CoastAdapt

Coastal ecosystems

Information Manual 10

Published by the National Climate Change Adaptation Research Facility 2016

ISBN: 978-0-9946053-9-9

Please cite this Manual as:

Paice, R., and Chambers, J., 2016: Climate change adaptation planning for protection of coastal ecosystems. CoastAdapt Information Manual 10, National Climate Change Adaptation Research Facility, Gold Coast.

Acknowledgement

This work was carried out with financial support from the Australian Government (Department of the Environment and Energy). We thank Alistair Hobday and David Rissik for their review and input.

CoastAdapt

Climate change adaptation planning for protection of coastal ecosystems

Information Manual 10

Robyn Paice and Jane Chambers
Environmental and Conservation Sciences VLS
Murdoch University

Murdoch University

NCCARF
National Climate Change Adaptation Research Facility

Australian Government
Department of the Environment and Energy

Contents

Tables

Figures

Preface

In 2014, the National Climate Change Adaptation Research Facility (NCCARF) was commissioned by the Australian Government to produce a coastal climate risk management tool in support of coastal managers adapting to climate change and sea-level rise. This online tool, known as CoastAdapt, provides information on all aspects of coastal adaptation as well as a decision support framework. It can be accessed at www.coastadapt.com.au.

Coastal adaptation encompasses many disciplines ranging from engineering through to economics and the law. Necessarily, therefore, CoastAdapt provides information and guidance at a level that is readily accessible to non-specialists. In order to provide further detail and greater insights, the decision was made to produce a set of Information Manuals, which would provide the scientific and technical underpinning and authoritativeness of CoastAdapt. The topics for these Manuals were identified in consultation with potential users of CoastAdapt.

There are ten Information Manuals, covering all aspects of coastal adaptation, as follows:

1. Building the knowledge base for adaptation action
2. Understanding sea-level rise and climate change, and associated impacts on the coastal zone
3. Available data, datasets and derived information to support coastal hazard assessment and adaptation planning
4. Assessing the costs and benefits of coastal climate adaptation
5. Adapting to long term coastal climate risks through planning approaches and instruments
6. Legal risk. A guide to legal decision making in the face of climate change for coastal decision makers
7. Engineering solutions for coastal infrastructure
8. Coastal sediments, beaches and other soft shores
9. Community engagement
10. Climate change adaptation planning for protection of coastal ecosystems

The Information Manuals have been written and reviewed by experts in their field from around Australia and overseas. They are extensively referenced from within CoastAdapt to provide users with further information and evidence.

NCCARF would like to express its gratitude to all who contributed to the production of these Information Manuals for their support in ensuring that CoastAdapt has a foundation in robust, comprehensive and up-to-date information.

1 Introduction to this manual

This manual provides information to support implementation of NCCARF's Coastal Climate Risk Management Tool, CoastAdapt. It aims to provide stakeholders with knowledge to underpin coastal climate change adaptation planning for coastal ecosystems.

Climate change presents risks for coastal ecosystems through direct impacts from climate change which will result in loss or changes to habitats and their associated organisms. Warming could force species to move to higher latitudes or elevations to maintain the same environmental temperatures. Sea level rise will be accompanied by saltwater intrusion into freshwater habitats, meaning some key species will be forced to relocate or die, thus removing predators or prey that are critical in the existing food chain.

Ecosystems present opportunities in adapting to climate change, principally through ecosystem-based adaptation which essentially involves the use of biodiversity and ecosystems as part of an overall adaptation strategy. Such approaches are generally softer, with lower impacts, and often cheaper than, for example, engineering approaches to adaptation. Well-designed ecosystem-based adaptation will deliver benefits for adaptation and for ecosystems. In many cases ecosystem-based options are considered as low-regrets because of the immediate and long-term benefits that are derived.

This manual provides information that can support managers to understand the impacts of climate change on a range of coastal ecosystems. It describes ecosystem components and processes, key concepts such as ecosystem services, some of the potential impacts that can occur because of climate change, and adaptation options for ecosystems and the services they provide.

The manual is built around conceptual models for ecosystems in temperate and tropical climates. For each of these climates four ecosystem types are defined: freshwater, estuarine, coastal interface and marine. These are the ecosystems that are, or will be, affected by climate change impacts in the coastal zone. Freshwater ecosystems are included to the extent that they influence coastal ecosystems or are directly affected by climate change impacts in the coastal zone. Finally, for each climate and each ecosystem, four aspects are explored:

1. components, processes and connectivity
2. services and stressors
3. impacts
4. adaptation options

Table 1.1 sets out the model components. The conceptual models are shown on pages 3 -10.Table 1.2 includes further detail on the four ecosystem types around their habitat type and distribution.

Table 1.1: The components of the conceptual ecosystem models used in this manual

Climate	Ecosystems	Aspects
Temperate Tropical	Freshwater Estuarine Coastal interface Marine	Components, processes and connectivity Services and stressors Impacts Adaptation options

Conceptual Ecosystem Models

On the following pages are conceptual diagrams with examples of different coastal ecosystems within temperate and tropical regions of Australia. These summarise information for:

A: Ecosystem components and processes (Section 2)

B: Coastal ecosystem services (Section 2)

C: Potential impacts of climate change (Section 3)

D: Potential adaptive management options (Section 4)

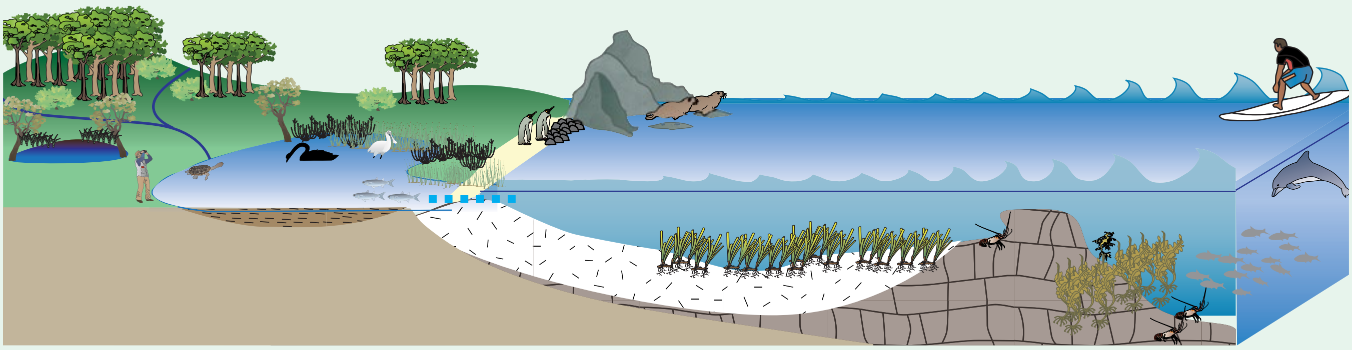
The summary information presented in these models is supported by more detailed information provided in the text in each of the Sections indicated above. This temperate/tropical subdivision is useful for managers to consider relevant ecosystems in their region, however several ecosystem types are common to both, and are combined in the main text.

Table 1.2: Types of marine, estuarine and coastal interface ecosystems that are, or will be, affected by climate change impacts in the coastal zone, which are included in this manual.

Ecosystem type	Ecosystem habitat type	Distribution
Marine	Coral reefs	North west and north east coasts and Gulf of Carpentaria
	Temperate reefs and macroalgal forests	Southern coastal zone
	Seagrass meadows	Widespread, more abundant and diverse in south east and south west coasts
Estuarine	Wave-dominated estuaries – coastal lagoons and river mouths	South east and south west coasts
	Tide-dominated rivers, wetlands and mangrove habitats	North west coast, Gulf of Carpentaria, north east coast
Coastal Interface	Sandy beaches and dunes	Throughout
	Rocky shores and headlands	Determined by geology, headlands more prevalent on the east coast
Coastal freshwater	Freshwater ecosystems and catchments	Throughout

Conceptual ecosystem model for **temperate climates**

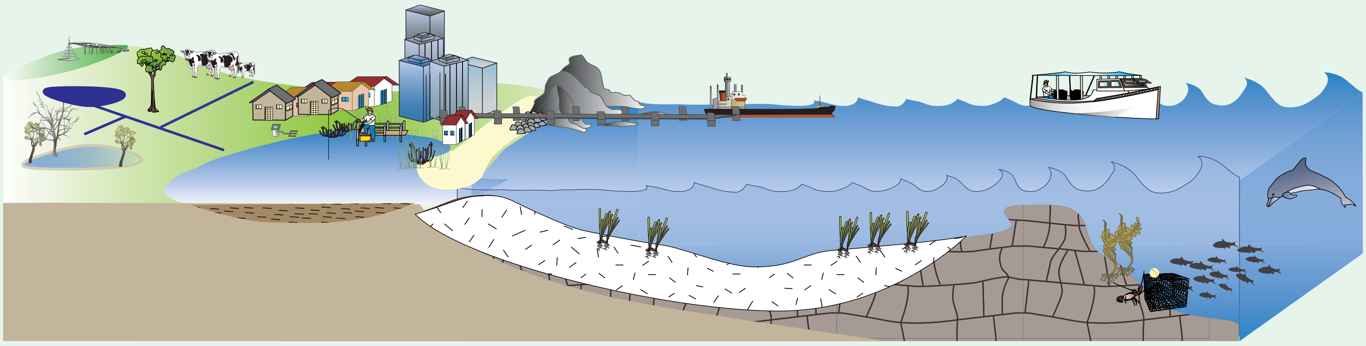
Ecosystem Model 1A: Temperate ecosystem components, processes and connectivity (Section 2.1)



	Freshwater	Estuarine	Coastal interface	Marine
Ecosystem types	Streams Wetlands/lakes Floodplains	Wave-dominated estuaries Coastal lagoons, river mouths, Saltmarsh	Sandy beaches and dunes Rocky shores and headlands	Temperate rocky reefs Macroalgal forests Seagrass meadows
Components	Plants, birds, fish, amphibians, reptiles, mammals, fish, fish migration	Fringing plants and submerged vegetation Aquatic invertebrates Migratory and residents birds Fish nursery, migration	Bird resting and breeding Rock and sand crabs Iconic species habitat (penguins, seals)	Macroalgae and seagrass, rock habitat, open waters, fish, seahorses, seadragons, molluscs, crustaceans, marine mammals
Processes	Interception of nutrients and pollutants in floodplain vegetation and waters	Accumulation of organic material supports high productivity, food web interactions, floodplains, carbon in sediments	Equilibrium in erosion/deposition forces that form coastline, vegetation and wrack stabilise coast	Reef dissipates wave action, seagrass wrick to beach, food web interactions, carbon in seagrasses
Connectivity	Sources of nutrients, sediments, organic material Assimilation processes	Nutrient/sediment trapping protects water quality Fish migration pathways	Seagrass wrack stabilises beaches and supports intertidal food web Coastal animals with marine food sources	Water quality influences seagrass and macroalgal health Wave dissipation protects seagrass Fish nursery in seagrass

Conceptual ecosystem model for **temperate climates**

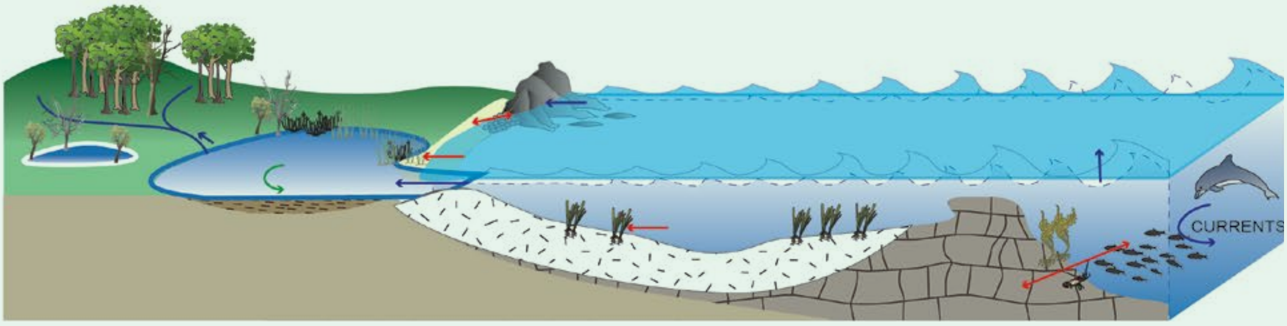
Ecosystem Model 1B: Temperate social value - 'ecosystem services' (Section2.2) and human-use stressors (Section 2.5)



Services (1.2)	Catchment	Estuarine	Terrestrial interface	Marine
Provisioning Services	Water supply – drinking, agriculture, industry Production – food, timber, mining resources Hydroelectricity	Water supply – industry Commercial fishing Urban development space Aesthetics, land value	Water supply – industry Port infrastructure, service development Aesthetics –land value Tourism – iconic species	Commercial fishing, aquaculture Tourism – fishing, surfing Transport routes Oil, gas, electricity (wave) Water supply – desalinisation
Regulating Services	Flood protection – runoff retention	Flood protection – retention of runoff and storm surge waters Carbon sequestration	Shoreline stabilisation	Carbon sequestration – mainly seagrasses, also macroalgae Wave dissipation
Cultural Services	Recreation– freshwater angling, hiking, camping, produce-based (food, wine) Research – agriculture, ecology	Recreation – bird-watching, fishing, aesthetics, water sports Research – flora and fauna, processes, eutrophication	Recreation– fishing Research – geological processes, intertidal ecosystems, iconic species	Recreation– fishing, diving, water sports, lifestyle Research – marine ecosystem biota and processes, iconic marine species
Supporting Services	Interception of pollutants Food web resources Habitat and biodiversity	Interception of pollutants Nutrient cycling Primary production Food web resources Fish and bird habitat	Fish migration passage Coastal habitat Coastal breeding areas	Primary production Ocean currents support migration and lifecycles
Human-use stressors (2.5)	Clearing, altered hydrology Habitat loss/ fragmentation Nutrient loading	Excess nutrients and sediments Physical modification Tidal barriers	Physical modification Habitat destruction Pollution	Sewage and pollution discharge Overfishing Shipping impacts

Conceptual ecosystem model for **temperate climates**

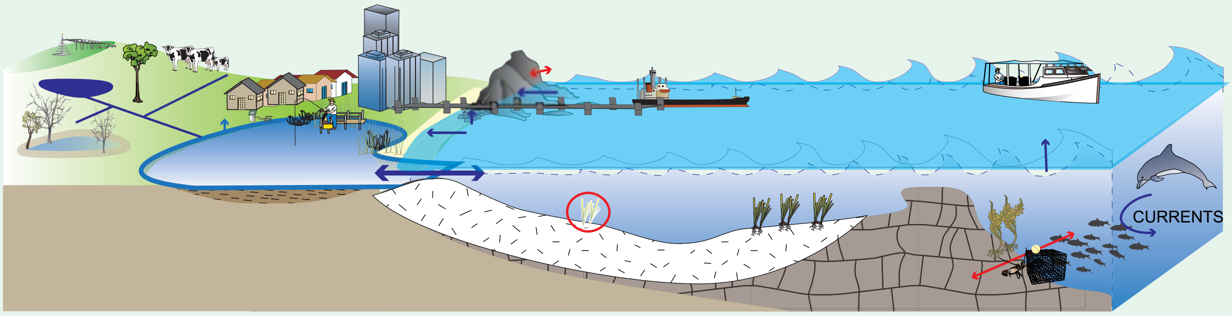
Ecosystem Model 1C: Potential climate change impacts on natural temperate ecosystems (Section 3)



