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Queensland's biodiversity under climate change:

impacts and adaptation – synthesis report

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A report prepared for the Queensland Government, Brisbane

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Cover photo: View across coastal estuaries to Hinchinbrook Island, Queensland (credit: Gregory Heath, CSIRO Land and Water, science image BU5468)

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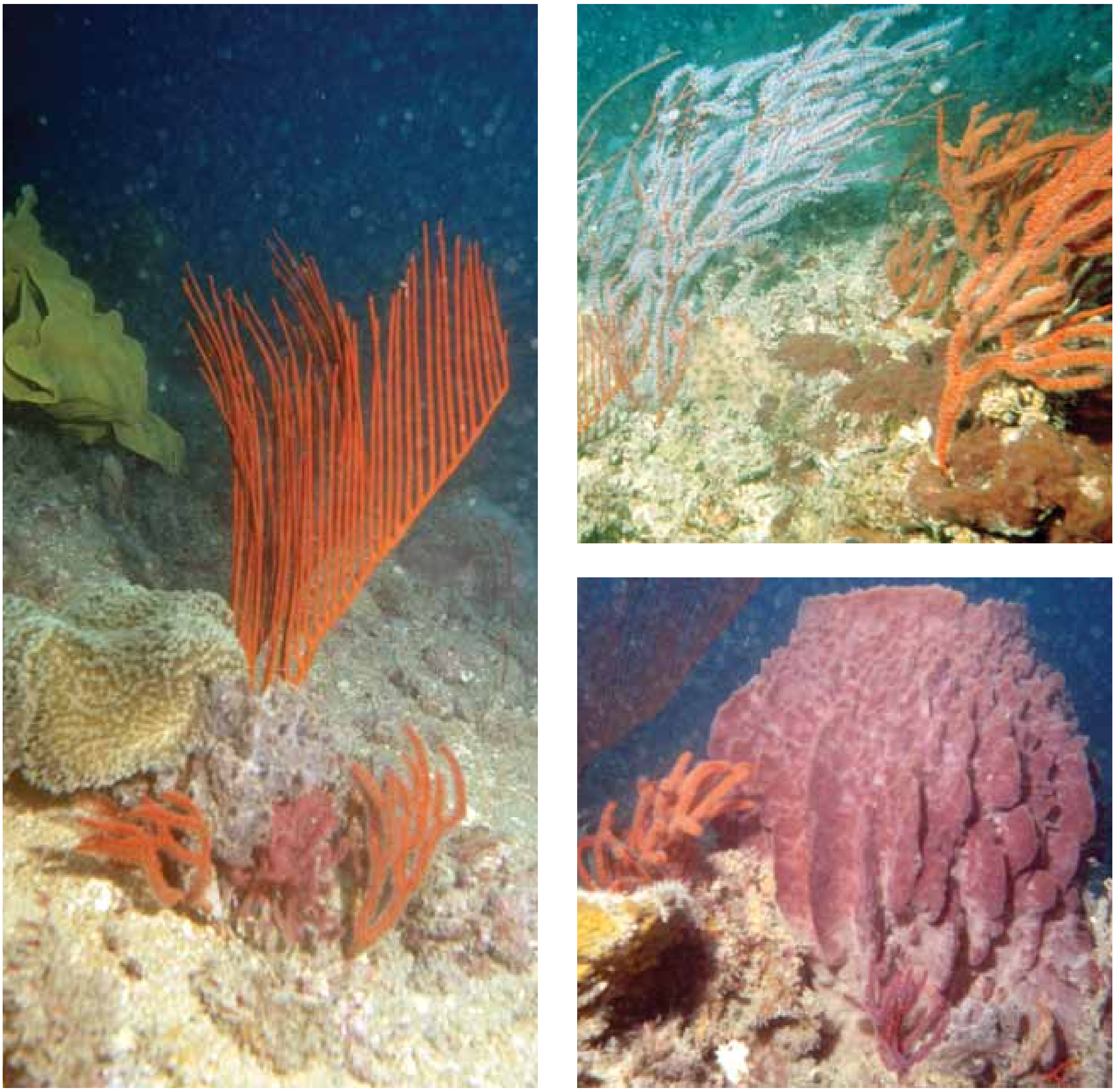


Gorgonian corals captured in the artificial light of CSIRO's remote operated research vehicle on the seabed off far northern Queensland. An area 50 km offshore between the coast and the Great Barrier Reef, known as the lagoon, hosts diverse gardens of marine life: soft corals, sponges, sea-whips and fish. A study by CSIRO Marine Research and the Queensland Department of Primary Industries found that prawn trawling in the region had a cumulative effect on this marine life, depending on trawling intensity and the capacity of individual species to recover between trawls (credit: CSIRO Marine and Atmospheric Research).

Key findings for Queensland

These messages were developed in consultation with staff in the Queensland Government. They represent a subset of the findings of the entire report that were deemed particularly relevant.

What are the likely implications of climate change for Queensland's species and ecosystems?

Climate and ocean changes will affect all of Queensland's marine, terrestrial and aquatic ecosystems in ways that are more widespread and, in many situations, more extreme than currently recognised. The modelling and synthesis undertaken in this report indicate that all ecosystems across Queensland are expected to experience significant environmental change.

Under a moderate global emissions scenario (consistent with two degrees rise in average global temperature), it is projected that environmental conditions are likely to be so different in many parts of Queensland by 2070 that, for any affected location, more than 50% of the plant species eventually occupying that location could potentially be different species to those occurring there today. Under a high global emissions scenario the level of environmental change by 2070 could be more profound, potentially resulting in less than 10% overlap in the plant species occupying an affected location in the future versus those occurring at the same location today. Even under the moderate emissions scenario, these changes may start to become evident in some Queensland regions as early as 2030.

Although there is a high degree of certainty regarding the overall direction of environmental change that Queensland's ecosystems are likely to experience, the way in which individual species and ecosystems will respond is less clear. The actual level of change in species composition at any location will depend on a wide range of interacting factors. These include delayed responses by long-lived species, capacity to tolerate adverse conditions, ability to move to more suitable habitat, the outcome of mismatched species interactions and the actions taken by humans to manage habitats and adapt also.

The projected change to environmental conditions in Queensland will benefit some species by increasing their abundance and distribution but there are likely to be widespread losses of many other species and familiar ecosystems. Terrestrial migration and dispersal rates will generally be slower than the rate of change of environmental conditions across many parts of Queensland. This may cause many species to become extinct locally, or entirely. Modelling suggests that these changes may initially occur more rapidly in the Gulf region and western Queensland.

Although the entire Wet Tropics region is expected to experience significant environmental change, species restricted to mountain-top ecosystems are expected to be the most vulnerable. By 2070 under a high emissions scenario (i.e., >4°C) some mountain top environments may disappear entirely. Low altitude species are less vulnerable because they may be able to migrate to higher altitudes with cooler temperatures.

Over the longer term it is projected that there will be a southward shift in tropical and subtropical environments down the Queensland coast and its offshore oceanic ecosystems.

Under the combined influences of warming, ocean acidification and storm activity, the Great Barrier Reef is generally expected to have its mix of species altered, be prone to disease and bleaching, have reduced coral cover and become more dominated by algae. Evidence to date indicates, with high confidence, that under a scenario of two degrees increase in average global temperature, ocean acidification will be severely affecting reefs by mid century. By 2100 coral reefs could be reduced to collapsed carbonate platforms that can only support simplified habitats and reduced species diversity.

Many of Queensland's ecosystems (terrestrial, freshwater, coastal, and marine) are already under pressure from existing non-climate pressures. Ecosystems will be further challenged by climate change directly and possibly also by some of the adaptive responses of industry and technology to climate change.

Managing weeds, pests and disease will be an ongoing challenge as environmental conditions change. Some introduced species that already exist in Queensland, in such low numbers that they are not considered pests under current conditions, may increase in abundance and become damaging under different conditions. New invasive species may continue to arrive naturally, accidentally or deliberately. In addition, native species that seek refuge by migrating to areas that they have not previously occupied could run the risk of being treated as pests or invasive species by the local by-laws of the newly occupied areas. Natural resource managers will need guidelines to help them decide whether the arrival and establishment of a species will be beneficial and should be facilitated, or whether it will impede management goals and should be resisted.

How will climate change affect ecosystem services in Queensland?

Queensland's natural capital is important to the economy as well as to broader societal wellbeing through its provisioning of goods and services such as water, timber, protection from floods, biodiversity habitat and carbon sequestration. The projected changes to Queensland's natural ecosystems, as a result of climate change, are expected to directly affect the ecosystem services currently provided. This report does not quantify the decline in quality or quantity of ecosystem services but it demonstrates that their increasing scarcity due to climate change has the potential to lead to increases in production costs and reductions in social and economic benefits.

Terrestrial ecosystems – as compared with technological options for treating and purifying water – cost-effectively and efficiently capture, filter and store freshwater for use by humans and a diversity of plant and animal species. Climate change is projected to alter the reliability and quantity of rainfall throughout Queensland. In some regions, lower rainfall will mean less freshwater being naturally available. Consequently, the cost of capturing, storing and reliably supplying freshwater for human and ecosystem uses will substantially increase. Where competition between humans and ecosystems for limited freshwater supplies intensifies, and occurs over an extended period, ecosystem functioning may be irreversibly compromised. Human needs may then have to be fulfilled through alternative costly and energy-intensive water-treatment technologies.

The cultural identity of the tourism sector in North Queensland depends on the integrity of ecosystems and biodiversity in the Wet Tropics and Great Barrier Reef. Projected changes in natural environments, associated with climate, coast and ocean change, will cause disruptions and potentially significant losses in economic and employment opportunities as tourism and recreation-related industries are forced to adjust.

Rural industries, such as the pastoral and agricultural sectors, depend on a range of ecosystem services that includes productive native pastures, shade trees and shelter-belts, pest control, pollination, photosynthesis, water filtering and nutrient cycling. Projected changes in Queensland's natural environments could lead to a decline in ecosystem services currently being experienced by rural industries and result in productivity issues, higher production costs and higher food prices. This could compromise the viability of many of these rural industries and communities depending on their resilience and capacity to adapt.

Over and above amenity and cultural services provided by coastal ecosystems such as beaches, dunes and estuaries, these systems provide the service of protecting coastal infrastructure from wave action and storm surge. Under climate change, sea levels are projected to rise and storm surges to become enhanced and possibly more frequent. This will increase the importance and value of the protection services provided by these coastal ecosystems, particularly since substituting them with hard, infrastructural defences will incur large upfront and ongoing economic costs. An additional concern is that these ecosystems will themselves be entirely and permanently inundated where human settlements and seawalls prevent them from migrating landward.

Marine ecosystems provide habitats and breeding grounds for Queensland's commercial and recreational fishing industries. Projected changes to Queensland's marine ecosystems (particularly the Great Barrier Reef) will alter the health, location and possibly even size and composition of fishery stocks. The economic and social consequences of this will be experienced in the form of increased costs, reduced revenues and rising unemployment in both the fishing and tourism industries. In addition there will also be declines in the social benefits derived from the cultural, spiritual and recreational services these ecosystems provide.

Of particular importance and value in the context of climate change is a range of services that emerge from biodiversity that if recognised and managed can support the successful adaptation of a wide range of Queensland sectors. These 'adaptation services' include: protection, where ecosystem structure provides the 'scaffolding' to help withstand climatic extremes; buffering, where ecosystem functioning provides resilience through substitution to ensure services continue under a range of possible environments; and options, where diversity in ecosystem composition supports flexibility in decision making, particularly in how ecosystems are able to transform.

What can be done to incorporate climate change into the management of species and ecosystems?

Minimising the impact that ecosystem change has on Queensland's biodiversity will require policy objectives shift from protecting the most threatened species or preserving the current state of ecosystems to prioritising ecosystem functioning and supporting the natural movement of species. Focussing on such objectives is expected to be more effective in preserving biodiversity as ecosystems change but will have significant implications for Queensland legislation and will challenge the prevailing worldviews and values of individuals and communities.

Early action will be required if the level of impact that ecosystem change has on Queensland's biodiversity is to be minimised. Activities to consider in an early-action response include:

- protecting and restoring habitat in selected areas to assist long-distance migration (corridors);
- enabling local adaptation and persistence of species by managing habitat diversity, local connectivity and disturbance;
- identifying and conserving areas now that will be important to ecosystem viability under future climate conditions;
- identifying areas that provide refuge from the direct impacts of climate change and other disturbances;
- building the capacity of managers to anticipate and appropriately account for future impacts in today's decision making; and
- attracting early, upfront investment and support from private and public actors in the design and implementation of adaptation activities.

Forests planted to sequester carbon, as part of the emerging 'carbon economy', have the potential to attract significant investment in landscape restoration and habitat connectivity. Careful thought needs to be given to how such projects are designed and located particularly in the context of climate change (i.e., long time horizons and uncertainty) and with due awareness of the tradeoffs between carbon, water, timber, food, and biodiversity.. Ecological-economic modelling can be a useful tool for assessing these tradeoffs in restoration initiatives over space and time in the context of projected environmental changes. The particular mix of compatible species selected for carbon sequestration projects in forests will also need to be assessed for resilience to future changes in environmental conditions for that area.

Minimizing the impact of non-climate-change pressures on ecosystems and biodiversity will reduce the overall pressure they face as the climate changes. This includes reducing existing threats and managing potential increases in pressures resulting from adaptation to climate change in agriculture, fisheries, forestry, water supply and other sectors that may further degrade or fragment natural areas. This is particularly relevant to Queensland's most vulnerable ecosystems, such as the Great Barrier Reef and certain parts of the Wet Tropics, where adaptation options may be limited.

The local and species-level impacts of climate change are still unclear and may only become clear as ecosystems and biodiversity actually begin to change. The risks posed by this uncertainty can be reduced by having a robust and flexible (adaptive) approach to the management of ecosystems and biodiversity. This could be supported by standardised methods for monitoring threats, measuring the health of ecosystems, evaluating the effectiveness of adaptation options and modifying management where and when necessary.

Executive summary

The Queensland Government commissioned this synthesis of climate change impacts and adaptation options for terrestrial, freshwater aquatic, coastal and marine biodiversity, its ecosystems and the services they provide. The information presented here represents a synthesis of the scientific evidence assembled to date.

Projected impact of climate change on biodiversity and ecosystems

This report draws on available literature, existing data, models and scientific inference to describe and summarise the different ways climate change is likely to affect biodiversity, ecosystems and ecosystem services in Queensland. Much of the science is concentrated on the Great Barrier Reef and the Wet Tropics. Less is known about the more arid regions and even less about the vast, and largely unexplored, deep water habitats off Queensland's coast. Information and examples from Queensland are therefore supplemented with national and international studies. Readers should be aware that, while we have presented the current state of knowledge, information about the implications of climate change continues to accrue rapidly.

The current scientific consensus is that substantial change can be expected in natural and human-altered systems. This change is largely driven by rising atmospheric CO_2, ocean acidification, increasing temperatures, declining rainfall, altered rainfall patterns, altered oceanic currents and changed disturbance regimes. The ensuing ecological changes will cascade through biological systems giving rise to shifts in species distributions, changed interactions between species and species extinctions. Future natural landscapes and seascapes will look and function differently from those of today.

It is important to note that climate change is additional to existing pressures acting on already stressed natural ecosystems. Climate change will interact with disturbance regimes (such as altered fire regimes), land use change, water abstraction, pollution, over harvesting, habitat degradation, disease and pathogens, eutrophication, invasive alien species and other agents of change. The result will be the emergence of 'threat syndromes' that could precipitate rapid ecosystem transformations and reduce the supply of familiar ecosystem goods and services. Land managers will benefit from additional support to identify sources of native or alien pests, weeds or diseases that are most likely to disrupt their ecosystems.

Two broad genetic mechanisms are available for species to respond locally and persist during rapid climate change: phenotypic plasticity and evolution. Some species may persist because they are able to adjust their behaviour, morphology, demography, biochemical or physiological properties to suit the new conditions. This is known as phenotypic plasticity. Plasticity can both provide a buffer against rapid climate change and assist rapid evolutionary adaptation. Evolution in a climate change context has the potential to generate rapid phenotypic changes that are genetically-based in some species. Other species may have limited capacity to cope or adapt and may become locally extinct in the short- to medium-term, or retreat to refugia. In this report, we mention the genetic basis for climate change adaptation and acknowledge the potential for ecological surprises, but we have not comprehensively reviewed this literature. Evolutionary genetic considerations could help shape adaptation strategies in regard to the benefits and risks of particular management actions. The research in this area, however, is not yet sufficiently mature to guide the human adaptation strategies that are the focus of this report.

Other response options available to populations experiencing increasingly unsuitable conditions are dispersal or migration. Biogeographic connectivity and adequate time to allow movements or adaptive responses are prerequisites for responding to climate change. Existing habitat degradation and fragmentation across intensively utilised regions points to the potential benefit of management interventions to facilitate such adaptive responses.

Areas of Queensland at particular risk of climate change include the Wet Tropics, high altitude and montane regions, tropical savanna-woodlands, drier rainforests types (including vine thickets), coastal floodplains and wetlands, the Great Barrier Reef, and particular concentrations of species or centres of endemism. Southern parts of the Great Barrier Reef, the Gulf of Carpentaria and southeast Queensland are marine regions that will experience the most change. An anticipated rise in the cloud layer blanketing coastal mountains will result in significant reductions in water intercepted by vegetation during the dry season and may lead to more sclerophyllous mountain-top communities. The majority of Queensland west of the Great Dividing Range is expected to rapidly change due to its low relief. Species will need to respond relatively quickly if they are to keep pace with the change. Features of the landscape that provided refuges and supported native species during past climate change are likely to be important for future persistence.

Rising atmospheric CO_2 concentrations will influence growth and resource allocation in plants. Changes in these processes will mean that many terrestrial plants become less nutritious and potentially more toxic for herbivorous animals.

Ocean acidification, due to absorption of atmospheric CO_2, is close to the point where calcareous organisms, such as corals and a number of planktonic species, may already be experiencing a weakening in their shells or skeletal structure. The growth of species that lay down aragonite (such as reef-building corals and some calcifying plankton) may be in jeopardy given projected increases in atmospheric CO_2 concentrations by 2035.

Due to the combined effects of temperature, acidification, storms, sea level rise and other pressures, the coral reef ecosystems of the Great Barrier Reef will be transformed by mid to late this century. They will be dominated by macro algae and herbivorous fishes. The shallow and emergent parts of coral reefs will be smaller in extent, of lower diversity and provide less of a buffer against ocean swells. Local seabird colonies may migrate southward, decline, or collapse.

The forest fire danger index for 2002-2010 increased by 5-35% compared with that calculated for the 1980-2001 period. Altered fire regimes have great potential to transform terrestrial ecosystems. Increased temperatures, additional plant growth through CO_2 fertilisation, changes in rainfall, and the spread of fire-promoting alien species will act together to alter the risk of fire. For example, a southern shift in cyclones could mean that coastal and hinterland forests will gradually become more disturbance-oriented and prone to burning during periods of drought. The development of new ecological fire management strategies will be required to deal with the threat posed by altered fire regimes.

A projected increase in sea level of 0.8m or more by 2100 will cause a shift in the boundary between fresh and estuarine systems. Sea level rise will be accompanied by inundation of coastal freshwater ecosystems, saltwater intrusion in coastal groundwater systems and upstream movement of tidal influences. High intensity cyclones interacting with sea level rise could irreversibly destroy marine and freshwater habitats and generate new ones, alter mixing patterns in lakes, wetlands, floodplains and estuaries, cause fish kills and bring about loss of seagrass ecosystems. Coastal ecosystems may retain their current land coverage if seaward losses are low and landward barriers minimal.

Projected decreasing annual precipitation, combined with increased pan evaporation, will lower lake levels, change salt concentrations, reduce annual river flow rates and inhibit groundwater recharge. There may also be a reduction in the spatial extent of wetlands and floodplains as well as loss of connectivity between river stretches. Climate change could extend arid and semi-arid conditions in an easterly and south-easterly direction. Western Great Artesian Basin spring wetlands may dry out. Release of sulphuric acid and metals from rewetted acid soils could be a severe problem following cycles of drought and flood.

Increased water temperatures in freshwater ecosystems will result in a higher incidence of eutrophication, enhanced toxicity of contaminants, more frequent and prolonged water column stratification, anoxic conditions (leading to fish death) and intensified blooming of possibly toxic cyanobacteria. These are problems for water management across all sectors.

The warming of Pacific Ocean surface waters (to 100-200m depth) has resulted in an increase in ocean stratification. This limits the vertical exchange of water and has major implications for the supply of nutrients to ecosystems and biodiversity in pelagic and benthic realms. As the East Australia Current extends its influence southwards so will the distribution range of tropical fish species, effectively displacing the southeast Queensland fish biota of temperate origin. Some commercial fisheries will expand (e.g., tropical tunas), others will decline (e.g., temperate sardine, blue mackerel and tailor) and fisheries based on squid may boom.

Catches of species subjected to commercial and recreational extraction (e.g., prawns, barramundi and mud crabs), which depend on summer rainfall patterns providing nutrient enrichment through terrestrial runoff, may decrease in size with declining summer rainfall. Sea level rise plus tidal and storm surges may also reduce the production area of habitat for prawns and estuarine fish, especially in the Gulf of Carpentaria.

A high level of certainty exists concerning the directionality and potential magnitude of environmental change related to CO_2, temperature, ocean acidification and sea level rise. There remains, however, considerable uncertainty in regional rainfall projections and location-specific ecological responses. This uncertainty is exacerbated by the fact that climate change is an additional pressure on natural ecosystems and that change is happening at a speed and extent potentially greater than that experienced in the past or even projected a few years ago.

Even though regional and local details are still unclear it is certain that climate change will have ongoing effects (sometimes positive but often negative) on Queensland's natural environment. This will happen even under the more optimistic of emissions mitigation scenarios. Effects will be more widespread and in many situations more extreme, than is currently recognized.

Modelling has an important role to play in determining the likely direction, magnitude and timing of change. Insight gained from models can inform policy and facilitate planning for adaptation. The results of ecological change models presented in this report, for example, suggest that there is potential for major change to occur in the composition of plant communities in many parts of Queensland. Even under a moderate global emissions scenario (consistent with two degrees rise in average global temperature) it is projected that environmental conditions are likely to be so different in many parts of Queensland by 2070 that, for any affected location, more than 50% of the plant species eventually occupying that location could potentially be different species to those occurring there today. The full impact of these changes will be evident as populations of the more long-lived species gradually decline or where the climate of local habitats may be cooler and as other ecological lag effects play out.

A wide range of different models of ecological change can be developed for different emission scenarios, biological groups, human and natural responses, and resolutions. These will vary depending on the particular context, and set of climate adaptation options, under consideration by different ecosystem managers. We present just a few key examples to demonstrate the general principles of the modelling approach to climate change impact assessment and adaptation planning. Further applications of this approach are best developed in collaboration with the program managers who are responsible for implementing climate adaptation policy.

Impact of climate change on Queensland's ecosystem services

Ecosystem services are the aspects of ecosystems utilized (actively or passively) to produce human well-being. They are often grouped into four types: provisioning, regulating, cultural and supporting, based on the Millennium Ecosystem Assessment conceptualization of the relationship between ecosystem structures and functions and the benefits humans derive from them.

Biodiversity provides the building blocks from which ecosystem services emerge. In the context of a changing climate, where the possibility of rapid non-linear change to ecosystem functioning exists, the importance of biodiversity will become critical. Ecosystems provide a range of services that can support successful adaptation to climate change in a wide range of Queensland sectors. These services can be drawn from all four categories of ecosystem service.

Here we recognise three broad types of 'adaptation services' provided by biodiversity: *protection*, where ecosystem structure provides the 'scaffolding' to help withstand climatic extremes; *buffering*, where ecosystem functioning provides resilience through substitutability to ensure services continue under a range of possible environments; and *options*, where diversity in ecosystem composition supports flexibility in decision making, particularly in how ecosystems are able to transform with climate change.

With climate change, these biodiversity adaptation services will have increasing value and importance to society, particularly where technological solutions cannot keep pace with the magnitude and rates of change expected under a >2°C warmer world. However, biodiversity will also be at risk from these changes and timely interventions will help to ensure these services and other social and economic values continue to be available in the future.

