodium and chloride must be regulated mainly by transport across the cell membranes in the outer layers of the root.

Despite the high efficiency of salt exclusion by mangrove roots, a significant amount of salt still passes across the root barrier and accumulates in the tree. Most laboratory studies with seedlings have found that salt uptake rises with increasing salinity, although not proportionally (i.e. an increase in soil salinity from say 15‰ to 30‰ does not necessarily lead to a doubling salt concentrations in the plant) (e.g. Clough, 1984; Paliyavuth et al., 2004). Furthermore, the

ratio of chloride to sodium in the xylem sap seems to vary between species and with the external salinity (Popp et al., 1993).

A substantial proportion of the salt that passes across the root to the xylem, perhaps most of it, is transported along with water to the leaves. Simple calculations based on known concentrations of sodium chloride in xylem sap, known rates of transpiration from leaves, and known concentrations of salt in mature mangrove leaves show clearly that the total amount of salt reaching a leaf over its lifespan is far greater than its actual salt content (Clough et al., 1982; Paliyavuth et al., 2004). What happens to this salt depends on whether or not a mangrove species has salt glands in its leaves.

Salt secretion

A few species of mangroves (in the genera *Avicennia*, *Aegialitis* and *Aegiceras*) have salt glands on either the upper (adaxial) or lower (abaxial) surfaces of their leaves. The structure of these glands, the mechanism by which they secrete salt, and rates of salt secretion are well-documented (e.g. Atkinson et al., 1967; Cardale & Field, 1971; Boon & Allaway, 1986). A detailed discussion of salt glands is beyond the scope of this book, but more extensive syntheses of their structure and function can be found in Tomlinson (1986) and Saenger (2002).

Published rates of salt secretion show an external salinity-dependent range of about 0.2–0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for both sodium and chloride, which are usually secreted in more or less equal amounts. Young leaves tend to have higher rates of secretion than older leaves at the same external salinity. However, there seems to be an inverse relationship between the efficiency of salt exclusion and the efficiency of salt secretion (Fig. 3.1). Evidently *Aegiceras*, which had an exclusion efficiency of almost 99%, was able to maintain acceptable leaf sodium levels with significantly fewer and less active salt glands compared with the other two species. This highlights some of the more subtle adaptations and interactions that may influence the distribution of different species along salinity gradients.

Although salt secretion is an active process that requires the expenditure of metabolic energy, it is clear that under most conditions species with salt glands can expel enough salt to avoid catastrophic salt overloading. However, species without salt glands must adopt alternative strategies.

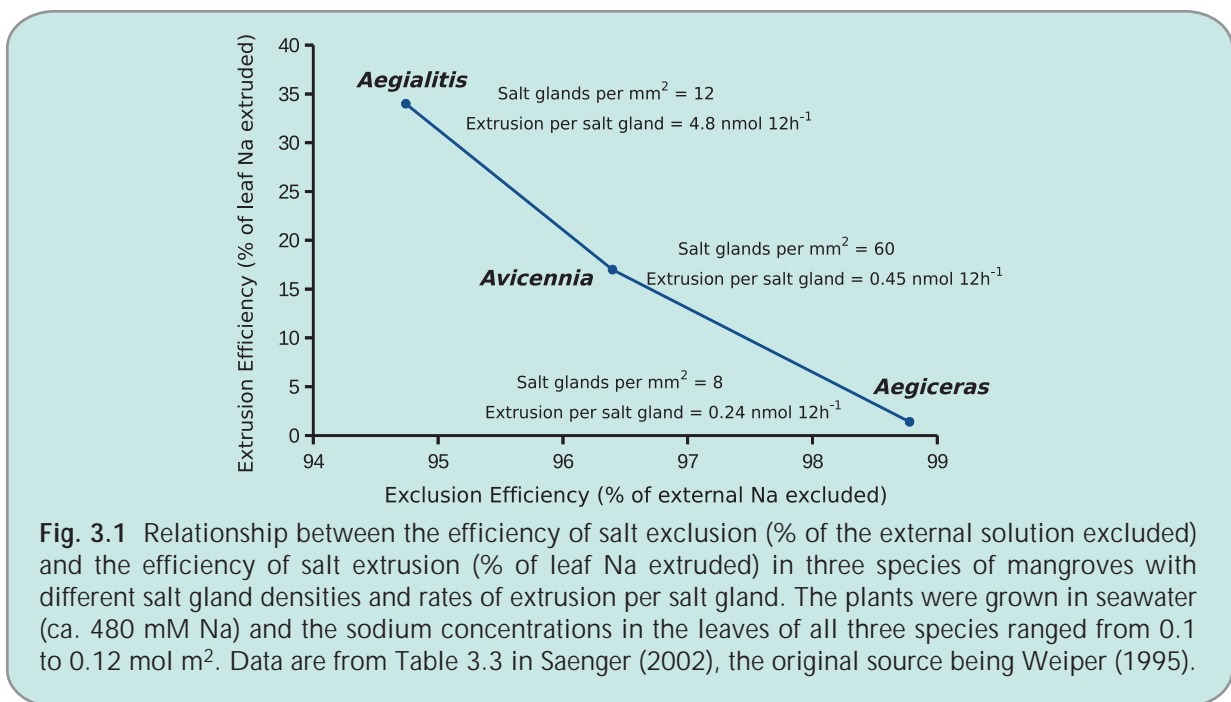


Fig. 3.1 Relationship between the efficiency of salt exclusion (% of the external solution excluded) and the efficiency of salt extrusion (% of leaf Na extruded) in three species of mangroves with different salt gland densities and rates of extrusion per salt gland. The plants were grown in seawater (ca. 480 mM Na) and the sodium concentrations in the leaves of all three species ranged from 0.1 to 0.12 mol m⁻². Data are from Table 3.3 in Saenger (2002), the original source being Weiper (1995).

Succulence

Leaf succulence is common in mangroves, especially in those without salt glands. In some species it results from the enlargement of mesophyll cells longitudinally, in others from the presence of a hypodermis with large, water-filled cells, and in yet others through the development of undifferentiated spongy mesophyll layer (Saenger, 2002), as shown in Fig. 3.2. Cells in all these tissues commonly have very large water-filled vacuoles in which the main ions are sodium and chloride. The degree of succulence tends to increase with salinity and probably with leaf age, although convincing evidence for an age effect has yet to be shown. Succulence has been found to be positively correlated with differences in salinity tolerance amongst some members of the Rhizophoraceae (Ball, 1988a)

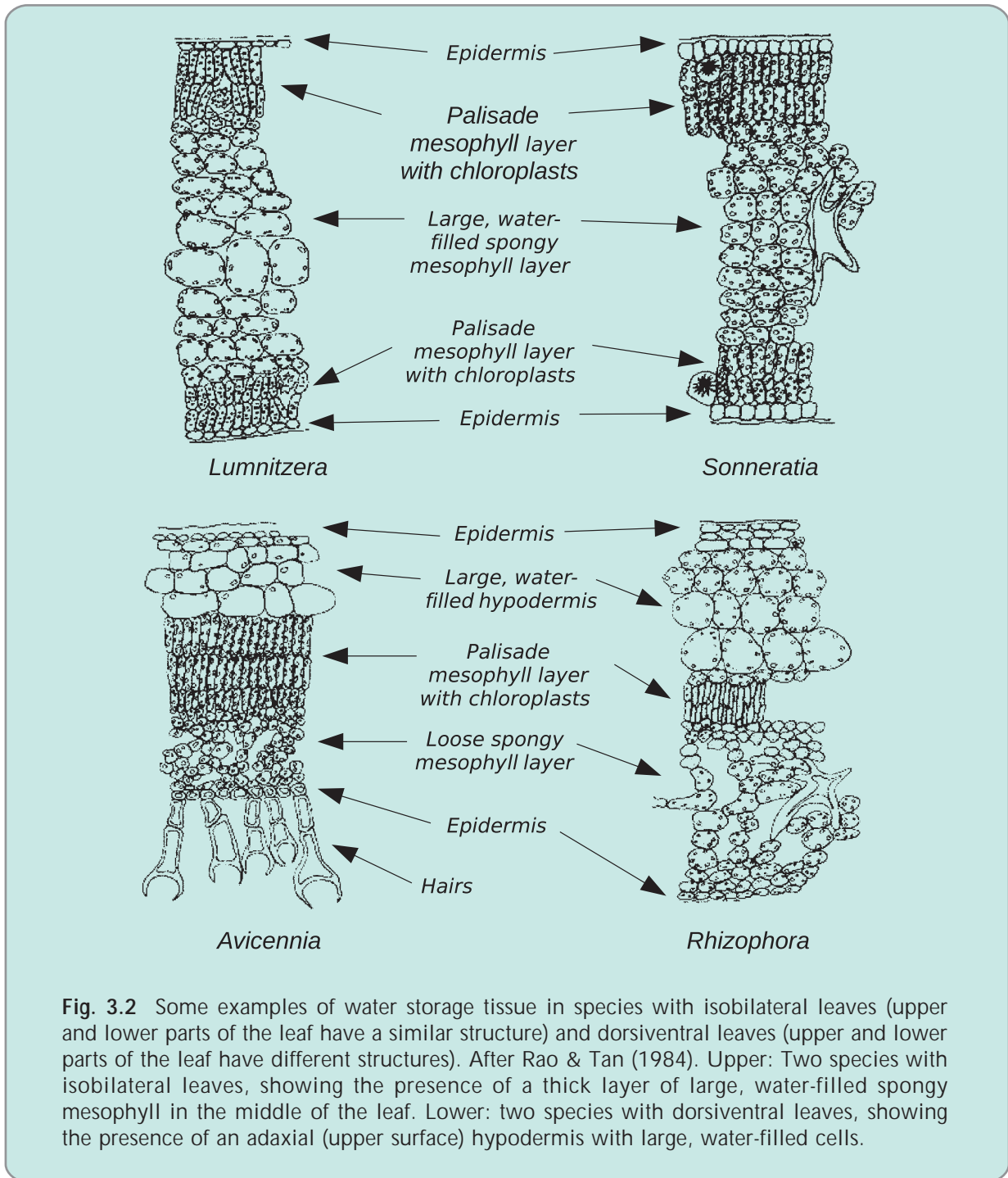


Fig. 3.2 Some examples of water storage tissue in species with isobilateral leaves (upper and lower parts of the leaf have a similar structure) and dorsiventral leaves (upper and lower parts of the leaf have different structures). After Rao & Tan (1984). Upper: Two species with isobilateral leaves, showing the presence of a thick layer of large, water-filled spongy mesophyll in the middle of the leaf. Lower: two species with dorsiventral leaves, showing the presence of an adaxial (upper surface) hypodermis with large, water-filled cells.

Storage in woody tissues

Despite the development of succulence in species without salt glands, it seems clear that this cannot account for the very large discrepancy between the actual content of salt in a leaf and the amount that it would be expected to receive over its lifespan, based on known transpiration rates and known salt concentrations in the xylem sap – unless of course transpiration rates, xylem sap concentrations or both have been grossly overestimated, which seems unlikely given their consistency across many studies. Although *Excoecaria* and *Xylocarpus* both shed their leaves annually there is little evidence that leaf shedding plays a significant role in removing salt in either of these species, or in other species without salt glands, since senescent leaves have only marginally higher concentrations of salt than mature leaves, and in any case their salt concentrations are much lower than those estimated from the product of xylem sap concentration and transpiration rate. However, leaf shedding and salt loading could still be linked, since it is possible that leaf shedding is triggered when salt concentrations in the leaf reach a point where the energetic requirements for internal regulation can no longer be met.

On a dry weight basis, salt concentrations in mangrove wood are somewhat lower than those in the leaves; for trunks sodium appears to be in the range of 1–3% of dry weight (Aksornkoae & Khemnark, 1984). Clough et al. (1982) suggested that non-salt secreting mangroves might avoid foliar salt overloading either by removing it from the xylem sap and depositing it in the wood as sap flowed from the roots to the leaves or, alternatively, salt could be re-translocated from the leaves along with the photosynthetic products used to construct new wood. Popp et al. (1993) tested the latter idea by ring-barking seedlings, but the results were inconclusive, and it has been argued that the levels of sodium in phloem are too low for translocation from leaves to other parts of the tree to be effective (Ball, 1988a).

Cellular compartmentation

At the cell level, sodium and chloride are stored in the cell vacuole where they do not interfere with normal metabolism. Osmotic adjustment in the metabolically active cytoplasm is maintained by compatible organic solutes, including a range of organic acids, low molecular carbohydrates, amino acids, methylated onium compounds and proline (Popp, 1984a; Popp et al., 1984; Popp, 1984b). This compartmentation strategy, although not unique to mangroves and other halophytes, enables them to accumulate both sodium and chloride in the leaves without adverse effects on normal cell metabolism. Salt accumulation in vacuoles accompanied by expansion of the vacuole due to the influx of water drawn in by osmosis is also the driving force for leaf expansion in virtually all plants after cell division has ceased.

Coping with a lack of water

At first sight, it might seem surprising that mangroves can experience a shortage of water when growing on more or less permanently waterlogged soils, for clearly there is no physical lack of water in most mangrove environments. The problem is not a physical lack of water, but rather that the low water potential of the soil makes it more difficult to extract. In saline waterlogged soils, for all practical purposes, the water potential is the same as the osmotic potential of the pore water, and the water potential of pore water in a mangrove soil is more or less proportional to its salinity. Soil water with a salinity of 35‰ has an osmotic potential and water potential of around 2.5 MPa, which makes it just as difficult for mangroves to extract water as it is for xerophytes (plants adapted to very dry climates) to extract water from the soil in an arid terrestrial climate. Conservation of water is therefore important, and mangroves, like xerophytes, have a range of leaf adaptations that can help to reduce water loss and conserve

water. These include sunken or otherwise hindered stomata, leaf hairs that cover the surface of the leaf, thick cuticles and waxy coatings (Saenger, 1982, 2002).

Water flows from soil to root and, via the xylem, to the leaves along a gradient of decreasing water potential. This means that leaf water potential must be lower (more negative) than soil water potential in order for leaves to replace the water lost by transpiration. The low water potential in leaves is generated by salt uptake and the osmoregulatory mechanisms described above.

In mangroves, as in most plants, the xylem water potential (a proxy for leaf or shoot water potential) shows a pronounced diurnal pattern (Smith et al., 1989; Lin & Sternberg, 1992; Gordon, 1993; Ong et al., 1995). Shoot water potentials are determined by the relative rates of transpiration (water loss) and water uptake via the roots (water gain). In the morning, when the stomata are usually widely open, transpiration is high and water is lost faster than it can be supplied by the roots; consequently, shoot water potential falls, generally reaching a minimum sometime between mid-day and mid-afternoon, and then rises again as solar irradiance declines in the late afternoon. Recovery of water potential continues overnight when the stomata are closed and there is no sunshine to drive transpiration, so that by sunrise the plant water potential is at a maximum value determined by soil water potential. In most mangrove soils the maximum recovery water potential overnight is set by the soil water potential and hence mainly by soil salinity. Even though mangroves are relatively shallow rooted, roots at different depths are likely to be exposed to different salinities, since the vertical salinity profile in a mangrove soil is related to its physical composition, drainage characteristics, the number, size and distribution of crab burrows, and in some cases to lenses of lower salinity water from landward drainage. Pre-dawn shoot water potentials are probably a reasonably reliable proxy for the integrated average soil water potential and soil salinity over the full rooting depth.

On cloudy days in tropical climates when solar irradiance is generally lower and the relative humidity is high, rates of transpiration seldom exceed about $5 \mu\text{mol H}_2\text{O m}^{-2} \text{s}^{-1}$ (often somewhat lower) and shoot water potential can fall to around -4 MPa (Fig. 3.3A). However, on cloudless, hot and windy days in dry, arid climates where soil salinity is very high, leaf temperatures may be as high as 40°C and transpiration rates can reach $8 \mu\text{mol H}_2\text{O m}^{-2} \text{s}^{-1}$ (Gordon, 1993), leading to day-time shoot water potentials of -7 MPa or lower (Fig. 3.3B).

At these extremes of low shoot water potential there is a risk that the formation of air bubbles in the xylem could cause embolism or cavitation leading to a potentially catastrophic collapse in the xylem's water conducting capacity and the supply of water to the shoot (Sperry et al., 1988; Tyree & Sperry, 1988).

The risk of embolism at low water potentials is related to the diameter of the xylem vessels and the permeability of inter-vessel pit membranes. Generally, mangroves have xylem vessels of less than about $100 \mu\text{m}$ in diameter (Tomlinson, 1986). However, the diameter of xylem vessels can change in response to environmental factors. As an example, Lovelock et al. (2006a) found that long-term addition of phosphorus to nutrient limited mangroves resulted in an increase in the diameter of xylem vessels, with a corresponding increase in xylem hydraulic conductivity, presumably with a greater risk of embolism when faced with a severe water shortage. An overall pattern of decreasing xylem hydraulic conductivity with increasing salinity has also been reported (Lovelock et al., 2006b). These studies suggest that environment plays an important role in the development of the hydraulic architecture of the woody parts of mangrove trees.

