3.4 Local management and rehabilitation of mangroves: present and future

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Abstract

This paper gives a brief introduction to the nature of mangroves and demonstrates the need for sustainable management of the forests. It considers how mangrove forests are managed in Australia at the National and State and local level. The present emphasis in the paper is on the management at a local level. The establishment of a base-line description at the local level using quantitative and qualitative measures is considered in detail. An approach to the rehabilitation of mangrove forests is outlined. The impact of anthropogenic induced climate change on mangrove forests is likely to be significant. The impact of sea level rise and the effect of other climate change factors are described. The impact of climate change will require adaptation management. Two forms of adaptation strategy: foresight and responsive are presented.

Introduction

Mangrove trees and shrubs are a common sight on sheltered coastlines, mudflats and river banks in Australia. They stand with their roots in salt water. As such they are a special form of vegetation existing at the boundary of two environments: the land and the sea. The species of trees and shrubs known as mangroves belong to a variety of plant families. The common characteristic that all mangroves possess is tolerance to salt and brackish waters. They normally grow in the intertidal zone. A brief description of mangrove biology is given.

In Australia, mangroves forests are managed by the Federal Government in conjunction with the States and Territories and local government through legislation covering fisheries, coasts, marine parks, wetlands and national parks. The main purpose of this paper is to consider the local management of mangrove forests. This is interpreted as the approaches to management to be taken in a specific area of mangrove.

An initial requirement of managing a mangrove forest is to determine its aerial extent. Many environmental factors influence the diversity and productivity of a mangrove ecosystem. These include climate, geomorphology, tidal range, fresh water input and soil characteristics. To manage a mangrove forest measurement of some of these environmental factors is essential. An examination of the methods available for determining all these parameters will be given. These quantitative measurements provide a base-line from which any change in the forest can be determined. A qualitative approach to managing mangroves is to devise health descriptors for the stand in term of visual characteristics. A combination of the quantitative and qualitative approach provides a powerful tool in the management of the mangrove forest.

If the mangrove area is severely degraded it may be necessary to rehabilitate the area by planting mangroves. The approaches and problems of rehabilitation will be considered in some detail.

The impact of global climate change will be felt strongly by mangrove forests, particularly with the rise in sea-level. The management of mangrove forests in the future must take into account the adaptations that may be required to safe guard the sustainability of the mangroves. The possible impacts of climate change on mangroves will be considered in detail and the adaptation strategies that could be employed to mitigate the effects will be outlined.

General comments on mangroves

Mangrove biology

The mangrove flora of Australia is some of the richest in the World with nineteen plant families and forty-one species recognised in Australia with the highest concentration of species in the tropics (Duke 2006).There is a rapid diminution of species as the latitude increases. The southern stands consist mostly of *Avicennia marina*. The total area of mangroves in Australia is estimated to be 9910km^2 (Spalding *et al*. 2010).

Several books have been written on the biology of mangroves (Field 1995; Saenger 2002). Mangrove forests flourish in conditions of heat, salinity and oxygen-starved mud that would overwhelm other terrestrial plants. To cope with this hostile environment mangroves have undergone selective changes. As time has passed they have adapted and emerged as the most successful coloniser of tropical coastal wetlands.

Aerial roots are the most noticeable adaptation. These come with various forms of architecture such as hoop stilts, buttresses or single unbranched structures rising elegantly from the mud to the sky and form breathing roots known as pneumatophores. Other adaptations include glands on the leaves for excreting salt, a tendency in some species towards succulence and roots that have an ability to exclude salt. The seeds are often viviparous. They are frequently buoyant, easily dispersed by tides and shaped so that they anchor in the mud.

Mangroves are considered to be amongst the most floristically species-poor forest ecosystem in the tropics but the biology of the swamp forest is complex. The mangrove ecosystem is important for fish and shell fish production and as habitat for many forms of wildlife and, increasingly, as a carbon sink. It also has a role in stabilising river banks and coast lines. An additional ecological value of mangroves is the preservation of biodiversity in the intertidal zone and beyond. Mangrove forests support extensive populations of birds, fish, crustacea, meiofauna, microbes and fungi. In addition, there are reptiles and mammals species. It is little used as a source of timber in Australia.

Mangroves are opportunistic colonisers of suitable land, usually in protected parts of the coastline, lagoons and estuaries. The occurrence and extent of mangrove forests is the result of geomorphic and hydrodynamic forces that create river deltas, estuaries and lagoons. Once the mangroves become established they tend to accumulate sediment and so modify tendencies towards erosion. The extent to which mangroves can stabilise land exposed to ocean currents and substantial fresh water inputs varies. If the forces are too great the mangroves can become ephemeral only to reappear at some other location when an opportunity presents itself.

In considering a mangrove ecosystem it is important not to see it in isolation (Alongi 2002). Mangrove ecosystems are known to interact with nearby ecosystems and in many instances the functioning of one system has important implications for the others. Saltmarsh is often found adjacent to mangrove communities. Like the mangroves, saltmarshes are considered to be a major source of organic material in the food chains. Another ecosystem that can occur adjacent to the mangroves is the seagrass meadows. A third ecosystem that can have an interaction with mangroves is the coral reef.

Loss of mangroves

It has been estimated that 17% of Australia's mangroves have been lost since European settlement (Duke 2006). This is low compared to an estimate of a 20% loss of mangroves world-wide over the last twenty years (FAO 2007). Most of the significant losses have been around areas of human population development. The development of Darwin was estimated to have removed 2% of pre-European mangroves in the area. These losses were all due to land clearing. Other smaller losses have occurred in north-east Arnhem land, Groote Eylandt and the Gulf of Carpentaria due to mining activities.

The construction of housing, marinas, ports, tourism developments and buildings for airports in Queensland, to meet increasing population pressures, has led to a wide spread loss of mangroves. Brisbane airport was built on reclaimed land with the loss of 850 ha of mangroves (Duke *et al*. 2003). Mangrove losses due to direct clearance for development in the other States have been relatively small. Some losses have occurred due to alterations to flows of nutrients and chemical pollution.