The agricultural, forestry, fishery, tourism and other natural resource sectors are all important contributors to the character, viability and wellbeing of Queensland's economy and communities. These industries depend on a wide range of ecosystem services provided by terrestrial, freshwater, coastal and marine ecosystems. It is only possible to estimate the economic (i.e., utilitarian and not intrinsic) value of an ecosystem service's contribution to a sector, individual or community if that service's value can be ascribed (i.e., not intrinsic or held values), measured at the margin, and expressed in terms of exchange. This is clearly possible for 'wild-harvested' fish and aquaculture from the Great Barrier Reef - which have an estimated gross market value for the tonnes of annually harvested product of about $150 million and $50 million, respectively for 2005/6 (Access Economics, 2007) – for example, but is clearly not possible for the intrinsic, spiritual, cultural, and indirectly useful (e.g., supporting services) values derived from these services.

Biodiversity that is clearly linked to economic returns of an industry sector tends to be conserved and appropriately managed. Examples are the Great Barrier Reef and its fisheries, or the tropical rainforests of north Queensland and tourism. Where this dependence of industry on biodiversity is less apparent, such as in intensive forestry, aquaculture and cropping systems, where new technologies increasingly make substitution of ecosystem services cheaper, biodiversity tends not to be a consideration. In the context of projected changes to the 'operating environments' of these modified agro-ecosystems brought about by multiple drivers of change, it is important that broader, more inclusive and holistic views of what is valued about ecosystems are needed (i.e., expanded beyond only the provisioning services to include the supporting and regulating services) because substitution or restoration of many of these ecosystems will likely be costly, impractical or even impossible.

More quantitative assessments will help highlight both the benefits that people derive from ecosystem services and the dependence of these services on biodiversity. Such assessments could build the economic case for biodiversity management by helping clarify the link between biodiversity and the Queensland economy. As progress in this regard is likely to be difficult and slow – due to the complexity of the dynamic and non-linear relationships between biodiversity, ecosystem functioning and ecosystem service provisioning – yet important and large-consequence decisions need to be urgently be made, it is essential that these are made within a risk-and-uncertainty management framework underpinned by principles such as: minimising regrets, building redundancy, and maintaining options.

Under climate change, the quality, quantity or type of ecosystem service could change. For example, as described above, some temperate fish species in southern Queensland will be driven further south and may be lost to local fishing fleets, but tropical species that replace them may support new fisheries in the future. By far the largest potential climate change impact on ecosystem services, and the one with the greatest uncertainty, will be the effect on freshwater supplies for consumptive and non-consumptive uses. Extraction of water for such uses will compete with environmental requirements for the maintenance of freshwater, estuarine and terrestrial ecosystems and the services they provide.

This impact of climate change on freshwater provision will be closely followed by impacts on the type, quality or quantity of ecosystem services available to the tourism sector and rural industries. These changes could have profound social, economic, and cultural/heritage impacts with likely serious implications for the cost of food and freshwater production and general health and wellbeing.

How can Queensland best prepare for the projected level of ecosystem change?

Adaptation to climate change is a new challenge for policy and natural resource management. In preparing for the projected level of ecosystem change, adaptation actions plans should account for the general principles (listed below) that are emerging from recent collective experience.

Climate change adaptation requires policy and management responses across multiple scales of change, prioritised according to the timing, location, magnitude and certainty of potential impacts. Where uncertainty exists to preclude such a prioritisation process, decisions need to be informed by a risk-and-uncertainty management framework underpinned by principles of minimising regrets, building redundancy, and maintaining options.

The uncertainty associated with how climate change will affect ecosystems requires the development of flexible, risk-spreading, and robust decision strategies that are implemented within iterative and participatory processes (i.e., active adaptive management) that can effectively respond to new information.

The likelihood that global average warming may exceed 2°C means that policy and management frameworks should consider when and how to switch from 'incremental' to 'transformative' responses that require new objectives and actions.

A paradigm shift in ecosystem management is needed because the current approaches have not been sufficient to halt biodiversity decline. A considerably greater response and/or different actions will be required under climate change. Elements of a paradigm shift include: increasing investment (financial, time and effort); managing for, rather than resisting, change; managing for significant loss of species and ecosystems; promoting coordinated and collaborative responses between government, industry, science and the broader community; focussing on ecosystem services, ecological and evolutionary processes and functional landscapes rather than species; understanding and managing changes in the values and preferences of society to accommodate the conservation paradigm shift described above; and planning over longer time scales and larger geographic areas.

Evidence for climate change, and the inevitability of change continuing, is clear. Adaptation to climate change needs to start now.

The processes of designing and implementing adaptation policies under a new conservation paradigm of managing for significant loss should try to account for the largely unpredictable responses to these policies due to the dynamics and interdependencies between peoples values, their understanding of the science, and the changing rules.

An initial set of seven priority themes for the development of adaptation pathways has been identified to enable Queensland to achieve multiple biodiversity outcomes. These themes are outlined below. Adaptation pathways, consisting of phased actions that incorporate new information as it becomes available, can be developed around each of these themes and integrated with existing Queensland Government programs by consultation with relevant agencies.

1. Reassessment of the objectives of biodiversity management to accommodate significant changes in the abundance and distribution of species, the structure and function of ecosystems, and the multiple ways in which biodiversity is experienced and valued by society (i.e., in the form of species, ecosystems and land- sea- and river-scapes). This will involve an iterative process of intense engagement, communication, negotiation and ratification between government, communities, industry and science.
2. Recognition and valuation of the 'adaptation services' provided by biodiversity in underpinning the resilience and capacity of ecosystems to absorb disturbances (such as cyclone damage, flood and storm surge) and adapt to climate change variability to ensure the sustained provisioning of ecosystem services to a wide range of community and industry sectors.
3. Preparation for the likelihood of substantial changes in biodiversity and ecosystem services and the associated need to substantially increase biodiversity management effort.
4. Implementation of initial actions to improve biodiversity management by ensuring that natural resource managers (encompassing public and private natural resource users and owners) better understand the implications of climate change and are more aware of how to respond through current programs.
5. Reduction and management of other pressures on biodiversity in order to increase the likelihood of biodiversity adapting to climate change. This includes managing the conflicts that will arise with agriculture, fisheries, coastal development and other sectors as they also adapt to climate change.
6. Proactive management of habitat to build the resilience of biodiversity and ecosystems across whole landscapes. Different types of management will be applicable in different situations. Actions that have long-term implications such as enhanced connectivity, revegetation and facilitated movement require strategic landscape designs and detailed risk assessments.
7. Proactive management of hydrological processes on land and in waterways in order to sustain human and environmental uses.

Queensland has already made substantial progress in managing the pressures of development on biodiversity and natural resources and in developing adaptation strategies and initiatives that begin to address the known adverse effects of climate change. Future action will be more productive if supported by environmental and ecological modelling based on critical monitoring and evaluation within an active adaptive management framework. Because active adaptive management has the ability to take the assumptions of likely responses to, and timing of, climate change into account, this approach can guide decisions about where adaptation actions will be most effective.

Glossary of acronyms

ABARE Australian Bureau of Agricultural and Resource Economics, Australian Government

BoM Bureau of Meteorology, Australian Government

BRS Bureau of Rural Sciences, Australian Government

CSIRO Commonwealth Scientific and Industrial Research Organisation, Australian Government

DAFF Department of Agriculture, Fisheries and Forestry, Australian Government

DCC Department of Climate Change, Australian Government

DEEDI Department of Employment, Economic Development and Innovation, Queensland Government

DERM Department of Environment and Resource Management, Queensland Government

DEWHA Department of the Environment Water Heritage and the Arts, Australian Government

DPIF Department of Primary Industries and Fisheries, Queensland Government

DSEWPaC Department of Sustainability, Environment, Water, Population and Communities, Australian Government

EPA Environmental Protection Agency, Queensland Government

FFDI Forest fire danger index

GBRMPA Great Barrier Reef Marine Park Authority, Australian Government

GCMs Global climate models

GDM Generalised dissimilarity modelling applied in climate change analyses

GHG Greenhouse gases

IPCC Intergovernmental Panel on Climate Change

NRMMC Resource Management Ministerial Council, Australian Government

OECD Organisation for economic cooperation and development

PES Payment for ecosystem services

QCCCE Queensland Climate Change Centre of Excellence, Department of Environment and Resource Management, Queensland Government

RAMSAR An international convention to conserve wetlands. Named after a town in Iran.

sCBD Secretariat of the Convention on Biological Diversity, based in Montreal, Canada

SCCCWEA Standing Committee on Climate Change, Water, Environment and the Arts, House of Representatives, The Parliament of the Commonwealth of Australia

SRES Special Reports on Emissions Scenarios

WMO World Meteorological Organization, United Nations, Geneva

Glossary of technical terms

In defining the following terms used in this report we aimed to place them within the context of climate change

Abstraction of water. The process of taking water from sources, such as groundwater.

Acclimatization. The physiological adaptation of animals and plants to changes in climate.

Accretion. Slow addition to soil sediments to land by runoff processes.

Acidity. Referring to the degree to which the pH of a solution is below 7.

Adaptation. How an organism adjusts to better exist under a set of environmental conditions.

Alien species. Plants, animals, and other organisms that have been introduced into an ecosystem in which they do not naturally occur.

Altered synchrony. Referring to actions that no longer occur simultaneously.

Anaerobic decomposition. Processes involving the breakdown of materials by microorganisms in the absence of oxygen.

Annualised. Refers to how values are adjusted to represent what is expected for a full year.

Anoxic. Without oxygen, representing an extreme case of hypoxia (low oxygen).

Anthropogenic. Events caused primarily by the activities of people.

Aragonite. Crystal form of calcium carbonate.

Asynchrony. When events fail to concur in time.

Atmospheric circulation. How air moves over the surface of the earth at larger scales (e.g., trade winds; jet streams).

Benthitic. Refers to events or processes occurring at the bottom of a body of water such as a lake.

Bioclimate. Formally, the study of how climatic conditions affect organisms.

Biodiscovery. Searching for biological materials or for specific biota, which on state lands in Queensland requires a permit.

Biodiversity. Referring to the variety of living organisms at all levels of organization: genetic, within species, between species, and in ecosystems and landscapes.

Biogeochemical. Where biological, chemical and geological processes operate to generate a phenomenon such as the breakdown of minerals and organic matter by micro-organisms to form soil.

Biogeography. Formally, the field of biology that studies how animals and plants are distributed in time and space. With climate change, biogeographic distributions will be altered.

Biomass. The total weight of biological material, such as grasses, in an area, and used, for example, to quantify the amount of fuel or forage.

Biomes. Broad areas on the earth with similar climatic conditions and ecosystem types, such as savannas.

Bioprospecting. Specifically searching for biological materials that potentially have medicinal or other commercial values.

Biota. All biological species such as animals, plants, fungi and microorganisms that occur at a given ecosystem.

Brackish. Refers to water that is more saline than fresh water, such as found in coastal estuaries.

Calcareous. Materials, such as soils, that are chalky because they contain calcium carbonate.

Calcifying biota. Organisms, such as red algae, that have the ability to build structures, such as reefs.

Carbon dynamics. The movement (cycling) of carbon, and its compounds, through ecosystems, from atmosphere to producers, consumers, microorganisms and soils, and into bodies of water such as oceans.

CFCs. Chlorofluorocarbons.

CH_4. Methane gas.

Climate change 'cascades'. Refers to how the effects of climate change have flow-on effects, such as through the different trophic-levels in an ecosystem (e.g., from producers to consumers), to alter ecosystem function and ultimately affect people through the quality, quantity and character of ecosystem services.

CO_2. Carbon dioxide.

Cyanobacterial blooms. Algal blooms in bodies of water such as lakes that are caused by cyanobacteria species. Typically these blooms are blue to reddish-brown, toxic and foul smelling.

Decadal. Consisting of tens, such as groups of ten years.

Dispersal ability. Refers to the capacity of species to move from one habitat patch to another at any stage of a life cycle.

Diurnally. A daily pattern such as how the activity of animals changes for day to night.

Dredging. An excavation activity, such as removing bottom sediments from a waterway.

Ecological. Referring to terms used in the science of ecology, such as ecosystems.

Ecological cascades. How disturbances, such as climate change impacts, are transferred through different trophic-levels in an ecosystem.

Ecosystem. A community of organisms in the specified area, which interact with one another and with the physical environment.

Ecosystem engineers. Refers to organisms that have the capacity to significantly modify an ecosystem or habitat.

Ecosystem functions. How ecosystems operate to capture energy from the sun, water from rainfall, and provide, for example, habitats for species.

Ecosystem services. Ecosystem services are the aspects of ecosystems utilized (actively or passively) to produce human well-being. They are often grouped into four types: provisioning, regulating, cultural and supporting, based on the conceptualization of the relations between ecosystem structures and functions and the benefits humans derive from them.

Ecosystem transformers. Organisms that can alter ecosystems (see ecosystem engineers).

Endemic/endemism. Species found in a particular area. For a region, endemism refers to the degree to which species are only found in that area.

Epigenetic. The study of genetic changes in organisms.

Eutrophication. Refers to the state of health of a body of water where the addition of nutrients and organic matter, such as material rich in nitrates (e.g., sewage), cause a depletion of oxygen, which negatively affects many fish species.

Evapotranspiration. The combined processes of evaporation and plant transpiration of water from vegetation to the atmosphere.

Extinction. Refers to the loss or disappearance of a species from a specified area such a bioregion.

Fire regime. A pattern of fire in an area defined by fire frequency and intensity.

Fishways. Refers to passages or structures, such as fish ladders, designed to promote the movement of fish along waterways, such as past dams and weirs in rivers.

Geohydraulic. How water moves or is effected by forces along geomorphic structures, such as along river and stream banks.

Grid cells. Pixels or square units observed, for example, in a remotely sensed image.

Habitat. Where individuals of a specified species live because conditions suit their survival.

Halocarbons. Compounds of carbon and halogens, such as fluorine and chlorine.

Hectopascal (hPa). A unit of standard atmospheric pressure, for example, 1000 hectopascals.

Hotspots. A term used by organisations such as Conservation International to refer to areas that are particularly rich in animal and plants species that are under threat.

Hydrate sources. Refers to bodies of water such as glaciers that can be studied, for example, for trapped green house gases such as carbon dioxide and methane.

Ions. Charged (+ or -) particles, such hydrogen ions (H+) and hydroxides (OH-).

Integrated modelling. Computer simulation models that aim to explore the combined and interacting effect of multiple factors (e.g., ecological and social).

Intrinsic. Refers to the inherent property of a species or an ecosystem, such as a species ability to adapt to climate change.

kW/m^2. A thousand Watts per square meter (see W/m^2).

Lag effects. Refers to actions where their impacts are delayed.

Landscape. Formally, an area defined by a set of ecosystems that are connected and function as a unit.

Littoral. Refers to that part of a body of water that is close to shore, usually referred to as the littoral zone.

Macroevolutionary processes. Evolution occurring over the large scale, such as species evolution over geologic time.

Maladaptation. Organism that are poorly adjusted to existing environmental conditions.

Match-mismatch effects. Refers to ecosystem situations where species interactions become asynchronous, such as predator-prey and plant-pollinator.

Matrix permeability. Refers to the degree to which species can readily move or disperse across a landscape between habitats, such as along vegetation corridors or over farmland. Matrix is the intervening landscape between suitable patches of habitat that inhibits movement.

Mesic. Ecosystems that occur where rainfall and available soil moisture are moderate, that is, between arid (deserts) and wet (rainforest) extremes.

Mitigation. Actions taken to moderate the effects of climate change.

Mixing patterns. Refers to how climate change could alter how the layers, for example of cold and warm water in a lake or the ocean, mix.

Modelling. The process of building and using computer-based models to simulate changes in climate and the responses of ecosystems to climatic drivers.

Montane. Refers to landscapes and vegetation types occurring in mountainous areas.

Natural capital. Encompassing all types of biodiversity from wild nature to managed ecosystems (i.e., agro-ecosystems and monocultures) that underpin ecosystem services.

Niche. Refers to how an organism makes a living, such as a decomposer of leaf matter in the soil.

N_2O. Nitrogen dioxide.

Ocean acidification. Refers to the ongoing decrease in the pH and increase in 'acidity' of the Earth's oceans caused by the uptake of anthropogenic carbon dioxide from the atmosphere.

Orographic. Refers to how masses of air, such as clouds, are influenced by obstructions such as mountain ranges.

Paradigm. A theory, methodology, process or pattern that is assumed to be accepted worldwide.

Pathogens. Microorganisms such as bacteria and viruses that cause diseases in animals and plants.

Pelagic. Refers to that part of a body of water that is not close to shore or the bottom, usually referred to as the pelagic zone, or describes a species in its habitat, such as pelagic fish.

pH. A measure of the concentration of hydrogen H+ ions relative to hydroxide OH- ions. Uses a scale from 1 (highly acidic) to 14 (highly basic), with 7 being neutral.

Phenology. Refers to the study of phenomena that occur over the seasons, such as how plants flower in late summer.

Phenotypic plasticity. The capacity of an organism to change its behaviour, morphology, demography, biochemical or physiological properties to suit new or varying conditions.

Phylogeny. The study of the genetic and evolutionary relatedness of groups of organisms such as populations or species.

Phytoplankton. Microscopic or small organism related to plants such as algae living in bodies of water.

Pollination. Refers to the transfer of pollen from the anther of a flower to the stigma of that or a different flower.

ppmv. Parts per million by volume.

Pulses (of sediment). Surges of soil particles carried in runoff that impact bodies of water, such as streams, rivers and estuaries.

Radiative balance. The comparative amounts of incoming and outgoing solar energy in the form of radiation.

Range shifts. Refers to changes in the distribution of a population or species, such as up a mountain-side.

Refugia. An area that remains relatively unaltered under climate change, hence, remains suitable habitat for species dependent on that habitat.

Resilience. The capacity of an ecosystem to recover and persist after being affected by a disturbance.

Ring-fencing revenues. Refers to income from a subsidiary or branch of a company, such as from a wind farm operation owned by a large utility company but operated as a separate entity.

Riparian. Refers to the area along an interface between land and a stream or river, usually referred to as the riparian zone.

Samphire. The common name given to a number of plant species typically growing in coastal saline areas, such as species of Salicornia, also known as glassworts.

Savanna. A broad vegetation type varying from grassland with scattered trees to open woodlands where the canopy is not closed as in a forest.

Sclerophyll/Sclerophyllous. Refers to those vegetation types characterised by a dominance of plants with hard leaves (sclerophyll) and short internodes.

Sequestration (of carbon). Processes that capture carbon dioxide, such as photosynthesis.

SO_2. Sulphur dioxide.

Space-for-time substitution. Where sites, such as restoration plots on mines, that are in different locations and of different ages are studied because there is insufficient time to study one site over time.

Speciation. The processes involved in the evolution of new species.

Stability. Refers to ecosystems that remain relatively unaltered when disturbed, for example, by a cyclone.

Stratified/stratification. Refers to how water columns in bodies of water such as lakes and oceans form distinctive layers.

Symbionts. Organisms that live together in symbiotic relationships, that is, where they are dependent on each other for survival.

Syndrome. A set of concurrent things that usually form an identifiable pattern.

Synergistic. The interaction of two or more agents or forces so that their combined effect is greater than the sum of their individual effects.

Taxon (plural: taxa). A group of (one or more) organisms, which a taxonomist adjudges to be a unit.

Tipping point. The point at which the buildup of minor changes or incidents reaches a level that triggers a more significant change.

Top-down approach. An approach to a problem that begins at the highest conceptual level and works down to the details. A type of information processing.

Translocation. The capture, transport and release; or introduction or reintroduction; of plants or animals from one location to another.

Trophic. Of, or relating to, feeding and nutrition.

Trophic level. Refers to the position that an organism occupies in a food chain (what an organism eats, and what eats the organism).

Tsunami. A series of ocean waves with very long wavelengths (typically hundreds of kilometres) caused by large-scale disturbances of the ocean.

Utilitarian. Designed for use rather than beauty.

Vapour pressure deficit. The difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated.

Water balance. The flow of water in and out of a system.

W/m^2. Watts per square meter, a SI unit for the amount of incoming solar irradiance.

Zooplankton. The animal constituent of plankton consisting mainly of small crustaceans and fish larvae.

Riparian vegetation, Beatrice River, North Queensland (credit: CSIRO).

1. Scope and purpose

1.1 Introduction

The natural environments of Queensland are a unique mix of ecosystems that provide habitats for a diverse array of native plants and animals. These ecosystems also supply an abundance of renewable natural resources that have played a key role in the development of the State's economy and lifestyle. In Queensland, and around the world, local communities are recognising that their wealth and wellbeing are intrinsically dependent on healthy ecosystems providing an array of services and functions (Millennium Ecosystem Assessment 2005). This understanding has developed as awareness of the environmental impacts of widespread intense utilisation of natural resources has grown, and the often insurmountable cost of remediation following the clearing of natural habitats has become apparent.

Feedback from many small and large scale land management practices, combined with the effects of industrial pollution, have affected the global climate system with wide-ranging consequences for healthy ecosystems and future sustainability. Baseline monitoring of weather has demonstrated that climates are rapidly changing as the atmosphere warms and that warming has accelerated in recent decades (Steffen 2009). Governments have moved from impact assessments to planning for adaptation so that local communities can be helped to adjust to changed living conditions. These adjustments include different ways of managing landscapes as the environment changes.

Climate change is already affecting the environment, ecosystems and species in many ways and the evidence suggests that the impacts will become more severe as climate change continues. These impacts are likely to be compounded by fragmentation and more intense utilisation of natural environments (sCBD 2010).

A large number of earlier reports have outlined the likely impacts of climate change on biodiversity and ecosystems in Australia (e.g., Dunlop & Brown 2008; Hilbert *et al.* 2007; Howden *et al.* 2003; Hughes *et al.* 2010; Low 2011; Steffen *et al.* 2009a). Australia is one of the countries considered most vulnerable to climate change because of extensive arid and semi-arid areas, highly variable annual rainfall, high fire risk, fragile ecosystems, and communities and industries that depend on healthy ecosystems that are already under pressure (Garnaut 2008; Hennessy *et al.* 2008; IPCC 2007a). Climate change is now recognised as a key additional threat to the conservation of Australia's biodiversity (DEWHA 2009a; Westoby & Burgman 2006) and adaptation responses are a central mission of new or revised biodiversity strategies (DERM 2010a; NRMMC 2010).

Taking into account the knowledge accrued from a wide range of scientific studies, reviews and commissioned reports, the Queensland Government commissioned this further synthesis. It focuses on the likely impact of climate change on biodiversity and the health of ecosystems in Queensland's terrestrial, freshwater aquatic, coastal and marine ecological realms. In order to better connect climate change impacts on ecosystems with climate change impacts on people, this report extends previous reviews by highlighting the importance of ecosystem services and the adaptation options available to conserve them.

When considering the effects of climate change on biodiversity we must include the array of environmental changes occurring as a consequence of global warming. These environmental changes will lead directly to an ecological cascade of change affecting biodiversity at all levels of organisation: from genes to individuals, populations and ecosystems, landscapes, seascapes and biomes (Dunlop & Brown 2008; Johnson *et al.* 2011; Steffen *et al.* 2009a). Many species will also be affected *indirectly* via their interactions with other affected species and ecosystems and via feedbacks to the environment. The cascading effect of climate change on biodiversity suggests multiple types of ecological change can be expected, with many different implications that vary regionally in different settings. The process of summarising these changes, identifying critical outcomes for biodiversity and ecosystem services, and their implications for adaptation decision making, is challenging because of the increasing level of uncertainty over long timeframes (Stafford Smith *et al.* 2011).

This report therefore draws on available literature, existing data and scientific inference to describe and summarise the different ways climate change is likely to affect biodiversity, ecosystems and ecosystem services in Queensland, and the array of adaptation principles and actions that decision makers may consider in managing these systems. However, while the background reports (see Section 1.2) capture some aspects, we did not undertake to review or assess the internal operational processes and management activities currently underway within the various Queensland and Commonwealth agencies. Their current and ongoing works and activities were not part of the scope of this report.

1.2 Report structure

The information presented here represents a summary of the scientific evidence assembled in seven more detailed background reports.