Impact	Freshwater (3.2.1)	Estuarine (3.2.2)	Coastal interface (3.2.4)	Marine (3.2.5; 3.2.6)
Sea level rise (3.1.1)	Greater tidal intrusion, impacts on lowland streams Freshwater plant deaths Species shifts, upstream range contraction	Altered sand bar dynamics, tidal exchange, flushing Lagoon expansion or shift, flooding of nearshore habitats Salinity regime affects aquatic plants and animals	Shoreline equilibrium disrupted, increased wave energy and erosion Flooding, landward habitat shift, redistribution of habitats	Depth reduces wave dissipation Altered disturbance and light conditions impact seagrass and macroalgae growth – contracting to protected, shallow zone
Warming (3.1.2)	Drought effects exacerbated Plant stress and death, southward distribution shifts Enhanced algal production	Plant stress and death, altered species composition Increased algal production Shift in migratory bird timing	Plant stress and death Heat stress in intertidal Animal heat stress forcing migration and changing seasonal migrations	Increased water temperatures Changes to ocean currents Metabolic impacts and behavioural responses Species range shifts
Rainfall change (3.1.3)	Increased drought and changes to seasonality may stress plants Freshwater systems retract Loss of animal refuge	Reduced freshwater flushing (nutrient accumulation) Reduced catchment inputs Low rainfall exacerbated increased salinity	Plant stress and death Rock pool habitats	Changes to transport of material from catchment Changes to tidal exchange affects nutrient and sediment transport to seagrass beds
Increased CO_2 (levels: 3.1.4) (acidification: 3.1.5)	CO_2 fertilisation of terrestrial vegetation	CO_2 fertilisation of aquatic plants, epiphytes and phytoplankton	CO_2 fertilisation of terrestrial vegetation	CO_2 fertilisation of seagrasses, but also epiphytes Ocean acidification may affect molluscs and crustaceans
Extreme events (3.1.6)	Seasonal changes to runoff	Changes to sediment dynamics	Increased erosion	Disturbance of rocky habitats and sediment dynamics

Conceptual ecosystem model for **temperate climates**

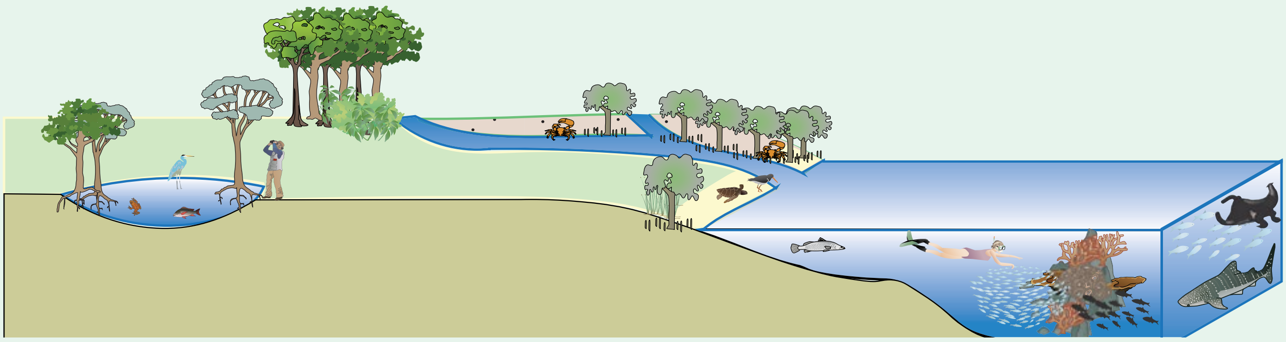
Ecosystem Model 1D: Potential adaptation options for temperate ecosystems (Section 4)



Outcome	Freshwater (4.1.)	Estuarine (4.2)	Coastal interface (4.4)	Marine (4.5; 4.6)
Reducing vulnerability	Catchment water quality protection actions Land use management for ecosystem protection Water-saving technology and wastewater reuse	Maintain aquatic plant communities and understand ecosystem thresholds Reduce fishing pressures Restrict development of existing saltmarsh habitat	Minimise nutrient export from sewage and stormwater, and other local pollutants and sediments from industry to protect receiving marine environments	Minimise physical disturbance from dredging and moorings, Review fisheries management Invasive species control Regulation of shipping routes and pollution potential
Managing habitat loss and change	Protect diversity to respond to changing conditions Restore/create new habitats to compensate for loss, with potential species translocation	Provide space for new areas of inundation and restore or create new habitat through revegetation Restore lowland river reaches as future estuarine ecosystems Tidal barriers to manage water levels, salinity and fish passage	Landward shift of activities Assisted colonisation Revegetation to create new habitat areas Species-specific management to cope with heat stress (seabirds, penguins, seals)	Shift to low-pressure uses (tourism) Assisted colonisation Reduce fishing and harvesting pressure Research potential range thresholds for macroalgae and seagrass species
Maintain coastal stability	Assess and upgrade stormwater and sewerage infrastructure Provide flood mitigation in catchment with water supply outcomes	Hard structures to reduce wave forces Revegetation to stabilise sediments Tidal barriers to manage exchange and storm surge Salt marsh revegetation/creation	Hard structures to reduce wave forces Beach replenishment Revegetation to buffer erosive forces Combine saltmarsh restoration with levees	Ecosystem engineering Hard engineering structures Oyster reefs

Conceptual ecosystem model for **tropical climates**

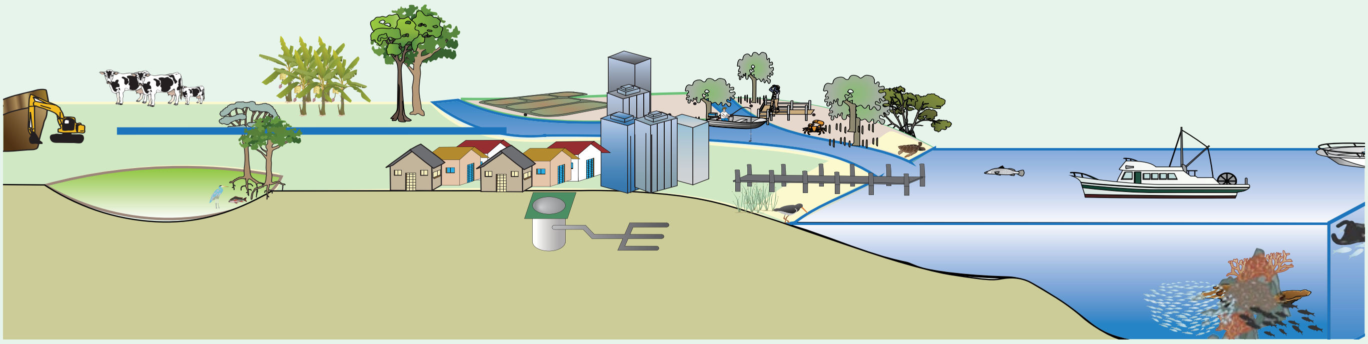
Ecosystem Model 2A: Tropical ecosystem components, processes and connectivity (Section 2.1)



	Freshwater	Estuarine	Coastal interface	Marine
Ecosystem types	Streams Wetlands/lakes Floodplains	Tidal river/creek Mangroves Salt marsh	Sandy beaches and dunes Rocky shores and headlands Mangroves	Coral reefs Seagrass meadows
Components	Plants, birds, fish, amphibians, reptiles, mammals, Fish migration	Mangroves and other plants, crustaceans, birds, fish, fish nursery, fish migration	Bird resting and breeding, turtle nesting, crustacean habitat	Corals, seagrasses, macroalgae, open waters, benthos, molluscs, sponges, echinoderms, fish, marine mammals
Processes	Surface and ground water recharge, food web resources, nutrient assimilation and sedimentation in floodplains	Plants intercept sediments and nutrients, organic cycling, food web resources and interactions Carbon sequestration	Plants intercept sediments and nutrients and stabilise shoreline Carbon sequestration	Reef dissipates wave energy, food web interactions, sedimentation processes, chemical balance, symbiosis Carbon sequestration
Connectivity	Nutrient and sediment trapping protects downstream waters	Nutrient and sediment trapping protects downstream waters Crab burrowing improves fresh/salt water exchange	Detrital food web resources from catchment and mangroves enter marine food webs Fish migration and fish nursery areas	Fish nursery habitat in mangroves important for marine fish species

Conceptual ecosystem model for **tropical climates**

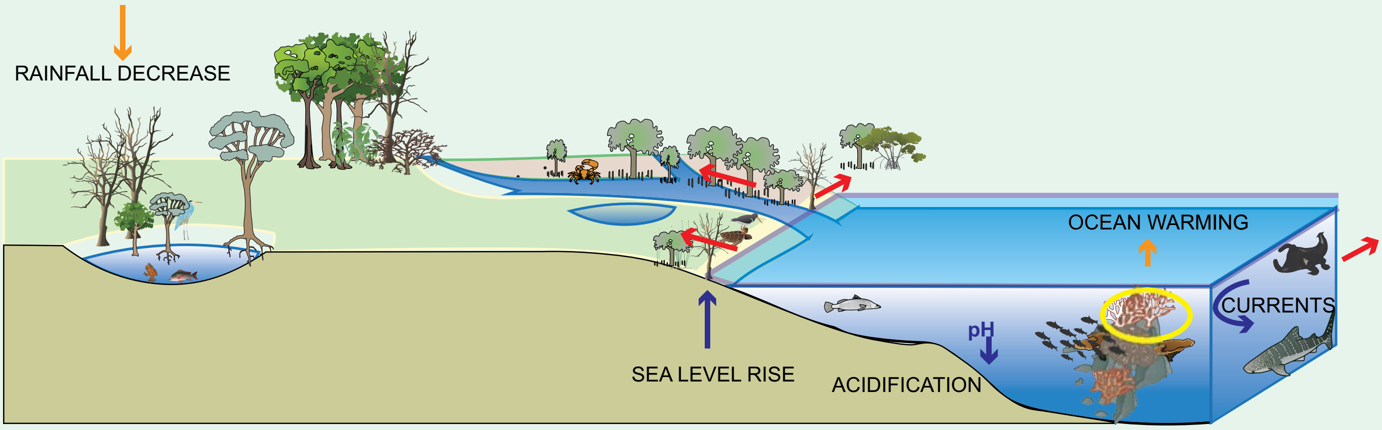
Ecosystem Model 2B: Tropical social value - ecosystem services (Section 2.2) and human-use stressors (Section 2.5)



Services (1.2)	Freshwater	Estuarine	Coastal interface	Marine
Provisioning Services	Water supply – drinking, agriculture, industry Food – agriculture, fisheries Mining resources Tourism – aboriginal culture	Water supply Fisheries, aquaculture Salt mining, mangrove timber Tourism icons – crocodiles Aboriginal food, medicine	Tidal electricity Port infrastructure, service development Aesthetics – land value Tourism icons – turtles	Food – diverse fisheries Tourism – diving, iconic species Transport routes Oil and gas resources
Regulating Services	Flood protection – extensive floodplains	Flood protection – retention of runoff and storm surge waters Carbon sequestration	Coastal stability – vegetation	Coastal stability – wave dissipation over reef
Cultural Services	Recreational fishing Enjoyment of unique natural landscapes Camping Traditional lifestyles	Recreational fishing – fish, crabs, prawns Bird watching Research – ecosystem processes	Diverse recreational pursuits Research – turtles, geology	Recreational – fishing, diving, water sports, lifestyle Research – Marine ecosystem biota and processes, iconic marine species
Supporting Services	Interception of pollutants Food web resources Habitat and biodiversity	Interception of pollutants, nutrients, sediments – mangroves and saltmarsh Food web resources Fish and bird habitat	Fish migration passage Coastal habitat – turtle breeding Coastal breeding areas	Primary production Ocean currents support migration and lifecycles
Human-use stressors (2.5)	Clearing, altered hydrology Habitat loss/ fragmentation Nutrient loading	Excess nutrients and sediments Infill, clearing Overfishing	Physical modification Habitat destruction Pollution	Sewage and pollution discharge Overfishing Shipping impacts

Conceptual ecosystem model for **tropical climates**

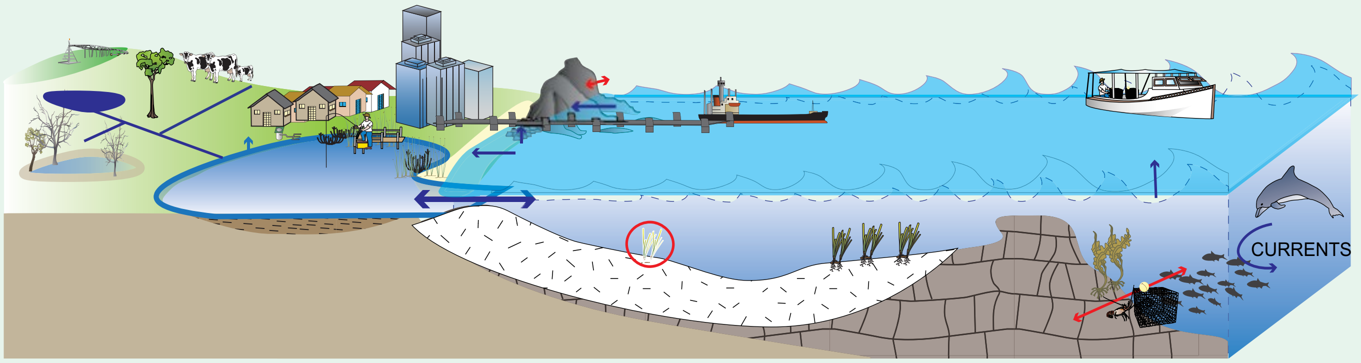
Ecosystem Model 2C: Potential climate change impacts on tropical ecosystems (Section 3)



	Freshwater (3.2.1)	Estuarine (3.3.3)	Coastal interface (3.2.4)	Marine (3.2.7)
Sea level rise (3.1.1)	Greater tidal intrusion Upstream shift of estuarine conditions Freshwater plant deaths	Greater tidal intrusion, altered exchange/ flushing Flooding, habitat shift Species shift according to salinity regime tolerance	Flooding of habitats, loss of beach, landward shift Shoreline erosion, worse due to plant loss Landward mangrove migration	Depth alters light for productivity, reduces wave energy dissipation Redistribution of marine and intertidal habitats
Warming (3.1.2)	Increased drought and changes to seasonality may stress plants Freshwater systems retract Loss of animal refuge	Species range shifts, migrations Altered species composition Animal heat stress forcing migration Shift in migratory bird timing	Drought stress for plants Species range shifts and migrations Shift in migratory bird timing	Coral bleaching Shift from coral to algae Changes to ocean currents Species range shifts and migrations
Rainfall change (3.1.3)	Drought effects exacerbated Altered species composition and distribution	Reduced freshwater flushing (nutrient accumulation) Effects on fish migration	Drought effects exacerbated Plant stress and death Animal heat stress forcing migration	Altered catchment inputs
Increased CO_2 (levels: 3.1.4) (acidification: 3.1.5)	CO_2 fertilisation may enhance growth, but also for weeds	Enhanced growth of less salt-tolerant mangroves may assist upstream migration	Ocean acidification effects on intertidal molluscs and crustaceans	Ocean acidification may limit calcification in corals, molluscs, crustaceans
Extreme events (3.1.6)	Seasonal changes to runoff	Changes to sediment dynamics	Increased erosion	Changes to sediment dynamics

Conceptual ecosystem model for **tropical climates**

Ecosystem Model 2D: Potential adaptation options for tropical ecosystems (Section 4)



Outcome	Freshwater (4.1)	Estuarine (4.3)	Coastal interface (4.4)	Marine (4.7)
Reducing vulnerability	Catchment and stormwater management to reduce nutrient and sediment export Land use change Invasive species control	Buffer natural ecosystems from land use impacts Reduce fishing pressures Protect remaining habitat Revegetate degraded habitat Reduce fishing pressure	Minimise coastal sources of pollution and sediments Restrict access in key conservation areas Invasive species management	Reduce fishing pressure Protection of low-risk areas Invasive species management Regulation of shipping routes and pollution potential
Managing habitat loss and change	Protect diversity to respond to changing conditions Restore/create new habitats to compensate for loss Translocate vulnerable species Tidal control structures to protect important coastal freshwater ecosystems	Provide space for new areas of inundation and restore or create new habitat through revegetation Managed realignment to direct physical habitat shift Relocation of land use to allow natural habitat shifts	Landward shift of activities Assisted colonisation of plants and animals Species-specific management to cope with heat stress (e.g. turtles) Intertidal habitat redistribution	Shift to low-pressure uses (tourism) Assisted colonisation Reduce fishing and harvesting pressure Research potential range thresholds for macroalgae and seagrass species
Maintain coastal stability	Flood management	Hard structures to reduce wave forces and flooding Protect and restore mangroves and saltmarsh for shoreline stabilisation	Hard structures to reduce wave forces, beach replenishment. Mangrove and saltmarsh restoration	Protection of reef systems New reef systems (hard/ ecological engineering)

2 Understanding ecosystems

Human values and goals for coastal ecosystems relate to the services they provide, which depend on natural components and processes; these in turn are affected by existing human use pressures (non-climatic pressures) (Figure 2.1). Understanding the functioning of coastal ecosystems and the existing pressures is essential to the assessment of potential impacts of climate change, the consequences for provision of ecosystem values and services, and the adaptation actions needed for their protection.