It is difficult to determine the extent of protection afford to mangroves in Australia. Duke (2006) states that about 8% of the Australian mangrove community are in protected areas. Queensland and New South Wales give legal protection to mangroves and clearance is not permitted without a licence.

Managing mangroves

The management of mangroves can be considered at two levels: the national level and the local level.

Managing mangroves at a national and state level

The Australian Federal Government has no legislation exclusively concerning mangroves. Mangroves are managed, in conjunction with the States and Territories and local government through legislation covering fisheries, coasts, marine parks, wetlands, and conservation of the environment. The object being the conservation and sustainable use of mangroves and the preservation of the vital linkages between mangroves and other ecosystems such sea grasses salt marshes and coral reefs.

This over-reaching approach appears have been successful in that no mangrove species is currently considered endangered and the national area of mangroves maybe increasing (Duke 2006). Nevertheless, pressure on mangroves persists as human populations require more and more coastal facilities.

Managing mangroves at a local level

Management at the local level refers to the management of individual mangrove forests and fringing stands of mangroves. Management at this level requires good knowledge of the physical parameters, environmental conditions and biological characteristics of the area under consideration. It also requires constant monitoring of the area under consideration. In order to manage a mangrove stand it is necessary to establish a base line description of the area. Many environmental factors influence the diversity and productivity of mangroves. These include climate, geomorphology, tidal range, fresh water input and soil characteristics, among others.

A guide to the local management of mangroves

A variety of methods are available to study the environmental characteristics and structure of a mangrove stand. Selection of the most appropriate method depends on time constraints, manpower and budget.

Aerial extent

The first thing to do is to get a measure of the aerial extent of the mangroves under consideration. This can be achieved using aerial photographs, satellite images or LIDAR (light detection and ranging) technology. The cost of this can become very expensive and the use of Google maps can offer a cheap alternative. The basic data can be displayed as a GIS (Geographic Information System) map of the area. This should reveal whether zonation exists in the forest. Recently, a shoreline video assessment method has been developed that provides a rapid assessment technique for measuring bank condition and the mangrove species present (Duke pers.com.).

As this information is to be used as a base-line measure, it is important, whatever approach is used, that it is accurately reproducible so that any changes in extent can be identified.

Transect line plots

In order to characterise the mangrove forest transect lines can be established through each of the main forest areas. Permanent plots can then be established along each transit line. This method can give a quantitative description of the species composition, community structure and plant biomass. This procedure enables regular monitoring for change to be carried out.

The transect line would normally be taken from the seaward edge of the mangroves at right angles to the edges of the mangrove forest. The precise location of the transect line should be established using GPS. The transect lines are dived into zones, such as low, mid, high intertidal zones. Randomly located replicate plots of equal size are then established for each zone. The mangrove species are then identified and the girth of the trees (>4 cm) at breast height determined. From these measurements a number of indicators can be calculated. Such as basal area (m^2 ha^{-1}), stems per hectare, relative density and importance value. The number of plants with girth less than 4cm can then be identified and counted. This enables seedling or sapling density to be calculated.

Sample site characteristics

Mangrove soils are typically waterlogged and anaerobic. All soils and sediments are composed of particles with a wide range of sizes. These can be divided into three main groups: gravel, sand and silt and clay (mud). The growth of mangroves is directly affected by the physical composition of the mangrove soils that in turn affects the permeability of the soil to water. A stainless steel D-section corer is used to determine soil characteristics. The nature of the soil can determined using the method of Buchanan (1984).

The water quality in the mangrove forest is of great importance. The following parameters are often measured in or around the pore created by the sampling of the soil: pH of surface and pore water, surface water salinity, pore water salinity, water temperature, dissolved oxygen and redox potential. The technical details of these measurements can be found in Ecosystem Health Monitoring program (2008).

Another important characteristic of the mangrove forest is the local topography with respect to tidal flooding and drainage patterns. A simple method is to lay out transects from low intertidal to the high intertidal. These transects can be those previously described. A tape with washable coloured dye is attached to stakes placed at 10 metre intervals along the transect. The water mark on each tape is then recorded at high tide. In this way the flooding pattern can be determined. A more detail account of a different method of determining inundation is given in Case Study 1.

Monitoring a mangrove area

The management of a mangrove area involves the continuous monitoring of the health of the stand. The measurement of the characteristics of the mangrove stand outlined above can give a base line so that any subsequent changes to state of the stand can be detected. It is probably unnecessary to record all the characteristics but a few important indicators should be measured regularly using permanent transects. Duke *et al*. (2010) have suggested a number of qualitative health descriptors. As an example, these classify areas of the mangrove stand as:

- Healthy mangrove: living trees with green leaves and limited epicormic growth;
- Unhealthy mangroves: living trees with receding canopies and abundant epicormic growth; and
- Mangrove dieback: dead or dying trees, with no evidence of new growth.

There are many different ways of classifying the area that will depend on the area under consideration and the degree of resolution required. A combination of quantitative and qualitative observations performed at regular intervals will give a good indication as to whether any remedial steps are required to ensure the proper management and sustainability of the mangroves.

An example of monitoring a specific mangrove area is given in Case Study 2.

Case Study 1: A Simple and Accurate Method for Tidal Mapping in Mangrove Wetlands

Swapan Paul

Sydney Olympic Park Authority

The planning and operation of a mangrove rehabilitation project required clear and precise information about the contour of the mangrove forest so that an accurate and effective alignment of the proposed channels could be decided. Contour information was needed to be obtained to a high degree of accuracy. Without a tidal contour map this information was almost impossible to obtain. Moreover, no conventional topographical survey of the mangrove area was cost effective because of the presence of trees, pools, soft bed, channels and runnels. The requirement for this information was the catalyst for the development of this simple but effective method for tidal contour mapping in mangrove forests.

The concept

The concept of the method is based on two simple principles:

1. physically marking the maximum periphery or maximum extent of a known tidal elevation when it stabilised within the mangrove forest; and
2. drawing a contour map after positioning these tide markers.

Preparatory survey

A detailed visual survey was conducted of the mangrove forest to have a preliminary understanding of the forest, including the following:

- general health of mangroves;
- rough location of constructed levee banks, bund walls, a disused tramline, pools, channels and runnels;
- characteristics of tides within the mangrove forest and the nature of the mangrove forest; and
- rough perimeter for a given tide. An idea of the length of tidal perimeter was important for working out the number of people required for the tidal mapping exercise.