Section 2 presents an overview of observed trends and projected changes in climate (summarised from Williams & Crimp 2012) together with an example of how modelling techniques can be used to indicate how much change might be expected for environments in Queensland and what these changes might mean for the ecological character of particular regions or ecosystems (summarised from Ferrier *et al.* 2012).

Section 3 outlines the potential ecological changes resulting from climate and environmental change for each biological realm: terrestrial ecosystems (summarised from Murphy *et al.* 2012), freshwater aquatic ecosystems (summarised from Kroon *et al.* 2012) and coastal and marine ecosystems (summarised from Bustamante *et al.* 2012).

Section 4 explains the relationship between ecosystems, natural capital and ecosystem services and their role in the Queensland economy (summarised from Williams *et al.* 2012).

Section 5 outlines the principles of adaptation and discusses a range of appropriate adaptation actions that could be implemented to conserve biodiversity, ecosystems and ecosystem services (summarised from Dunlop *et al.* 2012).

Section 6 identifies critical information and knowledge gaps to achieve adaptation and summarises the key concepts and findings of this report.

1.3 Biodiversity definition, adaptation and glossary

In this report we most often refer to biodiversity in general terms, as encompassing the full variety of all life forms on earth—the different plants, animals and micro-organisms; their genes; and the terrestrial, marine and freshwater ecosystems of which they are a part (DERM 2010a). However, for clarity or emphasis, we may also refer to species and ecosystems or to biodiversity and ecosystems or natural areas.

The term 'adaptation' may seem ambiguous because it has two meanings. Adaptation can refer to the genetic and ecological capacity of biodiversity to autonomously respond to changes in the environment. Adaptation in this report also describes human actions in response to climate change and in successfully facilitating autonomous or dependent adaptation by biodiversity.

These and other terms introduced throughout this report, that may be ambiguous or have specific scientific meanings, are listed in the glossary.

View across coastal estuaries to Hinchinbrook Island, Queensland
(credit: Gregory Heath, CSIRO Land and Water, science image BU5468).

2. Projected environmental change

Over the last 50 years, Queensland has warmed more rapidly than the Australian average with significant declines in rainfall across the central and coastal regions of the State over the same period. Pacific Ocean surface waters have warmed by 0.6°C to 1.0°C to a depth of 100 to 200m, and the East Australia Current is strengthening its flow southward. Sea level has risen 20cm globally since pre-industrial times and is currently rising by 2.5cm per decade. Extreme events, such as floods, drought, and tropical cyclone frequency and intensity, have also changed recently.

Various greenhouse gas emission scenarios explore alternative development pathways for demographic, social, economic, technological, and environmental futures. Current emission levels are tracking around the upper range of a high emissions scenario, which could lead to a doubling of carbon dioxide (CO_2) and a warming of 4°C, relative to pre-industrial levels, by the 2070s. This will further increase the dissolution of CO_2 in the ocean, and hence the concentration of dissolved hydrogen ions, resulting in unprecedented levels of acidification, that will hasten a tipping point for bicarbonate rather than carbonate formation in seawater. This change has the potential to cause the decline of calcifying biota in the southern ocean.

Projected temperature increases for Queensland regions by 2050 are in the range of 1–1.4°C for a low emissions scenario (B1) and 1.7–2.2°C for a high emissions scenario (A1FI). Annual rainfall projections are more uncertain but could decline by up to 5% for the low emissions scenario and up to 10% for the high emissions scenario. The number of 'exceptionally hot' years in Queensland is projected to increase from a baseline of one event every 22 years (mean for the period 1950 to 2009) to an average of one event every three years by 2050.

Ocean sea surface temperatures will continue to increase and the East Australia Current will flow further south with more intensity, modifying the tropical and subtropical extents of coastal climates and marine habitats. Tropical cyclone intensity may increase across the northern parts of the country, and cyclone genesis may increase at lower latitudes, exacerbating risks of inundation and coastal erosion processes with sea level rise.

Modelling can inform ecological interpretation of environmental change. However, the actual level of change in species composition resulting from climate change will depend on a wide range of interacting factors including lag effects, capacity for adaptation, dispersal capability, biotic interactions and access to refuges.

Modelling suggests potential for major changes in the ecologically-scaled environments, which would have major implications for species composition of plant communities in many parts of Queensland. Even under a moderate-emissions scenario, most locations could have experienced a level of environmental change by 2070 that is greater than the present-day environmental difference between locations with only 50% of their plant species in common.

Some current environments (and associated communities) may disappear completely from the State as a result of climate change. Environments not currently occurring currently anywhere in the State may also appear, and have the potential to support novel assemblages of species.

An example using the Moreton Basin subregion shows how ecological models can be used to visualise, in greater detail, potential impacts of climate change on the ecological character of particular regions or ecosystems within the State.

Modelling could also, in the future, be extended to other biological groups, ecological realms, and to different descriptors of species and ecosystems (genetic and phylogenetic composition, functional groups, life-form groups, habitat structural classes, and so forth).

This section is presented in two parts. A brief overview of observed trends in climate change and projections for Queensland (Section 2.1) is followed by an example, based on a model of terrestrial vascular plant occurrences, of what these changes might mean for ecological systems (Section 2.2).

2.1 Climate change context

2.1.1 Introduction

Overwhelming scientific evidence can now be found that links growing concentrations of greenhouse gases to changes in both global and regional climates (CSIRO & BoM 2007a; Houghton *et al.* 2001; IPCC 2007a; Solomon *et al.* 2007). As stated by the IPCC (2007a): *warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*.

During the 20th century, greenhouse gas concentrations in the atmosphere increased as a result of growing energy use and an expanding global economy. Industrial activity grew 40-fold, and the emissions of gases such as carbon dioxide (CO_2) and sulphur dioxide (SO_2) grew 10-fold (WMO 2011). The concentration of CO_2 in the atmosphere has increased since pre-industrial times from approximately 280 parts per million by volume (ppmv) at the beginning of the 20th century to 387 ppmv by the end of 2010. At current emission rates, atmospheric CO_2 is expected to reach double pre-industrial levels by about 2070 (Hay 2011).

Other important greenhouse gases include the oxides of nitrogen, notably nitrous oxide (N_2O) and halocarbons, including the chlorofluorocarbons (CFCs) and other chlorine and bromine containing compounds. For example, methane (CH_4)—which is formed by anaerobic decomposition of organic matter—rose from a preindustrial atmospheric concentration of around 700 parts per billion by volume (ppbv) to about 1,789 ppbv by 2007 (WMO 2011). Future projected climate change could accelerate the release of methane from hydrate sources like glaciers and permafrost, or from reservoirs buried in wetlands, but complex feedbacks of uncertain magnitude between climate, the atmosphere and these (and other) ecosystem processes mean exact calculations are not possible (Heimann & Reichstein 2008).

The build-up of greenhouse gases in the atmosphere alters the radiative balance of the atmosphere (IPCC 2007a). The net effect is to warm the Earth's surface and the lower atmosphere. This happens because greenhouse gases absorb some of the Earth's outgoing heat radiation and reradiate it back towards the surface. The overall warming from 1850 to the end of the 20th century was equivalent to about 2.5 watts per square metre (W/m^2). Of the gases involved, CO_2 contributed 60%, CH4 approximately 25%, and N_2O plus halocarbons make up the remainder (WMO 2011).

Greenhouse gases have contributed to global average temperatures increasing from 15.5°C to 16.2°C in the last 100 years. The warming effect that would result from a doubling of CO_2 from pre-industrial levels is estimated to be 4 W/m^2 (WMO 2011) and could be realised by 2070.

The rate of atmospheric warming over the last century or more has been buffered by the oceans and the melting of polar ice. Over the twentieth century, global sea level increased at an annual average rate of about 2mm each year (Willis *et al.* 2010), commensurate with ocean warming and thermal expansion (Bindoff *et al.* 2007). The ocean mass also provides a sink for greenhouse gasses, but absorption of atmospheric CO_2 leads to acidification of ocean waters (Sabine *et al.* 2004). As surface waters become more acidic, the concentration of carbonate ions decreases while bicarbonate and hydrogen ion concentrations increase. This change in chemical equilibrium causes a reduction in capacity of the ocean to take up additional CO_2 (Bindoff *et al.* 2007). Between 1751 and 1994 surface ocean pH is estimated to have decreased globally from approximately 8.25 to 8.14, representing an increase of almost 30% in 'acidity' (hydrogen ion concentration) (Orr *et al.* 2005).

2.1.2 Observed climate and ocean change in Queensland

In Australia at both national and regional scales, there is considerable evidence that changes in temperature and rainfall have occurred that are related to climate change (e.g., Alexander *et al.* 2007; Cai & Cowan 2008; Cai *et al.* 2011; Cai *et al.* 2003; Cai & Cowan 2006; CSIRO & BoM 2007a; Nicholls 2006; Nicholls 2007; Nicholls & Collins 2006; Trewin & Vermont 2010). In the discussion that follows we will present a synthesis of information highlighting both historical and projected changes in Queensland's climate.

Annual mean air temperatures in Queensland have increased approximately 0.5°C since the mid-1970s and about 1°C since the turn of the 20th century (Whitfield *et al.* 2010). Since the 1950s, the greatest change in mean temperature has been in southern Queensland, especially across the south western corner of the State. In the two decades to 2010, Queensland experienced only one year with an annual mean temperature below the long-term mean (BoM 2011) and the last decade has been the hottest on record. During the 20th century the average percentage of the State that experienced temperatures in excess of the long-term 95th percentile was about 4.6%. Since 1968 almost 11% of the State, more than twice the 20th century average, has experienced such exceptionally hot years (Hennessy *et al.* 2008).

Since the 1950s, Queensland has experienced declining annual rainfall in some populated coastal regions and increases in northern and inland regions (CSIRO & BoM 2007a; CSIRO & BoM 2010). Changes are evident in the total number of rainfall days, the number of very heavy precipitation days (at least 30mm rainfall) (BoM 2011) and the amount of precipitation on extremely wet days (those days with precipitation greater than the 99th percentile) (Alexander *et al.* 2007; BoM 2011). The decline in annual rainfall is largely attributed to an increase in the frequency of El Niño – Southern Oscillation (ENSO) conditions in the Pacific Ocean (Cai *et al.* 2010).

The recent drought in southeast Queensland (2001–2008) was the most severe on record. It surpassed the last recorded worst drought that occurred during the Federation period (1898 to 1903). Analysis of average rainfall deficits highlights the extensive and prolonged nature of recent drought conditions that have been exacerbated by higher temperatures and greater evaporation rates than those experienced in previous decades (Nicholls 2004).

Other extreme events in Queensland, such as tropical cyclone frequency and intensity, have also changed. A five year running-mean of occurrence shows an annual average of 3 storms per year before the 1930s, increased to 8 storms between 1955 to 1990 and declined again to around 3 storms since the 1990's (Stage 1 – Harper *et al.* 2001; Ocean Hazards Assessment – Queensland Government 2011). Whilst the frequency of storms has declined, the intensity of storm events has increased since the 1960's. This is evident in the decline of mean central atmospheric pressure within cyclones (measured in hectopascals) from 980hPa to 955hPa (Harper *et al.* 2001).

Substantial warming has occurred in the three oceans surrounding Australia, and the surface waters of the Coral Sea on the eastern coast of Queensland are indicative of this change. Surface waters of the upper tropical and west Pacific Ocean have warmed by 0.6°C to 1.0°C to a depth of 100 to 200m since 1910, with cooling in some regions at greater depths (Lough 2009). Sea surface temperatures in the Coral Sea vary with latitude (Figure 1a). There has been a greater increase in temperature in the southern parts and during winter (Lough & Hobday 2011). Higher surface water temperatures have resulted in increases ocean stratification, which limits the vertical exchange of water with implications for the supply of oxygen and nutrients into pelagic and benthic ecosystems. An El Niño-like pattern features prominently in the warming trend and warming is even stronger in the eastern Pacific (CSIRO & BoM 2007a). However, it is not yet clear how this pattern of ocean warming is responding to greenhouse gas induced global warming (Collins *et al.* 2010).

The South Pacific Gyre, system of rotating ocean currents, has increased in strength driven by a southward intensification of extra-tropical wind. This has altered the complex current system of the southwest Pacific and changed the structure of water temperatures in the region (Bindoff *et al.* 2007; Lough 2009), as described above. The main oceanographic currents off the coast of Queensland have strong biological and climatic influences on the land and coasts (Ridgway & Hill 2009; Suthers *et al.* 2011). These currents are: (i) the East Australia Current that flows south; (ii) Hiri Current that flows north; and (iii) the Gulf of Carpentaria Gyre that flows in a clockwise direction (Figure 2).

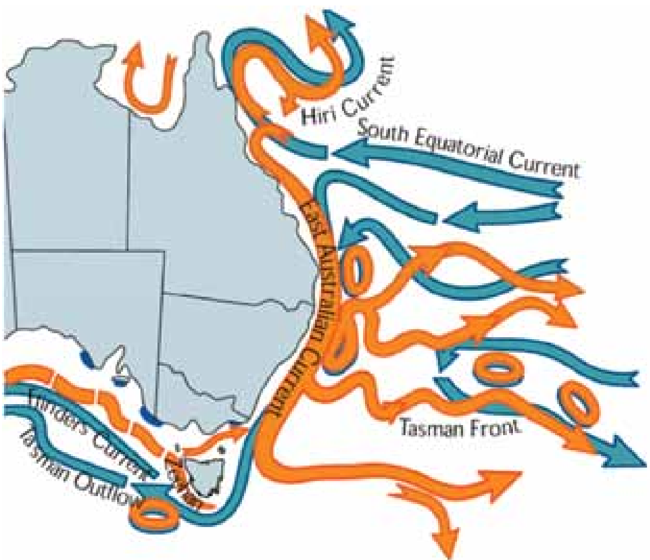


Figure 2: Major oceans current off Queensland (DEWHA 2008b).

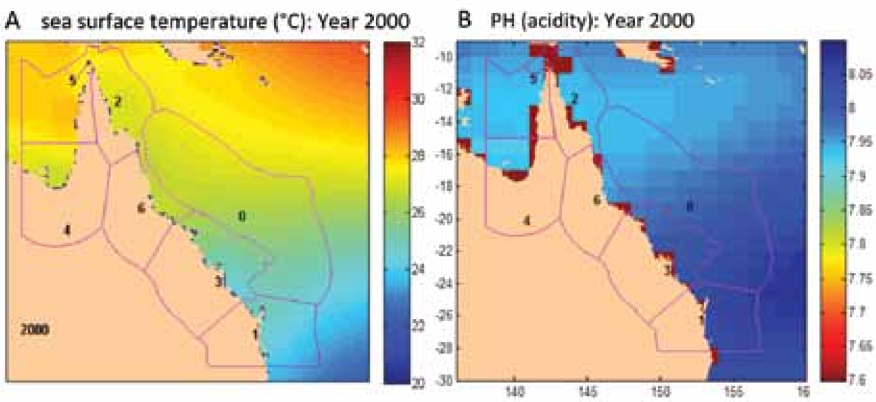


Figure 1: Current annual average sea surface temperature (a) and ocean pH (b). Boundaries are modified marine ecoregions (defined in Bustamante *et al.* 2011). Data from OzClim, 2012 (CSIRO 2007; Ricketts & Page 2007). The lower resolution ocean data is overlain by a detailed coastline – the fringing darker pixels represent land.

Sea level has been rising over the past 50 years. A rise of up to 3.4mm per year has been recorded at Cape Ferguson on the east coast of Queensland near Townsville (BoM 2010). This rate of sea level rise is much higher than the global average of 1.6 ± 0.2mm per year).

In the west Pacific, oceanic absorption of CO_2 has decreased the pH of the tropical Pacific Ocean by about 0.06 pH units, making the ocean more acidic. The acidity of ocean waters off Queensland's coast varies by location and water depth (Figure 1b). Spatial and temporal heterogeneity of the coast-ocean continuum may influence this regional variation in pH. However, the precise role of factors such as benthic topography, scale of spatial configuration in land, reef and island positions, and temporal (daily and seasonal) variations in ocean currents, is not clear, and therefore regional prediction of ocean water pH variation is currently uncertain.

2.1.3 Projected climate change in Queensland

Global climate change scenarios

Human induced emissions of greenhouse gasses, dominated by carbon dioxide (CO_2), are one of the mechanisms attributed to recent climate change (Friedlingstein *et al.* 2010; Kutzbach *et al.* 2010; Solomon *et al.* 2007). The other mechanisms – also attributed to human activity – are global changes to land surface, such as deforestation, and increasing atmospheric concentrations of aerosols (for details, see Forster *et al.* 2007). In 2007, the Intergovernmental Panel on Climate Change released their fourth assessment report (IPCC 2007a) in which the climate change implications of future emission scenarios in IPCC (2000) were updated.

The special report on emissions scenarios, ('SRES 2000', see IPCC 2000) is based on scenarios for four alternative futures (A1, A2, B1 and B2). Each of the four scenarios explores alternative pathways and resulting greenhouse emissions for demographic, social, economic, technological and environmental developments. The scenarios were quantified using a variety of modelling approaches. The SRES 2000 scenarios, without any likelihood attached, have been summarised in IPCC (2007a) as follows:

- The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B).
- B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy.
- B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability.
- A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change.

Different international groups have simulated changes in future global and regional climate patterns using global climate models (GCMs) driven by these SRES emission scenarios. For the IPCC Fourth Assessment report 23 GCMs driven with many different emission scenarios were used to understand potential changes in the future global climate. These multiple projections serve to reflect both the uncertainty regarding future emission pathways as well as the uncertainty associated with the atmospheric response to enhanced greenhouse gasses (GHGs). Incorporating both these elements of uncertainty results in a wide range of future projections particularly post 2030 when emission scenarios diverge (Figure 3).

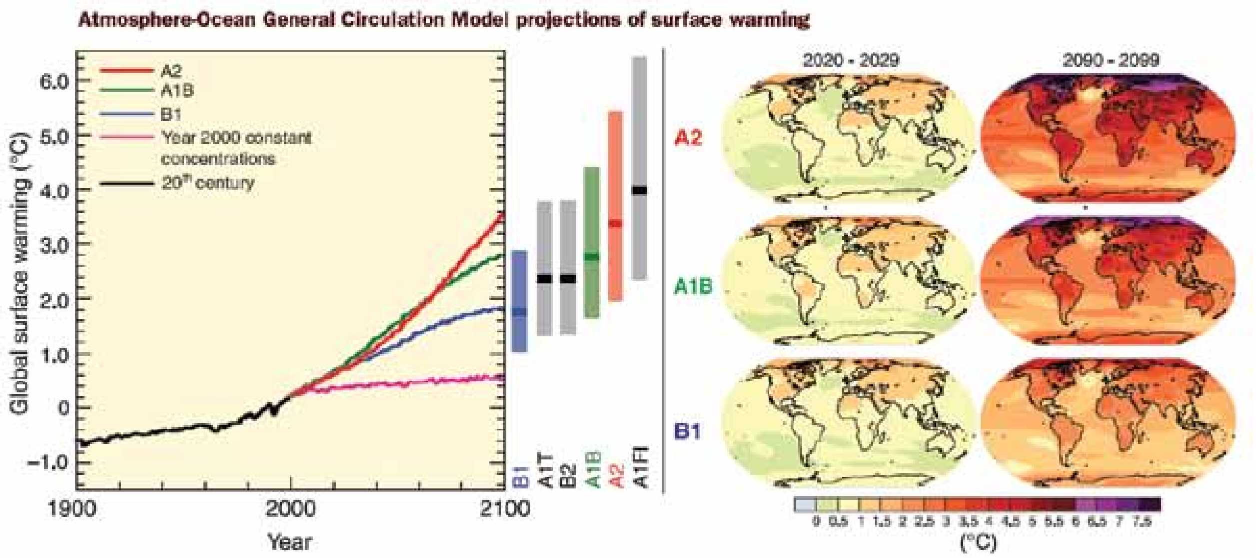


Figure 3: Multi-model global averages and range of surface warming for three SRES emission scenarios, reproduced from Figure 3.2 in IPCC (2007a).

Current emission levels are tracking around the upper range of the A1FI emission scenarios (Dolman *et al*. 2010; Le Quere *et al.* 2009) which could lead to a doubling of CO_2 and a warming of 4°C, relative to pre-industrial climates, during the 2070s. This makes the A1F1 alternative future a plausible scenario for climate impact assessment studies (Betts *et al.* 2011). The three IPCC scenarios most often used in climate modelling are the B1 lower emissions growth scenario, the A1B medium emissions growth scenario and the A1FI higher emissions growth scenario (for details see Whitfield *et al.* 2010, p. 14). By 2100 the projections for the A2 emission scenario, which represents a continuously increasing population with a more fragmented and slower uptake of technology, are greater than those of the A1FI scenario (Figure 3).

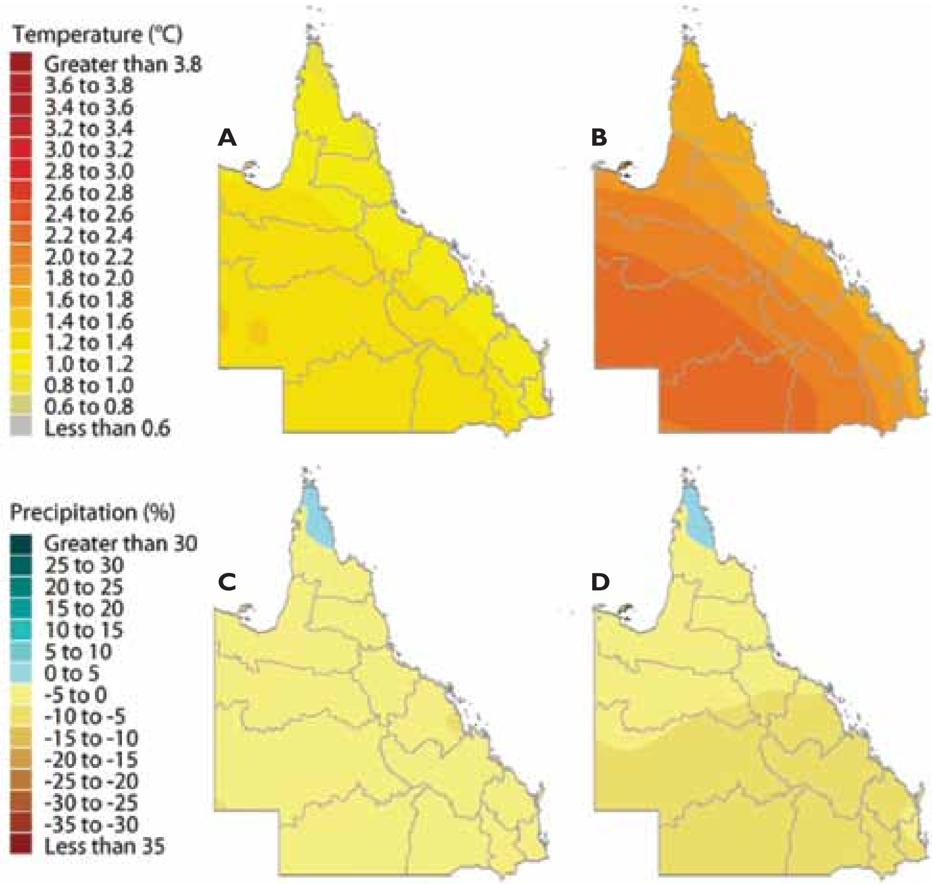
Two of the SRES scenarios (A1B and A1FI) are discussed in the context of projected terrestrial environmental change in Section 2.2. These scenarios are based on projections derived from the CSIRO Mk 3.5 GCM (Gordon *et al.* 2010) obtained through OzClim (Ricketts & Page 2007). An assessment of model 'skill' compared with observations shows large uncertainties in precipitation and cloud cover. Overall, the CSIRO Mk 3.5 model is much drier and more sensitive to emissions than most other global climate models[1]. All climate models available in OzClim provide plausible climate projections even though they may differ in their results.

Projected change in mean climates

The *State of the Climate* report (CSIRO & BoM 2010) indicates Australian climate conditions will be both warmer and drier in the future. Australian average temperatures are projected to rise by 0.6–1.5°C by 2030 and by 2.2–5.0°C by 2070 (CSIRO & BoM 2010). Extensive projection information is contained in Queensland's climate change strategy (DERM 2009c) summarised by planning region (DERM 2009a; Whitfield *et al.* 2010).