This section provides background information on:

- how ecosystems work in terms of their components and processes and connectivity within and between ecosystems (Ecosystem Model 1A and 2A)
- the services that coastal ecosystems provide to humans (referred to collectively as ecosystem services; Ecosystem Model 1B and 2B)) and that might further support adaptation actions (adaptation services)
- existing pressures on coastal ecosystems that affect how they will respond to impacts of climate change.

2.1 How ecosystems work

Ecosystem components are what we can see, including the plants and animals and their physical habitats. However, there are also likely to be inconspicuous components to consider, such as submerged aquatic plants in estuarine lagoons and aquatic invertebrates. There are many important components in coastal ecosystems:

- physical habitat: water, sediment, rocks
- biological habitat: living and dead plants, coral
- external food resources (from catchment or tidal exchange)
- primary producers (plants): e.g. phytoplankton, macroalgae, aquatic plants (e.g. seagrasses), mangroves, terrestrial plants
- invertebrate and vertebrate consumers (animals, bacteria and fungi): in a food web of herbivores, carnivores and decomposers.

Functioning of coastal ecosystems, in terms of key components, processes and connectivity, is summarised in Ecosystem Model 1A and 2A.

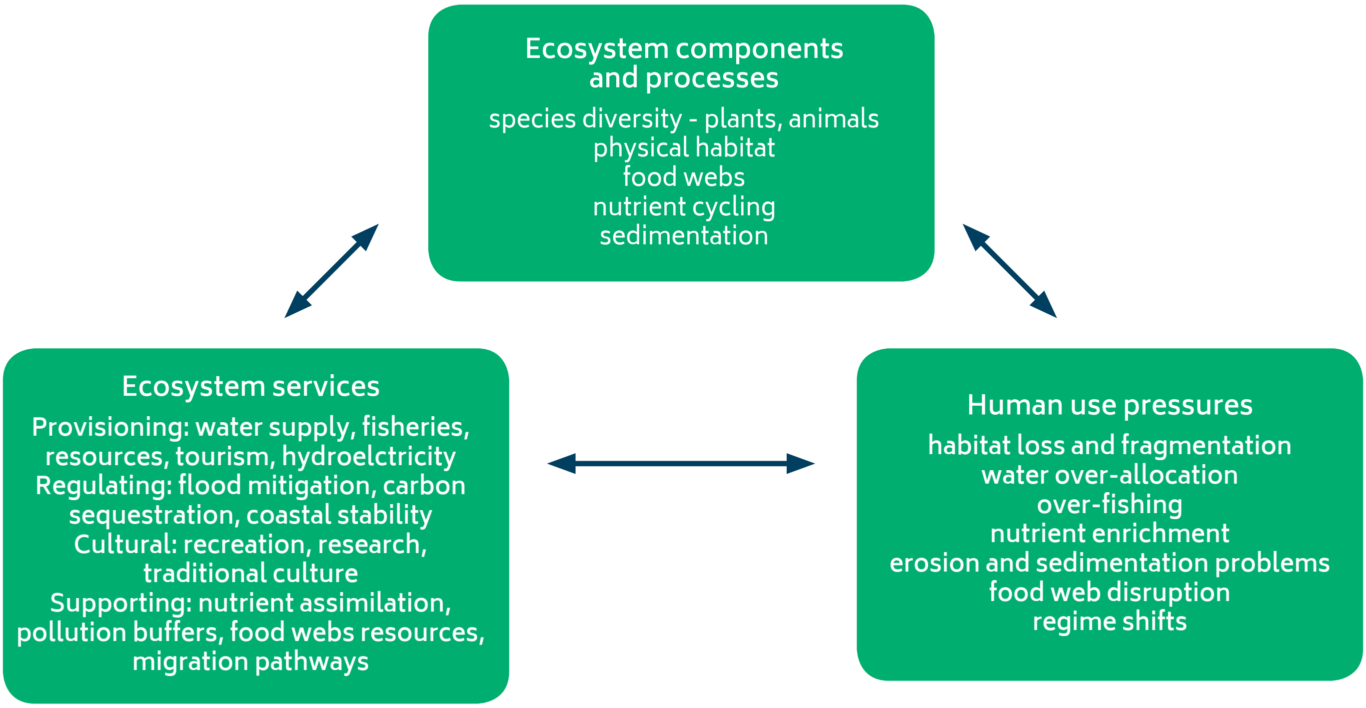


Figure 2.1: Interactions between natural ecosystems, use of ecosystem services and human use pressures. Source: adapted from MEA 2005 and Barbier et al. 2011.

These different ecosystem components are supported by many interrelated **ecosystem processes:**

- hydrological processes: surface and ground water flows and exchange, tidal exchange, evapotranspiration
- sediment processes: suspension and movement, trapping, sedimentation, stabilisation
- physical habitat: niche diversity, refuge from flow and predation, shade, nursery areas, seasonal water refuge
- food webs: predator-prey interactions, energy transfer, carbon cycling, photosynthesis, plant resources, detrital resources
- nutrient transfer and cycling: loading from catchment, storage in and release from sediments, nitrification and denitrification, plant uptake, nutrient release from animal wastes and decomposition
- biological: photosynthesis, food web interactions, reproduction, migration and dispersal.

> **Tip**: The OzCoasts website provides conceptual models for each of these key ecosystem processes in coastal ecosystems, and has a facility to build your own conceptual model[1] .

Climate change may affect organisms directly through changes to water availability, depth, temperature and physical disturbance. It may also influence many organisms indirectly through the changing ecosystem processes on which they rely (e.g. Increasing CO_2 concentrations can increase the rate of photosynthesis). These ecosystem processes create **connectivity within ecosystems.**

Corridors and migration pathways will become increasingly important in a changing climate, particularly north-south distribution ranges related to latitudinal temperature gradients. Increasing temperatures on land and in the ocean will change the location of tolerable areas for various plants and animals. For animals this may result in migration, and will rely on existence of adequate corridors allowing movement. For plants, distributional changes will depend on dispersal processes and available niches for colonisation. Thus connectivity through ecological corridors is very important for regional ecosystem adaptation.

As well as connectivity between different ecosystem components, there is extensive connectivity between ecosystems. Connectivity pathways between coastal ecosystems include the following processes.

- **Catchment flows** link ecosystems because water is a conduit for organic material and sediments, and provides for movement and dispersal of organisms. A common thread throughout protection of coastal ecosystems is the protection of water quality because it is fundamental to aquatic ecosystem health. Land use in the catchment that results in poor water quality can adversely affect estuarine and marine ecosystems, reducing resilience and adaptive capacity. Processes within some ecosystems provide an important function in protecting water quality of others (e.g. mangroves protecting coral reefs).
- **Tidal exchange** in estuarine and coastal interface ecosystems affects salinity regimes, fish migration, chemical processes (e.g. nutrient cycling and oxygenation) and the physical environment.
- **Wave energy** from the ocean has physical effects on the coast.
- **Geomorphological processes** along coastlines are important in shaping the location of rocky shores and headlands, sandy beaches and dunes, and the nature and timing of estuary openings.

These pathways will be directly affected by altered rainfall patterns, sea level rise and changes to frequency and intensity of storm events (Ecosystem Model 1C and 2C).

If there are high-value iconic or threatened species in your region that are a management priority, consider how they are connected within the ecosystem where they are located and with adjacent ecosystems. Also consider how these connections will influence the effects of and the response to climate change. In the coastal zone, water movement between the catchment and the ocean creates a high level of connectivity between ecosystem processes, and physical forces such as winds and currents shape the ecosystems along the coast.

[1] OzCoasts: Science Conceptual models of Australian estuaries and coastal waterways. www.ozcoasts.gov.au/conceptual_mods/science_models.jsp (accessed 4 May 2016).

2.2 Ecosystem Services

Ecosystem services are defined the benefits people obtain from ecosystems. Ecosystem services are classified as (MEA 2005).

- **Provisioning services** – benefits obtained directly from ecosystems, such as food (harvested and cultivated), water supply and material resources, space for development and hydroelectricity.
- **Cultural services** – benefits derived from cultural, recreational, spiritual and research activities within ecosystems.
- **Regulating services** – processes that directly or indirectly influence our use of the environment such as climate, flooding, coastal erosion, water quality, diseases.
- **Supporting services** – processes and connections ecosystem within and between ecosystems such as photosynthesis, nutrient cycling, sedimentation, and food web linkages.

Two examples of ecosystem services are provided in Ecosystem Model 1B and 2B.

The services that are used directly by humans are generally provisional and cultural services, however well-being and many human activities depend on regulating and supporting services (Abson and Termansen 2011). Identifying the different services that ecosystems provide, and their interlinkages, may help overcome conflicting goals of different stakeholders.

2.3 Climate adaptation services

Some coastal ecosystem services are specifically important to climate change adaptation. These services may not be of obvious value to stakeholders and so they may not necessarily be identified during consultation. Climate adaptation services are those 'benefits to people from ...the capability of ecosystems to moderate and adapt to climate change and variability' (Lavorel et al. 2015). Important examples include protection of coastal areas from erosion and flooding by rising sea levels, carbon sequestration within ecosystems, and provision of new social opportunities. Ecosystem-based management actions that enhance these services will become increasingly important and valued (IPCC 2014).

Understanding these services can be particularly important to gain social acceptance of adaptation actions to protect coastal ecosystems.

2.3.1 Protective services

Ecosystems can provide coastal protection from the effects of climate change, particularly erosion and flooding linked to sea level rise and more intense rainfall. Offshore reefs provide natural coastal protection by dissipating wave energy (Figure 2.2a, van Zanten et al. 2014). Coastal vegetation such as saltmarsh and mangroves provides structural stability, which can protect both the natural coastline and existing infrastructure from damaging effects of severe storm events (Figure 2.2b); such events may increase in intensity due to climate change (Borsje et al. 2011). Floodplains, coastal wetlands and estuaries can act as natural compensation basins during flooding from high rainfall and storm surges, which may increase in frequency as a result of climate change (Costanza et al. 2008).

Figure 2.2a: Outer reefs dissipate wave energy, protecting the coast. Photo: Robyn Paice.

Figure 2.2b: Saltmarsh stabilises shore and buffers flooding. Photo: © James Tempest.

2.3.2 Blue Carbon

Carbon sequestered[2] within oceans and coastal ecosystems is known as blue carbon—most of the Earth's sequestered carbon is stored as blue carbon. Some coastal ecosystems, particularly mangroves, saltmarshes and seagrasses, are crucial to this process, as they are very effective in sequestering and storing CO_2(Wylie et al. 2016) (see Table 2.1). These ecosystems cover only 2% of the Earth's surface, but store ten times more carbon per unit area than other ecosystems (Mcleod et al. 2011). Recent research also suggests potential sequestration within marine macroalgae communities (Hill et al. 2015).

2.3.3 Alternative livelihoods

As natural and human systems respond to climate change, there is likely to be changes in land use and potentially the loss of some economic benefits that rely on ecosystems. New opportunities may also arise however, as alternatives to unsustainable practices and as benefits of active ecosystem-based adaptation, or through increases in some existing uses (Lavorel et al. 2015).

We need to consider diversifying livelihoods to build social capacity in adapting to climate change. Examples related to coastal ecosystems include:

- timber production from newly established mangrove forests
- expansion of nature-based tourism
- land-based aquaculture in flood-prone areas
- new food resources from artificial oyster reefs established to protect coastal areas.

Table 2.1: Comparative organic carbon storage in different ecosystems in Australia (Lawrence et al. 2012). Values are average tonnes of equivalent CO_2 storage per hectare and per year for sequestration rate.

	Living biomass		Soil	
Ecosystem	**Carbon storage**	**Sequestration rate**	**Carbon storage**	**Sequestration rate**
Saltmarsh	52	-	1646	4.2
Estuarine mangroves	396	-	1710	5.5
Oceanic mangroves	896	17.7	1190	5.2
Seagrass	3	-	846	16.7
Temperate forests	1539	28.7	1118	0.1
Tropical forests	1341	40.9	543	-0.5
Croplands	-	-	106	-

[2] Carbon sequestration is the process of CO_2 removal from the atmosphere by uptake and deposition to a reservoir IPCC Glossary: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_Glossary.pdf

2.4 Management of ecosystems for adaptation

Climate change adaptation benefits from a vision developed in partnership with stakeholders, providing clearly stated broad objectives in terms of which values need protection. For example, Peirson et al. (2015) provides a potential vision statement for estuaries:

Estuaries will sustainably meet the needs and aspirations of society and maintain ecological integrity in the face of change, with appropriate recognition of the intertwined human and ecological values. This will be achieved through the adoption of integrated and holistic adaptive strategies.

Management goals will differ depending on ecosystem type and condition, level of human development and the different potential threats of climate change. Clearly the challenge for management is that such a broad range of stakeholders means there is potential for conflicting goals. Stakeholder uses in the coastal zone will fall broadly into two categories:

(i) those with **intrinsic values** of coastal ecosystems, based on natural benefits provided by ecosystems

(ii) those with **instrumental values** of coastal ecosystems, based on active use of resources (Peirson et al. 2015).

It is an important distinction, because stakeholders with intrinsic values will have goals related to conservation, while those with instrumental values will have goals relating to sustainable use of resources. Table 2.2 provides an overview of the different stakeholders, their use of coastal ecosystems and management goals. Conflicting goals of stakeholders may be overcome to some extent by improving understanding concepts of ecosystem services and the connectivity within and between ecosystems and humans.

2.5 Ecosystem services and resulting pressures

The exploitation of ecosystem services usually has consequences for ecosystem health (MEA 2005)[3]. Human activities based on the many services provided by coastal ecosystems (Ecosystem Models 1B and 2B) have resulted in a significant level of threat and decline (Barbier et al. 2011). Existing pressures on ecosystems need to be managed to ensure their long term sustainable use. These pressures also need to be considered in the context of climate change because:

- existing threats can be worse than those attributable to climate change (Kingsford 2011)
- non-climatic threats are often exacerbated by climate change (Russell et al. 2009)
- ecosystem health determines resilience to the effects of climate change (Koehn et al. 2011)
- opportunities to increase resilience may exist and are a key principle for climate adaptation (e.g. Saunders et al. 2013).