Based on this survey a rough map was drawn by hand to use as a reference.

Tide data

Available tide prediction data was obtained from the National Tidal Facility of Australia, operated by the Flinders University of South Australia. It was important to know the tide lag time between the reference tide data gauge and the study site so that the time of tidal peak could be accurately determined.

As a result of factors such as distance, rainfall, atmospheric pressure and narrowness of the creeks a tidal amplification factor is involved in this type of exercise.

Materials required

Bamboo stakes, 60-80cm long and 1-2cm diameter were selected to be used as tide markers. For different tides, different coloured stakes were used. The top 10-15cm of each bamboo stake was painted with clearly distinguishable colours. Each worker was given a two-way radio, a compass and up to 50 stakes to be placed at distances of about 4.0m apart. One of these 50 stakes had a flag attached to it to use as the starting point. In addition, each volunteer was provided with a preliminary map of the mangrove forest containing the pre-determined start and finish points, which was prepared based on the preliminary survey.

Marking the tide

The mangrove forest that was the subject of tidal mapping exercises has one channel through which tidal exchange occurs. This is known as the main channel. This entrance of the main channel is considered the reference point where the primary communicator was positioned to observe the movement of the tide. When the tide stabilized at this reference point it was assumed that within the next 15 minutes the tide would stabilise at locations closer to the main channel. This moment is considered as ‘time zero’. At this stage through radio communication, volunteers at these locations were instructed to start putting stakes into the mud to mark the tide limit for that particular tide. The volunteers were required to judge when the tide had stopped and was likely to start receding at that point. The volunteers started marking the tide and completed 200m of tidal edge within 10-15 minutes. About 15 minutes

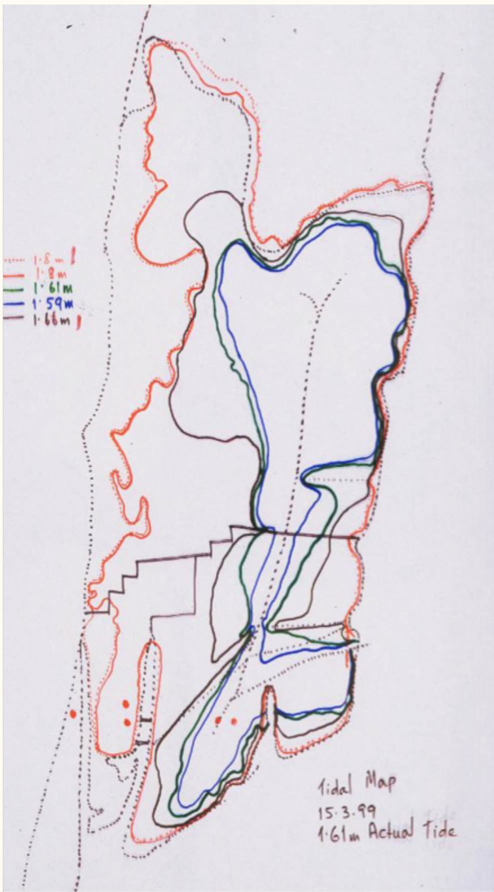

Figure 1a. Hand-drawn contour map.

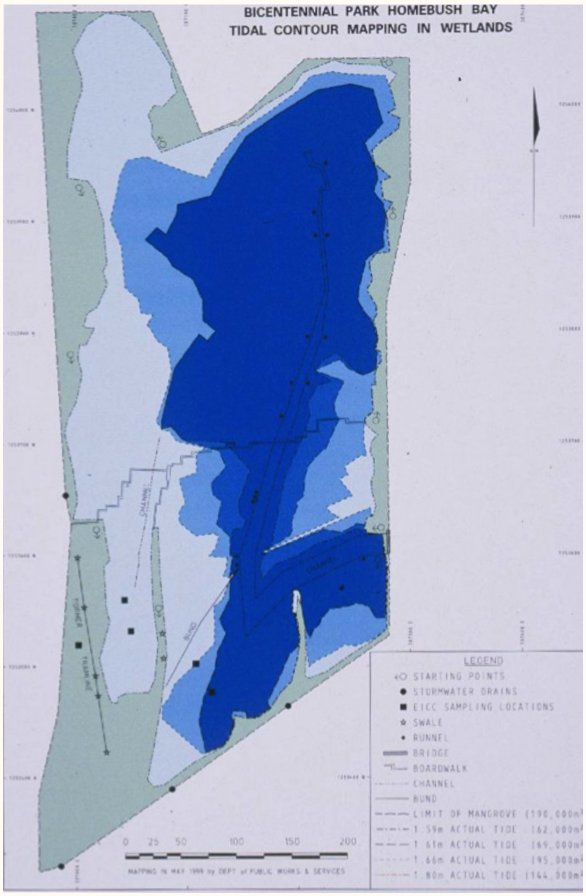

Figure 1b. GPS-aided contour map.

later volunteers at more further distant locations (from the reference point) were asked to proceed with marking the limits of tidal inundation and so on, until the furthest limit of the tide was reached. In this manner several tides were mapped.

Positioning the stakes and drawing contour maps

Maps were drawn based on the position of the stakes. The positions of the stakes were determined by a differential global positioning system (D-GPS) with sub-metre accuracy. Different coloured stakes were nominated for mapping different tidal contours. Stakes that deviated less than 1.0 metre from either side of a line between two points were considered to be on a straight line. Because of dense canopy cover in the mangroves and the tree heights, an 8-metre antenna mast was used to extend the antenna above the canopy. In the same manner, some other physical features of the mangrove forest were also mapped.

Contour maps

The outcome of these exercises was the production, for the first time, of accurate maps of the mangrove wetlands, incorporating key physical features. The extent of inundation under different tide heights is overlaid with these features (Figures 1a and 1b). Based on the maps that were generated, the area under tidal inundation at a known tide was estimated to vary from 32% at 1.61m actual tide to 75.8% at 1.8m actual tide. This clearly shows that with a difference of only 2.0cm in tide height there can be a difference of 7,000m^2 of additional inundated area of mangroves. This becomes more pronounced as the higher tides are considered.