Projected temperature increases for Queensland regions by 2050 are in the range 1–1.4°C for the low emissions scenario (B1) and 1.7–2.2°C for the high emissions scenario (A1FI) (Figure 4a, b). Annual rainfall is projected to decline by up to 5% for a low emission scenario and up to 10% for a high emission scenario (Figure 4c, d).

Figure 4: Maps showing projected changes by 2050 in a) temperature under a B1 low emission scenario, b) temperature under an A1FI high emission scenario, c) rainfall under a B1 low emission scenario and d) rainfall under an A1FI high emission scenario (source: QCCCE – Whitfield *et al.* 2010).



[1] Compare the CSIRO Mk 3.5 model response to global warming in terms of regional warming and rainfall change with other global climate model data used in the 2007 IPCC 4th Assessment Report, summarised for Australia at: https://wiki.csiro.au/confluence/display/ozclim/Science#Science-CSIRO35.

Future projections of ocean temperature, based on a suite of global climate models, indicate that ocean warming will continue into the next century. Absolute temperatures could reach 32°C in some regions (Ridgway & Hill 2009) (Figure 5). Off Queensland's east coast, the East Australia Current will transport greater volumes of warm water southward. Model projections indicate that sea surface temperatures in this region will warm by approximately 2°C by 2065 relative to the historical period (1870 to 2004) (Hobday & Lough 2011). The level of confidence in the likelihood of these changes is medium-to-high (Ridgway & Hill 2009).

Global projections of ocean acidification indicate that a further decline in pH of 0.2-0.3 units (i.e., an increase in acidity) can be expected under the B1 and A2 scenarios by 2100 (e.g., Orr *et al.* 2005). This projection represents an environmental change in the concentration of dissolved hydronium ions of about 90-120% since the 1850s. Such pH levels in oceanic waters have not been encountered for millions of years and this rate of change is unprecedented (e.g., Luthi *et al.* 2008). In Queensland the pH of adjacent oceans is already declining. By 2011 oceans in the far north and Gulf of Carpentaria are expected to become more acidic. The pH could reach a low of 7.6 (with slight regional variation) (Hobday & Lough 2011) (Figure 6).

Projections of sea level rise to 0.8m indicate that up to 25% of the land-based coastal zone of coastal regions will be inundated by 2100 (DERM 2011b; QCCCE 2011). Prominent examples are those areas adjacent to the population centres of the Gold Coast south of Brisbane (Figure 7a) and near Gladstone (Figure 7b) (Bustamante *et al.* 2012).

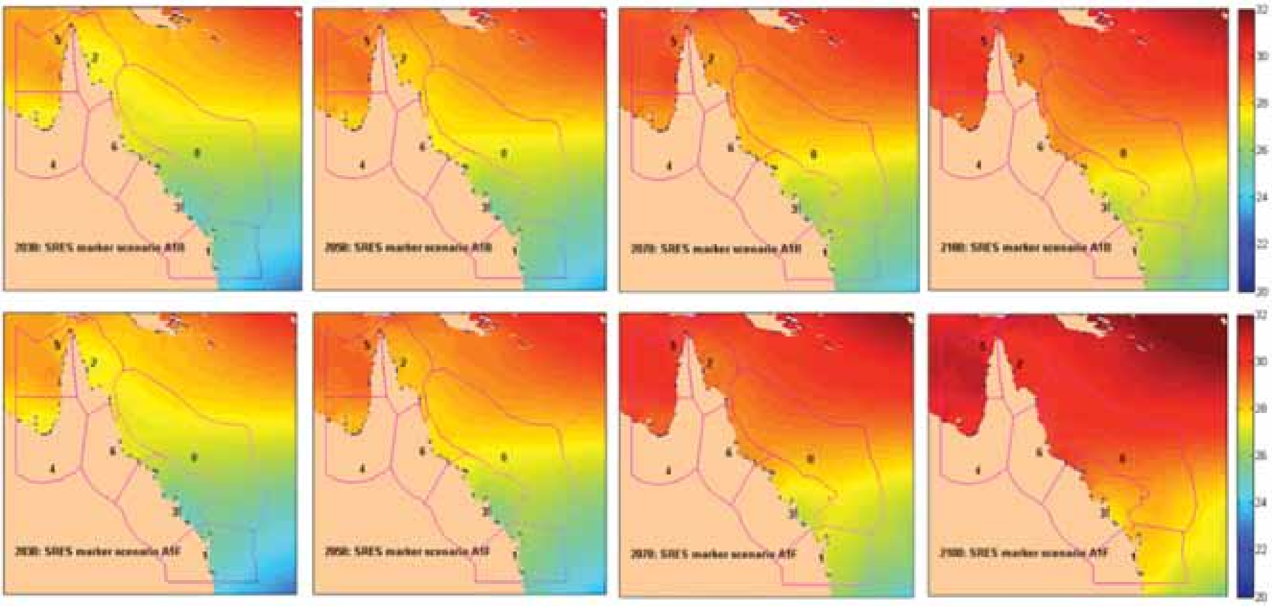


Figure 5: Projected average sea surface temperatures for Queensland: 2030 (far left), 2050, 2070 and 2100 (far right) and SRES scenarios (Nakicenovic *et al.* 2000; Nakicenovic & Swart 2000) A1B (top) and A1FI (bottom). Data from OzClim, 2011 (CSIRO 2007; Ricketts & Page 2007). Boundaries are modified marine ecoregions (defined in Bustamante et al. 2012). The lower resolution sea surface temperature data is overlain by a detailed coastline – the fringing black pixels represent land.

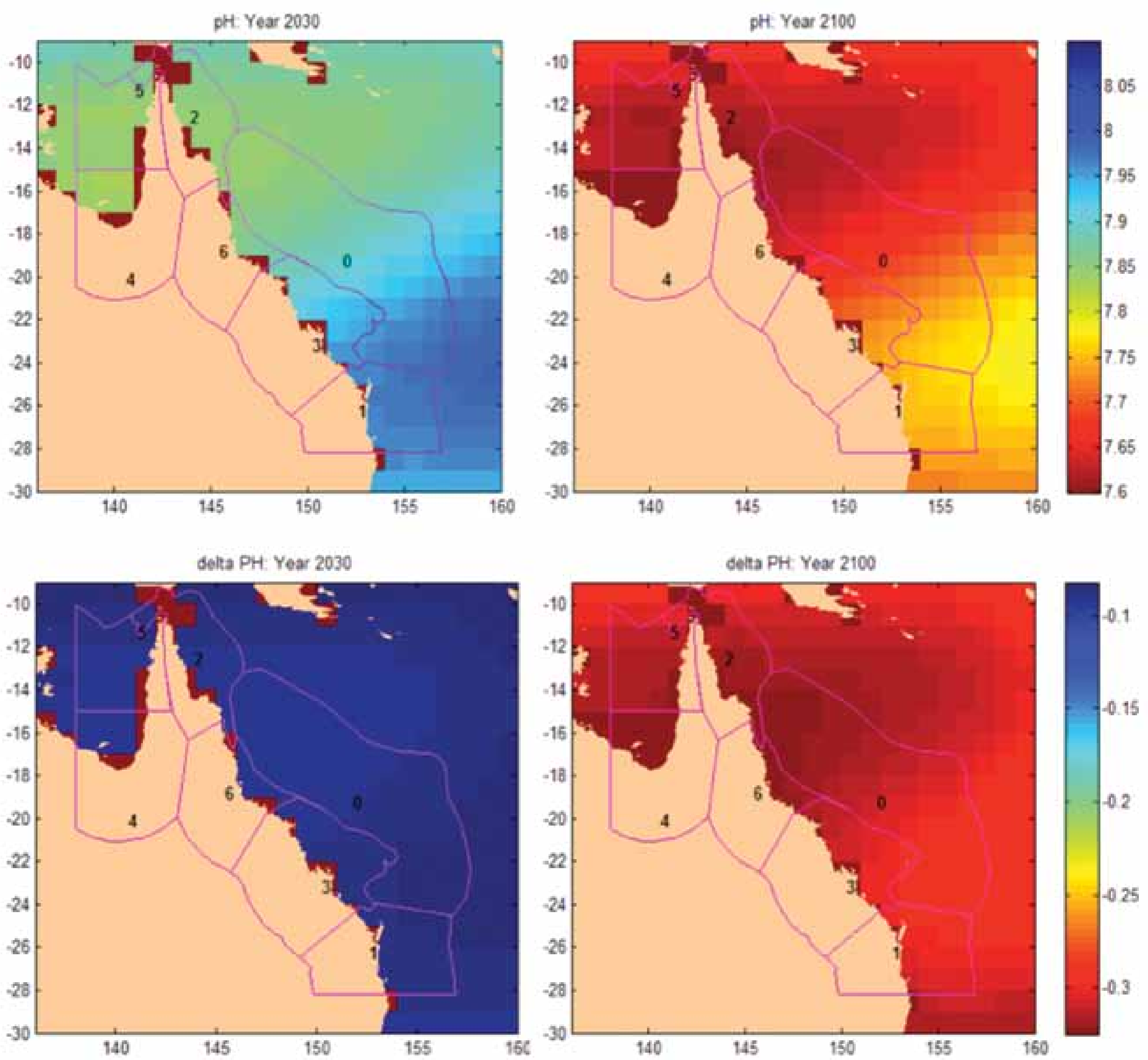


Figure 6: Projected ocean pH for the years 2030, 2100 (top); and change in pH for the years 2030 and 2100 (bottom), based on the A2 SRES scenarios (IPCC 2000). Data courtesy Richard Matear, CSIRO Marine and Atmospheric Research. Boundaries are modified marine ecoregions (defined in Bustamante *et al.* 2012). The lower resolution ocean pH data is overlain by a detailed coastline – the fringing deep maroon pixels represent land.

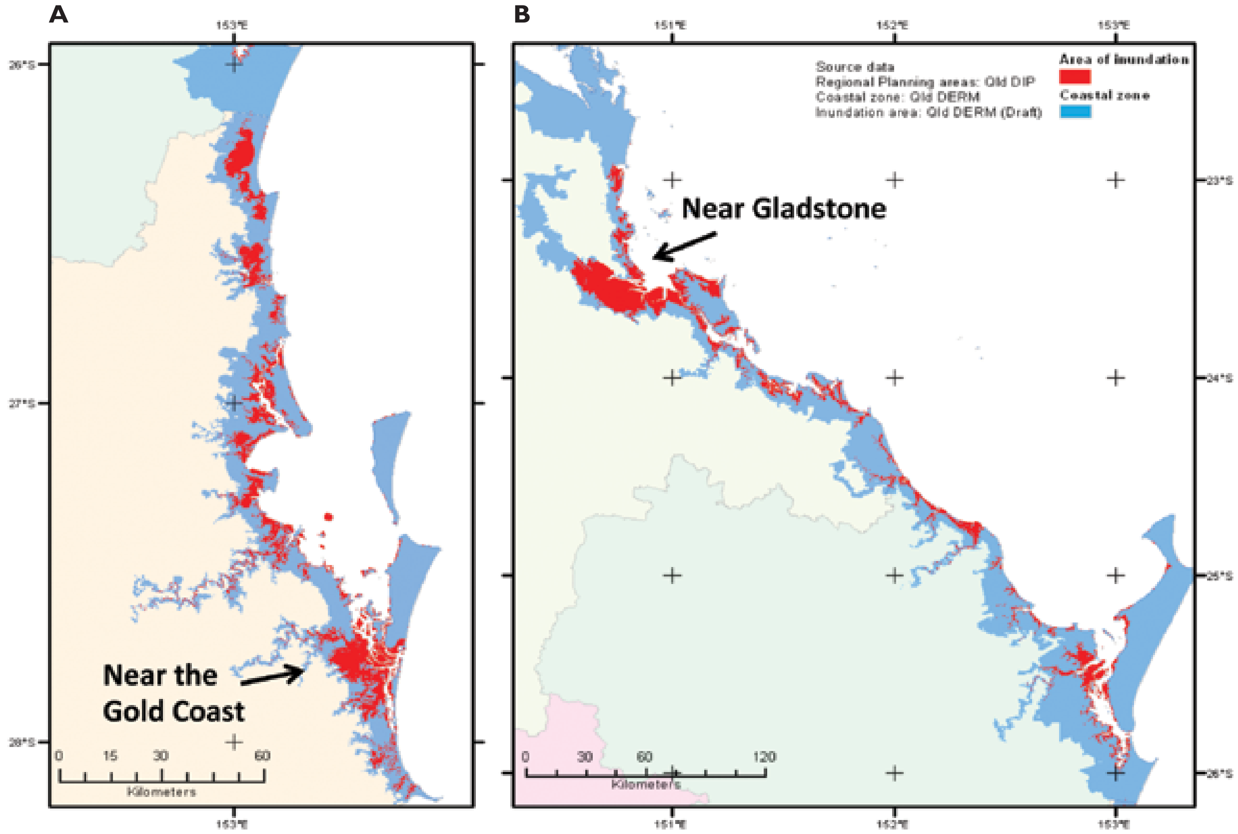


Figure 7: Examples of coastal inundation areas (red) projected for 0.8m sea level rise by 2100 in the coastal zone (blue). Examples for Coolangatta to Double Island Point (A) and Hervey Bay to Shoalwater Bay (B). Boundaries showing Coastal Plan Regions for southern Queensland (Environment Planning 2011). Coastal topography mapped by LiDAR (Light Detection and Ranging) technology – Coolangatta to Lucinda (QCCCE 2011). Data used with permission, Queensland Department of Environment and Resource Management, Brisbane.

Projected change in extreme weather events

Projections for Queensland indicate a significant increase in the number of 'exceptionally hot' years, from a baseline of 1 event every 22 years (mean for the period 1950 to 2009) to an average of 1 in 3 years by 2050. Climate change is also likely to affect extreme rainfall across much of the coastal high rainfall zone. A study of the intensity of extreme rainfall events in south-east Queensland by Abbs *et al.*(2007) found that significant increases were likely for 2-hour, 24-hour and 72-hour extreme rainfall events under all future emissions scenarios. Under an A2 emissions scenario, extreme rainfall intensity scenarios averaged over the Gold Coast sub-region are projected to increase in intensity by 48% for 2-hour events, 16% for 24-hour events and 14% for 72-hour events by 2070.

The effect of global warming on the number, duration and intensity of cyclones is unclear, but most global simulations project an increase in cyclone intensity (Webster *et al.* 2005). Regionally in Queensland, however, models project an increase in intensity and potentially an overall decrease in the number of cyclone events (CSIRO & BoM 2007b). Simulations for Queensland also show more long-lived tropical cyclones and a southward shift in tropical cyclone genesis-decay regions of between 2 and 3 degrees of latitude (Abbs *et al.* 2006; Leslie *et al.* 2007). Sea level rise in conjunction with storm surges, floods and more intense cyclones will impose widespread and highly variable coastal inundations with increasing impacts and costs (Figure 7) (see Section 3.4.2).

2.1.4 Environmental drivers of ecological change

The composition of greenhouse gases in the atmosphere affects global climates, ocean circulation and chemistry, and regional weather patterns and variability. The effects of climate change on the marine environment, for example, include changes to ocean water temperature and current patterns, sea level, water acidity, and the frequency and severity of ocean disturbance due to storms and cyclones. These and other changes in regional and local environmental conditions alter the physical habitat of biota across terrestrial, marine and freshwater aquatic ecosystems. The ensuing responses lead to changed species distribution patterns and ecosystem function that influence macroevolutionary processes (the balance between extinction and speciation). An understanding of environmental change is therefore essential to making inferences about ecological change. Below is a summary of some of the main drivers of environmental change that are expected to arise from global warming processes.

Rising atmospheric concentrations of CO_2 (see Friedlingstein *et al.* 2010). This is a major theme with substantial ramifications in the biosphere. It leads to increased acidification of water bodies (Caldeira & Wickett 2003; Orr *et al.* 2005), and is especially significant in marine ecosystems (Sections 3.4.2 and 3.4.3). Changes in atmospheric CO_2 concentrations alter primary productivity, water and nutrient dynamics, which affect the quality and quantity of food for herbivores (Section 3.2.2).

Increasing temperature (Solomon *et al.* 2007). Global warming will result in a permanent change in thermal living conditions experienced by biota across Queensland's terrestrial (Section 3.2.2), freshwater aquatic (Section 3.3.2) and coastal-marine environments (Section 3.4.2). Higher air temperatures are associated with increased nightly temperatures and lower diurnal ranges (CSIRO & BoM 2007a; Gilmore *et al.* 2008; Whitfield *et al.* 2010). As environmental temperatures increase, metabolic rates increase within structural and functional limits of body mass and phylogeny. Metabolic rate increases affect life cycles, phenology, survivorship and rates of evolution. Where species have the capacity to do so, geographic ranges will shift laterally and/or vertically and biotic interactions will change across trophic levels. This effect is common to all ecosystems in freshwater, the ocean and on land.

Changing ocean currents. A key driver of change in the marine domain is change in the flow of currents. Such changes have strong biological and climatic influences on land and coasts (Ridgway & Hill 2009; Suthers *et al.* 2011). Circulation of regional ocean currents is projected to change (Section 3.4.2). The south flowing East Australia Current and the north flowing Hiri currents are both projected to intensify. This may increase dispersal distances and help some marine species move to favourable environments. The southward expansion of the East Australia Current, which will extend tropical climate influences into south east Queensland, is expected to cause changes to biodiversity, population connectivity, ocean productivity and the distribution of pelagic species and their pelagic habitats (3.4.4).

Wind and cloud patterns. Changed atmospheric circulation patterns resulting from warming also affect local wind and cloud patterns. Increased surface wind speeds are expected in most coastal areas and extreme wind speed is also likely to increase but a stilling effect is also possible at mid-latitudes and higher elevations—an inference from recent observations (McVicar *et al.* 2008; McVicar *et al.* 2010). A rise in the cloud base will affect the availability of high and consistent moisture in coastal mountain habitats, especially during the dry season (McJannet *et al.* 2007).

Variable and declining rainfall and increasing evaporation. As mean annual precipitation decreases and evaporation increases, the water level of wetlands will drop (Section 3.3.2), and changes in the hydrodynamics of vegetation-driven evapotranspiration will alter landscape water balance (Huxman & Scott 2007). Changes in evaporation due to changes in solar radiation, vapour pressure deficit and wind speed have implications for water availability (Fu *et al.* 2009; Roderick & Farquhar 2002; Shen *et al.* 2010). Reduced runoff into streams, wetlands and groundwater systems can be expected, regardless of projected rainfall scenario. Changes in solar radiation-driven evaporation also depend on cloudiness and increased cloud cover may be related to an increased presence of aerosols in the atmosphere (Wild 2010). Increased cloud cover can lower evaporation rates but this countervailing effect is likely to be temporary as temperatures continue to increase and pollution control takes effect. Extended drought periods will further decrease water availability affecting all terrestrial ecosystems (Sections 3.2.3 and 3.2.4). The resulting disruption of connectivity in freshwater systems will prohibit avoidance reactions and range shifts of aquatic species, changing local species composition (Section 3.3.3). Changes in terrestrial runoff and stream flow also affect the marine environment. Reductions in summer rainfall and terrestrial runoff reduce breeding habitat for prawns, barramundi and mud crabs (Section 3.4.3).

Disturbance regimes. The frequency of extreme events (tropical cyclones, storm surge, heat waves, rainfall intensity, wildfire) is expected to change (some will increase and some decrease) and individual events will intensify (CSIRO & BoM 2007a; Gilmore *et al.* 2008; Whitfield *et al.* 2010). Both the event and the intervals between events will change. Species are adapted to particular ranges in the frequency and intensity of disturbance events. Climate change has the potential to change ecosystem composition, structure and dynamics through changes in disturbance regimes. Interactions between sea level rise, flood events, intense cyclones and ocean storm surges, will likely result in large episodic changes to coastal-marine influenced ecosystems (Cazenave & Llovel 2010; Rahmstorf *et al.* 2007; Willis *et al.* 2010) (Sections 3.2.2, 3.3.2 and 3.4.2). Increased temperatures, potential for additional plant growth through CO_2 fertilisation, and changes in rainfall could interact to alter the risk of fire (increase) and change fire regimes throughout the terrestrial environment (Sections 3.2.2 and 3.2.4).

These biophysical effects of climate change are discussed in more detail in the context of environmental drivers of ecological change in Section 3.2.2 for terrestrial ecosystems (Murphy *et al.* 2012), in Section 3.3.2 for freshwater aquatic ecosystems (Kroon *et al.* 2012), and in Section 3.4.2 for coastal and marine ecosystems (Bustamante *et al.* 2012). In the following section, we describe a model of ecological change which incorporates facets of environment and habitats that are relatively static (e.g., topographic position and soil characteristics) and climate, which varies dynamically within and between years and changes over time.

2.2 Ecological scaling of environmental change

2.2.1 Role of modelling

Projections of changing climatic conditions (such as those presented in Section 2.1.3) are often difficult to interpret from an ecological perspective. For example, what does a 1°C increase in mean annual temperature, or a 50mm decrease in mean annual precipitation, actually mean in terms of potential changes in the biological composition and character of ecological communities? This challenge is driving the increased use, around the world, of integrated modelling approaches to forecasting changes in biological distributions as a function of climate change (Ferrier 2011; Kearney *et al.* 2010). Many approaches to projecting future distributions are based on models of current distributions (e.g., Austin & Van Niel 2011; Elith *et al.* 2010; Kissling *et al.* 2010) by assuming space-for-time substitution of climatic predictors (see discussion in: Araújo & Rahbek 2006; Elith & Leathwick 2009; Guisan & Thuiller 2005; Isaac *et al.* 2011). Although the level of uncertainty and assumptions associated with distribution models sometimes limits their applicability to management decision-making (Sinclair *et al.* 2010), they continue to be useful in assessing potential trends and risks associated with alternative global-change scenarios, thereby informing high-level policy development (Alkemade *et al.* 2009; Leadley *et al.* 2010; sCBD 2010).

Previous efforts to forecast impacts of climate change on biodiversity have focused almost exclusively on modelling potential changes in the distribution and abundance of individual species (Elith & Leathwick 2009). This 'bottom-up' strategy plays an important role in planning for better-known species of particular ecological, social or economic concern. However, its capacity to address changes in compositional diversity as a whole (the full variety of biological elements across all taxa, and all levels of organisation) is challenged by the sheer number of elements involved, and the gross inadequacy of our knowledge of these elements and the interactions among them. In recent years interest has been growing in 'top-down' macro ecological approaches to addressing this problem. Such approaches focus on modelling change in emergent properties of compositional diversity at the community level (compositional turnover and richness) rather than change in the individual elements constituting this diversity (Ferrier & Guisan 2006; Fitzpatrick *et al.* 2011; Kerr *et al.* 2007; Mokany & Ferrier 2011). These approaches are not intended to replace or compete with species-level approaches to modelling global-change impacts but rather to complement and add value to these existing efforts.

In this section we present results obtained using a particular top-down macro ecological modelling approach – generalised dissimilarity modelling (GDM, Ferrier *et al.* 2007) – to reveal ecological implications of projected scenarios of climate change for Queensland. The analyses performed for Queensland were based on continental GDM models developed in two recent DEWHA (now DSEWPaC) funded projects, drawn from observations for over 12,000 species of vascular plants from more than 100,000 sites throughout the Australian continent (Williams *et al.* 2010a; Williams *et al.* 2010b). Facets of the 'current' climate in these models are based on monthly long-term average observations, approximately centred on 1960 (Hutchinson *et al.* 2000; Hutchinson & Kesteven 1998). Further detail of these models and analyses can be found in Ferrier *et al.*(2012).

The analyses presented here are based on a GDM model of vascular plants but this approach has also been applied to other terrestrial biological groups, such as birds, reptiles, amphibians, mammals and invertebrates (Williams *et al.* 2010a; Williams *et al.* 2010b). GDM-based models of compositional patterns in biodiversity have also been developed for freshwater (Leathwick *et al.* 2011) and marine habitats (Leaper *et al.* 2011). In addition, taxonomic or phylogenetic-species based indices (Rosauer *et al.* 2009) and genetic characteristics of species (Thomassen *et al.* 2010; Thomassen *et al.* 2011) have been used to gain a more refined understanding of evolutionary potential. A GDM-based approach could equally be applied to the functional or structural composition of ecosystems (where comprehensive observational or interpreted data exist). This would provide alternative ways to visualise degrees of landscape change or change in ecological function, or life-form groups, relating to ecosystem processes.