Descriptions for different types of ecosystems are provided below in sections 2.5.1- 2.5.4, in the context of interaction with climate change pressures, but there may be others that apply to your management area. Further information is available at the OzCoasts website, including effects of the following threats and stressors:

- dredging
- drainage and infill
- altered pH
- aquatic sediments
- connectivity
- disturbance to biota
- excess nutrients
- freshwater flow regime
- habitat removal/disturbance
- hydrodynamics
- litter
- organic matter
- pathogens
- pest species
- toxicants.

[3] Ecosystems and Human Well-being: Synthesis. http://www.millenniumassessment.org/documents/document.356.aspx.pdf (accessed 13 May 2015).

Table 2.2: Potential stakeholders (Peirson et al. 2015), their use of coastal ecosystems and goals for future management.

	Stakeholders	Use	Goals
Intrinsic importance	Local conservation agencies and managers	Conservation Employment	Ecosystem health Biodiversity protection
	Voluntary conservation workers	Conservation Social volunteering Training	Biodiversity Community enjoyment Maintenance of historical landmarks
	Observers of natural ecosystems and species	Ecotourism Passive recreation Personal knowledge	Biodiversity protection Iconic species Access
Instrumental importance	Recreational water and shoreline users	Swimming Water sports Fishing – boat, shore, diving, gathering, hunting	Water quality Access Infrastructure Stocks of key species Sustainable quotas
	Tourists and tourism industry	Ecotourism Recreational uses	Biodiversity protection Water quality Access Aesthetics Iconic species Stocks of key species (fishing) Accommodation Infrastructure provision
	Commercial fishers (aquaculture and hunters)	Fishing – boat, shore, diving, gathering, hunting	Water quality Access Stocks of key species Operational space Sustainable quotas
	Commercial/industrial operators	Port operations Infrastructure provision Mining Dredging Urban development	Operations viability Access Infrastructure protection Water supply Operational area Land value Coastal stability
	Farmers within the catchment	Production	Operational space Regulatory restrictions Land value Water supply Water quality
	Residents	Potentially involved in all uses through recreation, employment, lifestyle interests and investments.	Potentially all Land value Community resources Community health
	Local governments		Potentially all
	Utilities providers	Infrastructure provision Water supply Drainage Sewerage	Infrastructure space Infrastructure protection Water quality protection
Both	Indigenous people	Conservation Traditional food Traditional medicine	Ecosystem health Biodiversity protection Access Recognition Preservation of significant sites
	Researchers	Ecological interests Social interests Infrastructure interests	Ecosystem health Sustainable management Healthy communities Informed decision-making

2.5.1 Non-climatic pressures on freshwater ecosystems

Large areas of land in catchment areas are developed for a variety of land uses (e.g. urban, agricultural, extractive and industrial), with widespread impacts resulting from clearing, changes to hydrology and increased nutrient loads (Allan 2004). Clearing of natural vegetation reduces plant and animal species diversity through habitat loss and fragmentation, reducing resilience of organisms through lower genetic variation. With fewer niches available for recolonization, migration corridors for fauna are restricted and dispersal distances for plants are increased. Natural vegetation is replaced by agricultural production which often incorporates water abstraction and drainage. Increased runoff carries additional nutrients from fertilisers and livestock wastes and sediments from cleared lands. Other land uses in catchment areas, such as mining, have more localised effects but may contribute other pollutants and additional sediments to surface and ground waters. Nutrients, sediments and other pollutants directly affect wetland and stream health, and degradation is exacerbated by water abstraction and land clearing.

2.5.2 Non-climatic pressures on estuarine ecosystems

Changes to hydrology and anthropogenic inputs of nutrients, sediments and other pollutants have led to significant impacts on many estuaries (Mitchell et al. 2015). Degraded catchments have reduced capacity to intercept pollutants and sediments. Estuaries often naturally accumulate organic material and sediment, but additional export from the catchment leads to increased algal growth, and phytoplankton and epiphytes may restrict aquatic plant growth with loss of this habitat, which has implications for food webs (Scheffer and van Ness 2007).

Estuarine ecosystems located in the vicinity of urban centres may be impacted by residential, commercial and industrial development, including physical changes (e.g. marina construction) and pollution. There may be limited space for flooding or relocation resulting from sea-level rise where urban development is high (coastal squeeze). Managed tidal exchange is common in urban estuaries, which can impact water quality, but potentially may assist in climate change adaptation.

Impacts on mangrove ecosystems arise from removal and filling for human development in coastal areas, water quality decline, waste dumping, stock trampling and fishing[4]. In Australia, 17% of mangrove area has been lost, which is concerning but low in comparison to global levels.

2.5.3 Non-climatic pressures on coastal interface ecosystems

Coastlines are a focal point for human settlement in Australia, and many areas of natural habitat have been lost or modified as a result. Engineered coastal protection structures are often a threat to adjacent ecosystems (Spalding et al. 2014). Vegetated shorelines (e.g. mangroves and saltmarsh) stabilise coastal areas, but where they are compromised by coastal development, this protective function is lost and risk associated with sea level rise and disturbance events is increased (Gilman et al. 2008). As for estuaries, coastal squeeze limits natural physical shifts in response to climate change.

2.5.4 Non-climatic pressures on marine ecosystems

Marine ecosystems are affected by poor water quality from catchments, potential pollutants from shipping and offshore petroleum development, overfishing and destructive fishing methods, and pest species (Koehn et al. 2011, Bennett et al. 2015). As for other ecosystems, reduced resilience can limit natural adaptive responses to climate-related changes. The static position of reef ecosystems means that organisms that depend on them have limited potential for shifts in distribution.

[4] Information on mangrove ecosystems, threats and management can be found on websites produced by MangroveWatch Australia www.mangrovewatch.org and the Marine Education Society http://mesa.edu.au/mangroves/default.asp (both links accessed 13 May 2016).

3 Potential impacts of climate change

With a good understanding of your ecosystem(s), you are well-placed to assess the potential impacts of climate change. Climate change will affect many conditions that will impact ecosystems, as shown in Figure 3.1. Predicting ecosystem responses needs to consider:

- locally-relevant climate change projections
- specific ecosystem characteristics
- existing non-climatic pressures.

This section summarises current projections for climate-related changes and discusses potential impacts on coastal ecosystem types (summarised by Ecosystem Model 1C and 2C). Information is also provided on implications of climate change for invasive species: this information is applicable to all ecosystem types.

3.1 Major climate change projections and general impacts

The Bureau of Meteorology and CSIRO report biannually on climate trends and projections in the State of the Climate in Australia (Bureau of Meteorology and CSIRO 2014). The extent of current changes and future projections vary for different regions of Australia and models are continually being improved with the addition of new information. Up-to-date projections with information for specific regions can be obtained using the Regional Climate Change Explorer tool on the Climate Change in Australia website. (The climate change projections summarised here have been drawn from Bureau of Meteorology and CSIRO (2014) and the Regional Climate Change Explorer tool (CSIRO and Bureau of Meteorology 2015).)

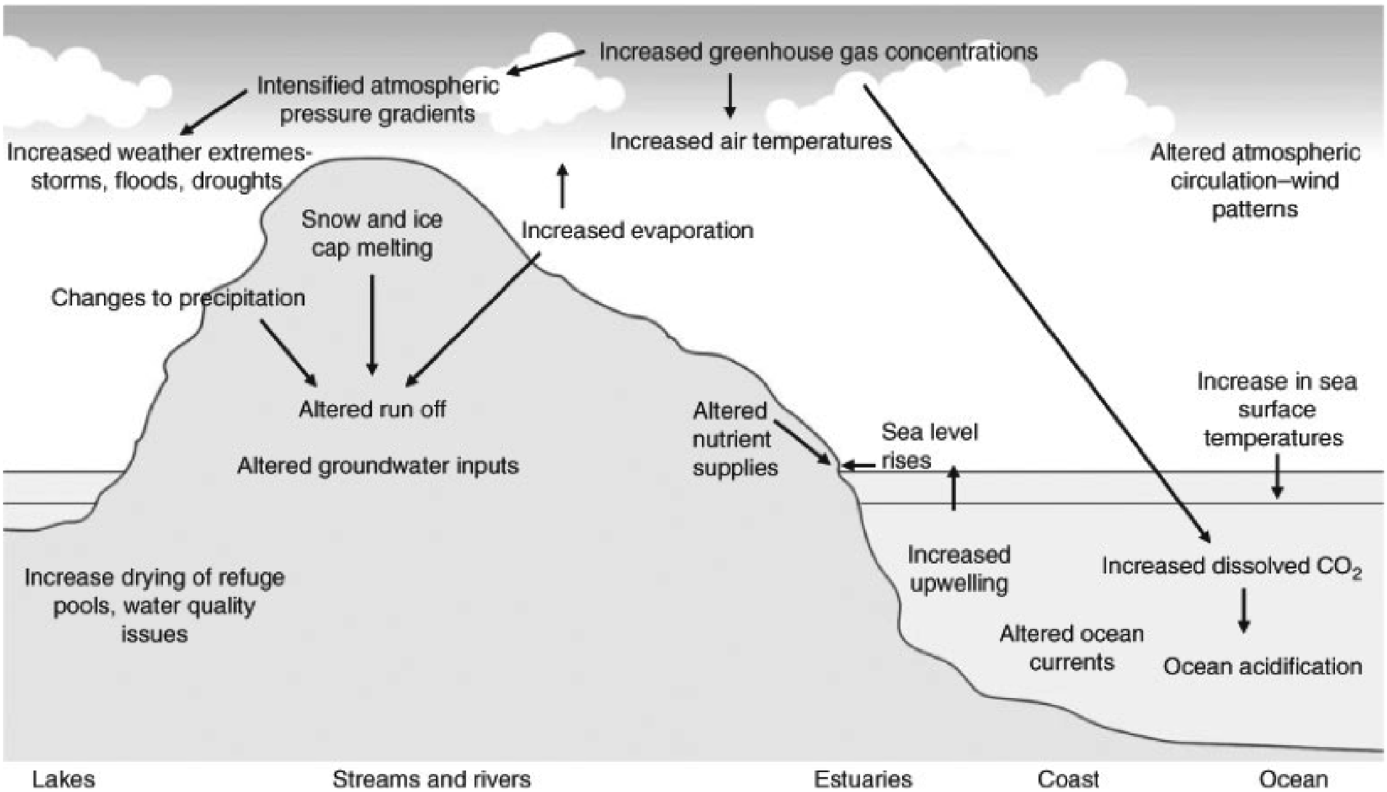


Figure 3.1: Main effects of climate change which will impact coastal ecosystems. Source: Reproduced from Koehn et al. (2011), with permission from CSIRO Publishing.

Tip: Use the Regional Climate Change Explorer tool and the information in current State of the Climate Reporting to assess climate change projections for your region. You may also find other helpful assessment tools on the Climate Change in Australia website - http://www.climatechangeinaustralia.gov.au/.

3.1.1 Sea level rise

Sea level rise is expected as a result of warming and consequent expansion of ocean waters and from melting of land-based ice sheets and glaciers. There is very high confidence that sea levels will continue to rise throughout Australia and that the height of extreme sea level events will rise. Regardless of emissions mitigation, mean sea level in Australia will increase by 0.06 – 0.19 m by 2030.

2090 Predictions for sea level rise under different emissions scenarios.

LOW	MEDIUM	HIGH
0.08-0.19m	0.27-0.66m	0.38-0.89m

3.1.2 Increasing temperatures – air and sea

There is very high confidence in projections that current trends of warming air temperatures will continue throughout Australia, particularly for southern coastal regions. Very warm months and extremely hot days are already more frequent and extremely cold days have declined. Regardless of emissions mitigation, temperatures will increase by 0.4-1.4°C by 2030.

2090 Predictions for air temperature increases under different emissions scenarios.

LOW	MEDIUM	HIGH
0.4-1.4°C	1.2-2.1°C	2.7-4.2°C

Surface ocean temperatures are increasing in response to air temperature. Increased water temperatures in eastern Australia are linked to intensification of the East Australian Current. A southern latitudinal shift in sea surface climate of 3° or 350km has been observed. South-eastern Australia is warming more rapidly than the rest of Australia, and dramatic marine heatwaves have been observed in the south-west.

2090 Predictions for sea surface temperature increases in different regions of Australia under a high emissions scenario.

NORTH	SOUTH	EAST
2.2-4.1°C	1.6-5.1°C	2.1-5.7°C

3.1.3 Rainfall changes

Rainfall patterns will be determined mainly by natural variation to 2030, but beyond that date they will reflect climate change. Changes to rainfall amounts and seasonal patterns are expected as a result of climate change, but predictions vary across Australia in terms of both magnitude and confidence. There is very high confidence in predictions of declining winter and spring rainfall in Southern Australia, ranging from a 15% reduction by 2090 under a low emissions future to 30% under a high emissions future.

3.1.4 Increased carbon dioxide levels

Increased atmospheric carbon dioxide concentrations are dependent on global actions to reduce emissions. Representative concentration pathways (RCPs) are used to assess future climate change scenarios (Figure 3.2).

- A 'business-as-usual', high atmospheric concentration scenario (RCP 8.5) with continued increase in emissions over time would result in a CO_2 level of 940ppm by 2100.
- Mitigation actions resulting in medium emissions could limit CO_2 concentrations to 540-660ppm by 2100.
- A low emissions future could limit atmospheric CO_2 concentrations to 420ppm by 2100, following a peak of 440ppm in 2040.

Carbon dioxide availability affects photosynthesis and respiration of terrestrial plants. Enhanced photosynthesis in response to greater CO_2 availability has a positive effect on plant growth. However other climate-related changes, such as increased heat and drought, may limit this effect of 'CO_2 fertilisation'.

3.1.5 Ocean acidification

There is increasing concern regarding the effects of ocean acidification (Figure 3.3), resulting from absorption of higher concentrations of CO_2 from the atmosphere. Increased absorption of CO_2 by oceans (30-50% of anthropogenic emissions) reduces pH and changes the carbonate chemistry. Dissolved CO_2 increases oceanic hydrogen and bicarbonate ions concentration, while CO_3- is reduced. An increase in acidity can limit growth of carbonate-dependent organisms, including corals and shellfish. The predicted surface sea pH decrease of 0.2-0.3 by 2100 would be the highest ocean acidity in the last 800, 000 years.

3.1.6 Extreme weather events

Extreme weather events include intense rainfall events, drought and severe storms including tropical cyclones. There is a general expectation that severe climatic events will increase in frequency and intensity, however predictions are uncertain and vary regionally. Tropical cyclones in northern Australia may decrease in frequency but increase in intensity (medium confidence). The intensity of extreme rainfall events is predicted to increase throughout Australia with high confidence, but the magnitude of these changes and alterations to frequency are unclear. There is high confidence of greater time spent in drought and increased fire-risk weather. Effects of increased ocean surface temperature on coastal winds may result in more intense storm events on the eastern coast. Predictions vary regionally. Large wave events have increased in frequency and intensity on the southern coast.