This method is very simple and reasonably accurate in mapping the extent of tidal inundation in mangroves. Since the vertical height of the tidal inundation is known, it is also called tidal contour map.

Case Study 2: Mangrove Condition Audit and Assessment in Sydney Olympic Park

Swapan Paul

Sydney Olympic Park Authority

Background

Sydney Olympic Park contains in excess of 75.0ha of Grey Mangrove (*Avicennia marina*) forest with isolated stands of River Mangrove (*Aegiceras corniculatum*) scattered across the site. These are located in three major sub-catchment systems: Newington Nature Reserve (NNR) Wetland System incorporating mainly the NNR Wetland and the Parramatta River foreshore; Haslams Creek System incorporating the Haslams Creek and Nuwi Wetland and the Powells Creek System incorporating the areas on either side of Powells Creek as well as the Badu Mangrove.

Purpose

Mangroves are protected under *Fisheries Management Act* 1994. Mangroves are managed under the Authority's various obligations, including those under the PoM 2010 as well as those under the Biodiversity Management Plan 2008. Management is implemented primarily through the Wetlands Operational Action Plan (WOAP) and the Habitat Management Plans.

Proposed Condition Audit Program

The approach that is proposed for mangrove monitoring is aimed at supporting management needs. For the purpose of comparing the pre- and post-Condition Audit, a pre-Audit score has been given as an indicative benchmark. The desktop scores are made as follows:

- Unhealthy (Score 1)- very bad condition, die back, leaves yellowing or dead, degrading main trunk, broken branches, canopy very open or twigs almost absent, suffering from lack of tidal flushing due to isolation or raised ground, not many seedlings due to a lack of fruiting, lots of broken branches and trees falling, severe insect herbivory, extensive epicormic growth;
- Average Health (Score 2)- generally in reasonable health, not as many broken branches but some sparse canopy, not many leaves yellowing, trees could be moderate height or young growth, seedlings smaller than knee-height and common, not many trees falling, tidal flushing and drainage regular, moderate or no insect herbivory, moderate or no extensive epicormic growth; and
- Healthy (Score 3)- excellent condition, with extremely good health and no apparent issues at all, almost no seedlings due to daily and deeper tidal influence, main trunk not affected, very tall and large trees, canopy very compact, leaves not yellowing, almost no insect herbivory, almost no epicormic growth, daily tidal flushing and drainage, almost no trees falling.

As an example, the approach to the NNR wetland is given in Table 1 and Figure 1. It can be seen that the mangroves in the area are considered of average health.

Approach and Techniques

The techniques for monitoring and assessment are shown in Table 2 below.

Reporting will be undertaken on annual (or where applicable on 3-yearly) basis. The reporting will be in a simple format and will include:

- Birds eye view reporting will simply contain list of areas that show obvious signs of dieback;
- On-ground view will contain any reconfirmation on dieback spotted by Birds eye view; identify management issues and award overall health score;
- Phenology will be reported at monthly intervals from the 20 marked branches for the behaviour of flowers and propagules;
- On-ground field data gathering will yield data from three replicates at each site and will include changes in: tree height, breadth at chest height, active crab holes, number and height of normal and abnormal pneumatophores, number of seedlings of one cohort, insect herbivory, tree falls and canopy gaps; and
- Based on the above, a score will be given to ascertain the overall condition. Further details assessment report will also include management recommendations.

Table 1. Mangrove Monitoring of NNR wetland.

Parklands Precinct	Section No.	Section Name	Broad Description	Score
NNR Wetland	1	Channel 2	Tidal restoration occurred in 1999 after nearly 6 decades of separation from Parramatta River; now drainage is effective; (previously) very sick trees have been regenerating, with lots of new trees grown over the past decade; tidal flushing is restricted but regular; seedling coverage moderate	2
	2	Middle	Tidal restoration occurred in 1999 after nearly 6 decades of partial separation from Parramatta River except minimum exchange through a middle pipe; now drainage is generally effective; trees are generally unhealthy, with lots of older trees showing signs of dieback; seedling coverage mainly in open patches	2
	3	Channel 1	Tidal restoration occurred in 1997 after nearly 6 decades of partial separation from Parramatta River; almost no exchange through the middle pipe; drainage was generally effective through Channel-1 but now limited to 10-20% of requirement; trees are in mixed condition, with some trees showing signs of recovery but other older trees are slowly dying back; seedling coverage thin, mainly due to higher elevations	2