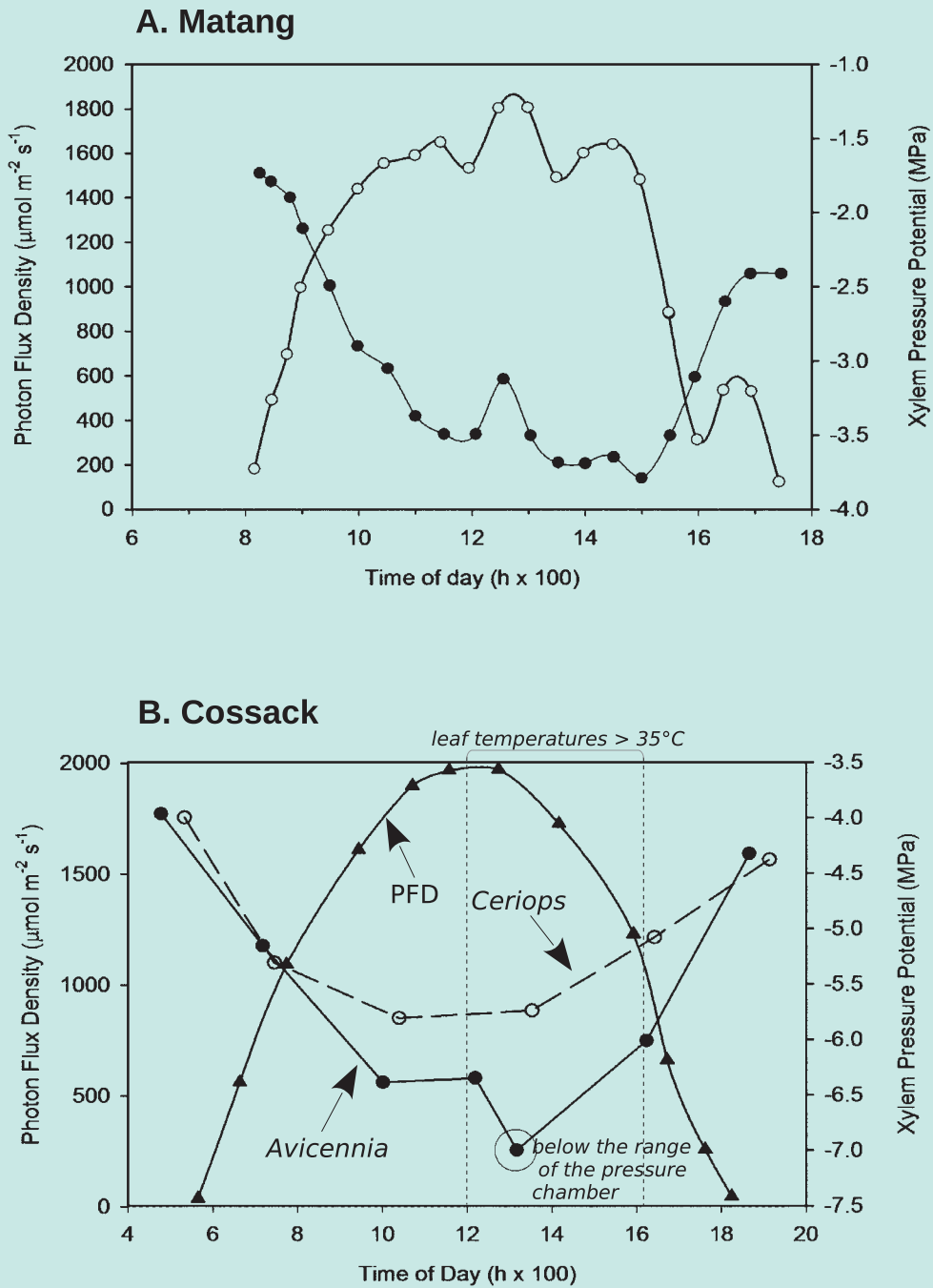


Fig. 3.3 Comparison of day-time changes in shoot water potential (xylem pressure potential) in relation to solar irradiance (photon flux density) in the wet (Matang) and dry (Cossack) tropics, showing that shoot water potential can drop to extremely low values under extreme conditions. **A.** In a 20 m tall *Rhizophora* forest in Matang, West Malaysia. The soil salinity was 20‰. Redrawn from Fig. 4 in Gong et al. (1992). **B.** In a dwarf (< 1.5 m high), open community of *Avicennia* and *Ceriops* at Cossack on the arid north-western coast of Australia. The soil salinity was 65‰. Leaf temperatures in both species were well over 35°C for most of the afternoon. Redrawn from Fig. 5 in Gordon (1993).

Coping with Anaerobic Soils

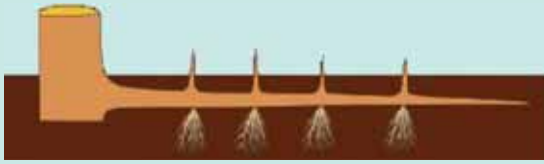
Waterlogged soils are anaerobic because the combined rate of chemical and biological oxygen consumption exceeds the rate that it can be replaced, due to the very low diffusion rate of oxygen in water and the tortuous path in the interstitial pores between soil particles through which it has to move. Tidal flushing helps to replenish oxygen in the soil, but the low water permeability of many mangrove soils with high silt and clay contents tends to restrict water and oxygen exchange to the upper part of the soil profile. Thus, tidal elevation, local topography and the drainage characteristics of the soil are also important factors determining the degree of anaerobiosis and the oxidation-reduction or redox potential (Boto & Wellington, 1984). Soil drainage and aeration is also enhanced greatly by the activity of larger burrowing animals such as crabs and some other crustaceans, particularly in areas with high populations. For these reasons, soil chemical and physical properties are often highly variable in space and time, both laterally across the soil surface and vertically with depth.

In addition to a lack of oxygen, low redox potentials change the chemical state of iron, manganese, aluminium, nitrogen, phosphorus and some other elements. Mangrove soils often have high iron and aluminium contents, and at low redox potentials their increased availability can potentially lead to iron and/or aluminium toxicity. Extreme anaerobiosis results in the formation of gaseous hydrogen sulphide (H_2S) which is very toxic to plant roots.

In order to cope with these conditions, most mangrove species (except *Excoecaria*, *Aegialitis* and *Nypa*) have specialised aerial roots that extend above the soil surface and supply the underground roots with oxygen. There are four main types of aerial roots, stilt or prop roots, pneumatophores, knee roots, and buttress-like plank roots (Fig. 3.4). Adventitious aerial roots arising from the stem or branches are also common in some species, but such roots seldom penetrate the soil. Some species produce more than one type of aerial root. Despite differences in the way they are formed, their structure and their appearance, they all have some features in common and they all serve the same purpose – to supply oxygen to the roots below ground.

All types of aerial roots in mangroves have two key features in common. Firstly, the presence of lenticels on their surface (Fig. 3.5), which provide a point of entry for oxygen; and secondly, a well developed aerenchymatous cortex (aerenchyma is tissue that contains a lot of air-filled spaces between cells) that provides a large, more or less contiguous path for oxygen to move from the lenticels to the roots underground.

In most species, the main root system consists of numerous and extensive woody cable roots buried underground, and the aerial roots are formed either by the periodic upwards and then downwards growth of the underground roots (e.g. *Bruguiera* and *Ceriops*), the vertical extension of the upper surface of the underground roots (e.g. *Xylocarpus* and *Heritiera*) or, as in the case of pneumatophores in *Avicennia* and *Sonneratia*, as vertical lateral branches of the main root (Tomlinson, 1986). In *Rhizophora*, however, the primary root system is formed by the arching stilt or prop roots above ground, which provide structural support as well as a pathway for oxygen supply to the smaller anchoring and absorbing roots underground. However, gas exchange is usually limited to smaller distal branches near to their point of entry into the ground, since the upper parts of the main supporting stilt roots are woody and do not have an aerenchymatous cortex (Fig. 3.6). This difference between *Rhizophora* and other species is also reflected in the distribution of root biomass above and below ground – in *Rhizophora* most of the living root biomass appears to be above ground (Ong et al., 2004), whereas in other species a much greater proportion is below ground (e.g. Clough & Attiwill, 1975; Saintilan, 1997; Comley & McGuinness, 2005). However, estimating the below-ground biomass of live roots in mangroves is very difficult; many studies have reported exceptionally high estimates for root biomass underground, but it is not always clear whether these include dead as well as live roots.



Pneumatophores: Pencil-like pneumatophores arising from extensive underground cable roots are typical of *Avicennia* (photo), *Sonneratia* and *Xylocarpus moluccensis*.



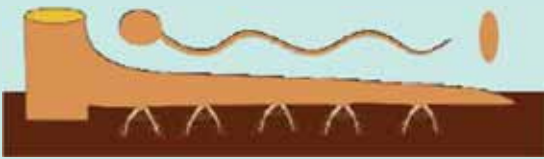
Photo: Hung Tuck Chan



Knee roots: Knee roots, which are produced by the upward and then downward growth of the main underground cable roots are typical of *Bruguiera* (photo).



Photo: Mami Kainuma



Buttress or plank roots: Large plank roots that wind sinuously across the soil surface are typical of *Heritiera littoralis* (photo) and *Xylocarpus granatum*.



Photo: Shigeyuki Baba



Stilt or prop roots: The woody stilt or prop roots of *Rhizophora* (photo). Unlike other mangroves, most of the root biomass is above ground.



Photo: Hung Tuck Chan

Fig. 3.4 The four basic types of aerial root systems in mangroves, with examples. After Tomlinson (1986).



Photo: Barry Clough

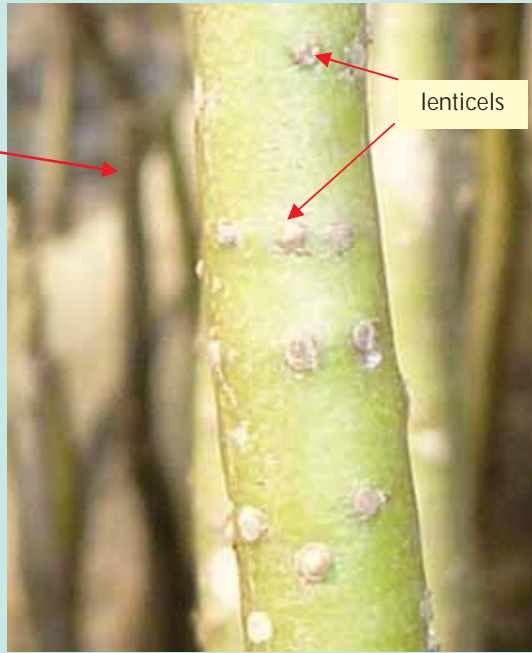


Photo: Barry Clough



Photo: Hung Tuck Chan

Fig. 3.5 *Avicennia* pneumatophores (top left), showing lenticels on the surface (right). The pneumatophores contain chlorophyll and are capable of photosynthesis (Dromgoole, 1998). Pneumatophores of *Sonneratia* (bottom left) and still roots of *Rhizophora* also have chlorophyll (Saenger, 2002).



Fig. 3.6 Cross-section through a still root of *Rhizophora apiculata* taken about 30 cm from the trunk. Note the absence of aerenchyma. When scanned on a conventional flat-bed scanner at 1600 dpi, the wood structure could be seen in some detail.

The density (number per square metre of soil surface) and height of pneumatophores appears to be related to the drainage characteristics of the soil. In *Avicennia*, for example, both the density of pneumatophores and their height tend to be greater in areas with poor drainage (Saifullah & Elahi, 1992). A similar pattern in *Avicennia* has been observed in areas with high sedimentation rates (Young & Harvey 1996). There is little quantitative information for other species, although qualitative field observations suggest similar patterns in *Rhizophora*.

Although mangrove root systems are comprised of many types of roots with different functions, at a broad level they can be thought of as an architectural construction where the main or primary root system (stilt roots in *Rhizophora* and cable roots in other species) provides both support and the plumbing (or connection) by which water and nutrients are supplied to the above-ground stem, branches and leaves from the smaller absorbing roots underground, while the aerial roots provide the oxygen needed to support the metabolism of underground roots.

While oxygen can certainly diffuse rapidly in the aerenchymatous cortex of pneumatophores (e.g. Curran, 1985; Curran et al., 1986), its entry into the root through lenticels appears to be facilitated by a 'tidal pumping' mechanism (Scholander et al., 1955; Allaway et al., 2001). At high tide when the pneumatophores are submerged, consumption of oxygen by root respiration reduces the pressure inside the pneumatophore. On its re-exposure at low tide, the reduced pressure inside the pneumatophore facilitates the rapid entry of air through the lenticels.

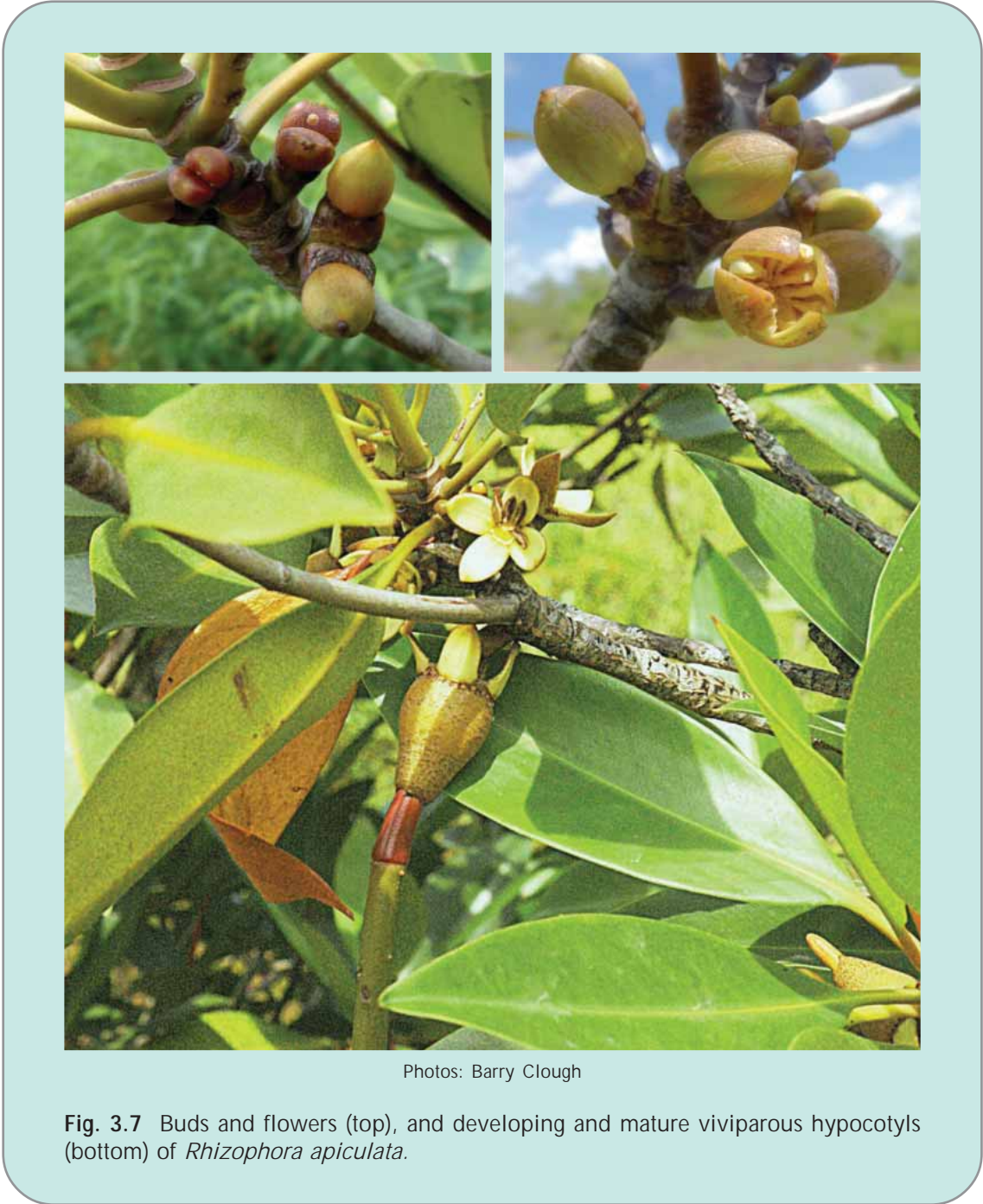
In most cases, the rate of oxygen transport to the roots below ground is more than sufficient to supply enough oxygen for root respiration and any excess oxygen diffuses into the soil around the roots, creating a thin oxidised rhizosphere of up to several millimetres in width. In principle this could be important in avoiding iron and perhaps aluminium toxicity; Youssef & Saenger (1998), for example, found that neither iron nor manganese accumulated in leaves when seedlings were exposed to high external concentrations of FeSO_4 or MnSO_4 . The presence of an oxidised rhizosphere also appears to be important in nitrogen uptake. Nitrate, the form of nitrogen taken up by most plants, is almost completely absent in anaerobic soils, nitrogen instead being in the form of ammonium, which is unavailable to most plants, including mangroves (Boto et al., 1985). Since oxygen or some other oxidising agent is needed for the chemical or microbial conversion of ammonia to nitrate, it is likely that this conversion takes place in the oxidised rhizosphere around the roots, or perhaps at the root surface.

Reproduction and Dispersal

As pointed out in Chapter 1, mangroves have propagules that are capable of being dispersed in water. The generic term 'propagule' is generally used because the main dispersal unit is not always a seed. In fact, mangroves have a wide variety of dispersal units, and only a few species are dispersed as seeds; these include *Excoecaria*, *Hibiscus*, *Pelliciera* and *Xylocarpus*. Most, but not all others are dispersed as either as some kind capsule containing one or more seeds, or as a viviparous hypocotyl. We will not be too concerned here with technical botanical jargon used to describe these dispersal units, but two terms, vivipary and cryptovivipary, are important because they appear frequently in the mangrove literature.

The term vivipary (or the adjective, viviparous) refers to seeds that germinate and produce a seedling while still attached to the parent tree, usually without any period of dormancy. All members of the family Rhizophoraceae (see Table 2.1 in Chapter 2) are viviparous, and their dispersal unit is an elongated seedling, called a hypocotyl, which germinates while still attached to its parent tree (Fig. 3.7). When it drops from the tree, it already has at least one pair of leaves enclosed in stipules at one end, and well-formed root meristems at the other. This means that it can become established very quickly when it drops from the parent tree, or when it

lodges between roots, rocks and debris after being carried around by the tide. In fact, it is common to see propagules with young roots floating on the tide.



Photos: Barry Clough

Fig. 3.7 Buds and flowers (top), and developing and mature viviparous hypocotyls (bottom) of *Rhizophora apiculata*.

In cryptovivipary, the embryo develops into a seedling that remains inside the fruit until it drops from the parent tree. On exposure to water or muddy soil the outer protective pericarp is shed, usually within a few days. Cryptoviviparous mangroves include *Aegialitis*, *Aegiceras*, *Avicennia*, *Laguncularia*, *Nypa* and *Pelliciera* (Saenger, 2002). However, the adaptive significance of vivipary and cryptovivipary in aiding dispersal is still debated because many other species without these traits are also dispersed very effectively.

The propagules of all mangroves float, and can be carried quite large distances by tides, provided they do not become entangled in roots and debris on the forest floor. However, most studies suggest that more than 70% of propagules move less than 10–300 m from their parent trees (Saenger, 2002), depending on tidal dynamics, topography and whether parent trees are located in the interior part of the forest or along its more exposed margins. The propagules of species that are prevalent in the inner areas of mangrove forest (e.g. *Bruguiera*, *Ceriops*, *Xylocarpus*, *Excoecaria* and others) tend to move shorter distances than those of species that are common along the outer forest margins (e.g. *Avicennia* and *Rhizophora*). Once they reach open coastal waters, propagules are sometimes carried for considerable distances by tides and near-shore currents, although it is more common for them to simply move in and out along with the tide until they become stranded in an area not far from their parent.



Photo: Takayuki Tsuji



Photo: Hung Tuck Chan



Photos: Shoko Yamagami

Some examples of propagules of different mangrove species: *Avicennia germinans* (top left), *Sonneratia caseolaris* (top right), *Bruguiera cylindrica* (bottom left) and *Bruguiera gymnorhiza* (bottom right).



Photo: Barry Clough

Propagules of *Avicennia marina* stranded amongst the pneumatophores of their parent and neighbouring trees in Vietnam.