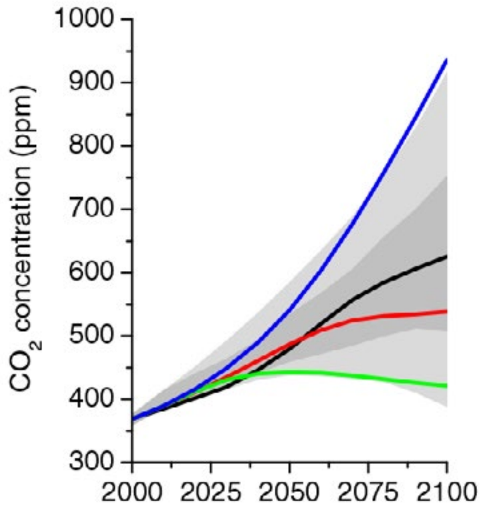


Figure 3.2: Projected CO_2 concentrations. Source: Van Vuuren et al. 2011.

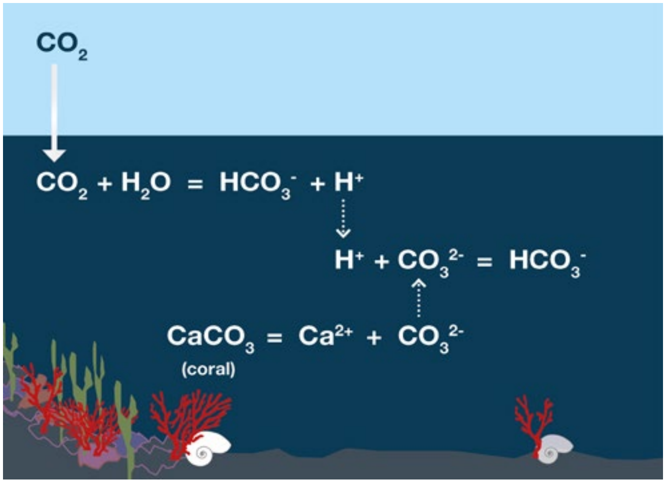


Figure 3.3: Ocean acidification results from excessive atmospheric CO_2 due to formation of carbonic acid. The additional H+ ion further combines with carbonate, which becomes less available to calcifying organisms. Source: © NCCARF 2016.

3.2 Specific impacts for coastal ecosystems

The following text describes in greater detail the implications of climate change for the different ecosystem types illustrated in the conceptual Ecosystem Model 1C and 2C. The presence of each ecosystem type in temperate and/or tropical zones is indicated by the reference to Model Temperate 1C and Model Tropical 2C after the ecosystem type heading.

3.2.1 Coastal freshwater ecosystems: Ecosystem Models 1C and 2C

Increased temperatures and drought will have direct negative consequences for freshwater ecosystems in Australia, particularly in southern regions. There is often limited capacity for natural migration of plants and animals in isolated aquatic environments in response to changes conditions; this means a contraction of existing communities is likely, with a shift to dominance by more tolerant species (Bond et al. 2011).

The decline in winter and spring rainfall in Southern Australia, and increased periods of drought expected throughout the country, will continue to directly affect aquatic and terrestrial environments in catchments through drought and loss of summer refuge habitat (Aldous et al. 2011). Changes to seasonality of rainfall will alter the water regimes of freshwater aquatic ecosystems and freshwater inputs to estuarine environments, with consequences for life cycles including fish breeding and migration (Elliot et al. 2007). There is likely to be localised extinctions, changes to species composition and overall reduction in biodiversity (Kauhanen et al. 2011).

Freshwater ecosystems throughout the catchment are connected with coastal ecosystems through conveyance of water, organic material, sediments and biota. In developed catchments they provide an important water quality protection service, but inevitably transport excess nutrients, sediments and pollutants to coastal ecosystems. Changing weather patterns will affect these processes through altered timing and volume of freshwater inflows to receiving coastal ecosystems (Gillanders et al. 2011), with additional effects of impacts on vegetation health and land use in the catchment on loadings of organic material, nutrients and sediments (Koehn et al. 2011).

Rising sea levels will change the connectivity of some freshwaters with the coast through flooding, and there is potential for conversion of some freshwaters to saline or estuarine environments through salt water intrusion (Lukasiewicz et al. 2013), with consequences for plant and animal community composition and migration pathways for fish species. Retraction of lowland freshwater communities upstream may be limited by increased temperatures and drought.

There is potential within catchments for CO_2 fertilisation for both natural vegetation and agricultural systems. For many species, this will be outweighed by effects of drought and heat, but it may promote colonisation of new areas south of existing ranges.

3.2.2 Wave-dominated estuaries: Ecosystem Models 1C and 2C

Wave-dominated estuaries are common in southwest and southeast regions of Australia at the end of river systems prior to discharge into the ocean. Complex changes to hydrology, from altered freshwater inputs and tidal exchange from sea will affect salinity regimes and a range of ecosystem processes (Gillanders et al. 2011). Periodic opening of natural sandbars is also likely to change, with additional effects from altered patterns of extreme water events.

Changes to hydrology are complicated by potential rainfall reductions in the catchment, which may restrict estuary opening if flows are substantially reduced. These changes have implications for water quality. Enhanced flushing of lower estuarine waters by increased tidal exchange, and reduced nutrient loads from catchments in response to lower flow volumes, may improve water quality (Peirson et al. 2015). However, lack of riverine flow may cause water quality issues to migrate upriver where long-term lack of flow could result in stagnation, deoxygenation and sediment nutrient release. Discharge of accumulated nutrients and sediments may impact receiving marine environments. In some systems, tidal interchange is regulated by physical structures and/or artificial opening, which may present an opportunity to manage the effects of climate change.

The ecological effects of altered hydrology, salinity and water quality will vary across systems and may be positive or negative owing to complex interactions (Day et al. 2008). Estuaries are generally highly productive and support substantial populations of birds and fish, providing fish nursery habitat and conduits for fish migration. Changes to aquatic plants will affect habitat and food webs. Inundation of land adjacent to the coast and estuaries has implications for fringing vegetation, and habitat for shorebirds may be flooded. Natural migration of these habitats to higher ground may be limited by the extent of adjacent human development.

Figure 3.4: The Murray River mouth at the Coorong. Source: © Government of South Australia, Department of Environment, Water and Natural Resources, 2016.

3.2.3 Tidal rivers and wetlands and mangrove ecosystems: Ecosystem Model 2C

Mangroves are widespread in northern Australia along the coastline and in estuaries and tidal rivers. Increasing temperatures and sea level rise have direct implications for species composition and distribution of mangrove communities (Gilman et al. 2008). Southern range extensions for some species are likely due to temperature increase (already observed but the link to climate change is unclear (Poloczanska et al. 2012)), as is a redistribution in relation to water levels, including potential upstream range increases in tidal rivers. Mangroves are adapted to large salinity and water level fluctuations and may therefore be well suited to natural adaptation in response to climate change. In addition, higher atmospheric CO_2 has the potential to enhance mangrove growth, and may facilitate colonisation of new areas.

While these changes may not restrict the long-term occurrence of mangroves generally, and indeed may increase overall distribution, there is a risk that the rate of change may exceed the time required for these plants to colonise new areas. Interim loss of mangrove habitat would have negative consequences for organisms that depend on them for habitat and a detrital food source, including species that are part of adjacent seagrass and reef ecosystems. It would also influence their important functions in intercepting nutrients, pollutants and sediments, and in stabilising soils during intense weather events (Gilman et al. 2008), which are likely to increase in intensity in northern Australia. Short and long term effects on their considerable value in carbon sequestration are also possible.

3.2.4 Coastal interface ecosystems: Ecosystem Models 1C and 2C

Coastal interface ecosystems, including rocky shores and headlands, rocky intertidal habitats, sandy beaches and dune systems are distributed according to geology and ocean dynamics. They are directly exposed to sea level rise and changes in frequency and intensity of extreme events, which will flood some habitats and affect physical coastal processes. Erosion and landward migration of habitats are likely, with redistribution of intertidal habitats (Hawkins et al. 2008). Human development in many coastal areas limits the potential for natural changes, which increases the risk of habitat loss.

Coastal environments present harsh and dynamic environments for biota, with shifting physical habitats and extreme conditions of temperature and inundation/drying experienced by biota in the intertidal zone. Research is emerging on biophysical effects of climate change on intertidal organisms (Helmuth et al. 2011) but it is not known whether broad tolerance may provide resilience to impacts of climate change, or make them vulnerable to further extremes.

Significant coastal breeding areas for penguins and other seabirds, seals, sea lions and turtles throughout Australia will be affected by increasing temperatures and habitat changes. Warming creates heat stress on animals and affects the breeding success of seabirds and turtles (Poloczanska et al. 2012). Populations of these species will be confined to smaller areas or need to seek new habitats. There may be limited capacity to find alternative breeding sites and habitats, particularly in the context of existing habitat degradation. Furthermore, species currently restricted to southern Australia have more limited capacity for migration in response to temperature.

3.2.5 Seagrass meadows: Ecosystem Model 1C

Seagrasses occur most extensively in protected waters in southern Australia, while distribution in northern regions is limited by high tidal fluctuations and seasonal freshwater inputs (although included in the tropical example of Ecosystem Model 2C). Climate change has potential for varying effects on seagrasses but there is likely to be an overall decline (Connolly 2012).

Figure 3.5: Australia fur seal colony, Montague Island, NSW. Photo: © Damien Dempsey, www.flickr.com/photos/yarra64/276102198/.

Warming waters may affect growth and reproduction for some species, and are likely to alter species composition and cause a southwards shift in distribution ranges; as already observed for tropical seagrasses on the east coast. Physical limitations to range extension in southern Australia pose a risk of extinction for some seagrass species, as shallow water conditions do not occur beyond the Australian coast. Growth may be enhanced by increased temperatures within tolerable limits, but warmer conditions may also favour epiphyte growth to the detriment of seagrasses (Connolly 2012).

Increased depth from sea level rise may restrict seagrass growth in some waters, while providing new areas suitable for colonisation. Reduced dissipation of wave energy by deeper protective reefs can create conditions of greater disturbance in protected areas occupied by seagrasses. Increased coastal erosion can reduce water clarity, limiting the depth at which seagrasses can grow, exacerbating growth restrictions due to sea level rise. Increased frequency of intense weather events would increase physical disturbance and restrict recovery, and increased intensity of high rainfall events may cause periodic high nutrient and sediment loads. Loss of seagrasses will reduce the potential for carbon sequestration (Lawrence et al. 2012) and have negative consequences for the organisms that depend on them for habitat and food, including turtles, dugong and many fish species (Blandon et al. 2014).

3.2.6 Temperate reefs and macroalgal forests: Ecosystem Model 1C

Ocean warming is the major direct impact of climate change on these ecosystems, with significant potential to change species distributions (Bennett et al. 2016). Southern expansion of habitat ranges for tropical species into southern waters and southward migration of cool-water species has already been seen. Large areas of this ecosystem type occur along the southern coastline of Australia with limited capacity for range shift, potentially resulting in species extinctions.

Southward migration of new species into these ecosystems can have cascading effects due to changes to species interactions. Two examples have already been observed:

- A southward shift in range extent for the black sea urchin in Tasmania has resulted from higher temperatures and strengthening of the East Australian Current. Black urchins heavily graze macroalgae (Ling et al. 2009). With reduced cover of macroalgae, there can be a shift to a less complex ecosystem which is dominated by turf algae.
- In 2011, a 'marine heatwave' in Western Australia had serious negative effects on macroalgal communities (Wernberg et al. 2013), and the southern extension in tropical grazing fish has prevented its recovery (Bennett et al. 2015).

Sea level rise causes increased depth which reduces the availability of light needed for plant growth (Hepburn et al. 2011). Greater depth over reefs may also reduce their capacity to intercept ocean swells, increasing physical disturbance of macroalgae. Although predictions of increased intensity and frequency of extreme events are unclear, this would exacerbate disturbance and limit ecosystem recovery.

No impacts have been attributed as yet to acidification, but continued CO_2 emissions increases may adversely affect carbonate-dependent organisms, including cold-water corals, calcareous algae, crustaceans and molluscs.

3.2.7 Coral reefs: Ecosystem Model 2C

Coral growth and distribution is restricted by limitations of temperature and ocean carbonate concentrations, and so coral reefs are highly sensitive to warming and ocean acidification resulting from climate change. Rising water temperatures and sea level also favour macroalgae, with potential negative effects on coral reefs.

There is a high risk of loss of coral reef ecosystems due to climate change, even under low emissions scenarios (Hoegh-Guldberg et al. 2007). This has significant implications for the structure of human communities that depend on the reefs (Pratchett et al. 2008), and for coastal protection during storm events (Villanoy et al. 2012).

Increased water temperatures that exceed tolerance levels for symbiotic zooxanthellae lead to coral bleaching with variable capacity for recovery (Hoegh-Guldberg et al. 2007). There have been coral bleaching events in the Ningaloo Reef (Moore et al. 2012) and the Great Barrier Reef, and these events are expected to increase. Bleached reef structures are more vulnerable to grazing organisms and to storm damage, which would be exacerbated by any future increase in frequency and intensity of extreme weather events.

Ocean acidification is increasingly being considered a major threat to coral reefs, with potential to restrict coral development, impact on existing reefs and adversely affect other carbonate-dependent organisms (Doney et al. 2009).

Figure 3.6: Coral bleaching on the Great Barrier Reef. Photo: © Commonwealth of Australia (GBRMPA).

3.3 Invasive species

The potential impacts of invasive species in response to climate change are relevant for all coastal ecosystems (Hellmann et al. 2008). Some native species may also become invasive, if they are able to tolerate high temperatures and there is an expansion of their range. Invasive plants and animals possess growth and reproduction traits that increase their success in new environments. They are a serious threat to biodiversity in many ecosystems through predation and interference with food webs, competition for habitat and resources, and direct health effects on native plants and animals.

Invasive species have broad tolerance of environmental conditions and are capable of rapid colonisation of new areas (Boulton et al. 2014). Therefore they have high capacity to increase in range and fill niches left by native species that are adversely affected by climate change, or available following storm or drought disturbances. As potential distribution ranges for native species change, competition with invasive species may limit their success in new locations. Furthermore, native species under stress due to climate change are less competitive.

4 Adaptation options

Adaptation is the process of adjustment to actual or expected climate change and its effects (IPCC 2014). Adaptation of ecosystems to climate change may occur through natural ecological responses (autonomous adaptation) or be facilitated by active human intervention (managed adaptation). Autonomous adaptation to climate change is possible for some species and ecosystems, but is often limited by impaired ecosystem health and the fast rate at which changes are occurring. Thus there needs to be greater consideration for managed adaptation actions to protect coastal ecosystems and maintain biodiversity and ecosystem services.

There are many ways to classify adaptation options. Potential managed adaptation actions can be broadly classified into two approaches: those that reduce vulnerability of ecosystems to climate change; and those that manage the direct impacts of climate change (Table 4.1). Direct management of climate change impacts includes responses to changing habitat conditions and potential species distribution ranges, and responses to maintain physical coastal stability.

This section describes ideas and examples of adaptation options for six major coastal ecosystem types: coastal freshwater ecosystems; estuarine ecosystems (wave-dominated and tide-dominated), coastal interface ecosystems; and marine ecosystems (temperate reefs and coral reefs). This is not an exhaustive list, but aims to generate thinking about potential direct actions and the use of multiple approaches.

For each ecosystem type, these actions are classified in terms of three overall climate change response outcomes for sustainability of coastal ecosystems.

- Reducing vulnerability through reducing exposure, reducing sensitivity or increasing resilience and capacity for autonomous adaptation (IPCC 2007).
- Managing habitat and species changes caused by increasing temperatures, higher atmospheric carbon dioxide, altered salinity regimes and changes to water levels from sea level rise.
- Maintaining coastal stability in the face of sea level rise and changes to extreme weather events.

This outcomes-based approach allows managers to consider what can be achieved, and emphasises the need to consider multiple measures that can be more flexible and have synergistic effects (Cheong et al. 2013). As well as interactions between specific actions, it is important to recognise interactions across ecosystem types due to connectivity and flow-on effects.