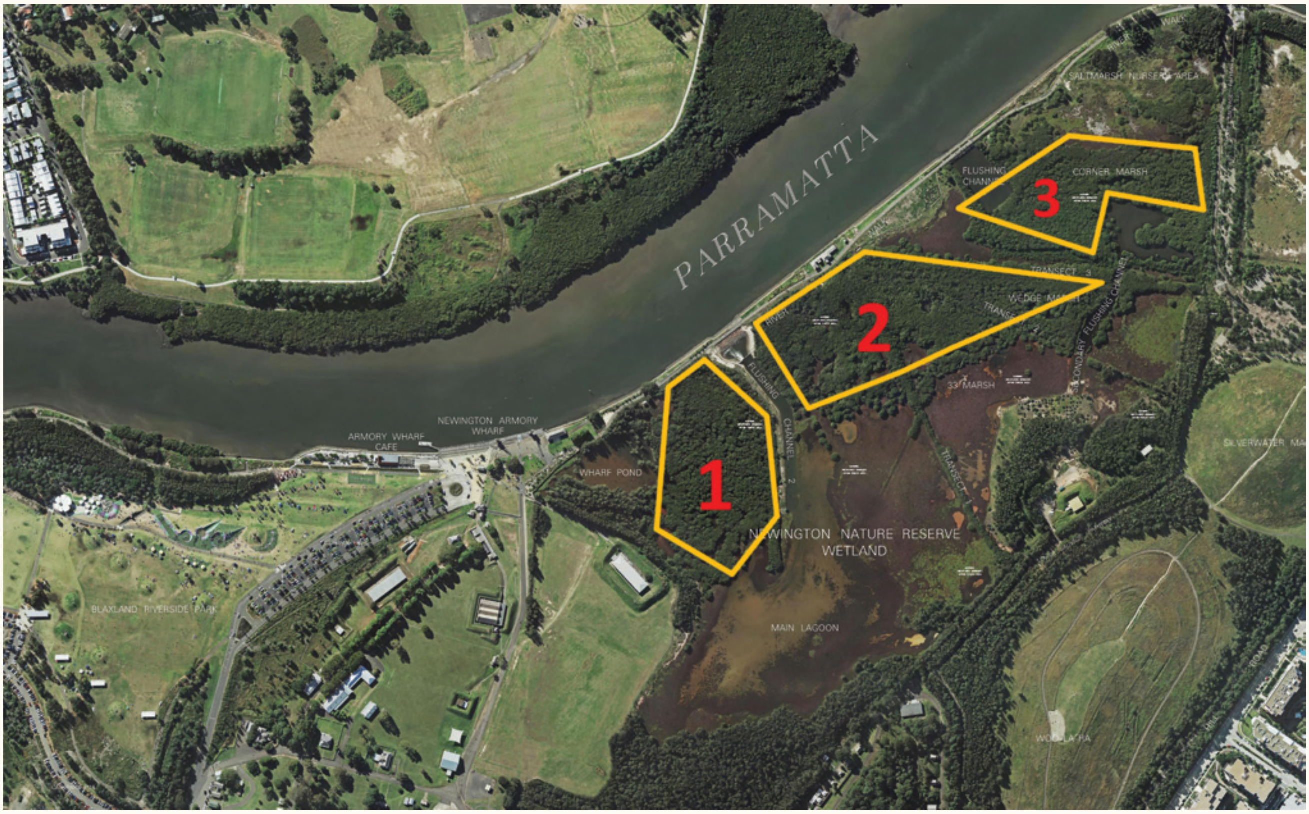

Figure 1. Newington Nature Reserve (NNR) Wetland Aerial View Areas. (Photo: Sydney Olympic Park Authority.)

Table 2. Approach and Technique of the Condition Audit.

Study Item	Technique/Approach	Parameters/Duration/Intervals
Birds Eye View of mangrove area	Aerial view from elevated structures to detect any sudden opening of the canopy structure, to detect any dieback.	Observe with the help of binoculars and best guess the location on respective aerial photos; once a year, preferably in December/January.
	Examine aerial photos that are taken in February each year to identify any major opening in the canopy and so to detect any dieback.	Visually scan the aerial photos to detect any dieback or major gaps in canopy
On-ground View of mangrove	On-ground view of the mangroves from the ground by walking along defined tracks to score overall health of the mangroves.	This should be undertaken once the aerial views and photos are analysed in April. This would be performed by employing various ground-based assessment tools such as ground coverage, tree height/breadth, canopy gap, pneumatophores and seedling count, tidal inundation, crab holes and gastropods, etc.
Phenology	The growth and flowering pattern of Grey Mangrove in Sydney area is erratic. Long-term monitoring could ascertain any linkage with local and/or climatic factors.	Abundance and behaviour of flowers and propagules on tagged branches in trees in the respective localities. There are 20 branches tagged in the Park.

The rehabilitation of mangroves

The degradation of mangrove lands poses the problem of repairing the damage (Lewis 1994, 2009; Field 1996, 1998). Rehabilitation is often the result of competition for land use, though at times it can arise because of climatic impacts that have destroyed the natural vegetation. In Australia, there has been few attempts at large scale rehabilitation of mangrove areas. It should be remembered that mangroves are aggressive colonisers and if the conditions are suitable natural regeneration will often occur rapidly.

Most of the attempts in Australia to rehabilitate mangroves have been on a small local level where the area of mangroves involved is often measured as less than a hectare.

However, it is essential that goals be defined as a first step in the rehabilitation process. Goals determine the rehabilitation process and help identify the elements that must be included to provide the project with a clear framework for operation and implementation. The establishment of criteria for the success of the rehabilitation process must be a priority. There are three general criteria for judging the success of a mangrove rehabilitation program:

1. The survival of the initial planting;
2. The effectiveness of the planting. This can be considered as the closeness to which the new mangrove ecosystem meets the original goals of the rehabilitation program; and
3. The rate of recruitment of flora and fauna. This can be considered a measure of how quickly the rehabilitated site stabilises and recovers its integrity.

It is important to appreciate the relationship between growth of mangroves and environmental factors that may be encountered. The most important environmental factor is the hydrologic regime influencing the chosen site. The three main environmental stresses, linked to the hydrology of the site, are water and salt stress, temperature stress and oxygen stress (Figure 3.4.1)

Hydrology

The failure of mangroves to occur naturally in a given environment means that the location is not suitable. This can be linked to the climate but is often due to an inappropriate hydrologic regime. Mangroves do not develop along high-energy coastlines, eroding shorelines or areas of high sedimentation. They also encounter problems in areas of poor drainage, infrequent tidal flooding or permanent waterlogging. Mangroves are sensitive to disruptions in fresh water runoff and ground water flow, the magnitude of the currents and the physical composition of the soil. The water circulation in the mangrove swamp controls the chemistry and biology of the swamp and the estuary and hence the growth of the mangroves.

The hydrology of the mangrove swamp can easily be changed by human intervention such as road construction, shrimp aquaculture, or diversion of fresh water inputs. Such changes frequently lead to a deterioration of the mangrove forest. In the case where rehabilitation is indicated, it is necessary to ascertain whether site preparation will be required to rectify the deficiencies in the hydrology of the site.