Predation by some kinds of crab can play an important role in the survival and establishment of propagules and seedlings; this appears to be both site-specific and species-specific. Predation on seedlings of *Avicennia* is particularly common in areas with high populations of sesarimid crabs (Smith, 1987, 1989), with up to 100% of the seedlings being eaten or damaged by crabs within about 20 days in some places (McGuinness, 1997). Significant predation of *Rhizophora*, *Bruguiera*, *Ceriops* and *Laguncularia* propagules has also been reported (McKee, 1995; McGuinness, 1997), but propagules of these species are probably less palatable than seedlings of *Avicennia* because they tend to have high tannin contents. Severe predation of propagules and seedlings can have an effect on forest regeneration and its species composition (Smith, 1989).

Attacks from the larvae of certain moths and beetles also reduce the viability and survival of some mangrove species. Such attacks are common in *Xylocarpus*, *Heritiera*, *Bruguiera* and to a lesser degree in *Rhizophora* (Murphy, 1990). No quantitative data are available, but personal observation suggests that around 20–30% of *Xylocarpus* seeds collected in north-eastern Australia are attacked by moth larvae. Insect herbivory on flowers and buds is also common (Murphy, 1990).

Apart from herbivory, a number of other physical and chemical factors are also important in seedling establishment and survival. These include light, pH, salinity, redox potential (and the presence of sulphides), soil water content and hardness and, along more exposed coastlines, wave action and soil stability. The interactions between these various factors and seedling survival seem to vary with species and local conditions, and are not well-understood. However, despite all the challenges faced by propagules and seedlings in becoming established, in most cases sufficient numbers survive to ensure the continuity of the forest over long periods of time.

In this chapter, we have seen how mangroves manage salt and water, cope with unstable, anaerobic soils, and disperse themselves in an inhospitable and ever changing environment. In the next chapter, we will examine briefly some of the animals and other plants that share the mangrove habitat and, together with the mangrove trees, form such unique and productive ecosystems.

Chapter 4

OTHER LIVING COMPONENTS

The most obvious component of mangrove habitats is of course the trees themselves. However, mangrove ecosystems are much more than just the trees, for they also contain a vast array of other plants, larger animals, insects and microscopic organisms. Some of these are mangrove specialists living only in mangrove habitats, others depend on mangrove habitats for at least part of their life cycle, but most are generalists that live in other marine and terrestrial habitats as well as in mangrove habitats. Together with the mangrove trees, all these other life forms create a complex, integrated, dynamic and functional living ecosystem, the 'mangrove ecosystem'. It is these interactions between the living components and the physical environment that give mangroves their unique role as the bridge between land and sea, and provide such a rich resource of goods and services to humankind.

Faunal Components

As is the case with the trees themselves, the fauna in mangrove habitats vary between geographic regions, with latitude, and with surface topography and elevation. Nevertheless, every group of animals – mammals, reptiles, birds, crustaceans, molluscs, fish, insects, worms, and microscopic organisms such as nematodes, fungi and bacteria – can be found in almost every mangrove habitat.

Many of the fauna found in mangroves and their role in ecosystem functioning have been well-described by (Kathiresan & Bingham, 2001; Hogarth, 2007; Nagelkerken et al., 2008). Here we can only provide an overview of some of the more common faunal components and their significance.

Mammals

The soft, muddy substrate of mangrove habitats is generally not well suited to ground-dwelling mammals, but a number of mammalian predators are often found in mangroves. These include tigers, other smaller wild cats, otters and raccoons, but none of these appear to be confined only to mangroves. A variety of common monkeys are also found in mangroves, including the crab-eating long-tailed macaque (*Macaca fascicularis*) and the silvered langur (*Trachypithecus cristatus*). However, mangroves provide critical habitat for the endangered proboscis monkey (*Nasalis larvatus*), which is restricted to mangrove, freshwater riverine and peat swamp forests on the island of Borneo (Meijaard & Nijman, 2000). Elsewhere, the critically endangered pygmy three-toed sloth (*Bradypus pygmaeus*) is only found on a small island off the coast of Panama (<http://www.arkive.org/pygmy-three-toed-sloth/bradypus-pygmaeus/>).

Other mammals, such as water buffalo, camels, cows, goats and deer also often forage in the drier, more elevated landward areas of mangrove forests. In particular, extensive grazing by camels has had a severe impact on *Avicennia* communities in Pakistan and parts of the Middle East.

Aquatic animals like the hippopotamus, manatees, dugongs and some dolphin species are also sometimes found in mangrove estuaries in Africa, but these do not feed directly on mangroves (Spalding et al., 2010). In north-eastern Australia, mangroves provide roosting sites for large populations of several species of fruit bats (locally known as flying foxes) belonging to the genus *Pteropus*.



Photo: Hung Tuck Chan



Photo: Shigeyuki Baba

A male silvered langur (*Trachypithecus cristatus*) perched on a rooftop (left) and a group of endangered proboscis monkeys (*Nasalis larvatus*) in the mangroves of Sabah, Malaysia (right).

Reptiles and amphibians

Estuarine or saltwater crocodiles (*Crocodylus porosus*) are common in mangrove habitats throughout much of tropical Asia, Papua New Guinea and Northern Australia, although they have now disappeared almost completely from the coastal area of some countries with dense coastal populations (e.g. Thailand and Vietnam). These can reach six to seven metres in length, and being the largest predator in the mangrove habitat they sit at the top of the food chain. In Africa the Nile crocodile (*Crocodylus niloticus*) is also common in mangrove habitats, but the American Alligator (*Alligator mississippiensis*) inhabits freshwater and brackish-water swamps, rarely straying into marine-dominated mangrove habitats. The mangrove monitor (*Varanus indicus*), a lizard that can grow up to about 1.2 m in length, is also widespread in northern Australia, Papua New Guinea and some other Western Pacific Islands. While common in mangroves, the mangrove monitor is also found in other terrestrial habitats, as are other smaller lizards that are often encountered in mangroves.

Apart from crocodiles and lizards, a wide variety of snakes are common in mangrove habitats, but few, if any, are true mangrove specialists. The mangrove or cat snake (*Boiga dendrophila*), an arboreal (tree-dwelling) snake common in mangroves in Australia and Asia, is often considered to be typical of mangroves, but it is also found in nearby terrestrial forests. Other snakes, such as the king cobra, green pit viper and rock python are found in the Sundarbans of Bangladesh (Kathiresan & Bingham, 2001).

Very few amphibians are adapted to saline conditions, restricting their presence mainly to landward margins or areas with significant freshwater inflows. Only the crab-eating frog of Southeast Asia (*Fejervarya cancrivora*) appears to be able to survive in more saline conditions (Hogarth, 2007).

Birds

Mangroves provide important habitat for a variety of land birds and water birds, including a number of endangered or threatened species. Species numbers and population densities vary considerably from one geographical area to another – 186 species have been recorded in wet tropical mangrove forests in north-eastern Australia, 104 in north-western Australia, 135 in West Malaysia, 125 in Guinea-Bassau and 84 in Trinidad (Nagelkerken et al., 2008), while over 300 species have been recorded from the much more expansive Sundarbans of Bangladesh (Kathiresan & Bingham, 2001). These figures imply that the use of mangrove forests by birds might depend on the areal extent of mangrove forest and its proximity to other suitable bird habitats nearby.

Most birds are not mangrove specialists and have a much wider habitat range – in Australia, for example, of the more than 200 bird species observed in mangrove forest, only 14 appear to be confined to mangroves, and a further 12 species are limited to them for at least part of their range (Schodde et al., 1982). Nevertheless, the proximity of mangroves to rich feeding grounds on tidal mudflats and in shallow coastal waters, makes them particularly attractive to waterbirds as roosting and nesting areas. Mangroves are also important stopover habitats for migratory birds.

Fish

All studies of fish populations in mangrove estuaries have shown that fish species diversity is very high. Species counts in tropical mangroves are seldom less than 100 and sometimes twice this, but the number of fish species found in mangroves decreases in sub-tropical mangrove habitats. Some are estuarine specialists, but most are of offshore origin. As with prawns, juveniles are especially abundant, in some cases up to 160 individuals per square metre of water surface with a total weight of 29 grams per square metre (Robertson & Blaber, 1992). A number of studies have shown that mangrove roots are important for shelter, and that the fish species composition varies according to the type of mangrove tree (Nagelkerken et al., 2008). Juvenile fish in mangrove estuaries feed predominantly on zoobenthos (very small or microscopic animals), the main components of which are copepods and, at some times of the year, sesarmid crab zoea (Robertson & Duke, 1990). In north-eastern Australian mangroves, larger carnivorous fish seem to feed mainly on juvenile shrimp and sesarmid crabs (Robertson et al., 1992).



Photo: Jin Eong Ong



Photo: Mio Kezuka

Mudskippers of the family Gobiidae (gobies). These amphibious fish absorb oxygen through their skin, mouth and throat, and have enlarged air-filled gill chambers. In order to survive their skin must remain wet.

Crabs

Of the smaller fauna, crabs are usually the most conspicuous occupants of mangrove habitats. However, the species and their numbers (population density) vary enormously from one place to another and with the position of the forest within the intertidal zone. Fiddler crabs of the genus *Uca* are very common on tidal mudflats to the seaward of mangroves and along the seaward mangrove fringe, but their numbers usually fall off rapidly inside the forest or in areas of higher elevation. Fiddler crabs feed on organic matter in the surface mud when it is exposed at low tide and then retreat to burrows when the tide covers the mud.

A number of crabs are tree-climbers, spending most of the day foraging for diatoms or other algae on exposed roots and trunks, and sometimes higher in the canopy where they scrape food off the underside of leaves (Hogarth, 2007). However, one group of crabs, the grapsid crabs, which includes the genus *Sesarma* and its close relatives, play a very significant role in processing detritus (dead and decaying plant material) on the forest floor (Robertson, 1986; Robertson & Daniel, 1989), in some cases consuming or burying up to 28% of the leaf litter in areas flooded twice daily by the tide, and up to 80% in high intertidal forests that are flooded less frequently (Robertson et al., 1992). While leaf material forms a large part of the diet of herbivorous crabs, they also consume flowers and propagules (e.g. Smith, 1987, 1989). Consequently, mangrove plant material can constitute 80% or more of the diet of many of these herbivorous crabs (Hogarth, 2007).



Photo: Barry Clough



Photo: Mio Kezuka

A male fiddler crab (*Uca* sp.) outside its burrow (left). The large claw is used for attracting females. Females are smaller, less brightly coloured and lack the large claw (right). Fiddler crabs forage on small particles of organic matter and algae on the mud surface. They are often present in very large numbers on mud flats and along the edge of mangroves, but are seldom found deep inside mangrove forest.

Another crab of significance is the mud crab (*Scylla*), an important commercial species caught mainly in or near mangroves in the Indo-West Pacific. However, mud crabs do not spend their entire life cycle in mangrove estuaries; the female moves out into offshore waters to spawn before returning to the relative safety of an estuary. After hatching, juvenile mud crabs pass through a number of development stages before migrating back to the relative safety of mangrove estuaries. *Scylla* is not found on East Atlantic coastlines, but other mangrove-dwelling crab species such as *Ucides cordatus* are equally prized as a delicacy.

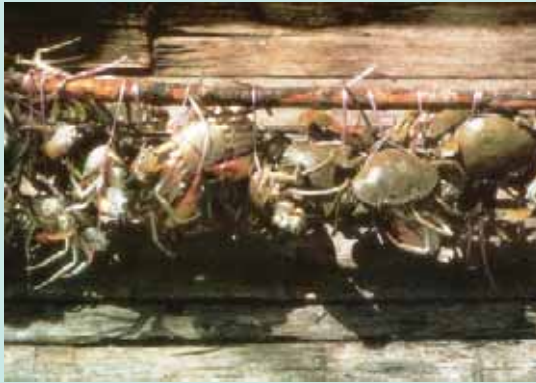


Photo: Hung Tuck Chan



Photo: Takayuki Tsuji

Mangrove crabs: *Scylla serrata* in Southeast Asia (left) and *Ucides cordatus* in Brazil (right).

Shrimp and other Crustaceans

Commercially important penaeid shrimp are abundant in mangrove estuaries, mostly as juveniles. These tend to congregate amongst mangrove roots along the edges of the estuary, where they find protection from predators and forage for food such as mangrove-derived detritus, amphipods and polychaetes. In northern Australia and Southeast Asia the diet of mangrove-dwelling juvenile *Penaeus merguensis* is based mainly on mangrove-derived detritus, whereas for other penaeid species in Central America mangrove detritus appears to represent less than 25% of their diet, these species instead feeding mainly on polychaetes and amphipods (Robertson et al., 1992).

One group of crustaceans, the barnacles, cause considerable damage to mangrove trees. Barnacles are very common on the aerial roots and trunks of mangrove trees where they capture particles of food in the water as it passes by. While high densities of barnacles might interfere with gas exchange in aerial roots, damage to adult trees is usually not too severe. However, barnacles that attach themselves to propagules and seedlings kill many of the seedlings, and often have a severe impact on both natural regeneration and mangrove reforestation efforts (see Chapter 7).

Gastropods and other molluscs

Gastropods include snails, slugs and a variety of other molluscs, usually with a cone shaped shell (although not all gastropods have shells). Probably the most common large gastropods in mangroves belong to the genus *Terebralia*, which is widely distributed throughout the Indo-West Pacific. There are, however, many more of these often bizarre animals in mangroves. While many gastropods are benthic (bottom-dwelling) detritivores, others are arboreal (tree-dwelling) and can be found grazing at all levels in the forest canopy.

In addition to gastropods, other molluscs are also very common in mangrove forests. These include, for example, oysters attached to mangrove roots, the mangrove clam (*Gelina* spp.) which can be found either on the surface of the mud or slightly buried for protection. A smaller bivalve, the blood cockle (*Anadara granosa*), found on mudflats seaward of mangrove is an important species for subsistence and income generation in many parts of Asia. A variety of other bivalves such as mussels are also found in mangroves.

A number of species of shipworms cause extensive damage to mangrove trunks and roots, particularly the stilt roots of *Rhizophora*. These bivalve molluscs bore into the wood and then eat the root from the inside out. The larvae usually enter the root in places where the tannin-rich outer layers of the root have been broken or damaged. Trees that have been severely damaged by shipworms become so weakened that they can collapse.



Photo: Takayuki Tsuji

Mangrove mussels in Brazil.

Insects

Given the ubiquity of insects in terrestrial habitats, it would be surprising if they were absent from mangroves habitats. In fact, insects are very common in mangrove habitats. Some are benign, living in relative harmony with the trees, but many are herbivores that attack the leaves, wood, propagules and seedlings of mangroves. One of the most comprehensive (but still incomplete) accounts of insects in mangroves is that of Murphy (1990), who described the biology of 102 insect herbivores in Singapore and southern parts of nearby West Malaysia. The larvae of some moths, and both larvae and adults of a number of beetles are the most common herbivores in mangroves. Some are specific to a particular mangrove species, but others are more generalist. Widespread tree mortality from insect pests has been reported, but seems to be uncommon. However, insect herbivory can cause extensive leaf damage which impairs photosynthetic carbon fixation and therefore the overall health and growth of trees. Severe damage from insect wood borers seems to be less common in adult trees, but attacks on propagules and seedlings by borers can have a significant impact on propagule viability and seedling survival (see Chapter 3).

Whereas many insects living in mangroves, especially moths and beetles, are destructive herbivores, ants are both common and beneficial. Some 22 species of ants have been recorded in Brazil and 16 in Australia. Large colonies of weaver ants (*Oecophylla smaragdina*) are common throughout Asian mangroves. Although they usually farm scale insects for their honey dew, weaver ants also provide a useful service as predators of other more destructive insects. A number of other ant species make their homes in epiphytic ant plants attached to mangrove stems and branches. Termites are also present in mangroves, but they are mainly tree-dwelling

since tidal flooding in most mangroves prevents ground-dwelling termites from constructing their mounds. In some cases, termites eat out the inside of the trunk of old mangrove trees, leaving only an outer shell to support the tree.

Bees are also common in many mangrove areas and are the basis for commercial honey production in India, Bangladesh, the Caribbean and Florida (Kathiresan & Bingham, 2001). They are also important pollinators.



Photos: Shigeyuki Baba

Predominantly terrestrial insects are also found in mangroves. A *Papilio* butterfly visiting the flowers of the mangrove *Bruguiera gymnorhiza* (left) and brightly coloured, luminescent bugs (right).

Small benthic invertebrates (meiofauna)

The meiofauna of mangroves consists mainly of hard-bodied copepods and nematodes, and soft-bodied turbellaria (flatworms). Little is known about turbellaria in mangroves because being soft-bodied and mainly buried in the mud, they are difficult to study.

Nematodes also live in sediments, but have been more extensively studied, with between about 25 and 100 species having been reported from a number of mangrove habitats in different parts of the world (Nagelkerken et al., 2008). However, the nematodes in mangroves do not seem to be significantly different from those in other marine benthic environments (benthic organisms are those that live in or on the mud surface).

Copepods are found both in the sediment and amongst leaf litter and other detritus on the forest floor. The species composition of sediment-dwelling copepods does not appear to be significantly different from that in other marine benthic habitats. However, there has been speculation that some of the surface litter inhabiting copepods may be mangrove specialists (Nagelkerken et al., 2008). As pointed out earlier, there is evidence that copepods (presumably those dwelling amongst leaf litter and other surface detritus) are an important part of the diet of juvenile fish.

Other Plant Components

Apart from mangrove trees, a number of other higher plants, ferns, lichens, macro-algae and planktonic diatoms and other unicellular algae are often found in mangroves. Giesen et al. (2007), for example, listed 262 higher plants (i.e. not including lichens and algae) found in mangrove habitats in Southeast Asia. Most are not specific to mangroves, but the larger plants enhance the floristic diversity of mangrove forests, while phytoplankton contribute to the overall net productivity of mangrove habitats. It is not possible to describe all of them here, but we will briefly consider the role of phytoplankton and benthic micro-algal communities in mangrove ecosystems.

Phytoplankton and benthic micro-algal communities contribute to the functioning of mangrove ecosystems in two ways: Firstly, they make a generally small but nonetheless measurable contribution to the overall net productivity of mangrove habitats (Boto & Robertson, 1990). The contribution of benthic micro-algae is likely to be limited by lack of light in forests with dense canopies (Alongi, 1994).

Secondly, considerable numbers of diatoms and other micro-algae are found on the aerial roots and other lower parts of mangroves flooded by tides. These form an important source of food for arboreal snails and other gastropods, many of which move up and down the trees with the tide to graze on whatever tiny morsels they can find. In addition, they can sometimes contribute significantly to the overall primary productivity of mangrove forests.

In this chapter, we have very briefly explored some of the wide diversity of animal life in mangroves and some of the interactions between the trees and the fauna. The picture which emerges is that of a complex food web with a strong interdependency between the plants and the animals that occupy the mangrove habitat. In the next chapter, we will examine how people use the forest and the other marine resources of the mangrove ecosystem.