2.2.2 Potential for ecological change

In Figure 8, continental GDM modelling of vascular plants, employing the CSIRO mk3.5 Global Circulation Model (GCM; see Ferrier *et al.* 2010; Ferrier *et al.* 2012 for details) has been used to scale environmental change expected for Queensland in 2030 and 2070 under two different scenarios – moderate emissions (A1B) / medium climate sensitivity, and high emissions (A1FI) / high climate sensitivity. This scaling is based on the assumption that the potential for change in species composition at location A as a result of climate change, will be equivalent to the compositional dissimilarity currently observed between location A and another location B with a current climate matching that projected for the future at location A. However, the actual change in biological composition resulting from climate change is likely to be shaped by many factors and associated sources of uncertainty beyond those considered in this modelling. For example, biotic interactions, indirect effects of changed fire regimes, dispersal ability, lag effects, adaptation capacity and plasticity can each influence the change in biological composition initiated by climate change. The level of compositional change projected by the GDM approach is therefore best interpreted as no more than a relative indicator of the potential (or the pressure) for such change, rather than as an expectation of the actual change that will occur at any given location.

The colours depicted in Figure 8 range from green for locations (1km grid-cells in this analysis) with least potential for change in the species composition of the plant community currently occurring at that location, through to reddish brown for locations with most potential for change in plant species composition. Two aspects of these results are worth noting, below.

First, the potential for compositional change is not evenly distributed across the State. Some regions and environments exhibit greater potential for change than others. These patterns arise from a combination of differences in the amount of change projected for climate itself (temperature, precipitation, cloud cover and evaporation) across different parts of the State (from the GCM), and of differences in the amount of change in species composition expected for a given change in climate in different environments (from the GDM). Other facets of environment in the model related to soil and terrain conditions interact with climate but are otherwise static between projections.

Second, the overall potential for compositional change is high, particularly by 2070. If the 'dissimilarity' values depicted in these maps are interpreted literally (see caveats above) then, even under the moderate-emissions / medium-sensitivity scenario, most of the State will have experienced sufficient environmental change by 2070 to result (over the longer term) in more than 60% change in the composition of plant species occurring at any given location. Under the high-emissions / high-sensitivity scenario, most of the State will experience even higher levels of environmental change, potentially resulting in more than 90% change in plant species composition for a large proportion of locations.

2.2.3 Disappearing and novel environments

In the left-hand map in Figure 9 the analysis from Figure 8 is taken one step further. This map depicts so-called 'disappearing environments' (the reddish-brown areas). Disappearing environments were first defined by Williams *et al.*(2007), as climates currently occurring within a region of interest that will not occur anywhere in this region under a particular climate-change scenario. In the analysis presented in Figure 9, this original concept has been extended by scaling disappearing environments in terms of predicted dissimilarity in plant species composition, based on the continental GDM model (see Ferrier *et al.* 2012). The disappearing environments mapped in Figure 9 are therefore ecologically-scaled environments (likely to support distinct assemblages of plant species) currently found in Queensland, that will not occur anywhere in the State (or elsewhere across the Australian continent) under the moderate-emissions / medium-sensitivity scenario for 2070. These environments include, for example, those currently occurring on the higher peaks of the Queensland Wet Tropics. Climate change is likely to see the unique combination of temperature and precipitation conditions that characterise this environment literally disappear from the tops of these peaks by 2070. Our analysis suggests, quite reasonably, that this particular environment is unlikely to be replicated anywhere else on the continent by 2070, at least for the climate scenarios considered here. A contrasting example is provided by the nearby coastal lowlands of the Wet Tropics, which is not identified as a disappearing environment in our analysis. While climate change is likely to see a shift in the distribution of this environment – to higher elevations – it is unlikely to disappear completely from the continent.

The right-hand map shown in Figure 9 depicts the potential distribution of 'novel environments' (the reddish-brown areas) as defined by Williams *et al.*(2007). These are environments expected to emerge in the future for which there is no current analogue (similar environment) anywhere in the State (or elsewhere on the continent for that matter) again scaled by the GDM modelling of plant composition. Comparison of the two maps in Figure 9 reveals some interesting patterns in the interplay between disappearing and novel environments. While these patterns can be summarised against a standard bioregional framework, as presented in Table 1, this summary hides some important detail. For example, as described above, the higher peaks in the Wet Tropics Bioregion are, quite understandably, mapped as disappearing environments. But the environments expected to replace these are not novel. That is, they are probably environments that already occur at lower elevations in this region. However the converse is true for the coastal lowlands in the wet tropics – the environment currently occurring here is not identified as disappearing (because it is likely to shift to higher elevations in the future), yet the future environment of this area is predicted to be highly novel – it will be unlike the current environment of any other part of the continent. A contrasting situation occurs in bioregions within Queensland's semi-arid and arid country, much of which is mapped as supporting both disappearing and novel environments – that is, the environments currently occurring in these regions are unlikely to be found anywhere else in the future, and will probably be replaced by environments unlike anything occurring elsewhere at present.

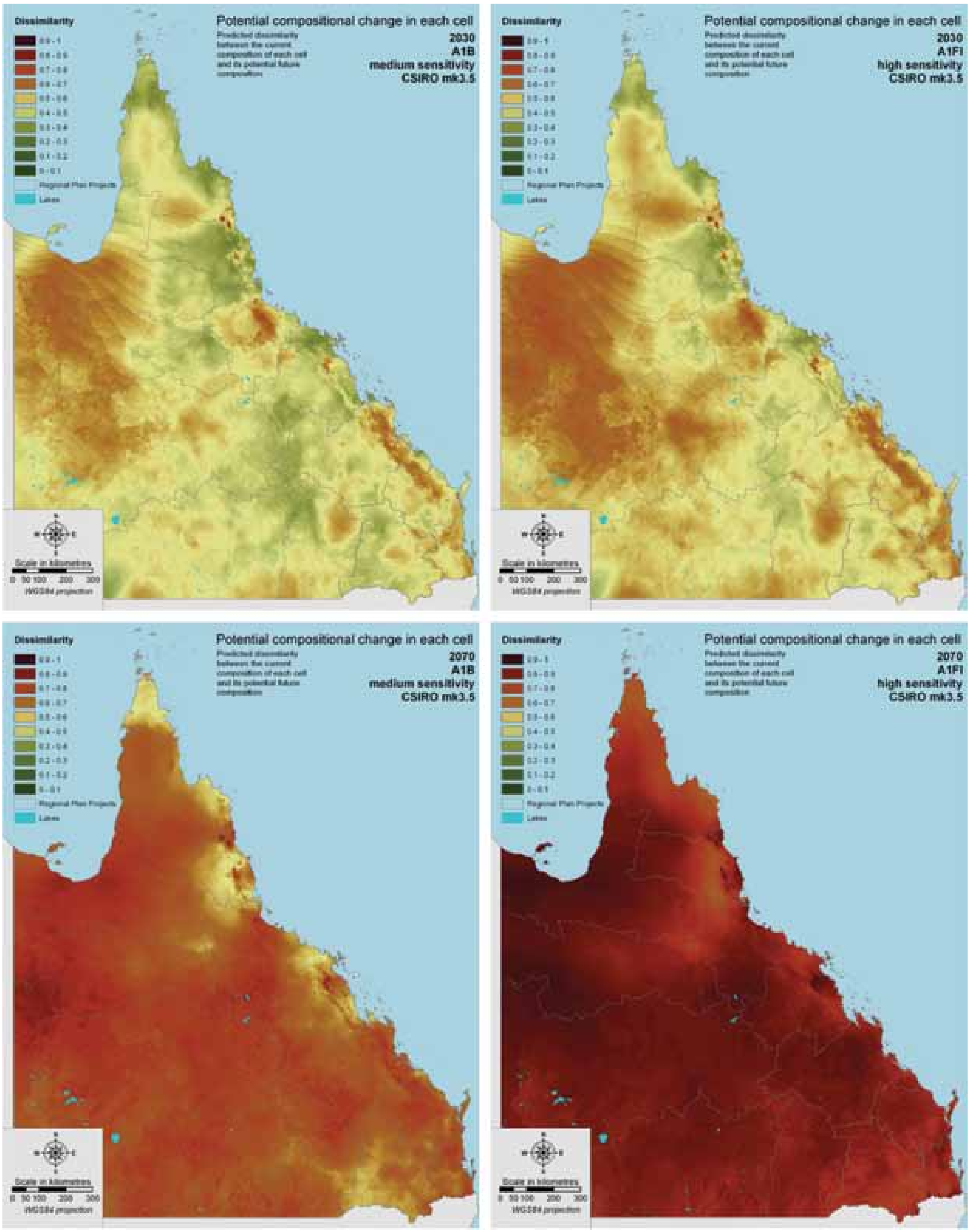


Figure 8: Potential ecologically-scaled environmental change, for four climate-change scenarios, based on modelling of species composition of vascular-plant communities. Green areas are those with least potential for change, while red areas have highest potential for change in composition. The analysis contrasts current observed and future projected bioclimates. Current observed bioclimates are 1960-centred averages from weather observations (1925-1975) before the onset of rapid climate change. Projected bioclimates (2030 and 2070, medium and high sensitivity to emissions) are based on outputs derived from the CSIRO Mk 3.5 global climate model (Gordon *et al.* 2010), downloaded from OZCLIM (Ricketts & Page 2007) and rescaled to 1km grids using ANUCLIM version 6.0 (beta) (Hutchinson *et al.*, ANU Fenner School, unpublished). This map shows only projected changes in environmental conditions. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). The ecological-scaling method is described in Ferrier *et al.* (2012).

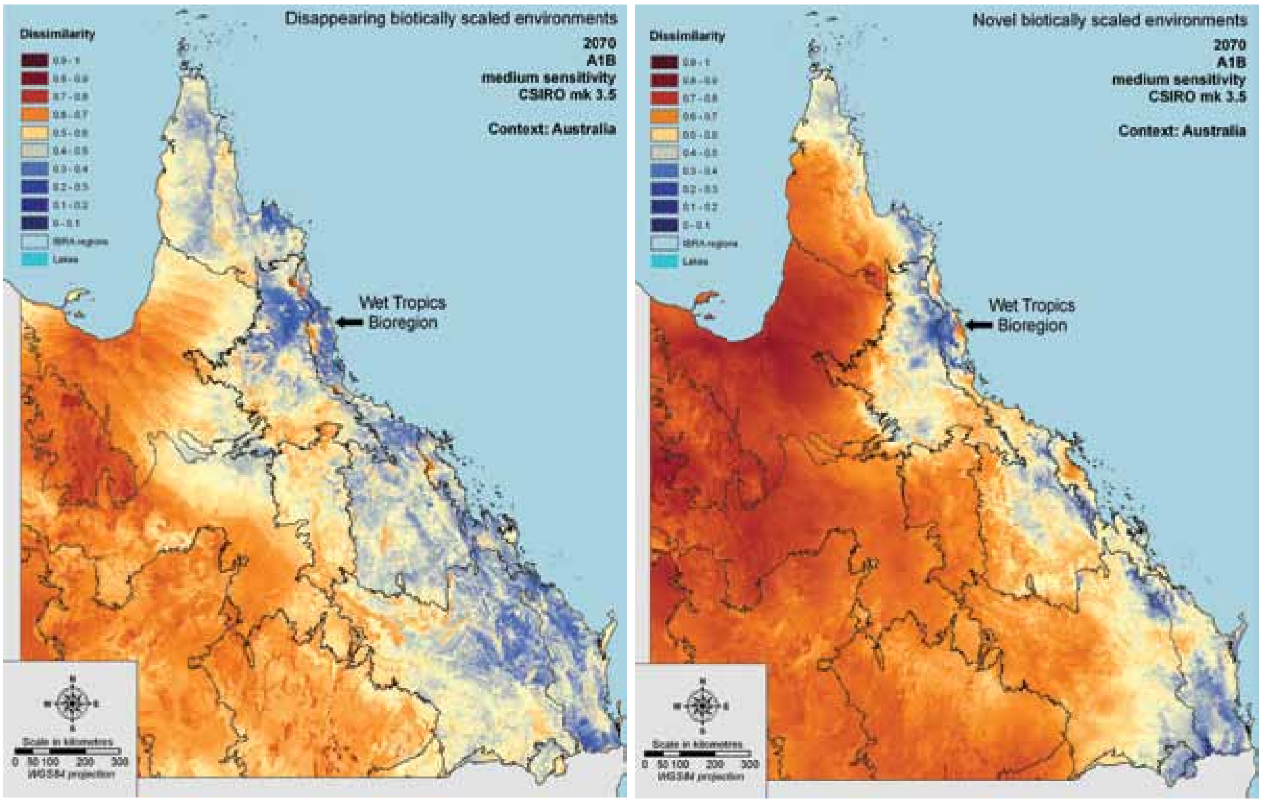


Figure 9: Potential distribution of disappearing and novel environments under the 2070 medium-impact scenario (scaled using modelling of species composition of vascular-plant communities). Black lines indicate boundaries of IBRA Bioregions where they occur in Queensland (IBRA version 6.1, DEWHA 2004). In the map on the left, red areas are those with current environments that are least likely to occur anywhere in Australia under this climate scenario, while environments in the blue areas are those most likely to be retained somewhere on the continent. In the right-hand map, red areas are those most likely to support environments without any current analogue throughout Australia, while environments in the blue areas do have current analogues. This map shows only projected changes in environmental conditions. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). Data sources as for Figure 8. The ecological-scaling method is described in Ferrier *et al.* (2012).

Table 1: Synthesis of bioregional patterns (IBRA version 6.1, DEWHA 2004) based on interpretation of GDM-based analyses of disappearing and novel environments presented in Figure 9.

Bioregion	Likelihood† of existing environments disappearing (from the continent)	Likelihood† of appearance of novel environments
South East Qld	Low-Medium	Low-Medium
New England Tablelands	Medium	Low
Nandewar	Low-Medium	Low-Medium
Brigalow Belt South	Low-Medium	Low-Medium
Central Mackay Coast	Low-High	Low-High
Brigalow Belt North	Low-Medium	Low-Medium
Wet Tropics	Low-High	Low-High
Einasleigh Uplands	Low-Medium	Low-Medium
Cape York Peninsula	Low-Medium	Low-High
Gulf Plains	Low-High	Medium-High
Gulf Falls and Uplands	Medium-High	Medium-High
Mt Isa Inlier	Medium	Medium-High
Mitchell Grass Downs	Low-High	Medium-High
Desert Uplands	Low-Medium	Medium
Simpson Strzelecki Dunefields	Medium-High	Medium-High
Channel Country	Medium-High	Medium-High
Mulga Lands	Medium-High	Medium-High
Darling Riverine Plains	Low-Medium	Medium

† Measures of 'likelihood' – low, medium, and high – are qualitative estimates of the continuous range in conditions derived from the respective GDM-based analyses presented in Figure 9. The method of assessment is described in Ferrier *et al.* (2012).

2.2.4 Projected change in the distribution of environments – an example

The analyses presented in Sections 2.2.2 and 2.2.3 provide information on how much change might be expected for environments in different parts of the State but shed little light on precisely where any particular environment will move to, or where there are present environments similar to that projected for a given place under climate change. As part of the current study we therefore developed an example, using the Moreton Basin subregion (of the South East Queensland Bioregion) to demonstrate how GDM-based modelling can be used to visualise, in greater detail, potential impacts of climate change on the ecological character of particular regions or ecosystems within the State. While this trial analysis is focused on a single subregion, the same approach could, in future, be readily applied to any Queensland region or subregion, or any other defined place such as a mapped ecosystem type.

Figure 10, Figure 11 and Figure 12 provide a visualisation of what might be expected to happen to the ecologically-scaled environment (or 'bioclimate') of the Moreton Basin subregion under the A1B 2070 climate scenario (see Ferrier *et al.* 2012 for further details). Figure 10 shows the distribution of places with a similar ecologically-scaled environment to that of the Moreton Basin subregion given current climatic conditions. These similar bioclimates extend both northwards from the subregion, and southwards into north-east NSW. Figure 11 then shows the distribution of places that are projected to have a bioclimate in the future (under climate change) similar to that of the current bioclimate of the Moreton Basin subregion. This provides an indication of where the current bioclimate of the Moreton Basin might move to under the A1B 2070 scenario – that is, a clearly discernable shift southwards and to higher elevations, with an overall contraction in the total extent of this bioclimate. It should be noted, however, that this is a projected shift only in the distribution of the environment (or bioclimate) of the Moreton Basin subregion, not in the distribution of species or ecological communities that currently occupy this subregion. Shifts in biological distributions will be affected by additional factors not considered here including, for example, lag effects, capacity for phenotypic, behavioural or evolutionary adaptation, dispersal capability and various biotic interactions (discussed in Section 3.2).

Finally, Figure 12 shows the distribution of places with a current bioclimate similar to that projected for the Moreton Basin subregion under climate change. This provides an indication of where one might look now, under current climatic conditions, to get a feel for what the future environment of the Moreton Basin could be like under the A1B 2070 scenario. Not surprisingly these places generally lie well to the north of this subregion.

Naturally occurring fire. In north Australian savannas, the high incidence of lightning strikes during the build up to the tropical wet season (October to November) ensures fire is a regular event (credit: CSIRO Ecosystem Sciences).

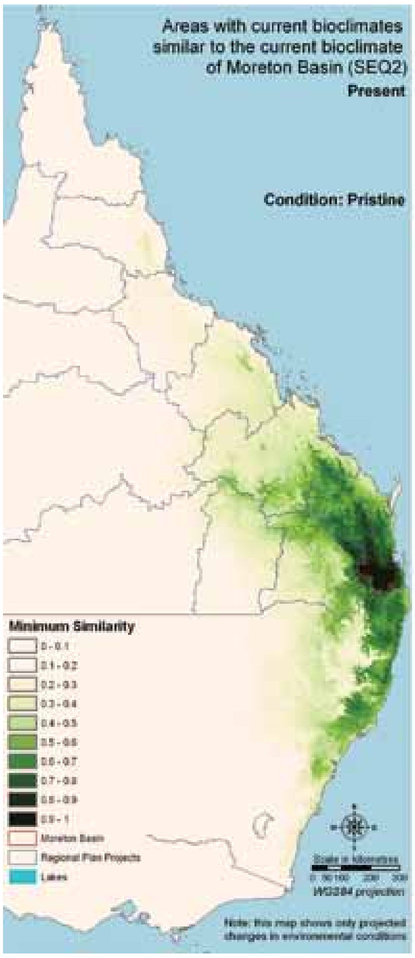


Figure 10: Surrounding areas with current bioclimates similar to that of the Moreton Basin subregion (located within the South East Queensland Bioregion). Green indicates areas with greater than 40% modelled similarity in vascular-plant composition to that of the Moreton Basin subregion, with darker greens indicating increasingly similar environments. This analysis is based on the 1960-centred average climate from weather observations (1925-1975) before the onset of rapid climate change, and assuming intact (pre-clearing) ecosystems. The ecological-scaling method is described in Ferrier *et al.* (2012). Climate interpolations used in the ecological model were derived from ANUCLIM version 5.1 (Hutchinson *et al.* 2000) and the 9-second digital elevation model for Australia (Hutchinson *et al.* 2008).

Figure 11: Areas with projected bioclimates (under climate change) similar to the current bioclimate of the Moreton Basin subregion of the South East Queensland Bioregion.

Green indicates areas with greater than 40% modelled similarity in vascular-plant composition to the current bioclimate of the Moreton Basin subregion, with darker greens indicating increasingly similar environments. The ecological-scaling method is described in Ferrier *et al.* (2012). The climates of the year 2070 used in the ecological model are based on the CSIRO Mk 3.5 (Gordon *et al.* 2010) modelled projections for the A1B emission scenario with medium climatic sensitivity (Ricketts & Page 2007). Legend is given in Figure 10.

Figure 12: Areas with current bioclimates similar to the projected bioclimate (under climate change) of the Moreton Basin subregion of the South East Queensland Bioregion.

Green indicates areas with greater than 40% modelled similarity in vascular-plant composition to the projected bioclimate of the Moreton Basin subregion, with darker greens indicating increasingly similar environments. The ecological-scaling method is described in Ferrier *et al.* (2012). The climates of the year 2070 used in the ecological model are based on the CSIRO Mk 3.5 (Gordon *et al.* 2010) modelled projections for the A1B emission scenario with medium climatic sensitivity (Ricketts & Page 2007). Legend is given in Figure 10.

It is thought that rocky landscapes offer stable, long-term habitat that is relatively buffered from short- and long-term variation in temperature and moisture. (Top) Boulder fields and rocky landscapes at Iron Range National Park, Cape York (credit: Dan Metcalfe, CSIRO). (Bottom) Boulder fields and rocky landscapes in high elevation montane landscapes in the Wet Tropics (credit: Andrew Ford, CSIRO).

3. Ecological changes

There is a solid base of information for this assessment but much of the information and science is concentrated on the Great Barrier Reef the Wet Tropics. Less is known about the more arid regions or the deeper pelagic waters and benthic habitats off Queensland's coast. Examples are therefore supplemented by studies conducted elsewhere.

Substantial change can be expected in natural and human-altered systems. This change is largely driven by rising atmospheric CO_2, ocean acidification, increasing temperatures, altered and declining rainfall patterns, altered oceanic currents and changed disturbance regimes. Ensuing ecological changes will cascade through biological systems and give rise to shifts in species distributions, changed interactions between species and extinctions.

Species and ecosystems will respond with changes in phenology, behaviour and interactions (food webs, competition, facilitation); abundance, distribution and resilience to climate variability; species resistance and exposure to disturbance, pathogens and disease; overall ecosystem productivity and nutrient status; ecosystems (through cumulative change in structure, function and composition); and landscape function and ecosystem services.

Climate change is an additional pressure on already stressed natural ecosystems. Climate change interacts with disturbance regimes, land use change, water abstraction, pollution, over harvesting, habitat degradation, eutrophication, invasive alien species, disease and pathogens, and other agents of change. These interactions lead to 'threat syndromes' that have potential to cause rapid ecosystem change and reduce capacity to provide familiar ecosystem goods and services.

Rising atmospheric CO_2 concentrations will lead to many plants becoming less nutritious for herbivorous animals. Higher temperatures, additional plant growth through CO_2 fertilisation, reduced rainfall effectiveness, and the spread of fire-promoting alien species will act together to alter the risk of fire. Altered fire regimes have the greatest potential to transform terrestrial ecosystems. A southern shift in cyclones, for example, could result in coastal and hinterland forests becoming more disturbance-oriented and prone to burning during periods of drought.

Ocean acidification is close to the point where calcareous organisms may already be experiencing a weakening in their shells or skeletal structure. As a result, the growth of reef-building corals may be in jeopardy by mid this century, given projected increases in atmospheric CO_2 concentrations. The Great Barrier Reef will be transformed to be dominated by macro algae and herbivorous fishes. The shallow and emergent parts of coral reefs will be smaller in size and provide less of a buffer to ocean swells. Local seabird colonies may decline, collapse or migrate southward.

Two broad genetic mechanisms are available for species to respond locally and persist during rapid climate change: phenotypic plasticity and evolution. Phenotypic plasticity can buffer species against environmental change but the rapid nature of climate change suggests genetically-based adaptation may be limited. However, there is potential for ecological surprises. The remaining response options available to species are dispersal, migration and extinction. Landscape and biogeographic connectivity will help counter the projected rate of climate change. Refuge features in the landscape that supported species during past climate change are likely to be important for future persistence.

Areas of Queensland at particular risk of impacts due to the adverse effects of climate change include the Wet Tropics, high altitude and montane regions, tropical savanna-woodlands, drier rainforests types including vine thickets, coastal floodplains and wetlands, the Great Barrier Reef, and areas of endemism. Southern parts of the Great Barrier Reef and southeast Queensland are marine regions that will experience the most change. A rise in the cloud layer blanketing coastal mountains will reduce water intercepted by vegetation during the dry season leading to the gradual dominance of species assemblages by more hard-leaved (sclerophyllous) species.