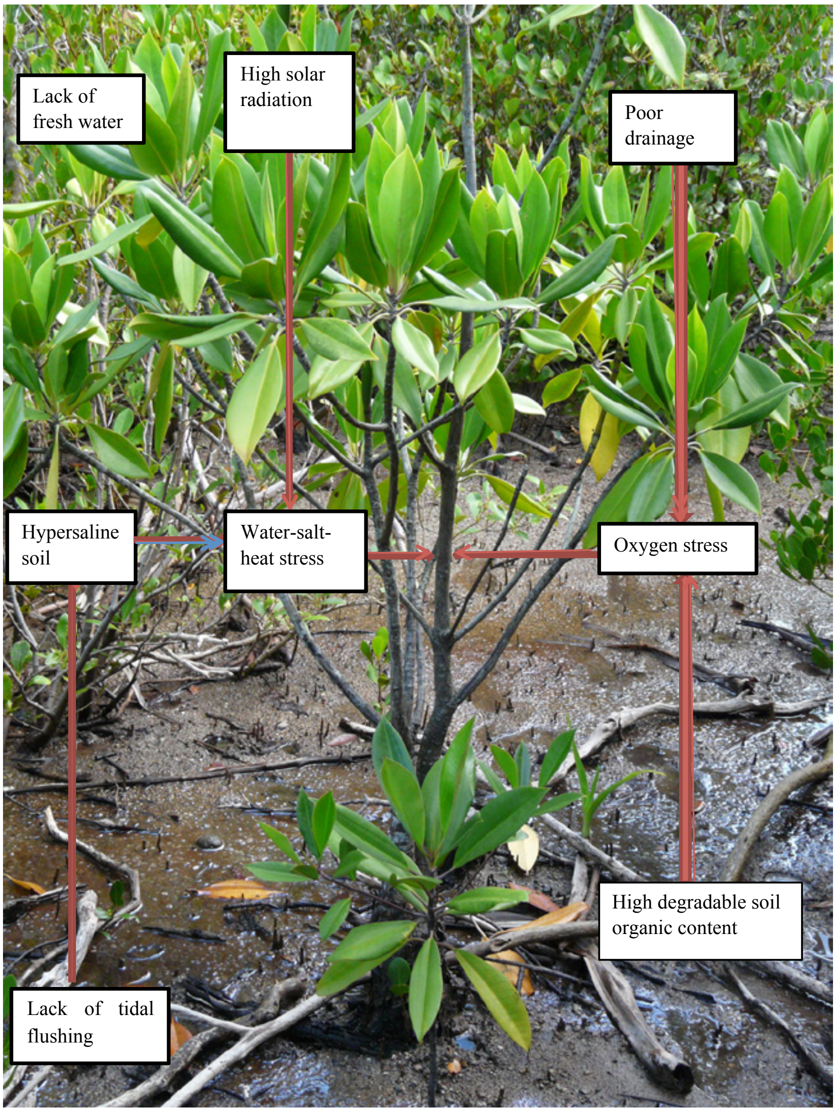

Figure 3.4.1. *Bruguiera* sp. seedling showing environmental factors affecting its development.

Water and salt stress

Mangroves require water like normal terrestrial plants though they can tolerate some level of salinity in the transpiration stream. The availability of water is limited by two factors: aridity and salinity. Aridity and high salinity can result from infrequent tidal flooding, lack of fresh water input and high evaporation rates. High salinity makes it difficult for the plants to take up water for osmotic reasons and it may have a direct effect on the metabolism of the plant. High salinity can cause an acute effect on damaged seedlings. Chronic effects will be seen where high soil salinity and infrequently flood soils lead to small stunted trees with extensive root systems.

Temperature stress

Mature mangroves have optimal leaf temperatures for photosynthesis very close to the average air temperatures found in the tropics. Assimilation rate is maximal at leaf temperatures ranging from 25 to 30°C. However, this declines rapidly with increase in leaf temperature above 35°C. It is interesting to note that mangroves with a higher salinity tolerance tend to avoid intense sunlight by developing leaves that have a high angle of incidence to the incoming radiation (Ball 1996). However, high air temperatures and lack of shade do increase the water loss from the leaves and so exacerbate the water and salinity stress.

High soil temperature also exacerbates the water and salinity stress. This is particularly important for newly plant seedlings where high soil temperatures can lead to a high mortality rate.

Oxygen stress

Mangrove soil is mildly aerobic to highly anaerobic due to the waterlogging of the soil. To combat this mangroves have developed specialised aerial roots that keep the underground roots aerated, like pneumatophores, buttress, stilt and knee roots. Aerial roots do not develop until 4–8 months after the seedlings become established so anaerobic conditions can be fatal for seedlings. Lack of oxygen is often caused by poor drainage: influenced by the hydraulic conductivity of the soils, elevation and distance of the site from low water mark.

Anaerobic conditions can also be caused by aerobic and anaerobic microbial metabolism. Sediment organic matter is a source of energy for microbiologically mediated reduction reactions. Therefore, a plentiful amount of sediment organic matter can lead to a lack of oxygen. Mangroves growing in waterlogged conditions may also be affected by the accumulation of soluble phytotoxins (reduced Fe, Mn, and organic gases) and concentrations of sulphides (Mckee 1993).

Such information is rarely employed in preparing and managing mangrove rehabilitation sites. One of the difficulties is that each site presents an almost unique set of environmental conditions. Very slight changes in one or more of the conditions can produce major effects in terms of the stability and growth of the mangroves.

The response of mangrove forests to predicted climate changes

This topic has been reviewed (Gilman *et al*. 2008) and the following is a synopsis of that review. It will be seen that mangroves, though relatively resilient (Alongi 2008) to climate change, will be subjected to possibly far reaching effects from the predicted disturbances. The effect of each individual climatic disturbance on the mangrove forest is difficult to predict because of lack of information.

Sea level rise

The appreciation that human induced climate change is occurring on a global scale has led to the situation that global sea level is one of the more certain outcomes of global warming. From 1870 to 2007, the global average sea level rose by close to 200mm. Sea levels rose at an average of 1.7mmyr^{-1} during the 20th century and about 3.0mmyr^{-1} from 1993–2009. These levels are global averages and because of the differing movements of ocean currents around the globe, results vary from place to place (CSIRO 2010). The prediction of global sea level rise from the beginning to the end of this century is in the range from 180mm to 590mm or a maximum rate of 5.9mmyr^{-1} (IPCC 2007). This is less than the estimated range of sea level rise of 10-15mmyr^{-1} in the Holocene but still has serious implications for mangrove forests.