The following text describes in detail the relevance of various adaptation options for the different ecosystem types illustrated in the conceptual Ecosystem Models 1D and 2D. **Key actions are highlighted in bold.**

In addition to these direct management actions, protecting ecosystems through reserves will be an important tool for adaptation. Climate change increases the urgency for protection of key ecosystems throughout Australia, and to ensure that the maximum area and diversity of habitat types are protected so that ecosystems and species can adapt (Dunlop and Brown 2008).

More information can be found in: Information Manual 5: Planning instruments, http://coastadapt.com.au/information-manuals/adapting-long-term-coastal-climate-risks-through-planning-approaches-and-instruments.

Table 4.1: Generic managed adaptation approaches for climate change response (adapted from IPCC 2014).

Overlapping approaches	Actions, examples	Outcomes, benefits, risks
Reducing Vulnerability	**Ecosystem management:** Ecosystem restoration, reducing existing pressures.	Increasing habitat connectivity, maintaining and enhancing diversity (species and genetic), increased resilience. Long term viability of restoration efforts in context of change.
	Planning tools: Environmental water provisions, development constraints in flood-prone areas, provision for migration pathways, systematic conservation reserves.	Potential for strategic, powerful change. Social resistance and conflicting values.
	Soft-engineering: Managed retreat, beach nourishment, beach drainage, temporary structures to enhance natural regeneration.	Manage coastal erosion and sedimentation processes and coastal flooding. May impact sediment-associated organisms, so requires careful implementation
Managing ecosystem response	**Ecosystem engineering:** Retrofitting of built structures in the coastal zone for habitat, salt marsh and dune grass for coastal stability, managed realignment of increased flooding, oyster and mussel beds as reef-building engineers, and assisted colonisation to enhance distribution shifts.	Coastal ecosystems and services are maintained or restored, new ecosystems are created, low maintenance. Potential synergies between engineering and restoration with multiple outcomes. Unintended consequences of translocations.
	Hard-engineering: Installation of physical protection structures, such as seas walls, groynes, offshore breakwaters, levees, training walls, using various materials; artificial reef creation. Tidal interchange regulation structures to manage freshwater/tidal exchange and upstream water levels.	Coastal protection, structural habitat, recreational opportunities. Risk of maladaptation – problems from interruption of natural erosional and depositional coastal processes. Physical impacts on natural habitats during building process. May prevent dramatic changes to water and salinity regimes of estuarine ecosystems, prevent flooding of shorebird habitat and adjacent property. May prevent dramatic changes to water and salinity regimes of estuarine ecosystems, prevent flooding of shorebird habitat and adjacent property. Interference with fish migration, reduced estuarine flushing can exacerbate nutrient enrichment.

4.1 Coastal freshwater ecosystems: Ecosystem Models 1D and 2D

Freshwater ecosystems in the catchment are important to consider for coastal ecosystem adaptation because they:

- are connected with coastal ecosystems in terms of water quantity and quality
- are important for migration of some fish species
- are potentially affected by changed conditions at the coast, such as flooding from sea level rise and increased exposure to salt water
- may become physically linked to coastal ecosystems through flooding.

The information here includes adaptation options related to freshwater ecosystems near the coast that are vulnerable to coastal effects of climate change, or which contribute to sustainability of other coastal ecosystems. It is applicable to all catchments, and so no differentiation is made here between temperate and tropical regions.

4.1.1 Reducing vulnerability

Significant existing impacts owing to clearing, hydrological changes and increased nutrient loading are widespread in Australian freshwater ecosystems. In some cases, these threats are greater than that of climate change (Kingsford 2011). There is substantial literature on how to reduce human use pressures on freshwater ecosystems (e.g. Boulton et al. 2014). Many **catchment management activities** undertaken through natural resource management (NRM) are effective in reducing vulnerability and exposure of freshwater ecosystems to the impacts of climate change (Lukasiewicz et al. 2013). For example:

- **Riparian zone revegetation** to provide cooler shaded refuge areas (Davies 2010) and to intercept nutrients and sediments.
- **Improving water quality** through implementation of best management practices (e.g. for dairy farming) to minimise impacts of enhanced algal production in warmer conditions.
- **Adapting environmental water provisions** where opportunities exist to compensate for reduced flow in a drying climate and to maintain key life cycle stages or migration patterns. In regions with extensive artificial drainage networks but declining rainfall, over-drainage can be addressed and water retained on the land to increase water in natural stream and wetland environments.
- **Alterations to land use** arising from inappropriate conditions for historical land use (Pettit et al. 2015), which have potential for lower impacts on ecosystems.

4.1.2 Manage habitat and species changes

Revegetation activities need to consider the long term viability of plant species in view of predicted changes to temperature and rainfall, and therefore may require consideration of **translocations** outside existing biogeographical ranges. For example, where lower riverine reaches are likely to be affected by greater tidal incursion, salt-tolerant plants will be needed. Some fish species may require **assisted colonisation** (Hoegh-Guldberg et al. 2008), where they have no natural capacity to shift habitats in response to drying of river systems in their existing range (Bond et al. 2011).

Protection of significant freshwater ecosystems in lower riverine reaches or coastal wetlands may require the use of **tidal control structures** to prevent salt-water intrusion. This approach must consider implications for interference of natural migration pathways for fish and other fauna as well as implications for water quality.

4.1.3 Maintain coastal stability

Catchment management activities that improve drainage design can protect coastal stability during flooding, and may be important in areas where the frequency of intense rainfall events is predicted to increase. Examples include:

- **flood retention basins** in catchments that can be used for other purposes (e.g. landscaped green space for recreation) but provide additional protection during extreme rainfall events
- **retrofitting of existing artificial drainage** networks to include additional wetland detention basins to slow the conveyance of water during high flow events.

Both of these options have the potential advantage of providing additional freshwater quantity and biodiversity refuges in regions where rainfall is predicted to decline (Bond et al. 2011).

4.2 Wave-dominated estuaries: Ecosystem Model 1D

Estuaries will experience changes in both freshwater and marine inputs, influencing water quality, salinity regimes and thus complex physical, chemical and biological processes, as well as changing areas of inundation. While the impacts of climate change are negative for many ecosystems, changes in estuaries can have potential to improve degraded systems (Peirson et al. 2015). For example, reduced catchment flows can reduce nutrient loading, and sea level rise may increase tidal exchange and flushing of lower estuaries.

4.2.1 Reducing vulnerability

For many estuaries the most significant existing stressor is nutrient enrichment. **Catchment-based water quality improvement** initiatives are important to increase resilience of estuaries, for example to increased algal productivity due to warming and increased CO_2 availability. There is already substantial literature on how to reduce human use pressures on estuarine ecosystems (e.g. NSW Government 2015). Maintaining aquatic plant communities and understanding thresholds for regime shifts[5] is also important to estuarine health. Algal-dominated systems support lower biodiversity with consequences for ecosystem services and the wellbeing of local communities.

Other options for improving water quality are:

- **sediment removal or remediation** to reduce internal sources of nutrients (sediment removal also has potential to increase depth, creating cooler refuges).
- **active management of tidal exchange** to increase flushing capacity, using structural barriers or *controlled opening of sand bars*.
- **creation of flat oyster reefs**; this has commenced recently in some southern Australian estuaries (Prince Phillip Bay in Victoria and Oyster Harbour in Western Australia: Nature Conservancy Australia 2015). This practice has potential to restore ecosystem services such as water quality protection through filtration (Cheong et al. 2013) and provides physical habitat that can support fish communities.

[5] 'Regime shift' here refers to the occurrence of two known states for shallow wetland systems: a turbid state dominated by phytoplankton and a clear-water state dominated by aquatic plants (Scheffer and van Ness 2007).

4.2.2 Managing habitat and species changes

Estuaries often provide an important service in flood management, through retention of floodwaters during high rainfall events, and also buffering the effects of storm surge and extreme tide events. **Providing space for inundation** and colonisation of new areas allows this service to be maintained. Where natural migration of flood prone areas is restricted by development there may be a need for the use of levees or other barriers to prevent inundation or guide inundation (**managed realignment**). In both these cases, **creating new habitat**[6] through revegetation of saltmarsh may compensate for habitat lost or compromised through sea level rise, intercept runoff and contribute to carbon sequestration (Cheong et al. 2013). Upstream migration of estuarine habitat into river channels and **assisted colonisation** of these areas with salt-tolerant vegetation can offer shaded, cooler refuges, which are often rare in temperate estuaries.

4.2.3 Maintaining coastal stability

Rising sea levels may compromise coastal interface areas between estuaries and the ocean, requiring active protection to maintain separation of estuarine lagoon ecosystems. **Saltmarsh restoration** promotes sediment deposition and organic matter accretion which raises the marsh base height to keep pace with sea level rise (Cheong et al. 2013). This also stabilises the coastal interface and makes it less vulnerable to erosion caused by extreme events and greater exposure owing to reduced dissipation by outer reefs (see also Section 4.4.3).

4.3 Tidal rivers and wetlands and mangrove ecosystems: Ecosystem Model 2D

Mangroves are foundation species in tide-dominated tropical estuarine systems. They support unique ecosystems through their provision of physical habitat, support of food webs through provision of detritus and influence on sediment and water chemistry. They are also important in maintaining adjacent marine ecosystems and contribute significantly to climate services of carbon sequestration and coastal stability. Adaptation in these coastal ecosystems therefore is often focused on conservation and restoration of mangroves and associated salt marshes. The role of these ecosystems in coastal stability is included in this section, and excluded from the section on coastal interface adaptation (Section 4.4).

4.3.1 Reducing vulnerability

Actions to **reduce existing pressures** on mangrove ecosystems include reduction of physical disturbance through controlling access to prevent damage and waste dumping, fencing from livestock, supported by **community education. Catchment-based water quality improvement** is also important because—although mangroves provide an important function in buffering adjacent estuarine and marine waters from catchment sources of sediment, nutrient and other pollutants— excessive inputs will adversely affect both the mangrove ecosystem and the provision of this protective service. **Conservation and rehabilitation** of areas with existing mangrove is a high priority because revegetation of new areas can be challenging (Lewis 2005).

Opportunities for **revegetation** of mangroves in degraded areas will also increase ecosystem resilience, by buffering existing mangrove communities from external impacts and providing additional habitat for associated fauna. This can be hindered by a lack of suitable sediments and the occurrence of high disturbance events during early stages of establishment. Successful mangrove revegetation projects require understanding and application of hydrology and sedimentation processes influencing mangrove establishment (Lewis 2005). Balke and Friess (2016) summarise effective techniques for a range of settings and suggest that reconnecting natural flows, high density plantings and the use of protective casings (and additional barriers) to protect plantings can also promote success. Melaleuca fencing as a **wave barrier and silt trap** has been shown to assist revegetation and promote natural recolonisation (van Cuong et al. 2015).

[6] See additional resources in WET eBook: Workbook for Managing Urban Wetlands in Australia: Section 3.05 Rehabilitation of saltmarsh habitat; and Section 3.07 Rehabilitation and reconstruction of estuarine habitats for shorebirds. www.sopa.nsw.gov.au/resource_centre/wet_ebook_workbook_for_managing_urban_wetlands_in_australia

4.3.2 Managing habitat and species changes

Potential habitat shifts resulting from changes to areas of inundation, and increasing temperatures must be incorporated into planning for mangrove conservation and revegetation activities to ensure long term success of these projects. Using **diverse species for revegetation**, and adopting **assisted colonisation** of mangrove species outside their current range or at the extremes of their inundation tolerance, will help prepare for future changes. Valuable for this approach is an understanding of inundation and temperature tolerance limits of mangrove species, combined with modelling tools to determine future ranges. If there is a need to translocate species into new areas, the availability of suitable sediments may be a limiting factor and innovative methods will be required (e.g. van Cuong et al. 2015).

Sea level rise will alter potential areas of inundation. Adaptation options include the provision of space for inundation to occur without intervention; or the use of levees or other barriers to prevent inundation or guide inundation (**managed realignment**). Appropriate actions will depend on local predictions for change and existing land use and infrastructure. As for temperature estuaries, these will require soft engineering approaches to **creating new habitat**[7] with multiple outcomes (Cheong et al. 2013). Managed realignment is preferable to flood prevention infrastructure, which has potential unintended impacts on adjacent ecosystems (Nordstrom 2014).

4.3.3. Maintaining coastal stability

Managing flooding by allowing water to inundate additional areas within estuarine ecosystems will contribute to coastal stability. Mangrove ecosystems extend beyond estuaries and are also characteristic of tropical coastlines. Mangrove conservation, rehabilitation and expansion has great potential to provide **climate adaptation services for coastal protection** through stabilising sediments and buffering the effects of wave action (Spalding et al. 2014). Although mangrove distribution is primarily in areas of low prevailing wave energy, mangrove trees provide an important coastal protection service during tsunamis and cyclones (Alongi 2008)[8]. In addition, sediment accumulation within mangrove roots can counteract the effects of sea level rise (Cheong et al. 2013). **Engineered protection** of mangroves from extreme disturbance events may be needed on a temporary basis during restoration; these include physical barriers and protective casings (Lewis 2005) or temporary fencing using material from nearby vegetation (van Cuong et al. 2015). More permanent protective structures may be appropriate where disturbance frequencies increase beyond the capacity of mangroves to recover.

4.4 Coastal interface ecosystems: Ecosystem Models 1D and 2D

Australia's coastline is a focal point for development which means that coastal interface ecosystems are subject to many existing pressures. Managing adaptation in the context of existing high-value development and infrastructure is a major challenge.

[7] See additional resources in WET eBook: Workbook for Managing Urban Wetlands in Australia: Section 3.05 Rehabilitation of Saltmarsh Habitat; and Section 3.07 Rehabilitation and reconstruction of estuarine habitats for shorebirds. www.sopa.nsw.gov.au/resource_centre/wet_ebook_workbook_for_managing_urban_wetlands_in_australia (accessed 13 may 2016).

[8] See also: https://ejfoundation.org/reports/mangroves-natures-defence-against-tsunamis (accessed 8 February 2018).

4.4.1 Reducing vulnerability

With such extensive development occurring in the coastal interface zone, there are many potential actions to **reduce existing pressures** and thereby increase resilience. These include:

- prioritising protection within areas with low projected change through reserve systems
- increasing connectivity and migration corridors through ecosystem restoration
- identifying barriers to natural adaptation pathways from existing development, and potential to overcome these
- restricting access to key conservation areas
- effective management of invasive species
- reducing fishing pressure
- minimising fire risk
- reducing pollution.

In addition to increasing ecosystem resilience, adaptation management should seek opportunities at the species level to enhance vulnerable populations through actions that **offset potential impacts** of climate change. For example, fencing of a rock ledge on Raine Island (Great Barrier Reef), successfully reduced deaths of green turtles (*Chelonia mydas*) which resulted in reducing vulnerability via a different pathway to the impacts of climate change (GBRMPA 2012).

4.4.2 Managing habitat and species changes

Plants and animals in coastal interface ecosystems will need to cope with hotter conditions. This may force southward migrations to cope with heat stress, however southern locations may not provide suitable habitat or food resources. In southern regions there may be no potential for southward migration. In addition, rising sea levels will reduce the size of existing and future habitat areas. In these situations, innovative adaptation responses may be needed to create suitable habitat and food resources; maintain tolerable conditions in existing locations; or to assist species to cope with new conditions. Some ideas for **directed adaptation for specific species** in these challenging environments are:

- creating cooler areas in existing land-based breeding habitats (e.g. for seals, turtles, penguins, seabirds) through planting vegetation around nesting areas, providing shade, designing man-made nesting boxes with insulation
- creating small inlets or artificial rock pools close to breeding habitats to allow animals to cool down in close vicinity to offspring, rather than needing spending additional time in the ocean at the expense of caring for their young
- active protection of burrows and breeding areas from flooding
- translocation to more favourable breeding areas (Hobday et al. 2015).