Chapter 5

UTILISATION AND VALUES OF MANGROVES

People have been living in or near mangroves for thousands of years. A ready source of timber for firewood, building houses, boats and fishing tools, together with their rich marine resources of fish, crabs, shrimp and shellfish were obvious attractions that led some ancient societies to make mangroves their home. Many native coastal communities still utilise mangroves today in much the same way as their ancient forebears. These traditional mangrove communities understand the rhythm of the mangroves and the benefits they provide, and for the most part they live in harmony with the ecosystem on which their lives so intimately depend. This is changing, however, due to rising coastal populations and more intense competition for finite coastal resources.

Larger scale exploitation of mangroves for timber and wood products also has a long history, with evidence of trade in mangrove poles between East Africa to Arab states for over 2,000 years and large mangrove timber having been used for construction in Egypt more than 1,000 years BP (Spalding et al., 2010). Another early (late 18th Century) user of mangrove products was the leather tanning industry in Brazil (Spalding et al., 2010). Historically, mangrove areas have also been used for agriculture and aquaculture; mangrove swamp rice cultivation, for example, has been carried out along the West African coast for around 1,000 years (Fields-Black, 2008), and the traditional tambak system of fish and shrimp culture in Indonesia is reported to have been practised by the 16th Century (Schuster, 1952; cited by Naamin, 1986). Unfortunately, the impact of these early uses and exploitation of mangroves on forest area and quality is not well-documented.

From the foregoing it is obvious that in the past mangroves were used in a variety of ways, some relatively benign, others quite destructive. In our modern, densely populated and industrialised world, however, our use of mangroves has been largely exploitive and destructive. In this chapter we will focus on the goods and services provided by mangroves and how they are used by coastal communities. The reclamation and conversion of mangroves for other uses, and destructive exploitation of mangroves will be discussed in Chapter 6.

Mangrove Goods and Services

The Millennium Ecosystem Assessment (2005) described a range of ecosystem services provided by or derived from wetlands. While conceptually this is one way to describe the values and uses of mangroves, the concept of ecosystem services is not deeply ingrained in the public mind or the mind of those who make decisions on coastal land use and development. It therefore seems more useful to describe their contributions in terms of goods (or products) and services, commercial terms that are understood implicitly by economists, decision-makers, and others who are involved in, or have responsibility for coastal planning and development.

Mangroves provide a variety of important goods and services to our modern society (Fig. 5.1). While the direct and indirect goods derived from mangroves are generally well-recognised, many of the ecological and environmental services they provide have been undervalued in the past. This is now beginning to change with increasing concern about the loss of biodiversity and, as we shall see later, perhaps to the realisation that many of the services provided by mangrove forests play an important role in adapting to, and mitigating the consequences of climate change.

Mangrove-Derived Products

As implied in the introduction to this chapter and in Fig. 5.1, mangroves provide a vast range of products, not only for the subsistence and daily livelihoods of communities living in coastal areas, but also for 'eco-friendly' commercial exploitation. Comprehensive, but probably incomplete, lists of the products (goods) derived from mangroves have been compiled by Saenger et al. (1983) and Hamilton & Snedaker (1984). These range from timber for construction, boat building, furniture and smaller wooden objects to paper, alcohol, glues, preservatives, medicines and foodstuffs like honey and tea substitutes (Table 5.1), in addition to fish, shrimp, crabs and other sources of protein caught within the mangrove ecosystem.

Timber products

The timber of most mangrove species is used in much the same way as that of terrestrial forest species, with uses ranging from heavy construction, boat building and housing, through to chipboards and paper and, of course, fuel (firewood and charcoal). The qualities of mangrove timber vary appreciably between species; some with particularly hard and durable timber are more suitable for heavy construction, pilings and buildings, whereas others have softer timber that is more suitable for furniture, carving and other decorative items. In practice, however, these uses are often dictated by what species are locally available, and the diameter and height of the trees. In some older households in the lower Mekong Delta of Vietnam, for example, beds, tables and flooring made from *Rhizophora* planks of 40–50 cm in width can still be seen,

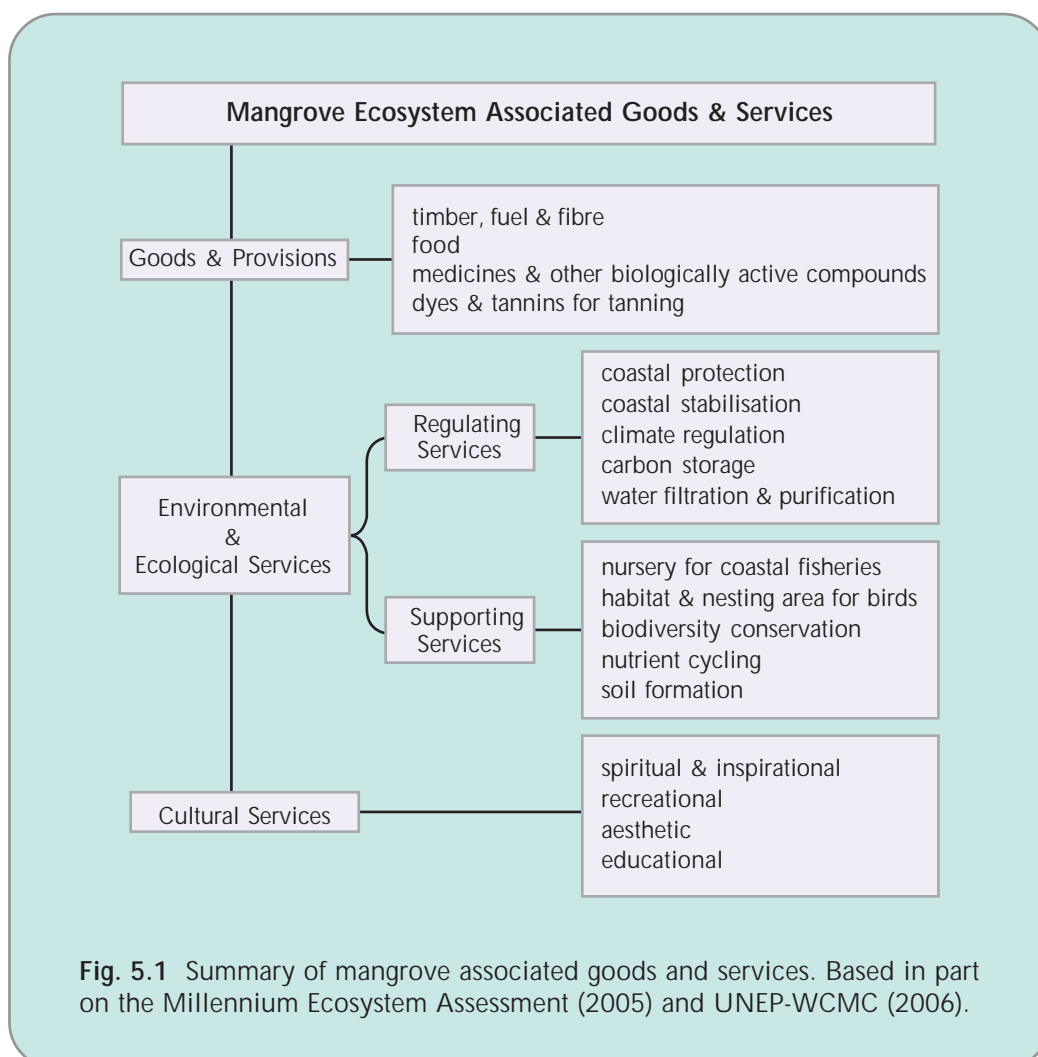


Fig. 5.1 Summary of mangrove associated goods and services. Based in part on the Millennium Ecosystem Assessment (2005) and UNEP-WCMC (2006).

Table 5.1 Present uses of mangroves (modified from Hamilton & Snedaker, 1984)

Genus	Use
<i>Acanthus</i>	medicines
<i>Aegialitis</i>	honey
<i>Aegiceras</i>	firewood, beams, poles for building, fish poison, paper, honey
<i>Avicennia</i>	firewood, beams, poles for building, fence posts, chipboards, glues, wood for smoking fish, fish poison, paper, pipes, fodder, green manure, propagules for food, medicines, pallets, charcoal, flooring, panelling, tannins for leather and dyes
<i>Bruguiera</i>	firewood, charcoal, timber, scaffolds, mining pit props, boat building, fence posts, pipes, chipboards, beams, poles for building, poles for fish traps, synthetic fibres (rayon), tannins for leather and dyes, propagules for food
<i>Camptostemon</i>	firewood, scaffolds, paper
<i>Ceriops</i>	charcoal, firewood, boat building, beams, scaffolding, poles for building, tannins for leather, net preservation and dyes paper, tea substitutes, medicines, honey
<i>Conocarpus</i>	firewood, charcoal, timber, scaffolds, boat building, beams, poles for buildings, flooring, panelling
<i>Cynometra</i>	firewood, heavy construction, flooring, panelling, honey
<i>Heritiera</i>	firewood, timber, scaffolds, heavy construction, dock pilings, beams, poles for building, flooring, panelling, flooring, furniture, fence posts, pipes, chipboards, glues, tool handles, rice mortar, tannins for preserving nets, matchsticks, tool handles
<i>Kandelia</i>	firewood
<i>Laguncularia</i>	firewood, charcoal, beams, poles for buildings, fence posts, pipes, chipboards, glues, tannins for leather, tool handles
<i>Lumnitzera</i>	medicines, firewood, heavy construction, railroad ties, mining pit props, boat building, dock pilings, beams poles for buildings, flooring, panelling, fence posts, pipes, chipboards, glues, poles for fish traps, wood for smoking fish, furniture, tool handles
<i>Nypa</i>	fuel alcohol, thatching for roofs and walls, matting, poles for fish traps, floats, raincoats, umbrellas, hats, sugar, vinegar, fermented drinks, alcoholic drinks, sweetmeats (propagules) cigarette wrappers, baskets, medicines
<i>Rhizophora</i>	tannins for leather and preserving nets, cloth dyes, wooden-ware, firewood, charcoal, timber, scaffolds, heavy construction, railroad ties, mining pit props, dock pilings, beams, poles for buildings, fence posts, pipes, chipboards, glues, poles for fish traps, furniture, Christmas trees, pallets, flooring, panelling, fodder, green manure, tea substitutes, honey, tool handles
<i>Scyphiphora</i>	firewood, fence posts, pipes, chipboards, glues, tool handles
<i>Sonneratia</i>	hats, firewood, heavy construction, boat building, dock pilings, beams, poles for buildings, flooring, panelling, fence posts, pipes, chipboards, glues, poles for fish traps, floats, cloth dyes, fodder, green manure, vinegar, sweetmeats and drinks (propagules), vegetables, furniture
<i>Xylocarpus</i>	cloth dyes, firewood, timber, scaffolds, railroad ties, boat building, dock pilings, beams, poles for buildings, flooring, panelling, fence posts, pipes, chipboards, glues, cloth dyes, paper, furniture, tool handles, toys, wooden-ware, carvings, pencils, railroad ties, hair-dressing oil, carvings

but nowadays it is rare to find mangrove trees of more than about 25–30 cm in diameter anywhere in Vietnam, restricting the direct use of mangrove timber mainly to poles for house frames, floors, pilings, monkey-bridges, firewood and charcoal in rural coastal areas.

There are only a few examples worldwide of mangrove forests that are managed for long-term sustained timber or other wood products, notably in the Sundarbans of India and Bangladesh, in West Malaysia and in several countries in Central America. Probably the most well-known example is the Matang mangrove, where the forests have been managed for sustainable production of poles and charcoal for more than 100 years. *Rhizophora apiculata* is usually the preferred species for good quality charcoal because of the high calorific value (~ 5 calories per gram) and density of its wood, and its relatively fast growth rate under suitable conditions. Charcoal and pole production from managed *Rhizophora* plantations is also common in Thailand but, unlike those in Malaysia and the Sundarbans, they generally have short rotation times of less than 15 years.

Mangrove silviculture for wood products is almost invariably based on the use of a single species (a monoculture). This approach is often criticised for its reduction in biodiversity. While there is certainly a reduction in the biodiversity of tree species, it appears to have very little effect on the biodiversity or productivity of adjacent coastal marine fisheries resources in West Malaysia (see the section on mangrove related fisheries later in this chapter).



Photos: Hung Tuck Chan

Wood products are the major outputs of the Matang mangrove as shown by the billets for charcoal production (left) and poles for piling (right).

Some species with softer timber, notably *Xylocarpus* and *Heritiera*, are very suitable for producing high quality furniture, wooden bowls and range of artefacts for household purposes. *Xylocarpus* is commonly known as the ‘cedar mangrove’ because the grain and colour of its timber resembles that of cedar. However, there appears to have been no widespread commercial exploitation of *Xylocarpus* for cabinet making and furniture. This is perhaps fortunate because all *Xylocarpus* species are relatively slow-growing and they are difficult to replant on a large scale.

Large-scale commercial exploitation of mangroves, mainly for woodchips and pulp, began in Sabah and Sarawak of East Malaysia in the late 1960s, and later spread to Indonesia (Saenger et al., 1983). Since this form of exploitation is very destructive and threatens large areas of well-developed mangroves, it will be discussed in more detail in Chapter 6.



Photo: Barry Clough



Photo: Hung Tuck Chan

Furniture and artifacts made from mangrove timber. A corner cabinet made from *Xylocarpus granatum*, *Heritiera littoralis* and *Bruguiera gymnorhiza* (left), and aboriginal sculptures carved from *Xylocarpus moluccensis* in Malaysia (right).

Tannins and cloth dyes from mangrove bark

The bark of all mangroves, especially those in the family Rhizophoraceae, contains a large amount of tannin which is suitable for tanning leather and preserving fishing nets. The commercial use of mangrove bark for tanning was once widespread, but in more recent times other substitutes have largely replaced it for this purpose, and by 1987 only the Philippines was reported to have commercial scale tanneries based on mangrove bark (Chan & Salleh, 1987). The use of tannins from mangrove bark for preserving fishing nets has also largely disappeared with the advent of nylon fishing nets. However, they are still used locally on a smaller scale, often as a cottage-industry, for dyeing cloth. Dyes extracted from *Rhizophora* bark seem to be the most widely used, but the bark of *Ceriops* and *Bruguiera* also yields dyes that are useful for fabrics.



Photo: Shoko Yamagami

Fabrics (left) and tie (right) dyed with extracts from *Rhizophora stylosa* bark, Iriomote Island, Japan.



Photo: Barry Clough

Thatching and other products from Nypa

Thatching made from the fronds of *Nypa*, the only true mangrove palm, is used widely for roofing and walls in coastal communities throughout Asia. Fronds are tied together and then laid in layers with their base towards the top of the roof or wall. A variation in Malaysia, the manufacture of woven shingles for roofing, has been described by Chan & Salleh (1987). The durability of thatched roofing varies with the pitch of the roof, the number of layers and the degree of overlap, but can last up to five years. Although the durability of thatching is limited, it is significantly cheaper than alternative materials for roofing and walls, and so it used more commonly by poorer households. The leaves of *Nypa* are also used for cigarette wrappers, matting and baskets.

The sap from *Nypa* inflorescences is also used for the production of brown sugar and, after fermentation, for alcohol and vinegar. The process has been described in some detail elsewhere (Hamilton & Snedaker, 1984; Chan & Salleh, 1987) and will not be discussed further here.



Photos: Koichi Tsuruda

In the Ayeyarwady Delta of Myanmar, leaves of *Nypa fruticans* harvested are tied into bundles (top left), woven into thatching (top right) and transported by boats to the market (bottom).



Photo: Hung Tuck Chan



Photo: Shigeyuki Baba



Photo: Koichi Tsuruda

Products from *Nypa fruticans* are used widely for house construction and consumed as food or beverages. The mangrove palm growing gregariously along the edge of a waterway, Malaysia (top), a rural house with walls and roof made from *Nypa* thatching, Myanmar (bottom right), and extracting the edible kernels from the palm fruits, Vietnam (bottom left).

Honey

Honey produced from *Aegialitis* and *Cynometra* is considered to be of very good quality, but neither of these species are particularly common. Most mangrove-derived honey comes from other more common species such as *Ceriops* and *Avicennia*.

Wild bee colonies are fairly common in mangrove forests, and the opportunistic collection of honey from their hives is probably widespread. Commercial-scale honey production from mangroves seems to be carried out mainly in the Sundarbans of India and Bangladesh, the Caribbean and Florida (Hamilton & Snedaker, 1984). In the Indian Sundarbans, for example,

an estimated 2,000 people were reported to be involved in producing around 111 tonnes of honey in the early 1980s (Untawale, 1987), presumably from a mix of wild hives and commercial beehives. More up-to-date information is not available.



Photos: Tran Sen Thi Mai

In Vietnam, beehives are located next to mangroves (left) and bees are freed to forage (right). Commercial honey production from mangroves is an important industry in India, Bangladesh, the Caribbean and Florida. It is a smaller local family-based activity in many other countries.

Other human foodstuffs

The propagules of *Avicennia*, *Sonneratia*, *Bruguiera* and *Heritiera* are used for human consumption in a number of Asian-West Pacific countries, although how widely is not known. In some cases, they have to be treated to remove tannins prior to consumption. This is usually done by soaking in a strong salt solution for several weeks to a month. In the case of *Bruguiera* propagules, in the Gulf Provinces of Papua New Guinea they are often shredded or ground to a paste, and then treated to remove tannins before consumption. A refreshing drink can be prepared from *Sonneratia* propagules which are commonly a little smaller than a tennis ball, and have very small seeds contained in a soft pulp, somewhat resembling custard apple (*Annona reticulata*) or guava (*Psidium guajava*). A much more extensive discussion of the use of mangroves for food and beverages can be found in the third volume of this book series (Baba et al., 2013).

Fodder

Avicennia foliage is grazed widely by camels in Pakistan and the Middle East, and by cattle, goats and water buffalo throughout Asia (Hamilton & Snedaker, 1984). Studies of the nutritive value of the leaves of the most common mangroves (*Avicennia*, *Ceriops* and *Rhizophora*) show that they contain most of the essential minerals, vitamins, amino acids, proteins, fats and crude fibre needed by livestock; in addition they contain salt and iodine, which are generally deficient in other kinds of fodder (Hamilton & Snedaker, 1984). Extensive grazing by camels in Pakistan has led to widespread defoliation and limited the height of *Avicennia* to less than about 3 m, and many areas have become seriously degraded. Some farmers on extensive mixed shrimp-mangrove farms in the southern Vietnamese province of Ca Mau claim that shrimp production is enhanced by supplemental feeding with *Avicennia* leaves.



Photo: Emad Al-Aidy



Photos: Shigeyuki Baba

Mangrove foliage is used for fodder in the Middle East, Pakistan and India. Camel grazing on *Avicennia*, Egypt (top), collecting *Avicennia* for fodder, India (bottom left) and feeding *Avicennia* to domestic cattle, India (bottom right).