Increased water temperatures will affect freshwater ecosystem metabolism and result in a higher incidence of eutrophication, enhanced toxicity of contaminants, more frequent and prolonged water column stratification, anoxic conditions leading to fish death, and intensified blooming of possibly toxic cyanobacteria. These changes will pose a problem for water management across all sectors.

Decreasing annual precipitation, combined with increased evaporation rates, will lower lake levels and increase salt concentrations. This will reduce annual river flow rates and groundwater recharge and has the potential to reduce the spatial extent of wetlands and floodplains, as well as connectivity between river stretches. Climate change may result in an extension of arid and semi-arid conditions in an easterly and south-easterly direction. Western Great Artesian Basin spring wetlands may dry out. Sulphuric acid released from rewetted acid soils can be a severe problem.

Sea level rise will inundate coastal ecosystems, allow saltwater intrusion in coastal groundwater systems and cause an upstream shift in the freshwater-saline water boundary. Coastal ecosystems may retain their current extent if losses seaward are low and barriers landward are minimal, but coastal erosion processes will alter habitat structures.

This section outlines the types of ecological change resulting from climate and environmental change for each biological realm – terrestrial ecosystems, freshwater aquatic ecosystems, and coastal and marine ecosystems. An overview of environmental change was given in Section 2.1.4. A synthesis of common themes of ecological change is presented in Section 3.1, followed by the specific types of change occurring or expected to occur in each biological realm. The implications of ecological change for ecosystem services are discussed in Section 4, and climate adaptation options are outlined in Section 5.

3.1 Common themes

3.1.1 Information and understanding

There is a solid information base for this assessment. In describing likely ecological change, we have used information and examples from Queensland where this is available, and supplemented this with national and international studies.

In addition to the wider scientific literature, a number of recent summary publications were a primary source of information, and in particular:

- International context: IPCC (2007) Fourth Assessment Report;
- National context: Dunlop *et al.*(2008; 2011) – climate change and the National Reserve System; Steffen (2009) – National assessment of climate change in Australia; Steffen *et al.*(2009a) – climate change and vulnerability of Australia's biodiversity; Poloczanska *et al.*(2009) – NCCARF Marine report card; Williams *et al.*(2009) – climate change, fire regimes and biodiversity management.
- Queensland and regional context: Whitfield *et al.*(2010) - Climate change in Queensland: what the science is telling us; Low (2011) – biodiversity and climate change in Queensland.

As with any assessment of climate change implications undertaken at a sub-continental scale, and in a State as large and diverse as Queensland, the knowledge base varies from region to region. Across the terrestrial ecological realm, there is a great deal of knowledge about the wet tropical rainforests of north Queensland, for example, but much less is known of the biota and their responses to climate change in the savanna and more arid regions (Section 3.2). Knowledge about freshwater biodiversity and the potential impacts of climate change across freshwater provinces and drainage divisions is variable and supplemented by overseas and Australian studies (Section 3.3). Across the marine ecological realm, information and science is concentrated in the Great Barrier Reef. There are large regional, environmental and ecological gaps in knowledge of the effects of climate change on Queensland's coastal-marine ecosystems (Section 3.4). However, some common themes of ecological change are emerging, as outlined in the next section.

3.1.2 Ecological change

This section outlines some common drivers of ecological change in relation to climate change. These impacts of climate change on marine, freshwater and terrestrial ecosystems will not be uniform across Queensland or offshore (Sections 3.2.4, 3.3.4 and 3.4.4). It is likely that areas with projected climates that are most dissimilar to current conditions will undergo the greatest ecological change (Sections 2.2 and 3.2.4).

Ecological change will be driven by biological responses and processes at the population and species level that lead to changes in the type, quality or quantity of ecosystem services. The drivers comprise biological responses and process such as: phenology (including behavioural responses and the timing of seasonal and life history events) and species interactions (including trophic, competition, facilitation, pathogens and disease); varying effects on physiology and environmental tolerances at the individual level; changes in species resistance, resilience and exposure to disturbance; changes in species' abundance (including demographic processes of reproduction and mortality); changes in distribution patterns (including range contractions, occurrence fragmentation and range shifts); changes in whole-of-ecosystem processes and functions (including productivity, water balance and nutrient status); geographic changes in ecosystem types through cumulative change in community structure, function and composition. These interacting change processes drive extinction and speciation.

Ecological cascades, synergies and magnifying effects. Climate change will be magnified in the natural biosphere through ecological cascades or 'knock-on' changes. These include feedbacks that may be synergistic. Synergistic interactions have outcomes that are greater than the sum of the individual components and have the potential to cause rapid ecosystem transformations. For example, in the terrestrial realm, the combined effects of warming and drying, plus changes in plant growth through CO_2 fertilisation, may alter fire regimes and create asynchrony in species interactions (Section 3.2.3). In the marine realm, synergies between seasonal carbon dynamics and the hastening of ocean acidification, plus warming and associated changes to the timing of predator-prey abundance (match-mismatches) will magnify the effects of climate change (Section 3.4.3). In the freshwater realm, magnifying effects may result from interactions between warming, stratification and the degree of hypoxia (Section 3.3.3). These interactions can lead to toxic cyanobacteria blooms, intensified cycles of drying and flooding (altering connectivity), drying and salinisation of arid lakes and wetlands, and marine flooding of coastal wetlands (Sections 3.3.3 and 3.3.4).

Threat syndromes. Climate change will not act alone but in combination with other factors. Changes are likely to interact with disturbance regimes, land use intensification, extractive water use, wild harvest quota, invasive alien species, disease and pathogens, and other agents of change resulting in 'threat syndromes'. Threat syndromes occur when a number of threats, both present and future, interact to increase concerns about the continued persistence of certain types of biodiversity (Burgman *et al.* 2007). The interaction between climate change and existing human-induced pressures on species and ecosystems are a particular concern because these could precipitate rapid ecosystem transformations and reduce capacity to provide familiar ecosystem services. Examples for each ecological realm are highlighted.

Genetic basis of adaptation. The rapid nature of climate change suggests that evolution as a mechanism for individual species to adapt to changing conditions may be limited but evolution has the potential to generate rapid changes and ecological surprises (Chevin *et al.* 2010; Hof *et al.* 2011; Nicotra *et al.* 2010). Over many generations and under stringent selection pressures, driven by climate change, some species' populations may evolve to adapt genetically (Hoffmann & Sgro 2011). In this report, we mention the genetic basis for climate change adaptation and acknowledge the potential but we have not comprehensively reviewed literature on this topic. The remaining response options available to species are persistence (through phenotypic plasticity), dispersal, migration, and extinction (discussed in Sections 3.2.3, 3.3.3 and 3.4.3). Determination of likely ecological transmission pathways (velocity and direction of change, potential for persistence or dispersal of species) will aid the planning of climate change reserves and corridors. A variety of responses to climate change among species contributing to ecosystem function is critical to resilience (Section 4). Knowledge of the adaptive capacity of ecosystems and their constituent species in the face of climate change is fundamental to developing adaptation options (Weeks *et al.* 2011) (Section 5).

Refugial habitats. Terrestrial, freshwater aquatic and coastal-marine environments contain habitats that may act as refuges for biota that provide permanent or temporary protection from unsuitable conditions, and allow species to persist over the long term. Refugia habitats are prominent in many of Queensland's terrestrial reserves. Identifying and maintaining refugia will be an important component of adaptation (Section 5). In marine ecosystems, however, ocean acidification will alter environmental conditions across all habitats (3.4.2).

Sea level rise. Rising sea-levels have general consequences for coastal inundation and will influence the interface between marine, freshwater and terrestrial ecosystems. For ecosystems in the coastal zone, rising sea levels will be associated with increased coastal erosion processes through the dynamics of interaction between storm-surges and tides. The effect will be particularly strong during extreme events such as the confluence of intense storms with king tides (further details are given in Sections 3.2.4 and 3.3.4).

Uncertainty. Despite a high level of certainty concerning the likelihood and causes of global climate change there is still considerable uncertainty surrounding the potential magnitude of impacts of climate change on Queensland's natural ecosystems. Nevertheless, while keeping uncertainty concerning the biophysical science in mind, the knowledge we have acquired to date provides valuable insights for choosing the most appropriate adaptation options (Section 5).

Knowledge about the impacts of climate change on biodiversity is far greater in some parts of Queensland than others but the current scientific consensus is that there is likely to be substantial change to natural and human-altered systems. This change will act through a cascade of effects on biological systems driven primarily by rising temperatures, altered rainfall patterns and changed disturbance regimes. These changes will result in shifts in plant and animal distributions and modify interactions between species. There will also be regional changes in threats and threatening processes such as the presence of invasive alien species, the frequency and intensity of fires and ocean acidification. Future natural landscapes and seascapes are likely to look and behave differently from those we know today.

3.2 Terrestrial ecosystems

3.2.1 Introduction

Queensland's globally-important terrestrial biodiversity is contained within a wide variety of landscapes that include tropical and subtropical rainforests, savannas, natural grasslands, stony and sandy arid lands, cool rocky woodlands and arid floodplains. The geographic distribution of these landscapes broadly corresponds with the 13 terrestrial bioregions occurring in Queensland (Queensland Herbarium 2011). The largest bioregions are in the western arid and semi-arid areas that have relatively shallow climatic gradients and low relief (see boundaries shown on Figure 9). The eastern coastal regions experience sharp climatic gradients in places of high relief. These diverse landscapes harbour a high level of endemic wildlife and a large proportion of Australia's total flora and fauna species (DERM 2010a).

Biodiversity in Queensland has already undergone significant change due to land clearing, grazing and invasive alien plants and animals. These all contribute to declines and fragmentation of habitat (Guymer *et al.* 2008; Wilson *et al.* 2008b). The remaining remnant vegetation has been classified and mapped into its component regional ecosystems for 83% of the State (Accad *et al.* 2008; Neldner *et al.* 2005). Of the 1384 defined regional ecosystems, 89 (6%) are represented by 10% or less of their original extents. These ecosystems occur mainly in fertile agricultural areas and coastal regions that have been extensively cleared (Queensland Herbarium 2011). As a result of land use change, 10% of the 185 regional ecosystems in the Wet Tropics bioregion are considered endangered (< 10% of their original extent remaining) with another 72% considered 'of concern' (<30% of their original extent remaining) under the *Vegetation Management Act 1999*. Many of these remnant habitats continue to provide services such as timber extraction, grazing, tourism and recreation, and some carry the legacy of degradation from past unsustainable land management practices. Taking into account these impacts on condition or ecological integrity of remnant habitats as defined by the 'biodiversity status' of these ecosystems, 42% are considered endangered and 47% are 'of concern' (i.e., vulnerable) (Queensland Herbarium 2011). These degradation processes are reflected in declining abundance of some native species and, where specific information is available about extinction risk, their listing under the *Nature Conservation Act 1992*. Queensland's draft strategy for the conservation of biodiversity therefore encompasses species, ecosystem and landscape level objectives and actions (DERM 2010a; DERM 2010b).

Climate change will be an additional driver of change in terrestrial ecosystems, it will interact with existing threatening processes to cause 'threat syndromes' (Burgman *et al.* 2007) that will alter constituent species and ecological process across Queensland. Continental and global reviews have identified areas of Queensland that are at particular risk from climate change impacts. These include the Wet Tropics of Queensland (Hilbert *et al.* 2001; Hughes 2011), high altitude and montane regions (Hilbert *et al.* 2001; Steffen *et al.* 2009a; Williams *et al.* 2003), tropical savanna-woodlands (Laurance *et al.* 2011), drier rainforests types including vine thickets (Laurance *et al.* 2011), coastal floodplains and wetlands (Laurance *et al.* 2011) and areas of high endemism (Thomas *et al.* 2004). Due to their low relief, the majority of Queensland areas west of the Great Dividing Range, comprising tropical and subtropical grasslands, savanna and shrublands, are expected to experience some of the fastest 'velocities' of climate change (Loarie *et al.* 2009). To keep pace with climate change the response of species in these areas will need to be faster than that of species in areas with slower velocities (e.g., mountainous areas) (see Section 2.2).

Other workers have identified particular taxa or localities at high risk of population decline or extinction arising from climate change. These include amphibians (Pounds *et al.* 2006; Steffen *et al.* 2009a), reptiles (Kearney *et al.* 2009) and endemic fauna of montane regions (Williams *et al.* 2003). Centres of species richness and endemism represent areas of special evolutionary history and possible centres of diversification (Jetz *et al.* 2004), where climate change may increase species extinction rates. Major centres of endemism for vascular flora in Queensland occur in the Wet Tropics, Border Ranges and Iron Range/McIlwraith Range area of Cape York (Crisp *et al.* 2001). The Channel Country of south-west Queensland is also highlighted as a vulnerable region because many animals in this area are already living close to their thermal limits during summer. If climate change causes even higher temperatures there could be catastrophic losses of wildlife in the area during heatwaves and drought (Low 2011). Rapid climate change may be experienced first in the Cape York and Gulf regions where novel environmental conditions (i.e., conditions not currently existing) are expected to arise and current conditions disappear by 2070 (Section 2.2.3).

In the following two sections we provide a synthesis of potential environmental drivers of change and the ecological changes expected in Queensland's terrestrial ecosystems (summarised from Murphy *et al.* 2012).

3.2.2 Environmental drivers of change

Changes in average weather conditions due to global warming will result in a permanent change in thermal living conditions experienced by biota across a diverse range of habitats and scales from arboreal to sand dune, in soil and in rocky landscapes. Some habitats will be buffered while others will be exposed to more extreme conditions. In this section we highlight climatic and environmental changes (rising CO_2, intensity of cyclones, cloud stripping, sea-level rise, altered fire regimes) that have the potential to directly influence terrestrial biodiversity and have flow on effects for ecosystem structure, function and services. An overview of the scientific evidence and basis of climate change, and a summary of the changes projected to occur over Queensland, is given in Sections 2.1 and 2.1.2.

While increasing levels of atmospheric carbon dioxide (CO_2) influence global temperature and climate, they also directly affect the growth, physiology, and chemistry of plants and related organisms and ecosystem processes. The effect results from the central importance of CO_2 to plant metabolism. Knowledge of plant responses to future atmospheric CO_2 concentrations comes from experiments comparing growth under ambient conditions with growth under conditions of increased CO_2. In a review of such knowledge, Hovenden and Williams (2010) found that for Australian plants, at the species level, the most overwhelming response to increased CO_2 was a reduction in plant nitrogen concentration and an increase in the production of secondary metabolites, particularly in woody plants. Scaling-up from the response of individual species, it can be expected that many plants will become less nutritious and potentially more toxic for herbivorous animals. This would result in significant changes to trophic interactions (Hovenden & Williams 2010) and have consequences for species competition and animal production based on natural systems.

Climate change models have shown that near-surface cloud layers will shift upwards in elevation with rising atmospheric carbon dioxide concentration (Still *et al.* 1999). This will possibly result in a significant reduction in cloud interception that could adversely affect high-altitude rainforest in the Wet Tropics and Gondwana Rainforest World Heritage Areas (Laidlaw *et al.* 2011; Williams *et al.* 2003). There is likely to be a decline in critical inputs of mist and water at high altitude. These sources of moisture are of particular significance during the tropical dry season (McJannet *et al.* 2007). A raised orographic cloud base will potentially affect many taxa that require high and consistent moisture levels (e.g., microhylid frogs, litter skinks, soil invertebrate faunas, microbes) (Williams & Hero 2001). These changes may indirectly impact insectivores and litter processes such as decomposition and nutrient cycling (Williams *et al.* 2003). This could result in compositional shifts from mesic to more sclerophyllous communities on tropical mountain ranges.

Global warming appears to be driving an increase in tropical cyclone intensity (Webster *et al.* 2005) and in the occurrence of cyclones that are more long-lived and have a southward shift (Abbs *et al.* 2006; Leslie *et al.* 2007). The frequency of cyclones in the future is unclear but it seems likely that frequency will decrease (CSIRO & BoM 2007b) (see Section 2.1.3). The main effects of tropical cyclones at landfall are heavy rain, strong wind and ocean storm surges. The destructive force of a tropical cyclone depends on its intensity, extent, location and rate of passage. Tropical cyclones strip forest canopies, remove vines and epiphytes from trees, damage branches and stems extensively and cause tree fall (e.g., Figure 13). The storm surge alters the landscape near coastal areas by moving and reshaping dunes and undermining littoral banks. Heavy rainfall destabilises soils in mountainous areas and triggers landslips. Terrestrial runoff scours land surfaces and loads of river sediments are deposited in wetlands and estuarine systems and can form plumes into coastal-marine habitats.

Recovery of terrestrial ecosystems after a cyclone has passed can take many years. Eventually a complex spatial disturbance mosaic develops (Murphy *et al.* 2010; Murphy *et al.* 2008; Turton 2008). The forest debris, dry beneath stripped canopies, provides fuel for wildfires during the following dry seasons. Forests are at risk of more permanent transformation until the regenerating foliage closes the canopy and restores humidity to the arboreal environment. Frequent cyclone disturbance can affect the structure and demography of lowland forests resulting in shorter canopy heights and higher stem densities (Gouvenain & Silander 2003; Webb 1958). Northern tropical landscapes are accustomed to tropical cyclones but these are rare events in the central and southern coastal landscapes of Queensland. With the southward shift of tropical ocean currents, southern cyclones will become more probable and, over time, the coastal and hinterland forests will become more disturbance-oriented and prone to burning if periods of drought follow. However, recent research by Levin (Levin 2011) provides historical evidence for a higher frequency of tropical cyclones impacting the coastal ecosystems of Fraser Island, than occurred in recent decades.

Alteration of disturbance regimes by climate change is very significant for terrestrial ecosystems. Fire is an important natural disturbance that has shaped Australian landscapes for millennia. The frequency, intensity and influence of fire (key components of fire regimes) are tightly coupled with weather and climatic conditions both at the time of the fire and leading up to the fire. The projected effects of climate change, such as increased temperatures, potential for additional plant growth through CO_2 fertilisation, and changes in rainfall and evaporation, may act together to alter the risk of fire. As a result, changes in future fire regimes are projected for Queensland (Lucas *et al.* 2007; Williams *et al.* 2009). Area burnt is strongly dependent on weather conditions (Bradstock 2010; Flannigan *et al.* 2005). There is emerging evidence that global warming is causing, and will continue to cause, increases in the severity of fire-weather (Lucas *et al.* 2007; Pitman *et al.* 2007; Westerling *et al.* 2006; Williams *et al.* 2009).

Figure 13: Damage to littoral rainforest with melaleuca north of Cardwell following Category 5 Tropical Cyclone Yasi (February 2011) (photograph by Dan Metcalfe, CSIRO).

A potential climate change signal has already been observed in a widely-used measure of fire weather called the Forest Fire Danger Index (FFDI). At long term weather stations in Queensland and northern NSW there has been a 5-35% increase in the annualised sum of the daily FFDI (∑FFDI) from 2002-2010 compared with the preceding period, 1980-2001. Modelling based on projected climate change indicates further rises in FFDI to 2050. Under a high emissions scenario ∑FFDI is projected to increase by between 11-37% by 2050. The number of days when fire weather is in 'very high' or 'extreme' categories ('VHEX' days) is also projected to increase by 7-71% by 2050 (Lucas *et al.* 2007; RJ Williams and C Lucas, unpublished data).

There are six broad landscape-ecological types or biomes in Queensland within which fire regimes vary (Murphy *et al.* 2012). Fire regimes already have been substantially altered from pre-European settlement by extensive clearing for agricultural and pastoral development, forestry, and/or urban development over the past 200 years (Dyer *et al.* 2001; Myers *et al.* 2004; Russell-Smith *et al.* 2009). In the tropical savannas of northern Australia, fire regimes are generally of high frequency and relatively low intensity (e.g., 1-5 year recurrence intervals and intensity <10,000 kilowatts per metre, kW/m). This is a consequence of the annual production and curing of grassy fuels and an annual hot, dry season (Williams *et al.* 2002). In contrast, in the eucalypt-dominated forests of the temperate regions of southern Australia, fire regimes are of relatively low frequency and high intensity (e.g., multi-decadal recurrence intervals and intensity >10,000 kW/m). This regime is a consequence of the infrequent co-occurrence of severe fire weather and prolonged drought (Bradstock 2008; Bradstock 2010; Gill & Catling 2002). Fires also occur in the arid zone at decadal frequencies. This is because several years with higher than average rainfall are required to produce enough grassy biomass for fire to propagate across the landscape (Allan & Southgate 2002; Russell-Smith *et al.* 2007).

The 'four switch' model of fire regimes (Bradstock 2010) could be used to explore the potential impacts of climate change on fire regimes and biodiversity in different regions of Queensland. The model proposes four primary drivers of fire activity – fuel biomass (amount), the availability of fuel to burn (moisture levels), fire weather, and ignition. All can be thought of as 'switches' and all four need to be turned 'on' simultaneously for fire to propagate across the landscape. The rates of turning 'on' and 'off' vary regionally because of differences in climate and fuels. For example, in biomes such as the tropical savannas and the brigalow, invasion by alien grasses, and their impact on fire regimes, is likely to pose a greater threat to these ecosystems than is a change to fire regimes caused solely by more severe fire weather (Bradstock 2010; Williams *et al.* 2009). For the rainforests and adjoining wet eucalypt forests more severe fire weather alone may not pose a threat. Instead, fire impacts are likely to depend on the recurrence rate of droughts, and possibly cyclones, acting in conjunction with more severe fire weather. All the factors that impact on fire regimes also have consequences for humans directly and so have the potential to alter support for fire management in affected regions.

3.2.3 Ecological change

Potential ecological change events were outlined in Section 3.1.2. Given the rapid nature of climate change, the primary options available to species can be summarised as persistence, dispersal, migration and extinction (Bashar 2011; Lawler 2009). Biological persistence responses to climate change expected in Queensland include changed growth and photosynthetic rates in plants (Cunningham & Read 2002, and summarised for Queensland in Low 2011), changes in phenological patterns (such as the migratory behaviour of Australian birds) (Parmesan 2006) and changes in behaviour, morphology and physiology (Shoo *et al.* 2010; Telemeco *et al.* 2009). Changes in metabolic rates have been demonstrated for terrestrial ectotherms such as reptiles (Dillon *et al.* 2010). Many species may minimise their exposure by adapting individual biology or by utilising cool, moist micro-habitats (micro-refugia) that act as buffers against climate change and extreme events (Shoo *et al.* 2010). The critically endangered beautiful nursery frog (*Cophixalus concinnus*) in the wet tropics, for example, may persist longer than predictive modelling indicates by sheltering during extreme or prolonged heat in high-altitude boulder fields. Temperatures within these boulder fields can be up to 10°C lower than surface conditions (Shoo *et al.* 2010).

Changes in population abundances and shifts in species geographic distributions are considered the most likely response of terrestrial biota to rapid climate change (e.g., up mountains, towards the poles, following rainfall events, toward the coast). Bioclimatic models suggest range shifts to the south and east within Queensland even by species that currently inhabit arid, semi-arid and savanna habitats of the state (Adams-Hosking *et al.* 2011; Kearney *et al.* 2010; Ritchie & Bolitho 2008). In the tropics, where the latitudinal temperature gradient is very shallow, range shifts for terrestrial species may be either upslope in mountainous areas (e.g., the Wet Tropics) or over long distances in flatter areas (e.g., the northern savannas). This is the case for both native and alien species (Kriticos 2005; Murphy *et al.* 2009). A consistent finding of bioclimatic models applied to wet tropical rainforest habitats is a decline in the geographic distribution of endemic faunal species (Hilbert *et al.* 2004; Meynecke 2004; Williams *et al.* 2003). These modelling studies predict dramatic declines in the range of all 65 regionally-endemic vertebrate species for temperature increases of 3.5°C. The extreme vulnerability to extinction of these species is indicated by the fact that their core habitat is predicted to disappear if temperatures increase by 7°C.