The available evidence shows that mangroves have persisted over millions of years in the face of changes in climate. They have followed the changing shoreline as the sea level has risen and fallen. Mangroves are clearly tenacious survivors and vigorous occupiers of available land. In order to consider adaptation strategies to combat the threats of sea level rise, it is necessary to look at the effects of sea level rise in detail. Sea level rise affects mangroves growing in various settings (Alongi 2008).

The reaction of mangroves to sea level rise is therefore very dependent on local conditions. It is important when trying to predict the effect on mangroves of sea level rise, and formulating adaptation measures, to be aware of the relevant physical and biological conditions at the site under consideration. The geomorphic setting of the mangrove forest, affecting the sources of sediment, sediment composition, and method of delivery (Adame *et al*. 2010) determines sediment accretion and erosion. Tidal inundation into the mangrove forest carries fine sediment particles. These settle on the forest floor during slack high tide. The structure and content of the mangrove forest can trap mineral sediment, and contribute to vertical accretion. Storms and extreme high water events can alter the mangrove sediment elevation through soil erosion and deposition. Gilman *et al*. (2008) report on processes that control the elevation of mangrove sediment surfaces. Biotic contributions to soil elevation can be very variable where surface processes include the accumulation of decaying organic matter such as leaf litter, and the formation of living microbial, algal or root mats. The accumulation of leaf litter reflects above ground production, consumption by detrivores, microbial decomposition and tidal flushing. When below ground root growth exceeds root decomposition, soil organic matter accumulates, causing a net increase in soil volume and contributes to a rise in sediment elevation. Root growth, or the lack thereof, has substantial control on mangrove soil elevation at some sites. Autocompaction, the lowering of the sediment surface and reduction in sediment volume, is caused by the decomposition and compression of organic material, and inorganic processes, including rearrangement of the mineral architecture, silica solution and clay dehydration. Hydrology directly affects wetland elevation through processes of compression and dilation storage. The more water that seeps into the sediment below the water table the more the sediment dilates increasing the elevation of the wetland sediment surface.

This topic has been reviewed (Gilman *et al*. 2008) and the following is asynopsis of that review. It will be seen that mangroves, though relatively resilient (Alongi 2008) to climate change, will be subjected to possibly far reaching effects from the predicted disturbances. The effect of each individual climatic disturbance on the mangrove forest is difficult to predict because of lack of information.

Atmospheric CO_2 concentration

The atmospheric concentration of CO_2 has increased 39% from a pre-industrial value, from about 280 parts per million by volume (ppmv) in 1880 to about 390 ppmv in 2010, rising at about 1.9ppmyr^{-1} (Tans 2010; CSRIO 2010). A direct effect of elevated atmospheric CO_2 levels may be increased growth and productivity of some mangrove species. The response to elevated CO_2 may be sufficient to induce substantial change of vegetation along natural salinity and aridity gradients though the effect in hypersaline areas may be minimal. Elevated CO_2 conditions may enhance the growth of mangroves when carbon gain limits evaporative demand at the leaves but not when salinity at the roots is the limiting factor. There is no evidence that elevated CO_2 will increase the range of salinities in which mangrove species can grow.

Temperature

The combined global land and ocean average surface temperature for June 2010 was the warmest on record since 1880 at 16.2°C, which is 0.68°C above the 20th century average of 15.5°C (NOAA 2010). Between 1906 and 2010, the global average surface temperature has increased by 0.8°C (NOAA 2010). The linear warming trend of the last fifty years (0.13°C per decade) is nearly twice that for the last 100 years. The range of estimates for the rise in global averaged surface temperatures from 1980 to 1999 to the end of the 21st century (2090–2099) is 1.1–6.4°C.

Increased surface temperature may change species composition, phenological patterns, productivity and range. Mangroves reach a latitudinal limit at the 5°C isotherm for air temperature of the coldest month, and they tolerate very little or no ground frost. There is also a good correlation with the 24°C isotherm. The optimum leaf temperature for photosynthesis is between 28 and 32°C, while photosynthesis ceases when leaf temperatures reach 38–40°C. The frequency, duration and intensity of extreme hot and cold events may explain the current latitudinal limits of mangrove distribution.

Precipitation

Clearly, the regional distribution of rainfall will be uneven. Increased precipitation is very likely in high-latitudes, and decreased precipitation is likely in most subtropical regions. Changes in precipitation patterns may affect mangrove growth and spatial distribution. Decreased rainfall and increased evaporation will increase salinity and decrease net primary productivity, growth and seedling survival. This will alter competition between mangrove species and decrease the diversity of mangrove zones. As soil salinity increases, mangrove trees will have increased tissue salt levels and concomitant decreased water availability, which reduces productivity. Reduced precipitation may result in mangrove encroachment into salt marsh and freshwater wetlands. Increased rainfall may result in increased growth rates and biodiversity, increased diversity of mangrove zones, and an increase in mangrove area.

Storms

The Intergovernmental Panel on Climate Change (2007) projects there will be an increase in wind intensities and precipitation intensities. Storm surge heights may increase if the frequency of strong winds and low pressures increase. The increased intensity and frequency of storms has the potential to increase damage to mangroves through defoliation and tree mortality. Changes to mangrove sediment elevation can also occur through soil erosion, soil deposition, peat collapse, and soil compression. Mangroves can be slow to recover from such events.

Ocean Acidification

The pH of the world's oceans is becoming more acidic, due to the absorption of carbon dioxide. Ocean acidification affects the growth of the corals and the shells of marine organisms, which in turn can have significant ramifications for aquaculture and fishing industries. Ocean acidification poses a threat to mangrove and seagrasses, which in turn can have an impact on the natural resources they provide and promote. In addition, the loss of mangroves forests, which contain the second highest stores of organic carbon after peatlands, threatens to cause significant carbon dioxide emissions in the region (WWF 2009)

Adaptation Strategies

Mangroves have survived enormous changes in the global climate over geological time and they are resilient and aggressive colonisers. There is good evidence that the global area of mangroves has declined over the last thirty years (FAO 2007). The main causes of the decline of mangrove forest are the pressures of human population, agricultural and aquacultural enterprises and industrial development in the coastal zones. Doyle et al. (2010) report that thousands of Km^2 coastal forest will be displaced in the Gulf of Mexico over the next century with a metre rise in relative sea level. Given the well-documented value of mangrove forests both in terms of the economics of the local people and its intrinsic value ecologically (Saenger 2002) it is timely to consider appropriate adaptation strategies.