Medicines

All traditional societies have 'bush medicines' and those dwelling in or near mangroves are no exception. People living in coastal mangrove communities use products derived from mangroves to treat a wide variety of common ailments, and a few serious medical conditions (Table 5.2). There is limited public information on the pharmacology of mangroves, but most species have high contents of anti-oxidant polyphenolic compounds (e.g. tannins), and a number of species are known to contain biologically active compounds that have anti-microbial or anti-fungal properties, while others show potential for the treatment of more serious diseases such as leukemia (Bandaranayake, 1998). It is likely that commercial drug manufacturers have more information on mangrove pharmacology of a proprietary nature, but this is seldom made public. A more detailed and reasonably up to date account of the current state of public knowledge on mangrove pharmacology can be found in Bandaranayake (1998) and Baba et al. (2013). What the present evidence does show, however, is that the widespread use of mangroves for 'bush medicines' is based on much more than just folklore.

Table 5.2 Reported medicinal uses of some mangroves and selected mangrove associates. Modified from Bandaranayake (1998). Ba = bark; Fr = fruit; Fl = flower; Ju = juice; La = latex; Le = leaf; Ro = root; Re = resin, Rh = rhizome; Sa = sap; Sh = shoot; St = stem.

Species	Medicinal Use
<i>Acanthus ilicifolius</i>	aphrodisiac, asthma, blood purifier (Fr); diabetes, diuretic, dyspepsia, hepatitis, leprosy (Fr, Le, Ro); neuralgia, paralysis, ringworms, rheumatism, skin diseases, snake bites, stomach pains (Ba, Fr, Le)
<i>Acanthus ebracteatus</i>	antiseptic, blood purifier, boils (Fr); colds (Ba, Fr); gangrenous wounds (Ba); rheumatism (Le); skin allergies (Ba); snake bites, (Ba, Fr, L).
<i>Acrostichum aureum</i>	Boils, wounds (Rh); rheumatism (Le)
<i>Aegiceras corniculatum</i>	asthma, diabetes, rheumatism, haemataria, leprosy, ulcers (Le, Ba)
<i>Avicennia alba</i>	anti-fertility, skin diseases, tumours, ulcers (Re)
<i>Avicennia germinans</i>	cancer, thrush, gangrenous wounds, lice, mange, ring worms, skin parasites, tumours, incontinence, rheumatism (Ba); throat pains, ulcers of the mouth (Le, Ba).
<i>Avicennia marina</i>	rheumatism, small pox, ulcers (St)
<i>Avicennia officinalis</i>	aphrodisiac, diuretic, hepatitis (Fr, Le); leprosy (Ba)
<i>Bruguiera cylindrica</i>	hepatitis (Fr, Le, Ro)
<i>Bruguiera exaristata</i>	anti-tumour (Ba)
<i>Bruguiera gymnorhiza</i>	eye diseases (Fr); diabetes, ulcers (Ba, Le)
<i>Bruguiera parviflora</i>	anti-tumour (Ba)
<i>Bruguiera sexangula</i>	anti-tumour (Ba)
<i>Ceriops decandra</i>	hepatitis, ulcers (Ba, Fr, Le)
<i>Ceriops tagal</i>	stops hemorrhages, diabetes (Ba)
<i>Clerodendron inerme</i>	antiseptic, arrests bleeding, uterine stimulant (Le); asthma, hepatitis, ringworm, stomach pains (Le, Ba, La)
<i>Conocarpus erecta</i>	catarrh (Ro); febrifuge (Le); gonorrhoea, malaria, stops bleeding (Ba)
<i>Derris trifoliata</i>	laxative (Le, Ro, St) ; arrests haemorrhages (Fr); antispasmodic, stimulant (Ba)
<i>Excoecaria agallocha</i>	epilepsy (Le, Sa), conjunctivitis, dermatitis, haematuria, leprosy (Le, Sa, St); purgative (Le, Sa); toothache (Sa)
<i>Heritiera littoralis</i>	diarrhoea (St)
<i>Hibiscus tiliaceus</i>	ear infections (Fl)
<i>Kandelia candel</i>	diabetes (Ba, Fr, Le)
<i>Lumnitzera littorea</i>	thrush (Le)
<i>Lumnitzera racemosa</i>	antifertility, asthma, diabetes, snake bite (Fr)
<i>Nypa fruticans</i>	asthma, diabetes, leprosy, rheumatism, snake bite (Le, Fr)
<i>Pluchea indica</i>	fever (Le, Ro), gangrenous ulcers (Le), rheumatism, scabies (Le, Sh); sinusitis (Ba, St)
<i>Pongamia pinnata</i>	clinical lesions of skin and genitalia (Ba, Le, St); fever, piles, rheumatism, scabies (Le); sinus (Ba); skin diseases, stomach pain and intestinal disorders (Ba); tumours, wounds, ulcers (all parts).
<i>Rhizophora apiculata</i>	anti-emetic, antiseptic, diarrhoea, haemostatic (Ba); hepatitis (Ba, Fl, Fr, Le); stops bleeding, typhoid (Ba)
<i>Rhizophora x lamarckii</i>	hepatitis (Fl, Le).

Species	Medicinal Use
<i>Rhizophora mangle</i>	angina, boils, fungal infections (B); antiseptic, diarrhoea, dysentery, fever, malaria, leprosy, elephantiasis, tuberculosis (Ba, Le), minor bruises, plaster for fractured bones (Ba)
<i>Rhizophora mucronata</i>	elephantiasis, febrifuge, haematoma, ulcers (Ba); hepatitis (Ba, Fl, Fr, Le, Ro)
<i>Rhizophora racemosa</i>	stops bleeding (Fl, Le).
<i>Scaevola taccada</i>	antiseptic, anti-inflammatory, coughs, diabetes, eye infections, gastro-intestinal disorders, headache, stings, bites (Ba, Le)
<i>Sesuvium portulacastrum</i>	hepatitis (Le)
<i>Sueda maritima</i>	hepatitis (Le)
<i>Sueda monoica</i>	hepatitis (Le)
<i>Sonneratia alba</i>	poultice in swellings and sprains (Fr)
<i>Sonneratia apetela</i>	hepatitis (Le)
<i>Sonneratia caseolaris</i>	bleeding, hemorrhages (Ba, Le, Fr); asthma, ulcers (Ba); piles, sprain poultice (Fr)
<i>Sonneratia ovata</i>	checks hemorrhages (Ju)
<i>Xylocarpus granatum</i>	cholera, fever, malaria (Ba)
<i>Xylocarpus moluccensis</i>	aphrodisiac, (Fr); fever, malaria (Ba)

Fisheries and other marine resources

As indicated in Chapter 4, mangrove habitats and their associated inshore mudflats and waters are especially rich in fish, crabs, shrimp, shellfish and other edible marine life. These resources are heavily used by coastal communities, both for subsistence and commercially for income generation. These uses have been extensively documented for many coastal regions with mangroves, for example, India (Untawale, 1987), Thailand (Plathong & Sitthirach, 1998) and Australia (Bird, 1986).

Mangroves are natural nursery areas for a wide variety of fish and shrimp. However, very few fish or shrimp species spend their entire life in mangroves – most come and go with the tide or spend part of their life cycle in mangrove dominated estuaries, using mangroves both for protection and as feeding areas. This inter-connectivity between mangroves, and adjacent tidal mud flats and coastal waters, which involves both the migration of fish and other marine species between mangroves and adjacent habitats, as well as flows of organic matter and nutrients between them, means that the contribution of mangroves to coastal fisheries can extend well beyond their seaward limit.

Many studies have demonstrated a correlation between mangroves and coastal fishery or shrimp production (e.g. Martosubroto & Naamin, 1977; Singh et al., 1994), although this appears to be site specific and depends, amongst other things, on the physical characteristics of the mangroves and the physical and biological characteristics of adjacent offshore areas. Nevertheless, a broad assessment from 38 localities around the world found a very strong correlation between shrimp catches and mangroves (Pauly & Ingles, 1999; cited by numerous authors). Mangrove habitats are important nursery areas for a number of commercially valuable shrimp species (Chong et al., 1990), but for fish they appear to be more important as feeding areas than as a nursery (Robertson & Duke, 1987; Chong et al., 1990; Primavera, 1998).

Declining coastal fisheries catches are due to many factors, including overfishing, destructive fishing practices (e.g. the use of explosives or poisons) and the loss or degradation of fish habitats. While it is not possible to say how much fisheries production is reduced for every square kilometre of mangroves lost, the loss of mangroves is believed to be one of the factors contributing to declining coastal fisheries catches.

Other Services Provided by Mangroves

Coastal protection

The value of mangroves for coastal protection has long been appreciated by traditional indigenous mangrove-dwelling communities. This role is also increasingly being recognised by the wider community, especially since the catastrophic consequences of the Asian Tsunami in December 2004 and the trail of destruction left by Cyclone Nargis which hit the coast of Myanmar in May 2008. However, the idea of planting mangroves for coastal protection is not new; planting mangroves for coastal protection began at least a decade ago in Vietnam and a number of other countries with coastlines vulnerable to erosion.

Mangroves can help to provide coastal protection in several ways – in some cases they can help to reduce the rate of coastal erosion – they can provide inland coastal areas with some protection from storm- or tsunami-generated waves – and they can provide some protection from strong winds.

Coastal erosion

Coastal erosion is caused mainly by strong nearshore currents and wind-driven waves, and is influenced significantly by the shape of the coastline, the direction of waves, wave energy, current velocity and tidal amplitude. Man-made piers and bund walls can also have a significant impact on local patterns of erosion.

Mangroves help to reduce coastal erosion in two ways – their dense below-ground root systems help to hold the muddy soils together – and their above-ground roots and trunks reduce the velocity of water flowing across the soil surface, thereby reducing surface erosion and often contributing to sediment accretion in areas with a rich supply of sediment in the incoming water. While there have been many recent studies of the role of trunks and above-ground roots in regulating water flow and wave propagation through mangrove forests (e.g. Wolanski et al., 1992; Mazda et al., 1997; Mazda et al., 2006), there seem to have been no quantitative studies of the role of below-ground roots in holding the soil together.

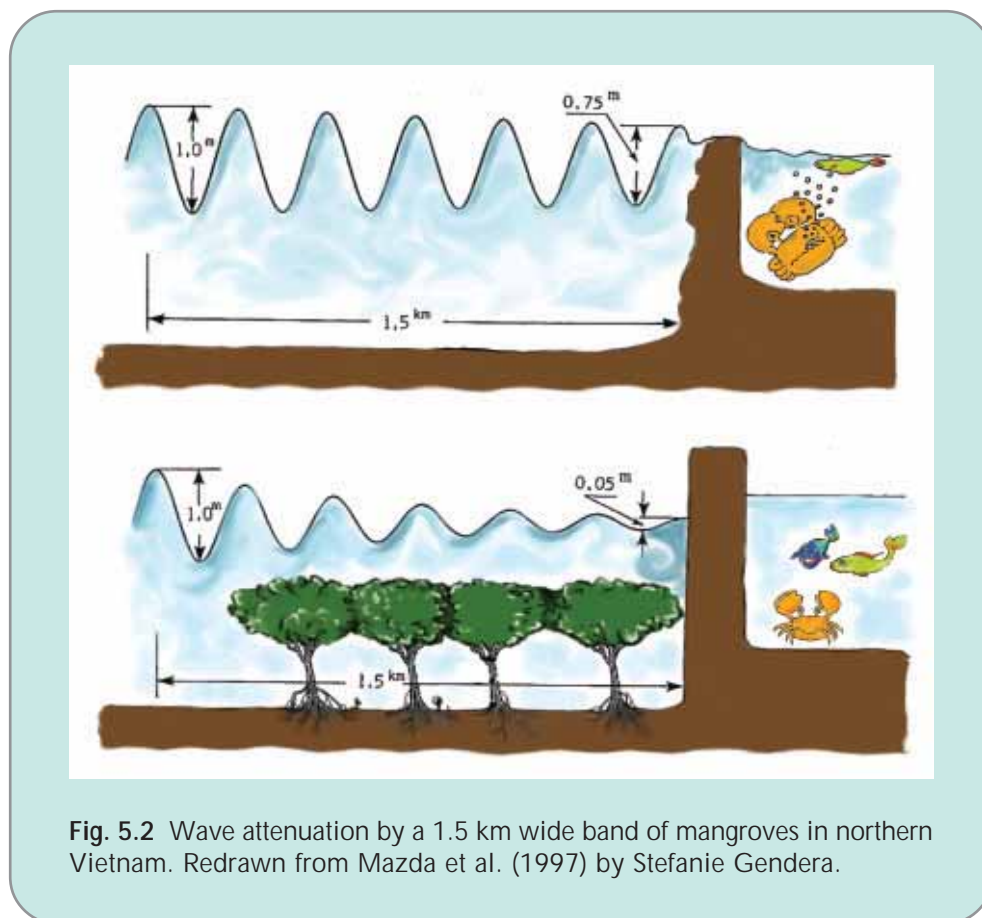
Coastal erosion is a very complex and dynamic process. The extent to which mangroves can prevent or help to reduce erosion tends to be fairly site specific. It depends amongst other things on wave energy, tidal range, coastal currents and the shape of the coastline and offshore mud or sand banks. In some places where erosional forces are weak, the presence of mangroves is sufficient to prevent erosion more or less completely; in others where erosional forces are stronger, mangroves may help to reduce the rate of erosion significantly; but along high energy coastlines, mangroves may provide only minimal or no protection against coastal erosion.

Protection from waves

There is good evidence that the energy and height of waves is significantly diminished as they pass through mangrove forests (Mazda et al., 1997, 2006). Mazda et al. (1997), for example,

found that a band of *Kandelia obovata* 1.5 km wide reduced wind-driven wave heights from 1 m to just 5 cm in an area of northern Vietnam (Fig. 5.2).

Modelling studies with the larger waves of tsunamis also suggest that a greenbelt of mangroves or other forest vegetation could reduce the impact of tsunamis significantly (Hiraishi, 2008). While these seem to support reports of less damage along some mangrove-protected coastlines during the 2004 Asian tsunami (e.g. Danielsen et al., 2005; Kathiresan & Rajendran, 2005), others have questioned the protective benefits of mangroves against tsunamis. Cochard et al. (2008), for example, concluded that mangroves were not effective in protecting coastlines near to the epicentre of the earthquake, but may have contributed to coastal protection along coastlines further away.



In a recent analysis of the economic value of some mangrove services, Barbier et al. (2008) estimated the value of coastal protection from storms to be about USD 1.6 million per km² of mangroves over a 20-year period. This is significantly greater than the individual values of wood products (USD 86,400 per km² over 20 years), mangrove-associate fisheries (USD 211,700 per km² over 20 years), or conversion their conversion to commercial shrimp ponds (USD 963,200 per km² over 20 years) (Barbier et al., 2008).

Carbon storage

Most of the world's coal deposits are derived from trees and other vegetation that died and became buried some 250 to 300 million years BP. The burning of these fossil fuels is a major cause of rapidly rising atmospheric carbon dioxide levels, believed to be one of the main contributors to present day global warming.

Worldwide, forests are particularly important in the global carbon cycle because they are long-lived and so provide longer-term carbon storage, much of which lies buried underground. By comparison with terrestrial trees, mangroves as a group have a very high proportion of their total biomass below ground. The death of roots and the production of new ones (root turnover) results in an accumulation of large amounts of organic matter (buried carbon), which decomposes slowly due to the wet anaerobic soil conditions of mangrove habitats.

The amount of carbon stored in the soil beneath a mangrove forest depends on the type of forest, its age, the depth of the soil, its geological history, the degree of disturbance, the type of substrate, hydrological characteristics and probably other factors. Figures for below-ground carbon stocks in mangroves from around the world are generally high (e.g. Matsui, 1998; Matsui & Yamatani, 2000; Donato et al., 2011). In a broad survey of 25 sites in Borneo, Bangladesh, Java, Sulawesi and Micronesia, Donato et al. (2011) obtained a mean of 972 tonnes C per hectare for estuarine sites and 792 tonnes C per hectare for oceanic sites, most of which was soil organic carbon rather than below-ground root biomass. These figures represent long-term storage over periods of hundreds to thousands of years.

Recent estimates of the rate of carbon burial in mangrove ecosystems suggest that globally they could bury around 18 million tonnes of carbon annually (Bouillon et al., 2008). What is clear from this is that in spite of their relatively small area globally, mangrove forests are important long-term sinks for atmospheric carbon dioxide, and that they play a crucial role in the global carbon cycle (Duarte et al., 2005; Bouillon et al., 2008).

Coastal wastewater treatment

In addition to being carbon sinks, mangroves also trap and process nutrients like nitrogen and phosphorus. This makes them potentially useful for the treatment of wastewater, tertiary sewage and shrimp pond effluent (e.g. Nedwell, 1974; Clough et al., 1983; Robertson & Phillips, 1995), provided that the wastewater is free of industrial wastes, which can contain high levels of heavy metals and other toxic chemicals. Constructed mangrove wetlands also appear to be effective in wastewater treatment (Boonsong et al., 2003).

Chapter 6

THREATS AND ENVIRONMENTAL IMPACTS

As we saw in Chapters 2 and 3, mangroves grow in a highly dynamic, often unstable habitat where they are at risk from a wide range of natural phenomena. These include severe storms, coastal erosion, changes in sediment distribution in large estuaries and other hydrological factors, as well as extremes in temperature and other seasonal weather patterns. Over the past century, however, the most significant impacts on mangroves have been of human origin. Mangroves have been destroyed on a large-scale to make way for coastal urban expansion, for ports and industrial development, for agriculture, for coastal aquaculture ponds, and for unsustainable extraction of timber and firewood. Undeniably, the main driver for this destruction has been the burgeoning global population with its quest for land, food and other resources.

It is clear that the area of mangroves has declined considerably over the past 100 years and especially in the last 50 years, particularly in Asia (Fig. 6.1). The causes of this decline vary from country to country; in the Philippines, it has been attributed mainly to conversion of mangrove to aquaculture and reclamation for urban expansion and industrial development (White & Cruz-Trinidad, 1998; Primavera, 2001); in Malaysia, conversion for rubber, oil palm and aquaculture, urban expansion and port development (Chan & Salleh, 1987); in Thailand, mainly conversion to shrimp ponds and reclamation for urban development (Plathong & Sitthirach, 1998; Barbier, 2006); in the Ayeyarwady Delta of Myanmar, mainly for agriculture (Blasco et al., 2001); and in Vietnam to the effects of war-time defoliants in the 1960s and, more recently, conversion to shrimp ponds (Hong & San, 1993). Mangroves have also been lost through conversion to shrimp ponds in Ecuador (Hamilton, 2011), and by conversion to swamp rice in West Africa (Sylla, 1994).

Based on current trends, these adverse human impacts on mangroves are certain to continue in the future. The world's population has risen from about 1.6 billion at the beginning of the 20th Century to a present day figure of around 7 billion, and is expected to reach 9 billion by 2050. Much of this population growth will occur in coastal areas where already more than 38% of the world's human inhabitants live, bringing with it an increasing demand for food, urban infrastructure and economic development. This is bad news for mangroves, particularly in Asia and West Africa, where there have already been massive losses from human activities over the past century.