Landward shifts of intertidal habitats due to sea level rise are likely, but will often be limited by differing physical habitats. Artificial habitats may be needed for protection of these ecosystems, and the services they provide both directly (e.g. abalone fisheries) and through their connection with terrestrial and marine food webs. **Hard engineering** structures off-shore have potential to prevent flooding of these habitats but may also have negative effects owing to disruption of natural patterns of water circulation and sediment movement.

Existing and future development can severely restrict the potential for adaptation activities in the costal interface zone. Protection of vulnerable high-value habitats or species in developed areas may therefore necessitate institutional and social change.

4.4.3 Maintaining coastal stability

In association with our extensive development in coastal locations, humans have a long history of actively managing coastal processes through engineering approaches which can be used for defence against climate change impacts. **Hard engineering structures**, such as sea walls, groynes, breakwaters and levee banks, can be effective for direct protection from sea level rise, extreme high tides and extreme weather events, to maintain port openings and to manage sand accretion on beaches. However disruption of natural coastal processes by these structures can have unintended negative consequences such as water circulation and sediment movement (Nordstrom 2014). However, imminent threats to high value infrastructure or ecosystems may necessitate the use of structures to defend the coastal foreshore. These should be designed to consider ecosystem benefits to compensate for flooded habitat, or habitat that has become unsuitably hot through climate change.

Soft engineering approaches (e.g. sand nourishment) and ecological engineering (e.g. salt marsh creation), or combining hard structures with **ecological engineering** (e.g. oyster reefs, see Section 4.6.3) may be more beneficial and provide multiple outcomes (Cheong et al. 2013). In the Netherlands, **sand nourishment** is used to protect coastal foreshores from coastal erosion, through the Building with Nature Program: Sandy Shores (www.ecoshape.com). This process must consider sand sources and associated impacts on marine biodiversity. Also in the Netherlands, **coastal salt marsh restoration** is used to stabilise sediments and reduce coastal erosion, with the additional advantages of contributing organic resources that benefit adjacent fisheries, intercepting nutrients and sediments from terrestrial runoff and facilitating carbon sequestration in sediments (Cheong et al. 2013).

4.5 Seagrass meadows: Ecosystem Model 1D

It is difficult to predict how seagrass will be impacted by the combined effects of changes to factors of increased depth, CO_2 fertilisation, increasing temperature, and increased disturbance. Protection and restoration of seagrasses is essential for maintaining biodiversity and ecosystem services, and importantly to maximise potential for carbon sequestration. Although more common in southern Australia, and not shown on the tropical Ecosystem Model, seagrasses are important ecosystems in Northern Australia, and the information here also applies to these.

4.5.1 Reducing vulnerability

For seagrass ecosystems that are under pressure from nutrient enrichment, **reduction of nutrient loads** from catchment sources (Section 4.1.1) has good potential to increase their capacity to tolerate impacts of climate change. Nutrient enrichment negatively affects seagrass by promoting epiphyte growth, smothering and seagrass leave and thus limiting light availability. Increasing temperatures and CO_2 availability under climate change are likely to worsen the effects of epiphytes by providing more favourable conditions for growth. However, if nutrient enrichment is minimised to effectively limit epiphytes, increased temperatures and CO_2 may favour seagrass growth. Clearly, protection of healthy seagrass ecosystems from future nutrient enrichment is a priority to maintain resilience.

Seagrasses are also subject to physical disturbance from dredging and boating activities and these impacts can be managed to prevent further decline. **Restoration of seagrasses** in degraded sites may be used to increase the extent of coverage and connectivity and thus improve capacity for autonomous adaptation of both seagrasses and associated biota. Seagrass restoration has been undertaken successfully in many cases, including Cockburn Sound in Western Australia and Oyster Harbor in South Australia. Current best practice includes ensuring adequate water quality and maximising the scale of planting projects to enhance positive feedback mechanisms that improve survival and growth (Van Katwijk et al. 2016).

4.5.2 Managing habitat and species changes

Seagrass restoration within degraded areas can compensate for unavoidable loss in nearby areas, providing alternative habitat and food for dependent fauna. To this end, expansion of existing seagrass meadows through restoration is also important prior to any detected loss in current extent. Rising sea levels will change the position of suitable seagrass habitat through increasing depth and there may be opportunities to **create new areas of seagrass landward**.

Activities to create new areas of seagrass habitat will need to consider temperature and depth tolerance limits during species selection to ensure long-term survival of restored meadows. They may require the use of species from outside their normal range. **Assisted colonisation** may also be necessary to preserve species at risk of extinction in existing locations, or to support dependent fauna which have been forced to migrate southwards (e.g. Dugong which graze on seagrass).

4.5.3 Maintaining coastal stability

Increased exposure of seagrasses through reduced wave dissipation over reefs may create a need for **protective structures** to either maintain important seagrass communities, or to allow introduction or restoration activities. Where engineering structures are being considered for coastal infrastructure protection, they should also consider ecological outcomes for protected ecosystems such as seagrasses.

4.6 Temperate reefs and macroalgal forests: Ecosystem Model 2D

The greatest threat to temperate reefs from climate change is increased ocean temperatures. Their capacity to adapt to this threat depends on maintaining high diversity at community, species and genetic levels, to increase potential for tolerance of new conditions. Connectivity to allow for shifts in distribution ranges also important, however some reef communities will have limited capacity to migrate southwards. Temperate reefs provide an important coastal protection function through dissipation of wave energy, but increased water depth due to sea level rise can impair this function and place additional risk on protect marine and coastal interface ecosystems.

4.6.1 Reducing vulnerability

Although Australia's temperate reefs are considered relatively healthy, pressures from human activities in coastal areas are increasing and localised impacts have the potential to manifest as regional impacts (Bennett et al. 2015). **Management of pollution inputs** is an important adaptation action to protect resilience of temperate reefs. Nitrogen enrichment from sewage discharge can lead to a regime shift from macro-algal to turf-algae dominated communities (Falkenberg et al. 2013), thus sewage upgrades have potential to protect reef ecosystems.

Harvesting of marine organisms has direct impact on particular species and can also influence the response of an ecosystem to climate change through complex biotic interactions, making **review of current and future fishing practices** in the face of climate change an important part of adaptation (Bennett et al. 2015). Overfishing of rock lobsters in Tasmania for example, has reduced their potential to control populations of black sea urchins: the urchins have now extended their range southwards and are causing significant overgrazing of important macroalgal forests (Ling et al. 2009).

4.6.2 Managing habitat and species changes

To provide for changing conditions, adequate protection through an **effective reserve system** is essential, and will likely involve additional research to ensure this is achieved (Bennett et al. 2012). Connectivity throughout the Great Southern Reef off Australia's southern coastline (described by Bennet at al. 2016) will facilitate natural adaptation responses. In addition, identification and protection of southern reef areas with low risks from climate change effects will help to conserve communities that have limited capacity for southwards migration (Poloczanska et al. 2012).

Active restoration of macroalgal forests using transplants is potentially a useful tool for increasing connectivity throughout the reef system, and for restoring degraded habitats following actions to improve water quality. This may involve assisted colonisation of species outside their historical range to ensure long term success in degraded sites and to facilitate southwards migration where natural capacity for this cannot keep pace with changing conditions. **Transplantation of macroalgae** into degraded habitats has been trialled successfully in Sydney (see Figure 4.1) (Campbell et al. 2014).

Figure 4.1: Crayweed (*Phyllospora comosa*) macroalgae transplantation trial. Source: © UNSW, A. Vergés.

4.6.3 Maintaining coastal stability

While sea level rise may have little effect on the underlying rock structure of temperate reefs, greater depth over reefs can reduce their capacity to intercept wave forces (i.e. less waves break on these reefs and so forces at the coast will be greater). This can have negative effects on coastal interface ecosystems and human environments, and also protected marine communities such as seagrasses. Additional measures may be needed to counteract reduction in this important coastal protection service, such as **artificial reef structures**.

Oyster reefs have been used extensively in the United States to protect coastlines from erosion (Scyphers et al. 2011), and could be used to adapt to increased erosive forces as a result of rising sea levels and increased frequency and/or intensity of extreme weather events. In Australia, oyster reef restoration has so far been initiated in estuarine environments[9], but is a potential option for coastal protection. Oyster reefs were historically a conspicuous component of temperate reef ecosystems, but have been lost through unmanaged exploitation during Australia's early settlement years (Alleway and Connell 2015). The process involves creating a hard structure (e.g. from rock or concrete) for oysters to settle on and distributing larvae directly over the area, which have been raised in controlled environments attached to oyster shells. In addition to dissipating wave energy and creating structural habitat, oyster reefs can improve water quality through filtration organic material, sediment and phytoplankton, contribute to fish production in adjacent waters and provide a direct future food resource (Cheong et al. 2013, Alleway and Connell 2015).

4.7 Coral reefs: Ecosystem Model 2D

While there are some options for protecting coral reef ecosystems through adaptation, mitigation of climate change is crucial for their long term sustainability. The high risks to coral reef ecosystems, even under low emissions scenarios, has significant implications for biodiversity and coastal protection during storm events. Owing to their high value and high vulnerability, coral reefs have been the focus of much research into climate change impacts and adaptation (Hoegh-Guldberg et al. 2007).

4.7.1 Reducing vulnerability

In terms of adaptation, the primary option available is to increase resilience through heightened management of existing pressures. There is some potential for autonomous adaptation of coral reefs to the effects of climate change (reviewed in Hadwen et al. 2011), although the rate of change expected is likely to outpace this capacity. Notwithstanding these limitations, it is important to maximise natural resilience to climate change by maintaining and enhancing the health of coral reef ecosystems through **reducing existing stressors** (GBRMPA 2012).

Key actions to achieve this include:

- ongoing catchment management activities to reduce nutrient and sediment inputs to the marine environment
- reviewing and adapting fisheries harvests
- invasive species management
- restoring damaged habitats.

Restoring damaged coral reef habitats through coral propagation and transplantation is a relatively new science, but is becoming increasingly common. Research is also emerging on to develop new methods to **enhance recovery of degraded coral reefs**, such as:

- using enclosures that retain coral spawn on reefs to boost settlement rates (ACIAR 2016)
- using specialised surfaces to increase larval settlement (GBRF, 2016)
- increasing resilience to environment stress through genetic manipulation
- the potential for formation of more tolerant coral-symbiont combinations (AIMS 2016).

[9] Shellfish reef restoration project in Port Phillip Bay, Victoria: http://www.natureaustralia.org.au/our-work/oceans/restoring-shellfish-reefs/port-phillip-bay/ (accessed 8 February 2018).

4.7.2 Managing habitat and species changes

Changing water temperatures and sea levels will alter potential areas for coral reef development. While this clearly has negative consequences, there is also potential for new areas to become suitable for coral development. This may occur naturally over time, and there may also be a role for **assisted colonisation** of these areas using transplantation techniques to facilitate such migrations.

4.7.3 Maintaining coastal stability

Many coral reefs in Australia are located in areas prone to tropical cyclones. Current predictions suggest a decrease in frequency but an increase in intensity of tropical cyclones in northern Australia (medium confidence, CSIRO and Bureau of Meteorology 2015). This places coral reefs at greater risk of physical damage with consequences for the coastal protection service they provide. As for temperate reefs, coral reefs provide a **climate adaptation service** of coastal protection (Villanoy et al. 2012). However this may be compromised in areas vulnerable to bleaching and acidification. So, in addition to **active restoration, engineered structures** could be used to compensate for loss of natural coastal protection services or for direct protection of the reef.

5 Using this information

5.1 Using the information

The information in this manual will assist you in the following important steps in adaptation planning:

- **Understanding ecosystem function** and how this links to ecosystem values and services, and the type and severity of the main non-climatic pressures affecting your ecosystem. Possibly this might be summarised as a conceptual model to facilitate communication, understanding and agreement by stakeholders.
- **Developing scenarios** of how climate change will impact different components and processes in your ecosystem(s) of interest and consequences of interactions between climate change and non-climatic stressors for provision of ecosystem values and services.
- **Identifying adaptation actions** (incorporating potential synergies) relevant to your ecosystems, values, services and likely climate change stressors.

Choosing appropriate actions to manage the impacts of climate change on coastal ecosystems is complex because of uncertainty in climate change predictions, uncertainty in ecosystem response and conflicting approaches for the protection of human and natural environments. When assessing adaptation options for your ecosystem(s), consider the importance of connectivity between and within ecosystems and the potential for:

- achieving benefits across ecosystems
- synergistic effects of using multiple actions
- unintended consequences of adaptation actions (maladaptation).

5.2 Implementation and monitoring

Managed adaptation to climate change is a new field of ecosystem protection. Some adaptation actions will be based on existing well-accepted restoration methods, although used in a new context, others will be innovative methods with a few existing examples, and some may be experimental. Due to the high levels of uncertainty associated with, not only climate change projections, but also the complex array of interactive variables inherent in the ecosystem(s) components, processes, functioning, values, services and non-climatic pressures with climate change, it is **essential**, not optional, that you regularly monitor the efficacy of your adaptation options so that actions and approaches can be changed if they are not fulfilling your needs. Monitoring of progress and outcomes of adaptation actions is essential to ensure that:

- resources are being used effectively
- desired results are being achieved
- actions are not having maladaptive outcomes
- knowledge is developed for future planning.

Ideally, implementation and monitoring of actions will include at least reporting of the process outcomes and preferably, a formal research component to ensure rigour and confidence in the results. This will contribute to this knowledge gap and provide necessary information for other management bodies in development and implementation of appropriate strategies. Regular reflection is needed not only to assess the monitoring information and the efficacy of your adaptation options but also to stay abreast of new information on climate change and adaptation options. Commitment to and focused comprehensive monitoring and reflection will pay dividends in ensuring impacts of climate change are minimised for your ecosystem(s).

5.3 Adapting to climate change should not be delayed

While the uncertainties associated with climate change and the potential effects it may have on coastal ecosystems are high, this should not be a cause for inaction. We know enough to be able to put in place good strategies, and by ensuring that they are adaptive we can rapidly learn and improve upon them. Sharing our successes and failures will greatly improve our chances of developing good, effective strategies. In many cases the best bet for managing ecosystems is to improve their resilience by reducing the effects of non-climatic stressors, while degree of climate change is less. Immediate, well-considered action is necessary if we are to maintain coastal ecosystem values and services into the future.

6 References

Abson, D.J., and M. Termansen, 2011: Valuing ecosystems in terms of ecological risks and returns. *Conservation Biology*, **25**, 205-258.

ACIAR, 2016: Coral reef restoration using mass coral larval reseeding. Australian Centre for International Agricultural Research. Accessed 13 May 2016. [Available online at http://aciar.gov.au/project/fis/2011/031].

AIMS, 2016: SeaSim coral spawning activities. Australian Institute of Marine Science. Accessed March 2016. [Available online at www.aims.gov.au/seasim-coral-spawning-activities].

Aldous, A., J. Fitzsimmons, B. Richter, and L. Back, 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research*, **62**, 223-231.

Allan, J.D., 2004: Landscapes and Riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution and Systematic*, **35**, 257-284.

Alleway, H.K., and S.D. Connell, 2015: Loss of an ecological baseline through the eradication of oyster reefs from coastal ecosystems and human memory. *Conservation Biology*, **29**, 795-804.