Climate adaptation refers to the ability of a system to adjust to climate change to mitigate potential damage, take advantage of opportunities, or cope with the consequences. Houghton *et al*. (2001) define adaptation as adjustment in natural or human systems to a new or changing environment. They go on to state that adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

There are essentially two types of adaptation strategy applicable to mangrove forests: foresight and responsive (Field 2011).

Foresight adaptation

This begins with mapping of the coastal wetlands so that a base-line is established and assumes that sufficient local knowledge exists to make cost effective decisions before damage occurs. In order to start this process it is reasonable to minimize any stresses, such as fishpond development, pollution, diversion of fresh water runoff and urban development. Regardless of climate change effects, this will improve the health of the mangrove forest and enhance its resilience.

It is important to allow the surface of the mangrove forest to adjust to any rise in sea level. Control of processes within the mangrove catchment can minimize reductions in mangrove sediment elevation, or enhance sediment elevation. Managing rates of groundwater extraction can be an important control on mangrove surface elevation. Also, avoiding and limiting human activities that reduce mangrove soil organic matter accumulation into mangroves can contribute to maintaining sediment elevation. Depending on the tree species and nutrient added, nutrient enrichment can affect mangrove productivity, changing root production and organic material inputs, thus affecting the rate of change in sediment elevation (McKee *et al*. 2007).

A further foresight strategy allows mangroves to retreat landward. This involves planning for suitable land to be available before the effects of rising sea level become apparent. The ability of the mangroves to successfully retreat will be constrained by the slope of the land, the topography and the accretion rate. Erosion will also be a factor determining the land availability for mangrove re-establishment. The species composition of the mangrove forest may change as it retreats, as the faster growing species will be favoured (Alongi 2008). As the sea level rises the composition, extent and position of mangrove forests will adjust naturally to the conditions, as they have during past climate events.

Responsive adaptation

This implies a more robust approach in the light of changes that are happening. Mangroves can provide a useful buffer for the impact of tropical storms and tidal surges on the coastline, though their effectiveness may be a function of the severity of the event (Sanford *et al*. 2009). It is expensive to replace mangroves with artificial structures but for some sections of a highly developed coastline adjacent to mangroves, the use of groins, seawalls, and revetments may be justified to halt erosion.

The effect of hard structures on the mangroves could be catastrophic as the movement of sediment may be inhibited, the tidal influence and hydraulic movement altered and the vitality of the forest impaired. In addition, surrounding ecosystems such as sea grasses, salt marsh and coral reefs may experience adverse effects. It may be difficult to preserve the health of the mangrove forest if further erosion of the coastline is prevented using engineering solutions. However, breakwater intervention aimed at reducing the amount of wave energy reaching the shore in order to shelter transplanted mangroves and augment deposition of sediments appears to have limited success (Hasim *et al*. 2010). In the end, there will be a trade-off between protecting existing human communities, agriculture and infrastructure and preserving the mangrove forests.

The possible degradation of mangrove lands poses the problem of repairing the damage (Lewis 1994; Field 1996, 1998). However, the lack of success of mangrove planting underscores the misunderstanding about the mangrove ecosystem functions and autecology of species (Lewis 2005; Bosire *et al*. 2008). In most cases, these failures are not due to funding limitations. Lewis (2009) is of the opinion that the failures are the result of a lack of both wisdom and real action on the ground based on the multitude of scientific documents generated each year. The earlier attempts at mangrove restoration in many countries met with mixed results with some being successful, while others were doomed from the start (Erftemeijer and Lewis 1999).There is some evidence that techniques for restoring mangrove forests are improving (Stanley and Lewis 2009; Matsui *et al*. 2010).

Conclusions

Mangroves are tenacious plants that have successfully survived several massive shifts in the earth's climate. Mangroves are aggressive colonisers when suitable niches become available and successful survivors in the face of rising sea levels on a geological time scale. There is a very substantial literature demonstrating that mangrove forests are important ecosystems (Field 1995; Saenger 2002; Duke 2006). This literature demonstrates the need for sustainable management of the forests.

Mangrove forests are managed in Australia at the National and State level through national parks and nature reserves. However, there is an additional need to manage a mangrove forest at the local level. At this level it is necessary to establish a base-line using quantitative and qualitative measures from which any changes in the mangrove forest can be detected. As a result of this monitoring it can be determined as to whether any remedial action is required.

The impact of anthropogenic induced climate change on mangrove forests is likely to be significant. The impact of sea level rise is the most visible effect of climate change. However, the involvement of other effects such as a rise in the atmospheric concentration of CO_2, a rise in land and sea temperatures, changes in precipitation, increase in frequency and durations of storms and ocean acidification, produces an intricate situation with unpredictable outcomes. The effect of a rising sea level at a local level is complex as it depends on the relationship between the floor of the mangrove forest and the tidal range. Sediment accretion and erosion, the water table and biotic factors govern this relationship.

It is important to know whether the area of mangrove forest is changing as a result of climate change. It is vital to use a standard methodology for compiling data for comparison purposes. The Australian government should be encouraged to use the latest technology to measure the extent of the mangrove forest.

There are essentially two forms of adaptation strategy: foresight and responsive. Foresight adaptation involves action before any damage due to climate change occurs such as minimising stress on the mangrove forest, allowing the forest floor to adjust to rising sea level, and providing land for mangrove retreat. Responsive adaptation involves a more robust approach in the light of damage arising from the effects of climate change. Such as using artificial structures and planting new mangroves. Both these approaches have their limitations.

Before recommending an adaptation strategy at the local level, it is important to resolve the difference between intrinsic factors and the effects of climate change. Systematic and careful collection of information at the local level is a mandatory requirement. This may involve using existing information, generating environmental and land use information, being aware of important social and economic information and collating such information. If such a process produces useful information for local land use managers, then ecology and management will begin to work together on both intrinsic problems and any that arise from climate change.

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