In this chapter, we will consider some of the ways that human activities have already impacted on mangroves, and what might be expected in the future if present trends continue. We will also discuss the hotly debated possible impacts of climate change on mangroves.

Conversion to Agriculture and Salt Ponds

Subsistence agriculture in mangrove areas has a long history. One of the earliest uses of mangroves for agriculture appears to have been the development of swamp rice cultivation in West Africa around 1,000 years ago (Fields-Black, 2008). Despite the difficulty of growing rice on saline, acidic soils, it has been estimated that about 20% of the West African mangrove area has already been cleared for rice cultivation, rice production in these areas accounting for around 10% of the total regional rice production (Agyen-Sampong, 1994). The expansion of swamp rice production forms an important part of national agricultural policy in many West African nations, directly threatening much of the remaining mangrove habitat. Clearing

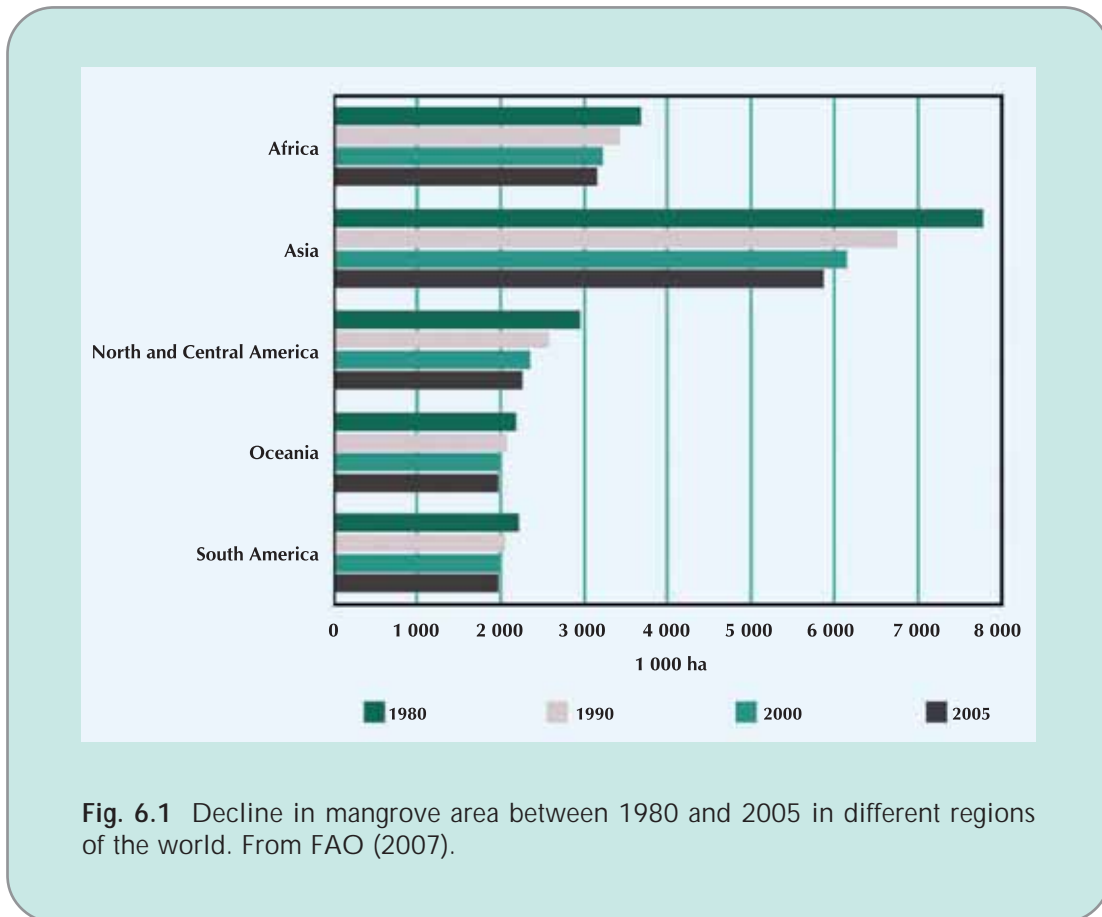


Fig. 6.1 Decline in mangrove area between 1980 and 2005 in different regions of the world. From FAO (2007).

mangroves for rice production is also common elsewhere, for example Myanmar, but in most other countries it accounts for a relatively small proportion of the loss in mangrove area.

However, given the strategic importance of rice as a staple food throughout the Asian region, the shortage of arable land and the increasing intrusion of saline water into existing rice growing areas in many parts of Asia and Africa, a considerable amount of research being carried out on management practices and rice varieties better suited to low-lying saline and acidic soils. It therefore seems highly probable that further mangrove areas will be converted for rice cultivation in the future.

Mangroves have also been cleared for other cash crops, mainly coconut, rubber, cocoa and oil palm in parts of Malaysia and Indonesia, but this practice seems to be on the decline owing to the high cost of ameliorating soil acidity and salinity.

Conversion of mangroves for agriculture usually involves the construction of bund walls or dikes to prevent inundation from the sea, and diversion of freshwater from streams and rivers for irrigation. These changes in freshwater flow and hydrology usually have a severe impact on any remaining mangroves and lead to a degradation in forest quality and ecosystem function.

Salt evaporating ponds are also relatively common in mangrove areas of sub-humid and drier parts of Asia, but many are small and globally their total area is much less than that converted to agriculture and aquaculture. The most extensive damage to mangroves appears to be in Benin (Saenger et al., 1983; Spalding et al., 2010) where the climate is only marginal for solar evaporation, and mangroves are cut for fuel to evaporate the brine.



Photo: Joseph Tengah



Photo: Barry Clough

Mangrove land reclaimed for an oil palm plantation in Malaysia (left) and salt ponds constructed in former mangrove areas, Bac Lieu, Vietnam (right).

Conversion to Aquaculture

Traditional tambak aquaculture has been practised in Indonesia since before the 16th Century (Schuster, 1952, cited by Naamin, 1986). Originally, it was basically just a fish trap, formed by building a dike around an intertidal mangrove area to trap fish and shrimp on the incoming tide and then catch them on the outgoing tide. Later, canals were dug within the mangroves to culture wild fish and shrimp without the addition of feed, fertiliser or chemicals. Similar forms of aquaculture were probably practised elsewhere in coastal areas; even today, this type of aquaculture is still carried out widely, in one form or another, in many parts of Asia.

Large scale commercial aquaculture began in the 1970s, with rapid expansion during the 1980s and 1990s. Conversion for aquaculture has been one of the leading causes of mangrove losses in Asia and parts of Central and South America. For example, Thailand lost 50-60% of its mangrove forests between 1961 and 1996, mainly to shrimp ponds (Barbier, 2006). In the Philippines, the mangrove area dropped from about 290,000 hectares in 1970 to around 140,000 in 1993, mostly due to conversion to aquaculture (White & Cruz-Trinidad, 1998; Primavera, 2001). In Vietnam, of the estimated 400,000 hectares in the 1940s (Hong & San, 1993), only about 100,000 hectares remain today (Spalding et al., 2010). Much of the loss in Vietnam can be attributed to the war-time use of herbicides in the 1960s, but more recent rapid expansion of subsistence and commercial aquaculture together with intense population pressure has seriously depleted and degraded the remaining mangroves in the southern Mekong Delta.

With similar reports from Ecuador of mangrove losses associated with shrimp pond construction (Hamilton, 2011), it is clear that conversion of mangroves for aquaculture has been a major contributor to the loss in mangrove habitats worldwide. Despite policies and regulations to limit the use of mangroves for aquaculture in many countries, these are seldom enforced effectively, so coastal aquaculture is likely to remain a threat to mangroves.



Photos: Barry Clough

Extensive shrimp ponds in mixed shrimp farming – mangrove forestry enterprises in Ca Mau, Vietnam. The ponds are constructed by digging channels inside the forest. *Rhizophora apiculata* is the preferred species because of its value for poles, charcoal and firewood. The soil surface on which the mangroves grow is usually above the highest water level in the pond, so they are only flooded on extreme spring tides.

Urban Expansion and Industrial Development

Past and present demographic shifts in population from inland to coastal areas have put great pressure on all coastal ecosystems, including mangroves. Reclamation for urban expansion, ports and harbours, industry, tourist resorts and other coastal development has been responsible for significant losses of mangroves, particularly in developed countries like Australia and the United States, where aquaculture and agriculture have had only a small effect on mangrove losses. This is also increasingly a problem in many developing countries, where some of the world's largest coastal mega-cities are now found, and where the rate of coastal urbanisation is very fast.

Figures for the area of mangroves destroyed for urban and industrial infrastructure are difficult to find because these activities are often highly localised, less transparent and seldom documented, in contrast to the highly visible impact of large-scale conversion for aquaculture or agriculture.

In addition to direct reclamation of mangroves for urban or industrial infrastructure, coastal development also has other impacts on mangroves. Even where mangroves are not directly destroyed, the construction of roads, jetties and seaward bund walls usually alters freshwater drainage patterns, tidal flows and the overall hydrology of adjacent mangrove areas, almost invariably leading to degradation of community structure and function, and sometimes to widespread mortality, especially when the normal drainage pattern of the swamp is altered and the mangroves become more or less permanently ponded.

Pollution

By the very nature of the soils on which they grow, mangroves are relatively tolerant of sewage and other organic wastewater from domestic sources (Nedwell, 1974; Clough et al., 1983). Nevertheless, excessively high levels of domestic organic waste can lead to severe anaerobiosis in mangrove soils (see Chapter 3), with adverse impacts on the whole ecosystem (plants, animals and microscopic organisms).

A more serious problem is that of industrial wastewater, which often contains high levels of heavy metals such as cadmium, lead, zinc and mercury, as well as synthetic organic toxins. These usually have a greater impact on mangrove fauna than on the trees themselves, leading to a disruption in food chains and other biological interactions, which impairs the quality, productivity and functioning of the mangrove ecosystem. However, damage to mangroves is not restricted to industrial wastewater. Herbicides in runoff from upstream agricultural areas (mainly sugar cane farms) appear to be responsible for severe mortality of *Avicennia* in a number of estuaries in north-eastern Australia (Duke et al., 2005).

Oil spills are particularly damaging to all life in mangrove habitats, plant and animal. Significant oil spills with dramatic impacts on both mangroves and nearby marine ecosystems seem to be more common in the Gulf of Mexico and along coastlines in Central America, the most recent being the blowout of BP's Deepwater Horizon oil rig off the coast of Louisiana. Chronic impacts are also common in mangrove areas adjacent to oil refineries.

The immediate effect of oil on mangroves is smothering of the soil surface and breathing roots, often killing the trees. The impact on mangrove fauna is equally dramatic. However, there are also longer term effects from chronic poisoning of both plants and animals by toxic components that remain in the soil for a long time.

Another widespread problem is the tendency for many coastal urban and rural communities in some countries to dump solid waste directly into coastal rivers and waterways. This often ends up in the mangroves which are littered with plastic bags and other non-biodegradable materials. While there is no definitive evidence to suggest that this has a direct effect on mangroves, it certainly detracts from their aesthetics.

Exploitation for Timber and other Wood Products

The exploitation of mangroves for timber and wood products can be divided into three broad categories – sustainable exploitation from silviculturally managed plantation forests – commercial exploitation without any attempt at reforestation – and exploitation by local communities for domestic purposes and income generation. Since this chapter concerns threats and environmental impacts, we will not discuss exploitation of sustainably managed plantations, as this does not constitute a major threat to mangroves at the present time.

Large scale commercial exploitation of mangroves (mainly for woodchips and pulp for export to Japan) began with forest concessions in Sabah and Sarawak of East Malaysia in the late 1960s and early 1970s (Saenger et al., 1983; Phillipps, 1984), although some of these concession are now believed to have exploited all of the suitable mangrove forest and are no longer operational, leaving the remaining mangroves in a very degraded condition (Ewel et al., 1998), In commercial operations of this kind, no attempt is made to utilise the mangrove forest on a sustained yield basis by reforestation – instead the area is simply abandoned and new forest concessions sought elsewhere. Since these activities often take place in remote and sparsely populated areas, their scale and the extent of damage is difficult to assess.

Globally, however, intense human pressure and deforestation through over-cutting for firewood, poles and other subsistence uses by poor and increasingly populous coastal communities in the developing countries of Africa and Asia may be a far more insidious and serious threat to mangroves than commercial exploitation for woodchips. The consequence has been and continues to be serious degradation of once extensive mangrove forests throughout Asia (Blasco et al., 2001), Africa (Saenger, 2002; Spalding et al., 2010) and parts of Latin America (Lacerda, 1993).

Climate Change

From our discussion so far it is clear that human activities and population pressures have had a dramatic impact on both the area of mangroves worldwide and their overall condition and health, and that this will continue into the future, although hopefully at a slower rate. The prospect of rising sea levels, greater storm activity, changes in weather patterns and other consequences of climate change pose a further threat and add a new dimension to the future for mangroves.

Over approximately the last 80 million years that mangroves are known to have existed, the Earth has experienced huge changes in climate, continents have moved vast distances, coastlines have changed and sea levels have risen and fallen by well over 100 m (see Chapter 2). These include the last major extinction event about 65 million years ago, when dinosaurs and most other living things over about 30 kg in weight disappeared. Yet mangroves of one kind or another have persisted despite these monumental changes. Undoubtedly over this long period of time, the area of mangroves globally, regionally and locally went through repeated phases of contraction and expansion as coastlines were transformed by continental drift, plate tectonics and changes in sea level. Changes in temperature through alternating ice age and 'hot house' conditions would also have had a dramatic effect on the area and distribution of mangroves. These changes are also likely to have led to the disappearance of some species and perhaps the appearance of others. The point here is that mangroves as an ecological unit have shown remarkable resilience to monumental changes in climate, sea level and coastline geomorphology in the past.

The big difference today is that the world has a population of around seven billion, soon to be nine billion humans who have modified almost every natural ecosystem and destroyed others, decreasing both ecosystem and species diversity, and thereby reducing the resilience of many ecosystems and a large number of the remaining plant and animal species to climate change. The degradation of mangroves through human activities has almost certainly reduced their resilience to climate change and, as we shall see, human settlement and land use in coastal areas will limit the scope of many mangrove systems to adapt to climate change in the future.

Climate change is complex and multi-faceted because it involves so many factors that can have an impact on the stability, integrity and functioning of mangrove ecosystems, including, for example, rising sea levels, rising atmospheric carbon dioxide levels, rising temperatures, shifts in seasons, changes in rainfall patterns, and increasing frequency and severity of extreme episodic events such as storms, droughts, floods, and extreme temperatures (Solomon et al., 2007). These changes are not now the same or occurring at the same rate in all coastal regions where mangroves are presently found, nor will they be in the future. Some, such as warmer temperatures along temperate coasts or higher atmospheric carbon dioxide levels, might be marginally beneficial for mangroves, but most are likely to add additional stresses for mangroves in an already stressful habitat.

Apart from the impact of sea level, we presently have only a very limited understanding of how mangroves themselves will respond to different combinations of this suite of factors, and even less understanding of their impact on both the abiotic (non-living) and the other living components that collectively make up a functional and usually productive mangrove ecosystem.

Sea level rise

Rising relative sea levels are likely to be one of the more important impacts of climate change on mangroves. The Intergovernmental Panel on Climate Change (IPCC) in its most recent 2007 report (Solomon et al., 2007) predicted a rise in relative sea level of around 0.2 to 0.6 m by the end of this century, but there are many who think that sea level could rise by up to 1 m or more by the beginning of the 22nd Century. Thus, while it is certain that relative sea level will be higher by end of this century, the rate of rise and by how much it will rise along different coastlines are still a matter for debate.

At any given place, relative sea level rise consists of two components, a global rise in eustatic sea level relative to a fixed global coordinate system (due mainly to thermal expansion of the oceans and melting of polar ice caps), and changes in local land levels as a result of sedimentation, erosion, subsidence or tectonic activity that moves land surfaces vertically up or down. Local subsidence, often linked to extraction of groundwater for human needs, is a major problem in many lowlying coastal areas with large populations, for example, in and around Bangkok and Hochiminh City.

Rising sea level is a threat because mangroves cannot survive at elevations below about mean sea level. In principle, they could keep pace with rising sea levels if the rate of sedimentation is equal to or greater than that of sea level rise. However, as we have already seen, mangrove environments are highly dynamic, and their surface elevations are the result of a complex interplay between sediment accumulation, sediment loss from surface erosion, and compaction. Consequently, the capacity of mangroves to keep pace with sea level rise is likely to be highly site specific (Bacon, 1994).

Deltaic and river dominated mangrove systems in the wet tropics that receive large inputs of sediment from upstream catchments may be able keep up with sea level rise if they trap enough sediment to maintain vertical accretion rates that are equal to or greater than the rate of sea level rise. However, sediment accretion rates alone may not be a good indicator that mangroves are keeping pace with sea level, as subsurface processes, mainly compaction, may offset sediment accretion (Woodroffe, 1999; Gilman et al., 2008).

In situations where the rate of sedimentation is sufficient to keep pace with sea level rise, the survival of mangroves also depends on their capacity to keep pace with sedimentation. There is ample evidence that burial of the aerating roots by the rapid deposition of large amounts of

sediment (for example, during large floods or severe storms, or by dredge spoil) can cause significant mortality (Ellison, 2009; personal observation). In this case, the aerial roots are simply smothered before they have time to adapt by producing new roots. Under more typical conditions, sedimentation rates of up to 3 mm per year are common (Saenger, 2002; Alongi, 2008; Ellison, 2009), with rates as high as 10 mm per year in some localities (Alongi, 2008), without apparent ill-effect on the survival of adult trees. However, there is almost no quantitative information on the ability of any mangrove species to cope with sustained sedimentation over periods 20, 30 or 40 years, as would be required for them to cope with the sea level rise scenarios predicted for this century, and at the same time retain most of their existing forest structure and ecological functions.