Alongi, D.M., 2008: Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, **76**, 1-13.

Balke, T. and D.A. Friess, 2016: Geomorphic knowledge for mangrove restoration: a pan-tropical categorization. *Earth Surface Processes and Landforms*, **41**, 231-239.

Barbier, E.B., S.D. Hacker, C. Kennedy, E.W. Koch, A.C. Stier, and B.R. Silliman, 2011: The value of estuarine and coastal ecosystem services. *Ecological Monographs*, **81**, 169-193.

Bennet, S., T. Wernberg, S. D, Connell, A. J. Hobday, C. R. Johnson, C. R., and E. S. Poloczanska, 2016: The 'Great Southern Reef': social, ecological and economic value of Australia's neglected kelp forests. *Marine and Freshwater Research*, **67**, 47-56.

Bennett, S., T. Wernberg, E.S. Harvey, J. Santant-Garcon, and B. Saunders, 2015: Tropical herbivores provide resilience to a climate-mediated phase shift on temperate coral reefs. *Ecology Letters*, **18**, 714-723.

Bennett, S., T. Wernberg, S.D. Connell, A.J. Hobday, C.R. Johnson, and E.S. Poloczanska, 2016: The 'Great Southern Reef': social, ecological and economic value of Australia's neglected kelp forests. *Marine and Freshwater Research*, **67**, 47-56.

Blandon, A., and P.S.E. zu Ermgassen, 2014: Quantitative estimate of commercial fish enhancement by seagrass habitat in southern Australia. *Estuarine, Coastal and Shelf Science*, **14**, 1-8.

Bureau of Meteorology and CSIRO, 2014: State of Climate 2014. Bureau of Meteorology and CSIRO. Melbourne, Australia. Accessed 13 May 2016. [Available online at http://www.bom.gov.au/state-of-the-climate/].

Bond, N.R., P.S. Lake, and A.H. Arthrington, 2011:. The impacts of drought on freshwater ecosystems: An Australian perspective. *Hydrobiologia*, **600**, 3-16.

Borsje, B.W., B.K. van Wesenbeeck, F. Dekker, P. Paalvast, T.J. Bouma, M.M. van Katwijk, and M.B.de Vries, 2011: How ecological engineering can serve in coastal protection. *Ecological Engineering*, 37, 113-122.

Boulton, A.J., M.A. Brock, B.J. Robson, D.S. Ryder, J.M. Chambers, and J. Davis, 2014: Australia *Freshwater Ecology: Processes and Management*. Second Edition. Wiley Blackwekk, UK.

Campbell, A.H., E.M. Marzinelli, A. Verges, M.A. Coleman, and P.D. Steinberg, 2014: Towards restoration of missing underwater forests. *Plos One*, **9**, e84106.

Cheong, S., B. Silliman, P. Wong, B. van Wesenbeeck, C. Kim, and G. Guannel, 2013: Coastal adaptation with ecological engineering. *Nature Climate Change*, **3**, 787-791.

Connolly, R., 2012: Seagrass. In: *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2012*, E.S. Poloczanska, A.J. Hobday, and A.J. Richardson, Eds., CSIRO, Australia. Accessed 13 May 2016. [Available online at https://www.nccarf.edu.au/sites/default/files/attached_files_publications/Marine_Report_Card_Australia_2012.pdf].

Costanza, R., O. Pérez-Maqueo, M.L. Martinez, P. Sutton, S.J. Anderson, and K. Mulder, 2008: The value of coastal wetlands for hurricane protection. *AMBIO: A Journal of the Human Environment*, **37**(4), 241-248.

CSIRO and Bureau of Meteorology, 2015: Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia. Accessed 13 May 2016. [Available online at http://www.climatechangeinaustralia.gov.au/en/publications-library/technical-report/].

Davies, P.M., 2010: Climate change implications of river restoration in global biodiversity hotspots. *Restoration Ecology*, **18**, 261-268.

Day, J.W., and Coauthors, 2008: Consequences of climate change on the ecogeomorphology of coastal wetlands. *Estuaries and Coasts*, **31**(3), 477-491.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science*, **1**, 169-192.

Dunlop, M., and P.R Brown, 2008: Implications of climate change for Australia's National Reserve System: A preliminary assessment. Report to the Department of Climate Change. Department of Climate Change, Canberra, Australia. Accessed 13 May 2016. [Available online at https://www.environment.gov.au/system/files/resources/917bb661-b626-44bb-bd52-325645ae7c49/files/nrs-report.pdf].

Elliot, M., A.K. Whitfield, I.C. Potter, S.J.M. Blaber, D.P. Cyrus, F.G. Nordie, and T.D. Harrison, 2007: The guild approach to categorizing estuarine fish assemblages: a global review. *Fish and Fisheries*, **8**, 241-268.

Falkenberg, L. J., S.D. Connell, and B.D. Russell, 2013: Disrupting the effects of synergies between stressors: improved water quality dampens the effect of future CO^2 on a marine habitat. *Journal of Applied Ecology*, **50**, 51-58.

GBRF, 2016: Novel Coral Settlement Surfaces. Great Barrier Reef Foundation. Accessed 13 May 2016. [Available online at www.barrierreef.org/our-science/research-we-support/solutions-adaptation/novel-coral-settlement-surfaces].

GBRMPA, 2012: Great Barrier Reef Climate Change Adaptation Strategy and Action Plan 2012-2017. Great Barrier Reef Marine Park Authority, Townsville. Accessed 13 May 2016. [Available online at http://elibrary.gbrmpa.gov.au/jspui/bitstream/11017/1140/1/GBR%20Climate%20Change%20Adaptation%20Strategy%20and%20Action%20Plan%202012-2017.pdf].

Gillanders, B.M., T.S. Elsdon, I.A. Halliday, G.P. Jenkins, J.B. Robins, and F.J. Valesini, 2011: Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review. *Marine and Freshwater Research*, **62**, 1115-1131.

Gilman, E.L., J. Ellison, N.C. Duke, and C. Field, 2008: Threats to mangroves from climate change and adaptation options: A review. *Aquatic Botany*, **89**, 237-250.

Hadwen, W.L., and Coauthors, 2011: Climate change responses and adaptation pathways in Australian coastal ecosystems: Synthesis report, National Climate Change Adaptation Research Facility, Gold Coast, 359pp. Accessed 13 May 2016. [Available online at https://www.nccarf.edu.au/synthesis/climate-change-responses-and-adaptation-pathways-australian-coastal-ecosystems].

Hawkins, S.J., and Coauthors, 2008: Complex interactions in a rapidly changing world. *Climate Research*, *37*, 123-133.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008: Five potential consequences of climate change for invasive species. *Conservation Biology*, **22**, 534-543.

Helmuth, B., L. Yamane, S. Lalwani, A. Matzelle, A. Tockstein, and N. Gao, 2011: Hidden signals of climate change in intertidal ecosystems: What (not) to expect when you are expecting. *Journal of Experimental Marine Biology and Ecology*, **400**, 191-199.

Hepburn, C.D., D.W.Pritchard, C.E. Cornwall, R.J. Mcleod, J. Beardall, J.A. Rave, and C.L. Hurd, 2011: Diversity of carbon use strategies in a kelp forest community: implications for a high CO_2 ocean. *Global Change Biology*, **17**, 2488-2497.

Hill, R., Bellgrove, A., Macreadie, P. I., Petrou, K., Beardall, J., Steven, A. and Ralph, P. J., 2015: Can macroalgae contribute to blue carbon? An Australian perspective. *Limnology and Oceanography* **60**, 1689-1706.

Hobday, A.J., L.E. Chambers, and J.P.Y. Arnould, 2015: Prioritizing climate adaptation options for iconic marine species. *Biodiversity and Conservation*, **24**(14), 3449-3468.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D.B. Lindenmayer, C. Parmesan, H.P. Possingham, and C.D. Thomas, 2008: Assisted colonization and rapid climate change. *Science*, **321**, 345-346.

Hoegh-Guldberg, O., and Coauthors, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318**, 1737-1742.

IPCC, 2007: Summary for policymakers. In: *Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson,Eds, Cambridge University Press, Cambridge, UK. Accessed 13 May 2016. [Available online at https://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf].

IPCC, 2014: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L Ebi, Y.O. Estrada, R.C. Genova, B. Gilma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White, Eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Accessed 13 May 2016. [Available online at https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf].

Kauhanen, K., J. Chambers, and F. D'Souza (eds), 2011): Report Card of Climate Change and Western Australian Aquatic Ecosystems. National Climate Change Adaptation Research Facility - Adaptation Research Network for Water Resources and Freshwater Biodiversity, Gold Coast. Accessed 13 May 2016. [Available online at https://www.nccarf.edu.au/publications/aquatic-report-card].

Kingsford, R.T., 2011: Conservation management of rivers and wetlands under climate change: a synthesis. *Marine and Freshwater Research*, **62**(3), 217-222.

Koehn, J.D., A.J. Hobday, M.S. Pratchett, and B.M. Gillanders, 2011: Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research*, **62**(9), 1148-1164.

Lawrence, A.J., E. Baker, and C.E. Lovelock, 2012; Optimising and managing coastal carbon: Comparative sequestration and mitigation opportunities across Australia's landscapes and land uses, FRDC Report 2011/084, Fisheries Research and Development Corporation. Accessed 8 February 2018. [Available online at http://bluecarbonportal.org/wp-content/uploads/downloads/2013/04/FRDC_final-report.pdf].

Lavorel, S., M. J. Colloff, S. McIntyre, M. D. Doherty, H. T. Murphy, et al., 2015: Ecological mechanisms underpinning climate adaptation services. *Global Change Biology*, **21**, 12-31.

Lewis, R.R., 2005: Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering*, **24**, 403-418.

Ling, S.D., C.R. Johnson, S.D. Frusher, and K.R. Ridgway, 2009: Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(52), 22341-22345.

Lukasiewicz, A., C.M. Finlayson, and J. Pittock, 2013: Incorporating Climate Change Adaptation into Catchment Management: A User Guide. Report No. 76. Charles Sturt University, Australian National University, National Climate Change Adaptation Research Facility. Accessed 13 May 2016. [Available online at http://www.conservation.org/publications/Documents/CI_WPC_2014_Incorporating-Climate-Change-Adaptation-into-Catchment-Managment_User-Guide.pdf].

Mcleod, E., G.L. Chmura, S. Bouillon, M. Bjork, C.M. Duarte, C.E. Lovelock, W.H.Schlesinger, and B.R. Silliman, 2011: A blue print for blue carbon: Toward understanding of the role of vegetated coastal habitats in sequestering CO^2. *Frontiers in Ecology and the Environment*, **9**(10), 552-560.

MEA (Millennium Ecosystem Assessment), 2005: Ecosystems and human well-being: current state and trends. Island Press, Washington, D.C., USA. Accessed 13 May 2016. [Available online at http://www.millenniumassessment.org/documents/document.766.aspx.pdf].

Mitchell, S.B., T.C. Jennerjahn, S. Vizzini, and Z. Weiguo, 2015: Changes to processes in estuaries and coastal waters due to intense multiple pressures – An introduction and synthesis. *Estuarine and Coastal Shelf Science*, **156**, 1-6.

Moore, J.A.Y., L.M. Bellchambers, M.R. Depczynski, R.D. Evans, S.N. Evans, S.N.Field, et al., 2012: Unprecendented mass bleaching and loss of coral across 12° of latitude in Western Australia in 2010-11. *Plos One*, **7**, e51807.

Nature Conservancy Australia, 2015: Great Southern Seascapes. Accessed 13 May 2016. [Available online at http://www.natureaustralia.org.au/wp-content/uploads/2015/02/Great-Southern-Seascapes-Brochure.pdf].

Nordstrom, K.F., 2014: Living with shore protection structures: A review. *Estuarine Coastal and Shelf Science*, **150**, 11-23.

NSW Government, 2015: NSW Coastal Management Manual. Part C: Coastal Management Toolkit. A guide to managing estuary ecosystems. Office of Environment and Heritage on behalf of NSW, Sydney. Accessed 13 May 2016. [Available online at http://www.environment.nsw.gov.au/resources/coasts/150808-estuary-health-guide.pdf].

Peirson, W., and Coauthors, 2015: Opportunistic management of estuaries under climate change: a new adaptive decision-making framework and its practical application. *Journal of Environmental Management*, **163**, 214-223.

Pettit, N.E., and Coauthors, 2015: Environmental change: prospects for conservation and agriculture in a southwest Australia biodiversity hotpot. *Ecology and Society*, **20**.

Poloczanska, E.S., A.J. Hobday, and A.J. Richardson (Eds), 2012: Marine Climate Change in Australia, Impacts and Adaptation Responses. 2012 Report Card. Accessed 13 May 2016. [Available online at https://www.nccarf.edu.au/sites/default/files/attached_files_publications/Marine_Report_Card_Australia_2012.pdf].

Pratchett, M.S, P. L. Munday, S.K. Wilson, N.A.J. Graham, J.E. Cinner, et al. 2008: Effects of climate-induced coral bleaching on coral-reef fishes – ecological and economic consequences. *Oceanagraphy and Marine Biology: An Annual Review*, **46**, 251-296.

Russell, B.D., J.I. Thompson, L.J. Falkenberg, and S.D. Connell, 2009: Synergistic effects of climate change and local stressors: CO^2 and nutrient-driven change in subtidal rocky habitats. *Global Change Biology*, **15**, 2153-2162.

Saunders, M.I., and Coauthors, 2013: Coastal retreat and improved water quality mitigate losses of seagrass from sea level rise. *Global Change Biology*, **19**, 2569-2583.

Scheffer, M., and E.H. van Ness, 2007: Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients depth and lakes size. *Hydrobiologia*, **584**, 455-466.

Scyphers, S.B., S.P. Powers, K.L. Heck, and D. Byron, 2011: Oyster reefs as natural breakwaters to mitigate shoreline loss and facilitate fisheries. *PLoS ONE*, **6**, e 22396.

Spalding, M.D., S. Ruffo, C. Lacambra, I. Meliane, L.Z. Hale, C.C. Shepard, and M.W. Beck, 2014: The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. *Ocean and Coastal Management*, **90**, 50-57.

Van Cuong, C., S. Brown, H.H. To, and M. Hockings, 2015: Using Melaleuca fences as soft coastal engineering for mangrove restoration in Kien Giang, Vietnam. *Ecological Engineering*, **81**, 256-265.

Van Katwijk, M.M., and Coauthors, 2016: Global analysis of seagrass restoration: the importance of large scale planting. *Journal of Applied Ecology*, **53**, 567-578.

Van Vuuren, D.P., and Colleagues, 2011: The representative concentration pathways: an overview. *Climatic Change*, **109**, 5-31.

van Zanten, B.T., P.J.H. van Beukering, and A.J. Wagtendonk, 2014: Coastal protection by coral reefs: A framework for spatial assessment and economic valuation. *Ocean and Coastal Management*, **96**, 94-403

Villanoy, C., O. David, M. Atreigenio, F. Siringan, P. Alino, and M. Villaluz, 2012: Coral reef ecosystems protect shore from high-energy waves under climate change scenarios. *Climatic Change*, **112**, 493-505.

Wernberg, T., D.A. Smale, F. Tuya, M.S. Thomsen, T.J. Langlois, T. de Bettignies, S. Bennet, and C.S. Rousseaux, 2013: An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, **3**, 78–82.

Wylie, L., A.E. Sutton-Grier and A. Moore, 2016: Keys to successful blue carbon projects: Lessons learned from global case studies. *Marine Policy*, **65**, 76-84.

NCCARF
National
Climate Change Adaptation
Research Facility

Australian Government
Department of the Environment and Energy

www.coastadapt.com.au