Extinctions may occur when local habitat conditions are no longer suitable, access to suitable habitat is beyond the migratory or dispersal range of species, or a resource base, such as prey, available water or suitable herbaceous vegetation, shifts too quickly. Extinctions potentially allow new species (either native or introduced) to increase in abundance and will result in a reshuffling of ecosystems and a modification of their function and appearance. Species having small ranges are predicted to have greater vulnerability to extinction due to range displacement as a result of climate change (Schwartz *et al.* 2006). For example, bioclimatic modelling for the very restricted microhylid frog *Cophixalus neglectus*, which is limited to altitudes between 1300 and 1600m in Queensland, shows complete displacement of its current range with just 1°C of warming (Meynecke 2004). Areas of endemism are particularly noteworthy in terms of their biodiversity value and the potential for climate change to have the most serious implications for species extinction rates. Narrowly endemic species are by definition rare and have small geographic ranges. They are therefore potentially highly threatened (Crisp *et al.* 2001) but some species may be more suited to the new conditions and increase in abundance.

Disturbance can cause rapid ecosystem change. This happens with large natural disturbances like fires, cyclones and droughts, or through human activities such as tree clearing. Most systems are able to recover from disturbance events but stressed ecosystems may transition to a new state following disturbance. Importantly, species are typically adapted to specific disturbance regimes rather than to the changing regimes expected with global warming. An increase in the severity of cyclones, or in the frequency and intensity of rainfall or fire events, has the potential to cause permanent vegetation shifts and seriously impact ecosystem productivity. A recent example occurred following prolonged flooding in the Gulf Plains region during 2009 where widespread pasture death was recorded. Gobius (2010, reported in Low 2011) also noted a striking loss of mound building termites. This flood disturbance highlights the critical importance of species, such as ants and termites, in overall ecosystem productivity. Recent and past research has shown that ants and termites provide valuable ecosystem services in arid climates by increasing spatial structure, soil water infiltration rates and improve soil nitrogen (Evans *et al.* 2011; Fox-Dobbs *et al.* 2010; Whitford 1996; Whitford *et al.* 1992). The loss of these ecosystem services, caused by the loss or decline of termites with repeated or more intense prolonged flooding, could slow pasture recovery or prevent the ecosystem returning to its original productive state.

As outlined in Section 3.2.2, climate change has the potential to increase the area burnt, increase fire intensity and shorten intervals between fires, all of which have major implications for ecosystem function (Bradstock 2010; Williams *et al.* 2009). The influence of changed levels of moisture, temperature and CO_2 will strongly affect biota in the interval between fires through effects on critical life processes such as regeneration, growth and reproduction. Such effects will interact with the direct effects of changes in fire regimes. For example, 'interval squeeze' may be induced by lower moisture regimes under climate change. Intervals between fires may shorten but, under a regime of reduced moisture, the period needed for species to achieve critical life stages may increase. This has implications for rapid, transformative change in vegetation function, composition and structure (Williams *et al.* 2009). This highlights the importance of understanding the interplay between disturbance regimes, variability in resources, climates and resulting biotic responses. Research into such complexity is in its infancy but will have major implications for management.

Preserving interactions among species is critical to the maintenance of food and material flows in terrestrial ecosystems but asynchrony in species interactions is a likely consequence of climate change. Asynchronous species interactions can cause temporal, spatial or functional shifts in the composition of species assemblages and disrupt important ecosystem processes. Plant species, for example, require synchronous interactions with pollinators, seed dispersal agents, herbivores and symbionts to complete their life cycles (Díaz *et al.* 2005). Some of these interactions are specific and some are more general. The cassowary is an important dispersal agent for plants that produce large fleshy fruits (Bradford *et al.* 2008; Crome & Moore 1990; Westcott *et al.* 2005). It distributes the seeds of more than 70 species of native rainforest trees (Latch 2007) (Figure 14). Continuing declines in cassowary populations, through the combined effects of habitat loss and climate change (e.g., starvation following cyclones) may leave many rainforest tree species without effective seed dispersal agents. Over time this would alter the composition and function of rainforest.

Figure 14: Cassowaries provide vital ecosystem services. They are the only animals capable of dispersing the very large seeds of more than 70 species of native rainforest trees and assist in the long-distance dispersal of at least another 80 species (WTMA 2011) (photograph by Adam McKeown, CSIRO).

Knowledge of the adaptive capacity of ecosystems and their constituent species in the face of climate change is fundamental to developing adaptation options. There is some evidence for phenotypic plasticity and adaptation at the individual organism level, particularly through behavioural and physiological changes. By and large, however, the capacity of individual organisms to adapt to climate change is very poorly understood. It may be underestimated for some species and overestimated for others. These unknowns contribute to uncertainty about the nature of ecosystem responses to climate change. This uncertainty is exacerbated because (a) climate change is an additional pressure placed on natural ecosystems that are potentially already stressed and (b) climate change is occurring in Queensland at a more rapid rate and at a greater magnitude than that experienced during past climatic cycles.

All species, in some way, contribute to overall ecosystem function. Therefore, the diversity of species and their potential responses to climate change is critical to ecosystem resilience (Elmqvist *et al.* 2003). Recent research consistently highlights the role of biodiversity in maintaining ecosystem function and services of importance to humans, such as productivity and water quality (Isbell *et al.* 2011; Steudel *et al.* 2011). A large body of work has demonstrated that high levels of species diversity enhance many ecosystem process rates, such as resource use and productivity, or biomass production, across a wide spectrum of organisms and systems (Balvanera *et al.* 2006). There is also general consensus among scientists that healthy, intact ecosystems with diverse habitats and rich biodiversity are likely to be the most resilient to environmental change (Díaz *et al.* 2005; Elmqvist *et al.* 2003; Hooper *et al.* 2005). Such ecosystems are thereby most likely to continue to deliver ecosystem services.

Two prerequisites must exist for species adaptive responses to be successful in countering the rapid predicted rate of climate change. These are landscape and biogeographic connectivity to allow organisms to reach suitable habitats or refugia plus adequate time to allow movements or adaptive changes (Williams *et al.* 2008). An intact heterogeneous landscape offers a diverse array of species with either the capacity to move into proximal suitable habitats or contract to micro-habitats that provide suitable future conditions. However, many of Queensland's terrestrial ecosystems are fragmented or degraded by multiple pressures such as weeds, feral animals, fire, land management and pollution that reduce their inherent resilience to further change. Special consideration should therefore be given to species diversity when planning ecosystem management and restoration, since it may contribute to the resilience of desired ecosystem states against disturbance, mismanagement, and degradation (Elmqvist *et al.* 2003).

Colonisation success in destination habitats is influenced primarily by three species-specific landscape factors. These are dispersal/movement distances, matrix permeability and physical barriers. All of these factors influence landscape connectivity in the context of particular species. However, connectivity is not just a function of colonisation capacity; it also incorporates habitat area, quality and arrangement (suitability) and thus is a complex and dynamic variable requiring whole-of-landscape assessment approaches (Drielsma & Ferrier 2009; Ferrier & Drielsma 2010). Species may experience crucial bottlenecks in their geographic range where low connectivity, or too few suitable habitat patches, inhibit spatial responses to climate change. Importantly, bioclimatic modelling for Queensland vertebrates indicates that suitable habitat for a large number of species becomes much more fragmented as range contractions occur. This will likely correspond with smaller population sizes and increased isolation. These are both factors that threaten population persistence (Beaumont & Hughes 2002; Hilbert *et al.* 2004; Ritchie & Bolitho 2008).

Refugial features in the landscape have been important to the persistence of native species during past climate change (Carnaval & Moritz 2008; Mackey *et al.* 2008). Climatic gradients, landscape heterogeneity and spatial patterning in the landscape all generate refugia in a number of contexts (Keppel *et al.* 2012). Landscape refuges provide protection from unsuitable or threatening conditions for plants and/or animals and foster persistence. Species with sub-populations in heterogeneous landscapes are less likely to go regionally extinct (Loreau *et al.* 2003). The protection of refugia habitats is likely to be important for the conservation of some terrestrial species. Such habitats are prominent in many of Queensland's reserves (NRMMC 2005; NRS 2010) and Australia's biodiversity hotspots (DSEWPaC 2009). For example they occur in the Carnarvon Gorge and coastal mountain regions like the Wet Tropics. It is important to keep in mind that protection of refugia habitats may in some cases (e.g. to maintain centres of evolutionary history) involve a reduction of connectivity or proactive management to counter the risk of invasive species and/or wildfires. Furthermore, some refugia will be dynamic as climates change. These will either move location, or disappear and other areas will begin to offer protection under a changing climate. Refugia are therefore best defined as environmental habitats with space and time dimensions that operate on evolutionary time-scales that have facilitated the past persistence of biota under changing environmental conditions (Keppel *et al.* 2012). Determining the persistence of refugia habitats in space and time, and how these may be affected by disturbance regimes such as fire is a high priority for research and management. Adaptation may essentially involve managing the same type of environment not just in different ways but also in different places (see Section 5).

3.2.4 Regional variation

The impacts of climate change on terrestrial ecosystems will not be uniform across the state of Queensland. This is because different parts of the state currently experience different levels of land use change and have different weather patterns associated with different geographies. These factors will interact with climate change to generate different degrees and types of ecological change over time (see Section 2.1.3 and 2.2). While the rate and extent of regional change is difficult to predict it can be visualised with the aid of ecological models (e.g., see Section 2.2.4). Current scientific understanding, however, has not determined how close many ecosystems currently are to their environmental limits, and knowledge is especially limited for rare and threatened species. As noted by Lawler (2009): *to successfully manage for climate change, a better understanding will be needed of which species and systems will likely be most affected by climate change, how to preserve and enhance the evolutionary capacity of species, how to implement effective adaptive management in new systems, and perhaps most importantly, in which situations and systems will the general adaptation strategies that have been proposed work and how can they be effectively applied.* Nonetheless, two driving forces of transformative ecological change will act in concert with global warming and regional geographies to reinforce regional patterns of terrestrial change. These are fire and water.

Figure 15 integrates knowledge about the direction of terrestrial ecological change processes in Queensland. The figure is based on climatic gradients that determine primary productivity and resulting fire regimes. We can use this understanding to consider the impacts of a change in rainfall pattern regionally and how this could lead to change in species presence, new fire regimes, and therefore a different appearance of ecosystems (structure, function and composition of species) to that currently seen in any one place.

Moisture is a fundamental prerequisite of life and regions subject to significant changes in the balance between rainfall and evaporation, both annually and seasonally, will see a corresponding change in vegetation biomass. This will affect the structure and function of supporting habitats for other species. Reductions in rainfall and drought due to climate change, although uncertain, have the potential to transform terrestrial ecosystems through interactions with temperature, evaporation, invasive alien species and fire (Bradstock 2010; Low 2011; Rossiter et al. 2003; Williams *et al.* 2009). In water-limited regions the effects of declining rainfall on primary productivity may be moderated by changes in water and nitrogen use efficiency as a result of CO_2 fertilisation (Hughes 2003; McMurtrie *et al.* 2000) but forage will be less nutritious. Dependent species may become malnourished and this could lead to a cascade of change in food web structures (Hovenden & Williams 2010; Stokes *et al.* 2005).

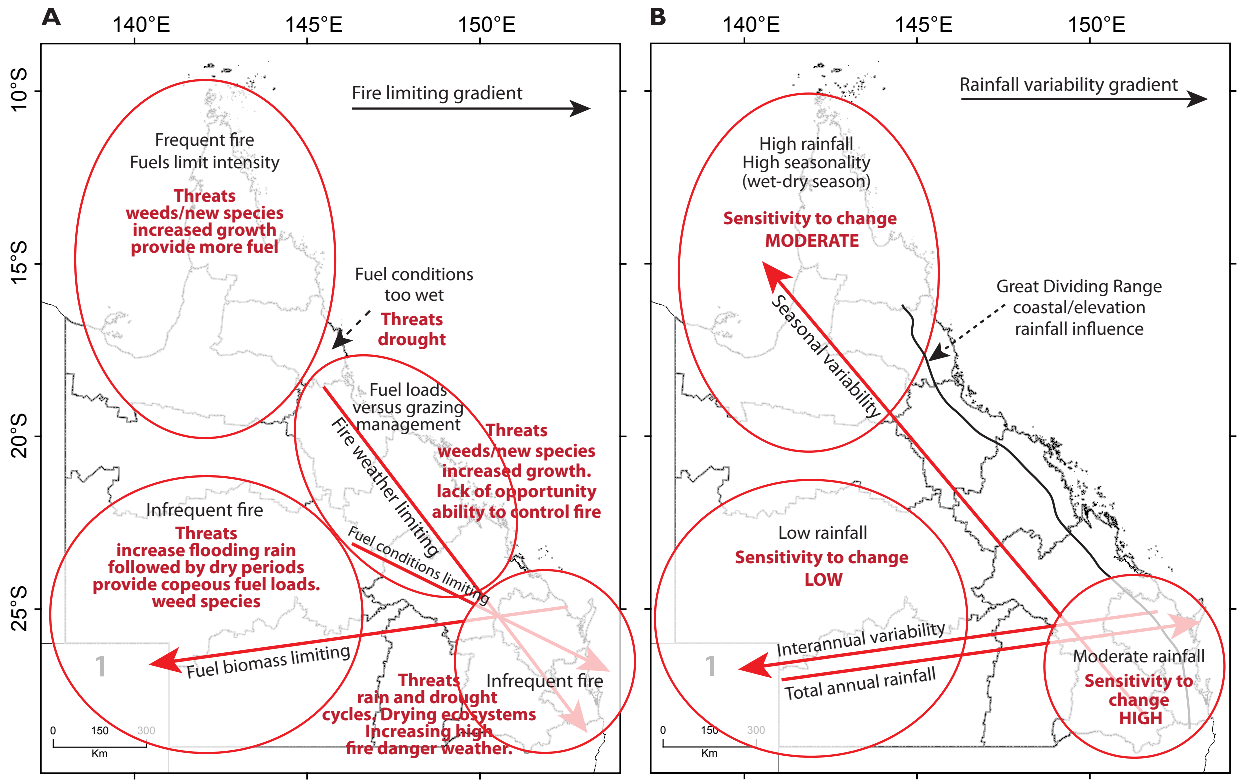


Figure 15: Conceptual summary of the regional influence of rainfall based on possible regional changes in fire regimes (A) and rainfall variability gradients (B) with climate change.

Western inland regions, which are already characterised by large temperature ranges and extended hot conditions, may support flora and fauna close to their thermal limits (although this needs further investigation) and such species could be vulnerable to even modest increases in the number of consecutive hot days (Low 2011). The tropical savannas in particular present a nationally important global change-fire regime problem: the spread of alien species, particularly grasses, because fire regimes in these systems are presently limited by fuel and ignition more than by climate (Bradstock 2010; Williams *et al.* 2009; Woinarski *et al.* 2007). With increasing temperatures, and cycles of flooding rain and drought (Whitfield *et al.* 2010), the subtropical sclerophyll forests of Queensland's south-east region are likely to experience an increase in fire activity and intensity beyond the current familiarity of local fire managers (Lucas *et al.* 2007; Williams *et al.* 2009). Across central Queensland, pastoral grazing pressure has suppressed fire activity (Dyer *et al.* 2001) but the dynamics of this system may change due to CO_2 fertilisation and, along with intense rainfall from cyclonic depressions at more southerly latitudes, result in more pasture production. Coupled with this phenomenon, increasingly severe fire weather conditions may limit the opportunity to undertake prescribed burning and so provide conditions for the propagation of unplanned fires (Figure 15a, b).

Regions most vulnerable to change are likely to be those containing species and ecosystems with restricted geographic distributions, narrow environmental tolerances or systems near the limit of their environmental tolerance and subject to synergistic threat syndromes. These are regions with high elevation mountain ecosystems (Hughes 2011; Laurance *et al.* 2011; Williams *et al.* 2003), dry rainforest types (Laurance *et al.* 2011), tropical savannas (Laurance *et al.* 2011), ecosystems of the Gulf region (Low 2011), ecosystems in arid and semi-arid regions (Steffen *et al.* 2009a) or in the Channel Country of south-west Queensland (Low 2011) and areas with a high number of narrow-range endemic species (Crisp *et al.* 2001).

Box 1: An example of how change in regional environmental conditions may be visualised (see illustrations of environmental change in Section 2.2.4).

Here we provide a commentary on what types of ecological responses might be observed if we were living in the Moreton Basin subregion of South East Queensland. The current suite of environmental conditions associated with the subregion has occurrences with varying levels of similarity that radiate geographically in close proximity (e.g., Figure 10). By 2070, these environmental conditions could have shifted and contracted southward and to higher elevations. They appear spread across the New England Tableland and Nandewar bioregions of northern New South Wales (e.g., Figure 11). The future environmental conditions are less similar to the current environments because the available combinations of future climate, and existing substrate and terrain in this new region are different. Higher levels of similarity characterise places more like the Moreton Basin subregion and lower levels of similarity indicate places less like that subregion. These upland plateau and mountain regions of northern New South Wales, in part connected to Moreton Basin through the Border Ranges, appear to offer habitats that are potentially within the range of environmental conditions of migrating species, assuming capacity for movements of 100km or more over the 100 years since 1960. For some species the rugged terrain represents a significant barrier to movement and assisted migration may be necessary for the species to persist. Cleared areas occupied by other land use (not shown in the figures) may also preclude establishment by species once they arrive at a destination.

By 2070, the environment of the Moreton Basin subregion has changed. These new conditions appear to be similar to those today in northern parts of the South East Queensland bioregion and the northern and coastward parts of the Brigalow Belt subregions (e.g., Figure 12). The future combination of environmental conditions associated with the Moreton Basin subregion is not completely unlike the present combination of environments (e.g., compare Figure 10 and Figure 12). Many species that presently make up the ecosystems of Moreton Basin may be expected to remain, if also able to tolerate the generally drier and warmer conditions or find refuge in cooler microhabitats. However, some species abundances and geographic ranges will have contracted sharply, and species dominance may also have changed. These changes will affect the appearance, structure and function of ecosystem. Some species will not be able to survive in situ and, if they are unable to migrate with the decadal drift in climatic conditions, may need intervention or be allowed to go extinct. Remaining species will also need to contend with competition from formerly low density co-occurring species that sharply increase in abundance and begin to dominate. These may be species that previously were at the southern margins of their geographic ranges that now find themselves located in more suitable habitat. Refuges become contested locations for establishment and survival. Increasing numbers of vagrants, moving southward from their northern habitats, are starting to occupy spaces that are now only loosely held by the former resident species. Some of these invading species may be alien to Australia, expanding from nearby gardens and farmlands and naturalising in the surrounding hills. While others are natives, potentially displaced by the relatively inhospitable environment of their normal habitat, but only a few have the capacity to reach new places and establish in more suitable habitats.

Ecological projections from Section 2.2.3 of this report highlight that many regions in the future may experience novel environments and that these changes will likely be associated with changes in ecosystem structure, function and composition. Projected environments that are most dissimilar to current conditions, for example, may undergo the greatest ecological change. The difficulty in projecting change is evident and while there is a large degree of uncertainty (associated with lag effects, capacity for evolutionary adaptation, dispersal capability, and various biotic interactions) a range of plausible ecological change scenarios would usefully inform management and policy decisions. By applying ecological understanding to indicative climate change projections it is possible to develop a future vision of ecosystem change. For example, if we take one place (or ecosystem) such as the Moreton Basin subregion of the South East Queensland bioregion, and consider how regional environmental conditions may change (see Sections 2.2.4), a story unfolds in considering how species might respond in relation to their source and destination habitats (Box 1). This example highlights how more specific ecosystem scenarios could usefully test ecological understanding and provide a framework for identifying hotspots of change over time. Monitoring of early warning signals in these hotspots would allow land managers to respond in the most appropriate way and at the right time. In particular, such analyses can help managers to identify where they may expect pressures from future invasive species to come from and where they might expect some of the species under their management may need to move to in future (see Section 5).

3.3 Freshwater aquatic ecosystems

3.3.1 Introduction

Freshwater aquatic ecosystems provide essential services that benefit society, including habitat and breeding areas for fish and other aquatic animals, pollutant filters, freshwater for consumption, agriculture and industrial uses, recreation and cultural values (Bennett & Whitten 2002; Davis *et al.* 2007; Harrison *et al.* 2010a; Harrison *et al.* 2010b). Aquatic ecosystems in Queensland cover approximately 4.1% of Queensland's mainland area, or nearly 71,000 km^2, defined as "*areas of permanent or periodic/ intermittent inundation, whether natural or artificial, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6m*" (EPA 1999). Seasonal and intermittently inundated wetlands comprise 69% of the total, with tidal (mangroves and saline coastal flats) contributing 14% and other wetlands making up the 17% remainder. Permanently inundated wetlands cover only 0.7% of Queensland (approximately 12,000km^2) and include more than 1,125,000km of major waterways. While the term 'wetland' describes every inland freshwater system in Queensland (DERM 2011d), here we use the classical definition of streams and rivers, lakes (including reservoirs and ponds), floodplains, and wetlands (e.g., see Polunin 2008) in order to highlight ecological responses to climate change that are specific to different 'wetland' components.

Queensland's freshwater ecosystems occur over a large gradient in climatic conditions from tropical and sub-tropical to warm temperate and hot arid climate zones. Knowledge of freshwater biodiversity and potential climate change impacts across these provinces and drainage divisions is variable. As for other regions around the world, freshwater biodiversity in Queensland is threatened by overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002). While wetland mapping and classification is complete state-wide (DERM 2010c; DERM 2011c), regional aquatic conservation assessments which provide baseline ecological information for natural resource management and planning processes are only complete for a subset of coastal catchments (DERM 2011a).

In this section, we provide an outline of our review on potential environmental and ecological changes in Queensland's freshwater ecosystems as a result of climate change (summarised from Kroon *et al.* 2012). Whilst climate change phenomena have already been detected in aquatic environments across the world (e.g., Rosenzweig *et al.* 2008; Walther *et al.* 2002), examples are not published as widely and extensively as those reported for terrestrial (see Section 3.2) and marine (see Section 3.3.4) ecosystems. Studies specific to the implications of climate change for Queensland's freshwater ecosystems are only now starting to appear in international scientific literature (e.g., Kingsford 2011; Koehn *et al.* 2011; Morrongiello *et al.* 2011). Therefore, we mostly refer to overseas and Australian studies with reference to Queensland information where available.

3.3.2 Environmental change

In general, changes in freshwater aquatic systems will be driven by changes in boundary fluxes[2] like evaporation and precipitation rates, or by changes in local air temperature and wind fields. Rising atmospheric CO_2 levels will raise pH levels in aquatic systems and, in combination with land-use changes, freshwater can become more acidic

[2] Here we do not look at hydrological aspects describing the boundary fluxes at the bottom of water bodies, that is, volume exchange rates of streams, flood plains, and lakes with groundwater. Such processes can heavily impact the water balance of a 'wetland'. However, these processes are not directly climate driven but are a local geohydraulic problem. As well we do not include contaminant inflow from groundwater into water bodies; for example, from mining operations. This is largely an anthropogenic effect, although biogeochemical processes triggered by this will be modified by climate change.

(Tibby *et al.* 2003). Specific to coastal regions, sea level rise will be a key driver of change in aquatic systems. A projected increase in sea level of 0.8m by 2100 (IPCC 2007a) will result in inundation of coastal freshwater ecosystems, saltwater intrusion in coastal groundwater systems, upstream movement of the tidal influence, and associated shift in the freshwater-saline water boundary (DCC 2009; Schallenberg *et al.* 2003). Changes in aquatic biogeochemical processes may also affect ecosystems indirectly by altering, for example, dissolved oxygen, nutrient (e.g., phosphorous, nitrogen, silica) or heavy metal concentrations. Release of sulphuric acid and metals from rewetted acid soils can become a severe problem due to their toxicity for a wide range of aquatic species and for human use (Simpson *et al.* 2010). Aquatic ecosystems are also affected by disturbance regimes such as short-term extreme events like cyclones, flash floods or heat waves, or long-term extremes like prolonged drought conditions.

Increased air temperature will result in increased water temperature in all aquatic ecosystems. This well known effect started last century (Fang & Stefan 2009; Kaushal *et al.* 2010; van Vliet *et al.* 2011). In stratified lakes and reservoirs, increasing temperatures interplay with decreasing wind speeds. On average this will lead to early onset of seasonal stratification and longer stratification periods. Altered levels of stability will depend on changes in winter air temperatures (Peeters *et al.* 2007; Winder & Schindler 2004). Trophic metabolism is expected to increase (Trolle *et al.* 2011) and cause reduced levels of dissolved oxygen in the bottom layers of lakes and reservoirs that can lead to more frequent anoxic conditions (Fang & Stefan 2009). Rivers and floodplains will also experience a decrease in dissolved oxygen that can lead to local fish kills and reduction in recreational amenity (Hamilton 2010).