As we saw in Chapter 3, different mangrove species have different kinds of root systems, and species with root systems that can adapt quickly to changes in sea level or sediment level are likely to fare better than those with less adaptive capacity. A superficial assessment of the structure and development of the four main kinds of root systems (see Chapter 3) described by Tomlinson (1986) suggests that species with knee roots (e.g. *Bruguiera*) and plank roots (e.g. *Heritiera littoralis* and *Xylocarpus granatum*) are not well adapted to dealing with fast rates of sea level rise or high rates of sedimentation, the main reason being that they need a significant investment in woody roots which take both time to construct and a large proportion of the tree's photosynthetic production. In the case of those species with stilt roots (e.g. *Rhizophora*) gas exchange is restricted to the lower, less woody sections of the stilt root and adaptation to rising sea level or rapid sedimentation requires the production of new lateral extensions to existing stilt roots or the production of new stilt roots from higher up on the trunk. These also require the development of new underground root systems. In *Rhizophora*, the development of new root systems above and below ground not only takes time, but also involves the allocation of a considerable part of photosynthetic production for the formation of new roots. Thus in a climate change scenario that involves a wide range of potential stresses that could affect plant metabolism and growth, the capacity of *Rhizophora* to adapt to rising sea levels might be limited. This apparent vulnerability of *Bruguiera* (knee roots) and perhaps *Rhizophora* (stilt roots) to rapid sea level rise is supported by evidence from the rapid rise in sea level in the Holocene some 10,000 years BP, when neither could keep pace with rates of sea level rise above 12 cm per 100 years (Ellison & Stoddart, 1991), a rate well below future projections.

On the other hand, genera with upward growing pneumatophores as aerial roots, such as *Avicennia* and particularly *Sonneratia*, might be better equipped to handle moderate rates of sea level rise and sedimentation than *Bruguiera* and *Rhizophora*. Pneumatophores apparently can be produced rapidly in response to changes in sedimentation patterns (Young & Harvey, 1996), and since the growth meristem is at the top of the pneumatophore it can continue to grow upwards in response to sea level or sedimentation. The capacity for vertical extension appears to be more limited in *Avicennia* than in *Sonneratia*. On old *Sonneratia* trees, pneumatophores can extend to over 2 m above their point of attachment to the main cable roots (for example, see Fig. 5.5 in Tomlinson, 1986), presumably reflecting a long history of adaptation to sedimentation.

Mangroves growing in areas with limited sediment input, such as along coastal fringes and in embayments, are unlikely to be able to keep pace with sea level rise. In low-lying and remote, sparsely populated regions, it may be possible to retreat landwards, as happened along some low, flat coastlines during the Holocene rise in sea level 10,000 to 6,000 years BP (Woodroffe, 1992, 1999). However, landward retreat along more densely populated coastlines, such as those in much of low-lying Southeast Asia will almost certainly be constrained by present land uses and infrastructure. Proactive and long-range land use planning, possibly including mangrove

re-afforestation (see Chapter 7), will be required in these areas to provide land suitable for mangroves.

Opportunities for natural migration landwards in response to rising sea levels depend not only on the availability of hydrologically suitable land, but also on a regular annual supply of propagules. In a rapid sea level rise scenario, one might imagine a sequence of progressively younger forest from seaward to landward, with the older, more seaward trees progressively dying off when they can no longer keep pace with sea level. The question then is whether or not there would be enough 'seed trees' to maintain the landward wave of migration. Under present climatic conditions, most species seem to be able to flower and produce propagules by ten years of age, often as early as two or three years of age, although propagules produced at an early reproductive age may be smaller and/or have low viability. While there is one report of an earlier onset of reproductive capacity in *Rhizophora mangle* at elevated atmospheric carbon dioxide levels (Farnsworth et al., 1996), it is not clear how interactions between all of the factors associated with climate change will affect flowering and propagule development. There is already evidence for changes in the phenology of leaf production and flowering in some temperate terrestrial tree species in response to climate change (e.g. Peñuelas & Filella, 2001; Alcamo et al., 2007). It is not known whether there could be similar shifts in phenology in mangroves in response to temperature, or to more complex interactions between two or more factors involved in climate change, but if there were, they would probably be more likely to occur along subtropical and temperate coasts at higher latitudes. In a worst case scenario, a delay in reaching reproductive age, a reduction in reproductive capacity, or lower propagule viability could pose a risk for landward migration in response to sea level rise.

The most vulnerable mangrove systems to sea level rise are those on small lowlying oceanic islands in the Western Pacific and Indian Oceans where mangroves are usually restricted to narrow fringes and coastal lagoons without significant inputs of sediment. Some of these islands are likely to be completely submerged in the future, and for many others the opportunity for landward retreat may be severely limited by landform or human activities and infrastructure.

High atmospheric CO₂ concentrations

The response of mangroves to rising atmospheric CO₂ concentrations is not clear. Only a very few species have been tested in laboratory studies with seedlings of less than two years of age. Generally, they show that rising CO₂ concentrations are unlikely to have much impact on growth, although there seem to be subtle differences in response amongst different species. For example, in *Rhizophora apiculata* and *Rhizophora stylosa* seedlings, growth rates over a 14 week period were enhanced at low atmospheric humidity, but not at high salinities (Ball et al., 1997). Other studies with eastern Pacific and western Atlantic species have shown enhanced growth and earlier onset of reproductive capacity in *Rhizophora mangle* (Farnsworth et al., 1996), higher photosynthetic rates and instantaneous water use efficiency in *Avicennia germinans*, *Rhizophora mangle*, *Conocarpus erectus* and *Laguncularia racemosa* (Snedaker & Araújo, 1998). In the latter study, however, despite higher photosynthetic rates in all species at elevated CO₂ concentrations, there was no increase in net primary production in *Avicennia germinans*, *Rhizophora mangle* and *Conocarpus erectus*, while there was a drop in net primary production in *Laguncularia racemosa* (Snedaker & Araújo, 1998).

It is still not known if adult trees growing in a highly unstable and variable environment will respond to elevated atmospheric CO₂ levels in the same way as seedlings grown under relatively constant experimental conditions, particularly with a mix of changes to a wide range of climatic factors. In addition, higher overall respiration rates as a result of higher temperatures could offset any photosynthetic gains from elevated atmospheric carbon dioxide levels.

Temperature and rainfall

Since mangroves are predominantly tropical trees that grow best in wet tropical climates, warmer temperatures (Solomon et al., 2007) could benefit mangroves growing along subtropical and temperate coastlines. With an adequate supply of fresh propagules and suitable sites, some species of mangrove might extend their present latitudinal distributions polewards. Given the broad relationships between latitude, tree size, growth rate and productivity described in Chapter 2, warmer temperatures are also likely to enhance the growth and productivity of mangroves along subtropical and tropical coastlines. However, in the southern hemisphere, the growth and productivity benefits of warmer temperatures could be offset by the lower rainfall predicted for subtropical coastlines (Solomon et al., 2007).

The upper limit for survival of most plants is a tissue temperature (e.g. in the leaves and other parts of the plant) of somewhere between 45° and 50°C, although air temperatures might be slightly above this because the leaves and other parts of the plant are cooled evaporatively. Mangroves growing along already hot and dry, or seasonally hot and dry coastlines (e.g. the Middle East, North Africa, and north-western Australia) may already be close to their upper thermal limit. It may be possible for species living in these difficult conditions to adapt to an increase in average temperature but short periods of extreme temperature (as in a heat wave) could push them beyond their thermal or other physiological limits, particularly if higher temperatures are also accompanied by a decrease in cloudiness and lower rainfall. In addition, respiration is more sensitive to temperature than photosynthesis, so higher respiration rates are likely to reduce the ability of mangroves to cope with higher temperatures.

In addition to any impacts of sea level rise described earlier, higher temperatures along hot, arid coastlines are likely to lead to a further reduction in species diversity and perhaps the complete loss of mangroves from some sections of coastline where mangroves are already near their upper thermal limit.

Storm frequency and intensity

An increase in the frequency and ferocity of coastal storms, particularly along mid-latitude West Atlantic and West Pacific coastlines, and in the East Indian Ocean and Bay of Bengal is considered to be one of the more certain outcomes of climate change (Solomon et al., 2007), and a series of particularly devastating storms in these areas over the last decade (e.g. Hurricane Katrina in 2005 in the Gulf of Mexico, Cyclone Nargis in 2008 in Myanmar) may be an indication of what is to come more often in the future.

Mangroves are moderately resilient to storms with wind speeds of up to about 80 km per hour, but significantly higher wind speeds can be quite destructive. Unlike local gap formation by lightning strikes, cyclones, typhoons, hurricanes and other severe tropical storms tend to cause damage over a wide area, resulting in defoliation, stripped branches, snapped trunks, uprooted trees and erosion of seaward margins; in some cases the aerial roots are also smothered with sand or mud. The extent and type of damage depends on wind speed, wind direction, the nature of the storm (principally the presence or absence of small, intense tornadolike vortices), the structure and species composition of the forest, and the degree to which mangroves are sheltered.

The impact of storms on forest (and ecosystem) structure, and subsequent natural recovery after the event often depends on the mangrove tree species present (Kauffman & Cole, 2010; personal observation). Mature trees of *Rhizophora* and other members of the family Rhizophoraceae, one of the core groups of mangroves globally, appear to have a very limited capacity to recover from the loss of the terminal shoots on branches after a severe storm. Early recovery of forests

dominated by members of this family tends to be limited to smaller saplings or trees that might have survived the storm, or a fresh supply of propagules. In contrast, both *Avicennia* and *Sonneratia*, also considered to be core mangrove genera, have the ability to coppice by producing new shoots along their branches and trunks following complete defoliation, and the loss of branches or the upper part of the trunk. These differences in recovery mechanisms between species may lead to a change in the species composition of a mangrove ecosystem following a severe storm.

Interactions and uncertainties

Adaptation to stress, including that likely to be imposed by climate change involves both relatively short-term plastic phenotypic responses to changing climatic regimes, and much longer-term genetic or evolutionary changes. The time frame for phenotypic adaptation varies from weeks to years, but genetic or evolutionary adaptation can take hundreds or thousands of years, especially in trees, which have much slower growth rates and longer lifespans than short-lived annual plants. Our understanding of the short-term plastic responses of mangroves to changing climate is still very limited. To date, most studies of the impact of climate change on mangroves have been restricted to one or at most two factors under otherwise relatively constant environmental conditions, and most have been carried out with seedlings or relatively young trees. Moreover, they have been limited to just a few of the seventy or so species recognised as mangroves. If the more widely studied and better (but still incompletely) understood responses of terrestrial trees and forests to multifactorial climate change are any guide, mangroves as an ecological assemblage and as an ecosystem are likely to respond and adapt to climate change in some unexpected ways. A more holistic approach to the assessment of the effects of climate change on mangrove ecosystems is needed. This must necessarily involve not only the responses of individual species to multiple climate change factors, but also, at the community level, interactions between different tree species, and between the trees and key fauna that help to shape ecosystem structure and contribute to the maintenance of core ecosystem functions.

As mentioned earlier, human disturbance and other activities have almost certainly reduced the capacity of mangroves to adapt to climate change, although this is hard to demonstrate quantitatively. Forest degradation, habitat fragmentation and destruction, and hydrological alteration are all additional stresses superimposed on top of climate change which are likely to have as much if not more effect on what happens to mangroves in a future more populated and climatically less predictable world.



Photo: H.T. Chan

Chapter 7

CONSERVATION AND MANAGEMENT

The topic of mangrove conservation and management could easily fill an entire and separate book, and here we can only cover some of the main issues and provide some overall guidelines for their conservation and management. I have deliberately avoided using the term 'sustainable management' in this chapter because it means so many different things to different people and it is used in different ways in different contexts. I much prefer the term 'wise management', which conveys the idea that management is (1) based on the best available understanding of how mangrove ecosystems function and their importance to human well-being, and (2) that best management practices are used to manage mangroves as a valuable natural resource in a way that maintains their many benefits for present and future generations.

Concern for the dwindling area of mangroves and calls for their conservation and better management date back to at least the early 1970s, and since then there have been many assessments of the global status of mangroves, most of which have also included some recommendation for conservation and management (e.g. Saenger et al., 1983; Hamilton & Snedaker, 1984; FAO, 1982, 1985, 2007; Umali et al., 1987; Clough, 1993; Lacerda, 1993; Diop, 1993; Spalding et al., 2010). In addition, in 1991, the International Society for Mangrove Ecosystems (ISME) adopted and disseminated a Charter for Mangroves (see Box 7.1). Perhaps all of these have helped to reduce the rate of mangrove loss below that which it might otherwise have been without them. Yet, despite these efforts and a huge volume of supporting scientific literature, mangroves continue to be destroyed or degraded at an alarming rate, raising the spectre of a future world without mangroves, possibly within the next 100 years (Duke et al., 2007). Some of the drivers for the continuing destruction of these highly valuable coastal ecosystems were discussed in Chapters 5 and 6. Nevertheless, it is reasonable to ask why there has not been a more concerted effort to conserve and manage an ecosystem that provides such obvious benefits to a very large percentage of the world's population living in coastal areas. The answer to this question is complex, and varies from place to place, but there seem to be four broad, for want of a better term what we might call governance issues that have contributed in one way or another to the continuing rapid loss of mangroves. These are discussed briefly below.

Firstly, in the market economy of the modern world, decisions on the use of land and other natural resources are based on the economic costs and benefits of utilising a given resource for a particular purpose. It is relatively easy to put a monetary value on the direct benefits of marketable products derived from mangroves, for example products like timber and honey, and even the conversion of mangroves to agriculture and aquaculture. However, it is far more difficult to put an economic value on the ecological and environmental services they provide, because most of them are not bought and sold. These services are what economists call 'public good services' that are available to everyone, in most cases free of charge. Since they are services for which it is difficult or impossible to collect payment, that is, they are not marketable, they are usually ignored in decision-making. We will not consider the economic theory or approaches to the valuation of wetland services any further here, but for those who are interested, Barbier et al. (1997) provide a clear explanation of the rationale and methodology for economic valuation of wetland goods and services.

In the past, decisions on how mangroves should be used or managed were taken without decision-makers and the general public being fully aware of the value of the ecological and environmental services they provide, or the potential long-term costs of their destruction and degradation. This situation still exists today, even though the importance of mangroves is

known more widely, and it is now possible to assign approximate economic values to many mangrove derived ecological and environmental services (e.g. Barbier et al. 2008). A further problem is that most decisions are made with an eye on short-term economic benefits, public opinion and re-election prospects at the next election. Long-term ecological and environmental benefits such as coastal protection, preservation of biodiversity, support for coastal fisheries and climate regulation are seldom considered, and even when they are, they tend to be undervalued (Barbier et al., 1997).

Secondly, land ownership and access rights (or a lack thereof) are important issues affecting mangrove conservation and management (Walters et al. 2008). In most countries, coastal wetlands, including mangroves, are under the legal custody of the state, but in some cases traditional indigenous communities also have custodial responsibility, either through formal legal tenure or through historical precedent. In Australia, for example, indigenous aboriginal communities have legislated legal tenure over a very large area of freshwater and coastal wetlands in the Arnhem Land region of the Northern Territory, to which access to 'outsiders' is only possible with formal permission from the governing body of the community. In this case, mangroves are generally well protected due to a combination of low human population density, and the deep spiritual respect for the land and its resources that is an integral part of indigenous Australian Aboriginal culture. Where traditional community-based management of 'common property' coastal resources is practised elsewhere, it also appears to be generally effective in limiting access to 'outsiders' and protecting mangroves. However, in many parts of the world, weak environmental governance, lack of enforcement of regulations and corruption lead to 'open access' to mangroves and other coastal resources, usually resulting in uncontrolled exploitation and very large human impacts.

Thirdly, conservation and management decisions are also complicated by the difficulty of defining the boundaries of a mangrove ecosystem. Mangroves are open ecosystems, with inputs of sediment, water and nutrients (and potentially also toxicants) both from landward catchments and from the sea. Thus human activities that take place in landward catchments, on seaward mudflats and in offshore marine waters beyond the immediate boundaries of mangrove forest itself often have impacts on its health and stability. This problem can be amplified by conflicting sectorial interests between those responsible for catchment land management and those responsible for coastal management. Approaches for dealing with these issues include integrated catchment management (ICM) and integrated coastal zone management (ICZM). However, there seem to be very few working examples where mangroves are managed within an ICM or ICZM framework, although the UNESCO MAB Biosphere Reserve framework goes part way towards their implementation. Additionally, catchments that drain into mangrove areas are sometimes trans-boundary, meaning that they cross national borders and extend into neighbouring countries. This adds further complexity to the use of integrated catchment management as a tool for protecting and managing mangroves.

Finally, and fourth, existing guidelines for conservation and management tend to be generic. Mangrove ecosystems are naturally variable from one place to another, and human impacts also differ in nature and intensity from one place to another. Generic guidelines can provide an overall framework for conservation and management, but in practice, an adaptive management approach has to be applied to suit local physical, biological and socio-economic conditions. While a flexible and adaptive management approach is often used intuitively by traditional community-based managers of 'common property' mangrove resources, it is not generally a feature of the 'top-down' decision-making process common in many countries.

All these issues have contributed to the loss of mangroves in one way or another and, unless they are redressed, it seems unlikely that mangrove conservation will fare much better in the future.

Management Frameworks

There are at least two international frameworks that potentially cover the conservation and management of mangroves, the Ramsar Convention on Wetlands, and the UNESCO Man and the Biosphere Reserve program.

Firstly, the 1971 Ramsar Convention on Wetlands provides a generic framework for the conservation of all wetlands:

'At the centre of the Ramsar philosophy is the 'wise use' concept. The wise use of wetlands is defined as 'the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development'. 'Wise use' therefore has at its heart the conservation and sustainable use of wetlands and their resources, for the benefit of humankind.'

Source: <http://www.ramsar.org/cda/en/ramsar-home/main/ramsar/140000>

However, the primary purpose of the Ramsar Convention is to protect wetlands of special significance as habitat for water birds. Presently, almost 2 million hectares of wetlands in more than 160 countries worldwide have been recognised as wetlands of special value by the Ramsar Convention. Although figures are not readily available, mangrove wetlands probably represent only a very small part of this total area.

Secondly, the UNESCO MAB (Man and the Biosphere) Biosphere Reserve Network, which was established in 1977 with the mission:

'To ensure environmental, economic and social (including cultural and spiritual) sustainability through:

- *the development and coordination of a worldwide network of places acting as demonstration areas and learning sites with the aim of maintaining and developing ecological and cultural diversity, and securing ecosystem services for human well-being;*
- *the development and integration of knowledge, including science, to advance our understanding of interactions between people and the rest of nature;*
- *building global capacity for the management of complex socio-ecological systems, particularly through encouraging greater dialogue at the science-policy interface; environmental education; and multi-media outreach to the wider community'*

Source: http://en.wikipedia.org/wiki/World_Network_of_Biosphere_Reserves

Currently, there are approximately 600 biosphere reserves in 117 countries, of which at least 15, and probably many more, include mangroves. Some examples of biosphere reserves where mangroves are an important component include the Shankou Mangrove Biosphere Reserve in China, the Can Gio Biosphere Reserve in Vietnam, the Ranong Biosphere Reserve in Thailand, The Gulf of Mannar Biosphere Reserve in India, Laguna de Términos Biosphere Reserve in Mexico, Delta del Orinoco Biosphere Reserve in Venezuela, the Sundarbans Biosphere Reserve in India and Bangladesh (transboundary) and the Boloma Bijagós Biosphere Reserve in Guinea-Bissau.

Most biosphere reserves embody three important elements, an agreed zoning system that specifies what can and cannot be done in each zone, multiple use of resources, and consultation with local communities. Biosphere reserves are usually divided into full protection zones without direct human use, buffer or limited-use zones where certain activities are permissible, and production zones where the land can be used for domestic and commercial purposes. However,

being within a biosphere reserve does not necessarily guarantee that mangroves will be protected and managed wisely, as there is no binding legal requirement to comply with the spirit of the biosphere reserve concept. Biosphere reserves can be removed from the UNESCO list at any time at the request of the host country, or as a result of an unfavourable periodic review of their operation by UNESCO. Despite this, biosphere reserves appear to offer one of the better formal frameworks for the conservation and wise use of mangroves. In the end, their success depends greatly on the cooperation of local people to respect the zoning system and protect their common pool of resources, backed by informed, consistent and transparent government policy.

Other conservation frameworks at the national, state or provincial level can also be useful for protecting mangroves. These include, for example, national parks, conservation areas, wildlife sanctuaries, nature reserves and fisheries or marine reserves. In many cases, these, like biosphere reserves, are zoned to restrict access and usage.

Conservation Strategies

The primary objective of mangrove conservation and wise management must be, as far as possible, to maintain and preserve the ecological functions and essential ecosystem services they provide. This does not necessarily preclude their silviculture for commercial timber production or their use for other direct products such as honey, fisheries and fuel by local communities, provided that such activities are strictly managed and do not have too much of an effect on the core objective of maintaining ecological functions and essential ecosystem services. However, it does mean halting or severely restricting highly destructive land use practices such as conversion for aquaculture, agriculture, and urban and industrial expansion. It also requires a solution to the problem of systematic degradation and fragmentation of mangrove habitats by the rapidly rising population of subsistence coastal dwellers in some developing countries.

Habitat fragmentation is a serious problem because, in general, species richness (number of species present) is positively correlated with the size of the mangrove area – i.e. the larger the mangrove area, the more species present (Duke et al., 1998a; Ellison, 2002). Rare or uncommon species are seldom found in small isolated stands. Thus habitat fragmentation is highly likely to lead to the loss of mangrove species, particularly those that have restricted distributions or are limited to small localised populations. The extinction of only one or two mangrove species represents a significant loss of genetic diversity in a specialised group of plants that at most includes only about 80 species globally. Furthermore, it is generally agreed that the loss of species leads to a reduction in functional diversity, particularly in mangrove ecosystems, which have complex biotic interactions internally and equally complex external biotic and abiotic links with other adjacent ecosystems (Ellison, 2008). This, in turn, impairs their ecological functions and their ability to provide normal ecosystem services.

As we have already seen in earlier chapters, mangrove ecosystems are extremely diverse at all spatial scales, global, regional and local. Some of the physical causes of this variability were discussed in Chapter 2, and some contributing socio-economic factors and other human impacts were discussed in Chapters 5 and 6. Natural variability and differences in the type and intensity of human disturbance mean that there is no general 'cookbook' recipe for wise management, in other words, there is no universal management strategy that fits all mangrove areas. Instead, flexible and adaptive management strategies need to be tailored to suit specific sites or areas according to their ecological characteristics, their vulnerability to rising sea level and other components of climate change, the socio-economic conditions of local people, and external impacts from the landward or seaward. This requires a much more forward-thinking and proactive approach to coastal planning and management than that generally prevailing today and it requires a more holistic consideration of external drivers from outside the immediate mangrove boundary, including human population pressures.

With these ideas in mind, the most effective general approach seems to be the assignment of mangrove systems into something like the following categories depending on the particular physical and biological characteristics of each system and local socio-economic conditions:

Preservation systems

These are fully protected in order to maintain genetic and functional diversity, and important ecosystem services such as coastal protection, habitat and nurseries for coastal fishery, birds and other fauna, and the regulation of climate and water quality. Since these are what we might call core mangrove ecosystems, ideally, they should be part of an integrated catchment management program to limit upstream impacts, and attention should also be given to limiting the impact of offshore activities. Selection of a mangrove ecosystem for preservation should also include consideration of opportunities for landward migration in response to rising sea levels, including existing land use, which may require contingency plans to make land, now used for other purposes, available for future migration of mangroves landward. Fishing in the associated mangrove waterways would be permissible provided that the mangrove forest remains untouched, there is no alteration of hydrological conditions by the construction of permanent fish traps or other structures, and overfishing does not lead to impairment of nursery functions.

Restricted-use systems

These are systems in which some carefully regulated and rigorously monitored direct human use is permitted. This might include, for example, small-scale extraction for fuel and food. Obviously, those activities that are regarded as permissible are likely to vary with local conditions, but the key criterion for deciding what is and what is not permissible is the extent to which the activity impairs core ecosystem functions and services. It should be noted that it is not easy to measure or monitor changes in ecosystem function or services, and there is considerable debate in the scientific literature on the best way to do this. Therefore the precautionary principle, or a conservative approach, should be applied in deciding what activities are permissible.

Production systems

This category recognises mangrove systems in which silviculture has been practised for a long time for the renewable supply of timber and other forest products, as, for example, in the Matang mangrove of West Malaysia and the Sundarbans of India and Bangladesh. Although there is evidence of declining timber harvests over time in Matang, some core ecosystem services seem to be undiminished (Ong, 1982, 1995). It might even be desirable to consider converting some existing degraded mangrove systems to production systems, and manage them for a renewable supply of timber and fuel wood in areas where there is widespread dependence on, and indiscriminate cutting of mangroves to meet basic subsistence needs. This could reduce the amount of indiscriminate cutting, thereby reducing degradation resulting from this activity.

These categories do not represent a zoning approach per se, because in many cases it is important to keep an entire mangrove ecosystem intact, rather than zone it for different uses. For example, some of the important ecosystem services provided by a riverine system draining a large catchment and flowing into sensitive offshore marine systems, such as coral reef and seagrass ecosystems, are likely to be adversely affected by allowing parts of it to be disturbed by human activities. It would not make sense to zone different parts of it for preservation, restricted use and/or production. However, in other cases, zoning a particular mangrove ecosystem into preservation, restricted-use and production systems might be appropriate. Thus the need for a flexible and adaptive management approach as outlined earlier.

The question then arises, how much of a nation's mangrove area should be designated for preservation, limited-use and production? There is no definitive answer to this question, since it depends on the national extent of mangroves, their geographic location, their relationship to each other, their size, floristic composition and functional diversity, and their present condition. It should also be recognised that even mangrove systems that have reduced floristic diversity and are exposed to human impact have ecological value and provide some ecosystem services, albeit perhaps not the full range. This brings us to the question of mangrove afforestation and rehabilitation.

Afforestation and Rehabilitation

The terms 'reforestation', 'afforestation', 'restoration' and 'rehabilitation' are often used interchangeably. However, there is a significant difference in meaning between them. Afforestation is a general term for planting an area with trees to form a forest, irrespective of whether or not there was forest there before; reforestation is generally used to mean that trees are planted in an area that was formerly forested. Strictly speaking, both of these terms refer to planting trees only. The terms 'restoration' and 'rehabilitation' are used in a more ecological context. Restoration is used to describe the process of returning something (in this case an ecosystem) to its original or presumed original state. There are two problems if we accept this definition. Firstly, the 'restore point' or the original condition to which we want to restore it, for, given both the natural and human induced changes that have occurred in most ecosystems, we have no way of knowing what its original condition was, nor what particular attributes and characteristics it had at that time. Secondly, it is hardly possible to recreate a complex, fully functional ecosystem with all the original species, functions, interactions and natural ecosystem services (even if we knew what they were) in a few years, a task that takes nature decades or centuries to do (but see Lewis, 2005). The term 'rehabilitation', on the other hand, has somewhat more relaxed definition, in the sense that it means to return something (again in this case an impacted or degraded ecosystem) to a condition where it is a functional, self-sustaining unit, though not necessarily to its 'original' condition. Here we will use only three terms, planting (or replanting), afforestation and rehabilitation.

Mangroves are opportunistic colonisers and, left to themselves, they will usually regenerate and colonise new areas naturally if there is a supply of propagules and the hydrological conditions are suitable. Where propagules are available, a lack of, or poor natural regeneration can usually be traced to unsuitable hydrological conditions, either of a natural origin or due to human impacts of some kind. From an ecological viewpoint, natural colonisation or regeneration is preferable, but in some cases it is desirable to plant mangroves manually in order to rehabilitate degraded habitats, or for other special purposes. The two most common situations are, firstly, the rehabilitation of former mangrove areas that were converted to aquaculture or agriculture and later abandoned when they became unproductive (Stevenson, 1997; Stevenson et al., 1999); and secondly, planting mangroves where natural regeneration is insufficient to provide effective coastal protection or some other important ecosystem function or service.

Mangrove afforestation in one form or another has probably been carried out for at least a century, in the first instance as part of sustainable silviculture for timber and wood products in Malaysia (Watson, 1928) and the Sundarbans of India and Bangladesh around the beginning of the 20th Century, and later by the French in Vietnam during the early to mid 1900s and most likely by colonial foresters elsewhere in Asia around the same time. Planting mangroves for shoreline stabilisation, coastal protection and general afforestation has also taken place since at least the early 1970s, for example, in Florida (e.g. Teas et al., 1975) and in parts of Southeast Asia, notably in Vietnam following the cessation of war in 1975 (Hong & San, 1993). In recent years, mangrove afforestation and rehabilitation for a variety of purposes has become common

around the world. Replanting of course is part of the management plan for sustainable mangrove silviculture, for example in West Malaysia and in the Sundarbans of India and Bangladesh. Larger scale mangrove afforestation has been carried out in Bangladesh (Saenger & Siddiqi, 1993) and in southern Vietnam. However, most mangrove afforestation activities have been relatively small and limited in scope, carried out for specific purposes, such as coastal protection or enhancing the well-being and livelihoods of local communities. Unfortunately not all projects have been successful, mostly due to a lack of appropriate site assessment and poor selection of species.

Site hydrology is by far the most important factor to be considered in any mangrove rehabilitation project (Lewis, 1999, 2005), so planting strategies and techniques are highly site-specific, and we will not discuss them in detail here. However, some general guidelines and techniques for planting for different purposes and in a variety of different site conditions can be found in Field (1996).

As indicated in Chapter 6 and again earlier in this chapter, indiscriminate cutting for fuel wood and construction materials, and a variety of other activities such as the construction dikes and embankments to channel irrigation water to rice fields or shrimp ponds which alter the natural hydrology of mangrove ecosystems, has led to serious degradation of mangrove systems in many parts of the world, notably in Africa and Asia. In addition, there are a large number of abandoned shrimp ponds in former mangrove areas in many parts of the world (Stevenson, 1997; Stevenson et al., 1999). While these may or may not be suitable for full ecological restoration in the sense described by Lewis (2005), some form of rehabilitation to return them to a self-sustaining mangrove system with at least some ecological functions and services is both realistic and practical.

Concluding Remarks

A flexible and adaptive approach to conservation and management of mangroves should not be interpreted as opportunity for decision-makers and coastal managers to do nothing. Difficult and challenging though it is, it simply reflects the reality that no two mangrove ecosystems are identical, and that management practices for one may not be the most appropriate for another. We must also recognise that management needs are not static and will almost certainly need to adapt over time in response to the impact of climate change and changing socio-economic conditions. What is needed is a more proactive and forward-looking approach to mangrove conservation and management by policy-makers, decision-makers and coastal managers, supported by sound scientific and technical advice, and an informed, environmentally-aware public. Is this too much to ask? We will know the answer in less than 100 years!

Some Useful Links to Online Materials

The links below might be useful for coastal managers, teachers, students and general readers interested in mangroves and other wetlands. While their focus is on Australian wetlands and coastal resources, the educational material and much of the other information they provide has a far wider scope.

OzCoasts - Australian Online Coastal Information

Site: <http://www.ozcoasts.gov.au/index.jsp>

Queensland Government Wetlands Information

Site: <http://wetlandinfo.derm.qld.gov.au/wetlands/index.html>

Box 7.1 ISME Charter for Mangroves

The International Society for Mangrove Ecosystems (ISME) has adopted a Charter for Mangroves that complements a World Charter for Nature that the General Assembly of the United Nations proclaimed on 28 October 1982 affirming that nature shall be respected, genetic viability on earth shall not be compromised, conservation shall be practised, sustainable management shall be utilised by man, and nature shall be secured against degradation.

ISME being aware that:

- a) Mangrove forests are unique intertidal ecosystems that occur primarily in tropical regions of the world;
- b) The total world-wide mangrove area is estimated at not less than 170,000 km² and that there are some sixty species of trees and shrubs that are exclusive to the mangrove habitat;
- c) Mangroves support genetically diverse communities of terrestrial and aquatic fauna and flora that are of direct and indirect environmental, economic and social value to human societies throughout the world;
- d) Sustainable development of mangrove ecosystems implies the maintenance and rational use of the natural resource to ensure ecological resilience and economic opportunities for present and future generations;
- e) Mangroves must be conserved in various parts of the world to prevent the occurrence of degraded coastal lands;

Convinced that:

- a) Destruction and degradation of mangrove forests are world-wide phenomena, as a result of activities related to the non-sustainable use and over-exploitation;
- b) The value of mangrove lands is consistently underestimated when the areas are converted for non-sustainable purposes;
- c) The sustainable use of mangrove ecosystems would provide a better use of the resource;
- d) There is an urgent need to restore degraded mangrove ecosystems for economic, social and conservation reasons;

Persuaded that:

- a) Mangroves are a valuable natural resource with distinctive genetic diversity, high intrinsic natural productivity and unique habitat value;
- b) Mangroves sustain important economic and ecological values in adjacent terrestrial and marine systems;
- c) Mangroves play an important role in the economic and social resources available to subsistence coastal dwellers in the tropics;
- d) Mangroves play an important role in coastal protection and in the reduction of coastal erosion;
- e) Mangroves buffer coastal waters from undesirable land-based influences, such as sediment, contaminant or nutrient runoff;

Reaffirming that people must acquire the knowledge to use natural resources in a manner which ensures the protection and enhancement of species and ecosystems for their intrinsic values and for the benefit of present and future generations.

Convinced of the need for appropriate measures at individual, collective and national levels to manage, conserve and promote understanding of the mangrove ecosystem.

I GENERAL PRINCIPLES

1. Mangrove ecosystems shall be respected and their intrinsic characteristics shall be preserved wherever possible.
2. The genetic diversity inherent in mangrove ecosystems shall be safeguarded to this end the necessary habitats must be preserved.
3. Mangrove ecosystems that are utilised by people shall be managed to achieve and maintain sustainable productivity without degrading the integrity of other ecosystems with which they coexist.
4. Mangrove ecosystems shall be secured against indiscriminate destruction, natural hazards, pollution and damage resulting from disturbance of surrounding areas.
5. The sustainable utilisation of mangrove ecosystems by traditional users shall be recognised and provided for to improve the welfare of the indigenous people.
6. The acquisition and dissemination of knowledge with respect to structure, function and management of pristine and disturbed mangrove ecosystems shall be encouraged by all possible means, including international research and technical cooperation.

II FUNCTIONS

7. The decisions affecting the management of mangrove ecosystems shall be made only in the light of best existing knowledge and an understanding of the specific location.
8. Decisions on how to manage a mangrove ecosystem shall be informed by definition of the following parameters:
 - (i) the biological components and the physical characteristics of the area under consideration, by means of inventories, maps and the collection of physical and biological data;
 - (ii) the needs of people in relation to sustainable uses of the resource while ensuring adequate reserves for preservation purposes;
 - (iii) the national and international significance of the resource as habitat and as a genetic reservoir;
 - (iv) the national and international significance of the site for coastal stability and fisheries production;
 - (v) the local requirements for education, recreation and aesthetic values;
 - (vi) the requirements that must be satisfied for non-sustainable uses of the resource;
 - (vii) the extent to which rehabilitation and compensation mechanisms can be used to mitigate the impact of non-sustainable use.
9. The information collected in (8) shall be used to define the areas necessary for preservation, to define strategies for the management, restoration and preservation of the resource, or to define areas necessary for sustainable use.
10. Decisions on the use of mangrove ecosystems shall include consideration of the need:
 - (i) to utilise the mangrove resources so that their natural productivity is preserved;
 - (ii) to avoid degradation of the mangrove ecosystems;
 - (iii) to rehabilitate degraded mangrove areas;
 - (iv) to avoid over exploitation of the natural resources produced by the mangrove ecosystems;
 - (v) to avoid negative impacts on neighbouring ecosystems;
 - (vi) to recognise the social and economic welfare of indigenous mangrove dwellers;
 - (vii) to control and restrict non-sustainable uses so that long term productivity and benefits of the mangrove ecosystems are not lost;
 - (viii) to introduce regulatory measures for the wise use of mangrove ecosystems.

III IMPLEMENTATION

11. The principles set forth in the present Charter should where possible be reflected in the law and practice of each state, as well as at the international level.
12. Knowledge of the structure, function and importance of mangrove ecosystems should be communicated by all possible means at local, national and international levels.
13. Knowledge of the structure, function and management of pristine and disturbed mangrove ecosystems should be enhanced.
14. Educational programmes and regional centres should be provided to train scientists, planners, managers and the general public and to encourage an awareness of the importance of mangrove ecosystems.
15. All planning should include the establishment of biological, physical and socioeconomic inventories of the mangrove ecosystems under consideration and assessments of the effects on the systems and their surrounds of the proposed activities. All such considerations should be open to public scrutiny and comment prior to any decision.
16. Resources, programmes and administrative structures necessary to achieve the sustainable use of mangrove ecosystems should be provided.
17. The status of mangrove ecosystems should be monitored nationally and internationally to ensure evaluation of current practices and to enable early detection of adverse effects.
18. States should establish specific statutory provisions or regulations for the protection and management of mangroves and mangrove ecosystems.
19. States, other public authorities, international organisations, non-government organisations, individuals, groups and corporations, to the extent that they are able, should:
 - (i) co-operate in the task of managing mangrove ecosystems for sustainable purposes;
 - (ii) establish procedures and methodologies for assessing the status of mangrove ecosystems and for managing them;
 - (iii) ensure that activities within their jurisdiction do not cause unnecessary damage to mangrove ecosystems within or beyond their jurisdiction;
 - (iv) implement national and international legal provisions for the protection and conservation of mangrove ecosystems.
20. Each state should where possible give effect to the provisions of the present Charter through its competent organs and in cooperation with other states.
21. All persons, in accordance with their national legislation should have the opportunity to participate, individually or collectively, in the formation of decisions of direct concern to the conservation and sustainable use of mangrove ecosystems.
22. Affected people should have means of redress when their mangrove ecosystems have suffered damage.
23. Each member of ISME has the duty to act in accordance with the provisions of the present Charter, acting individually, in association with others, or through participation in a political process. Each member shall strive to ensure that the objectives and requirements of the Charter are met.

International Society for Mangrove Ecosystems,
November 1991, Bangkok

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