Global scale analyses demonstrate that climate change, through changes in precipitation and evaporation, will result in alterations in ecologically relevant river flow characteristics (Döll and Zhang 2010). For Queensland, this study revealed that climate change may double the effect of anthropogenic flow reductions (i.e., long-term average annual discharge and monthly low flow Q_{90}) in most river basins by the 2050s compared with past water resource developments. In the Murray-Darling Basin, however, the long-term average river discharge will be less affected by climate change than by past water withdrawals (Döll and Zhang 2010). In hot arid regions, declining annual precipitation, combined with increased evaporation rates, will lower lake levels and increase salt concentrations (Roshier *et al.* 2001; Williams 2002). This will reduce annual river flow rates (Chiew *et al.* 2009) and groundwater recharge (Crosbie *et al.* 2010) and has the potential to reduce the spatial extent of wetlands and floodplains (Bond *et al.* 2008). Extreme changes in precipitation and evaporation can result in more intense and/or more frequent occurrence of floods and droughts (Vörösmarty *et al.* 2000). Reduced runoff will also lead to a reduction in long-term average water availability (Chiew *et al.* 2011).

Rivers, lakes and other wetlands – as integrators of water received from large catchments – will experience a range of changes in nutrient levels, dissolved oxygen and other abiotic constituents (Schindler 2009; Williamson *et al.* 2009). The direction of change depends on a variety of physical, chemical and biological interactions. For example, reductions in dissolved oxygen may be related to the timing and duration of lake stratification interacting with microbial decomposition of organic matter. Since river discharge is a main contributor of sediments and nutrients to the marine environment, changes in the freshwater realm will contribute to changes in the marine environment (see Section 3.3.4).

Extreme events will likely modify the physical environment of freshwater ecosystems. Short-term events like heat waves have the potential to increase stratification stability in lakes and reservoirs and significantly increase surface water temperatures. If these events continue for long enough they may generate favourable conditions for the growth of potentially harmful algal blooms (Jöhnk *et al.* 2008). An increase in wind speeds with more intense cyclonic activity, however, will alter the mixing regime of coastal lakes and disrupt stratification events. Pulses of sediment and nutrient resuspension are another consequence of such wind extremes (James *et al.* 2008). More intense rainfall events will lead to short-term flash-flooding with increased sediment and nutrient levels, increased sediment concentration during flood events, reduced light levels, higher rates of river bed erosion and changed connectivity patterns across floodplains (Lake *et al.* 2006; Tockner *et al.* 2010). Reduction of wetland area due to climate change could severely hamper flood-control efforts in some regions (Gopal *et al.* 2008).

On a longer time-scale, droughts, due to an expected increase in the number of hot years, might affect most parts of Queensland by 2040 (Whitfield *et al.* 2010). Droughts are associated with reductions in annual stream flows, loss of connectivity between river stretches due to drying out, increased water temperatures, drying out of shallow lakes or wetlands and an increase in salinisation (Bond *et al.* 2008; Lake 2008; Timms 2005; Williams 2002). These changes will be in combination with population growth and increased human demand for fresh water (Kenway *et al.* 2008; Lake & Bond 2007; Syktus *et al.* 2008).

3.3.3 Ecological change

Aquatic ecosystems are particularly sensitive to climate change because numerous hydro-ecological processes respond to even small changes in environmental drivers (see Section 3.3.2). These processes may adjust gradually to changes in climate, or abruptly as environmental or ecosystem thresholds are exceeded, causing a dramatic switch in species composition or a changed system state. Thresholds may be physical (e.g., CO_2, pH, temperature), chemical (e.g., salinity, dissolved oxygen), or biological (e.g., algal blooms, invasive species). Depending on the context of the aquatic environment, the environmental drivers through which climate change affects ecological change may act individually or synergistically.

Range shifts are a common phenomenon in aquatic ecosystems, particularly along river stretches where species respond by moving diurnally, seasonally or annually to occupy habitats with favourable environmental conditions (e.g., Tockner *et al.* 2008). For example, freshwater species have specific physiological and behavioural thresholds of temperature, dissolved oxygen, salinity and pH that determine, in part, their distribution (e.g., Pörtner & Peck 2010). When these thresholds change due to climate change, local adaptation may occur where species that have the phenotypic capacity to do so acclimatise to chronic changes in these environmental drivers. Other species may move into new habitats where connectivity exists (e.g., Ficke *et al.* 2007) or become (locally) extinct if dispersal is restricted (e.g., Parmesan 2006). For example, increased water temperature may extend the distributional range of invasive alien species, such as *Gambusia holbrooki* (Meffe 1991) and *Tilapia mariae* (Shafland & Pestrak 1982), into sub-tropical and elevated regions of Queensland. This response contrasts with that of freshwater species with restricted or fragmented distributions and includes species listed under the *Nature Conservation Act 1992* that are likely to be further threatened with extinction due to climate change.

Increased surface water temperature has also been associated with increased occurrence of disease outbreaks, particularly in aquaculture facilities (e.g., Chi *et al.* 1999, and references therein), whilst increased acidity of surface waters may result in increased susceptibility of fish to infections (e.g., Callinan *et al.* 1996). Overall, environmental thresholds have been documented for many of Queensland's freshwater organisms, however, specific responses attributed to climate change have not (yet) been recorded in the field.

In contrast to terrestrial and marine ecosystems, very few changes in phenology have been documented in freshwater environments (e.g., Thackeray *et al.* 2010). Two examples of detailed studies in freshwater ecosystems comprise advances in seasonal phytoplankton blooms (Winder & Schindler 2004) and spawning of fish (Ahas 1999). Seasonal advances in temperature as a result of climate change may promote an earlier start of cyanobacteria blooms (e.g., Paerl & Huisman 2008; Paerl & Huisman 2009) and, in combination with advances in the timing of seasonal flooding, promote the timing of spawning in freshwater fish. It is likely that extreme events, such as floods and droughts, will affect the exchange of genetic material by either expanding or limiting dispersal pathways (Lake 2008). However, neither phenological nor genetic changes in adaptation to climate change have yet been documented in Australia's freshwater species.

Interactions across trophic levels may be severely disrupted by climate change due to altered synchrony (Visser & Both 2005). In freshwater environments changes in precipitation and evaporation will result in temporal and spatial shifts of primary productivity and food web dynamics. For example, predator-prey peak interactions may change due to increasing asynchrony, such as altered peak phytoplankton bloom and zooplankton abundances documented in a USA lake (Winder & Schindler 2004). Increased water temperatures will affect a wide range of ecosystem processes (Kaushal *et al.* 2010) including biological productivity and stream metabolism (e.g., Yvon-Durocher *et al.* 2011). As a consequence, a higher incidence of eutrophication can be expected that will have implications for water quality affecting ecosystem health and human uses (Trolle *et al.* 2011). Both asynchrony and changes in primary production will have subsequent flow-on effects to higher levels of the food web, although the exact impacts are difficult to predict in complex systems. To the best of our knowledge, long-term time series in Queensland's aquatic ecosystems have not been examined for the occurrence of altered asynchrony across trophic levels.

The effects of climate change are superimposed upon existing threats to freshwater ecosystems, namely overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002). Queensland's freshwater fisheries mainly comprise recreational and indigenous fisheries (Henry & Lyle 2003). Whether these fisheries are overexploited is currently unknown and subject to further monitoring. Many fish of significance in coastal and marine commercial fisheries depend on freshwater habitats and flows (e.g., Robins *et al.* 2005), and these fisheries may be exposed to altered flow regimes with climate change. Water pollution, particularly high concentrations of total phosphorus and total nitrogen from agricultural and urban runoff which cause eutrophication, is a concern in most rivers across seven of nine regions for which information is available (Coysh *et al.* 2008).

In combination with low flow conditions (e.g., Bowling & Baker 1996), high water temperature (Mehnert *et al.* 2010) and stratification (Jöhnk *et al.* 2008), high nutrient concentrations may lead to intensified blooming of possibly toxic cyanobacteria (Paerl & Huisman 2009).

Although information on contaminants in Queensland's freshwater ecosystems is not readily available for the Great Barrier Reef catchment (but see Brodie *et al.* 2012) it is predicted that increasing water temperature will result in enhanced toxicity of contaminants (Noyes *et al.* 2009; Schiedek *et al.* 2007) and have unknown synergistic impacts. Extractive use of water is another significant threat to freshwater ecosystems (Ronan *et al.* 2008) and may affect the hydrology of freshwater ecosystems more than climate change (Lake & Bond 2007; Vörösmarty *et al.* 2000) at least in the short to medium term. Intensive land uses such as land clearing, plantation forestry, irrigated and non-irrigated cropping, horticulture, animal production, mining, dredging and river stone extraction, have resulted in freshwater habitat destruction and degradation. Climate change, and associated spatial and temporal changes in intensive land uses, may further exacerbate these impacts. Finally, with long-term changes in environmental drivers, invasive species have the potential to expand their distribution further west and along the coast (Wilson *et al.* 2008a).

Disturbances experienced by aquatic ecosystems include natural events such as cyclones, floods and droughts, in addition to anthropogenic impacts. In most freshwater ecosystems, natural and anthropogenic disturbances interact, resulting in additive, synergistic or antagonistic responses. The predicted increase in high intensity cyclones may irreversibly destroy some freshwater habitats and generate new ones, alter mixing patterns in lakes, wetlands, floodplains and estuaries in the coastal zone, and may cause fish kills in coastal wetlands. The combination of predicted increase in air temperature and continued large-scale extractive use of water is likely to increase the effect of droughts. Major impacts are likely to be 'the loss of water and habitat availability, and the reduction, if not severing, of connectivity (lateral, longitudinal, and vertical)' (Bond *et al.* 2008). River floods and major flood events will increase as a result of increased frequency in extreme rainfall events in the Cape York region throughout the year and in western Queensland and the Gulf region in summer and autumn (Whitfield *et al.* 2010). In combination with reduced river flow rates, severe floods will result in, as yet unknown degrees of, temporal and spatial shifts in connectivity between aquatic habitats and in habitat availability. They will also alter primary productivity and food web dynamics.

3.3.4 Regional change

To evaluate the implications of climate change for regional aquatic ecosystems, we overlaid wetland mapping with current (1990) and future climate change projections (2030 and 2070, moderate and high emission scenarios A1B and A1FI respectively, based on the CSIRO Mk 3.5 climate model). Using mapping to visualise change, we compared current and projected mean annual temperature, evaporation, and mean precipitation for dry and wet seasons, for basins, wetlands habitats and river flow regions (see details in Kroon *et al.* 2012). Over the next few decades under the high emission scenario, high mean annual temperatures could extend south-east, reaching levels in southern Queensland currently experienced in the Cape and Gulf region[3] (Figure 16a, b). Evaporation rates are generally expected to increase. While Cape York and coastal regions are less affected, other inland regions will experience higher levels of evaporation in the future. This might lead to an extension of arid and semi-arid conditions in an easterly direction since there is an equivalent decrease in precipitation during the wet quarter season for south-eastern Queensland (Figure 16c, d). Changes in precipitation rates during the dry quarter season also show possible decreases, shifting towards the south-east. While there is a possible drop in precipitation over large parts of Queensland under climate change scenarios, the western part of Cape York, the Gulf and northern parts of coastal and sub-coastal regions may experience less change with respect to average annual precipitation. However, the probability of extreme river floods will increase due to an increasing probability of extreme precipitation events.

Expected changes in precipitation (declining) and evaporation (increasing) will most likely change the frequency and duration of inundation of some arid and semi-arid swamps and shallow lakes, mainly in the Lake Eyre and Bulloo region, possibly leading to a permanent loss of such wetlands. Western Great Artesian Basin spring wetlands will experience an increase in evaporation and may dry out. Decreased water inflows will likely lead to reduced extent of coastal and sub-coastal lakes and non-floodplain clay pan lakes in the western Murray-Darling region. Further salinisation of lakes in the arid and semi-arid region due to higher evaporation and less frequent freshwater inflow will occur.

Due to generally increasing temperatures, cyanobacteria blooms will most likely increase in intensity and pose a state wide problem for water management and drinking water reservoirs as well as recreational activities like fisheries. Another consequence of increasing temperatures

[3] These inferences are based on climate change projections generated by the CSIRO Mk 3.5 model (Gordon et al. 2010) which, when compared with other global climate models (GCM), is relatively sensitive to emissions. Therefore, higher levels of climate change are projected (warmer and drier) for the Queensland region for a given level of emissions than by other GCMs.

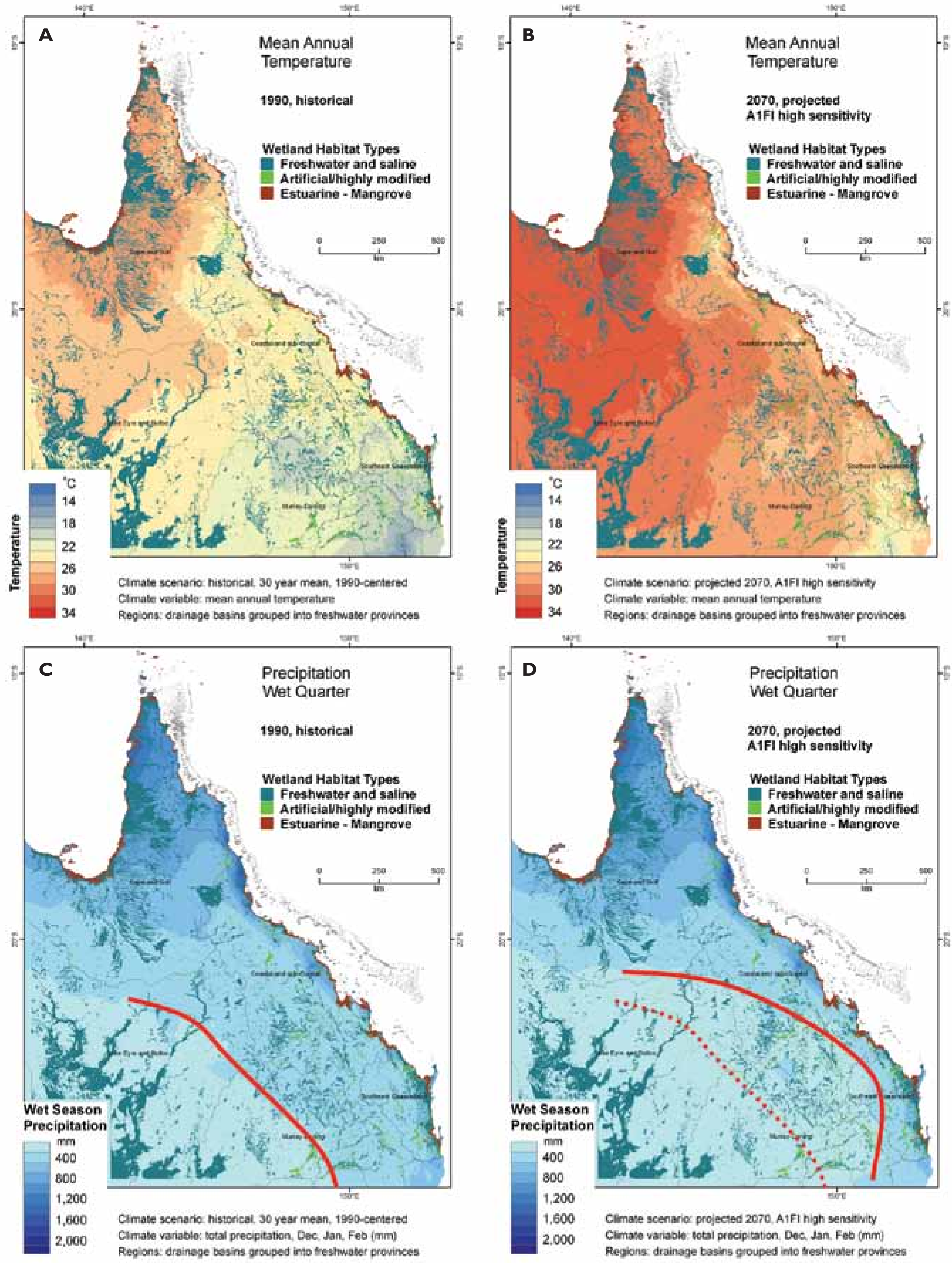


Figure 16: Examples of climate change interacting with aquatic ecosystems across Queensland. Upper two figures: mean annual temperature observations centred on 1990 (A) compared with projections for 2070 (B) (A1FI, high sensitivity, CSIRO Mk 3.5). Lower two figures: mean total precipitation of the wettest quarter observations centred on 1990 (C) compared with projections for 2070 (D) (A1FI, high sensitivity, CSIRO Mk 3.5). The red lines demonstrate the general direction and shift (between dotted and continuous line in D) in rainfall regimes between 1990 and 2070.

is prolonged stratification periods in lakes, which will lead to a reduction in oxygen levels and loss of fish habitat. This will affect mainly coastal and sub-coastal lakes. Coastal dune lakes will probably suffer from salt water intrusion as a consequence of sea level rise.

Overall, in Queensland the biggest impacts of climate change on environmental drivers of freshwater ecosystems are likely to be a reduction in water volume, an increase in water temperature, an increase in salinity in arid and coastal regions, a possible decline in levels of dissolved oxygen, a possible increase in the release of metals from acid soils, and nutrient enrichment during floods. Extreme events may also change the biogeographic settings by altering the connectivity in stream networks, increasing it during flooding conditions while reducing it under drought conditions. The estimated strength and direction of change of each of these environmental drivers is presented for each of the five freshwater regions in Queensland (see Table 2 in Kroon *et al.* 2012), acknowledging that there is currently large uncertainty in the projection of regional change in such environmental drivers (because of uncertainty about rainfall in current climate models) and, therefore, uncertainty in response by freshwater biota.

Example of the impacts of bare ground on water quality, effects of cattle grazing in the Burdekin River catchment, Queensland (Credit: CSIRO Land and Water).

3.4 Coastal and marine ecosystems

3.4.1 Introduction

Oceans and coasts are changing in response to human-driven climate change (Richards *et al.* 2008; Rosenzweig *et al.* 2008; Valdés *et al.* 2009). These changes are more evident when they are considered as part of an escalating dialogue between climate change, conservation, and sustainable uses of natural resources (Rice & Garcia 2011). A recent synthesis of our current knowledge of the global impacts of climate change on the marine and coastal ecosystems states that '…the impacts of anthropogenic climate change so far include decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a greater incidence of disease' (Hoegh-Guldberg & Bruno 2010). Many of these observed changes are projected with some certainty for Australia marine biodiversity (Hobday *et al.* 2006a; Hobday *et al.* 2006b) and mounting observational and expert evidence is being gathered (Poloczanska *et al.* 2009).

The State of Queensland is developing a number of initiatives to confront the challenges of climate change (e.g., Queensland Government 2011b) (outlined in Section 1.1) but presently, there is no overarching approach for dealing with Queensland's overall response to climate and ocean changes. Much of the information and science is narrowly focused, fragmented and largely concentrated on the Great Barrier Reef (GBRMPA 2009; Johnson & Marshall 2007). This means there are large regional, environmental and ecological gaps in the knowledge of climate impacts on Queensland's coastal-marine ecosystems.

In this section we outline the most relevant and readily available published information and knowledge about Queensland's coastal-marine ecosystems (Bustamante *et al.* 2012). These include global, regional and local assessments and studies, both observational and model-based, that can reveal the likely impacts of climate change and guide the development of adaption strategies for managing Queensland's coastal and marine ecosystems. New scientific research on the effects of climate change on the marine ecological realm is appearing rapidly (e.g., Koehn *et al.* 2011) and to the extent possible, we synthesise the most up-to-date and high impact sources. Here, various global and local reviews and publications of the Department of Climate Change and Energy Efficiency[4] and the National Climate Change and Adaptation Research Facility's Marine Report Card[5] (Poloczanska *et al.* 2009) were the main sources of information, as well as a number of key reports and web-based material lodged in web sites of Australian Government and Queensland State agencies.

[4] www.climatechange.gov.au/publications.aspx
[5] www.oceanclimatechange.org.au/content/index.php/site/welcome/

3.4.2 The physical changes on the coasts and oceans

Oceans around Australia have been warming at a similar rate to the global average, but warming is greatest in the ocean waters off eastern and southern Australia. Queensland's waters have an intermediate increase in sea surface temperature (Lough, 2009). This warming has altered the complex current system of the southwest Pacific and changed the structure of water temperatures in the region (Bindoff *et al.* 2007; Lough 2009). The East Australia Current is transporting greater volumes of warm water southward and, over the long term, will increasingly contribute to a southward shift in tropical environments and biota down the Queensland coast (Ridgway & Hill 2009). Projected increases in ocean stratification will affect the supply of nutrients and oxygen into deeper pelagic and benthic ecosystems with implications for their biodiversity (Hobday & Lough 2011).

In the west Pacific, ocean acidification is close to the point where calcareous organisms, such as corals and a number of planktonic species, may already be experiencing a weakening in their shells or skeletal structure. This reduces their fitness and increases their vulnerability to predation and to disturbance events such as storms (Hoegh-Guldberg *et al.* 2007; Wernberg *et al.* 2009). Under an A2 emissions scenario, aragonite (the more soluble of the two natural forms of crystalline calcium carbonate) saturation levels in the tropical west Pacific Ocean are expected to fall below 3.25 by 2035 – 2040. This change will jeopardise the growth of species such as reef-building corals and some calcifying plankton (Erez *et al.* 2011; Hoegh-Guldberg 2011; Veron 2011). Severe consequences for coral reefs are likely if the aragonite saturation level decreases to 2.4 as it is expected to do in 2100 under A2 (Hofmann *et al.* 2010; Howard *et al.* 2009).

Global sea levels have risen by about 20cm since pre-industrial times and 6cm since 1960. The rate of increase is currently around 2.5cm per decade globally and appears to be accelerating due to more rapid ice melt and thermal expansion of the upper ocean (Church *et al.* 2009). The implications for coasts of Queensland include increased risk of inundation and coastal erosion during storm surge events. These physical environmental changes will vary locally and regionally and are likely to affect coastal and near-shore intertidal habitats such as beaches, mangroves, salt marshes, seagrass beds and rocky shores (QCCCE 2011).

3.4.3 Ecological change

As outlined in Section 3.1.2 a wide range of ecological changes and impacts from climate and ocean changes are expected in the marine realm of Queensland (Richardson *et al.* 2009b). However, in the case of regional fish production (Brander 2007; Lobell *et al.* 2008) both positive and negative ecological changes are expected. Many of the negative changes are centred on the interplay between climate related and human-induced stresses such as fishing, eutrophication, pollution, species introductions and diseases (Perry *et al.* 2010). Potential interactions could shift whole coastal and marine ecosystems beyond tipping points and move them into new ecosystem states that will affect the provision of ecosystem goods and services (Hoegh-Guldberg & Bruno 2010; Hoegh-Guldberg *et al.* 2007).

Phytoplankton form the basis of the marine ecosystem food web. The nature of ecological change in phytoplankton biodiversity is highly uncertain. As the ocean warms range expansions southwards are expected for warm-water species, such as tropical algae, together with changes in their abundance and seasonal growth. These simple changes will have cascading and 'match-mismatch' effects on higher trophic levels in marine ecosystems. Toxic algal blooms of tropical dinoflagellates may increase in frequency and intensity and have high local variability. Sub-tropical planktonic species could have increasing episodes of harmful algal blooms in south-eastern waters due to extreme rainfall events and warming (Richardson *et al.* 2009a). These changes are currently stated with medium-to-low confidence but are supported by growing international evidence (Hallegraeff *et al.* 2009). For the next highest trophic level, the zooplankton, there are also high levels of uncertainty, largely due to a lack of long-term observation and studies (e.g., phenology, species diversity, abundance) in Australia. Some evidence indicates that subtropical zooplankton species are extending their range as the East Australia Current penetrates further south (Hobday 2011). In addition to increasing sea surface temperature ocean acidification is a major concern for calcifying zooplankton such as pteropods (Richardson *et al.* 2009c). Even though the level of confidence in projected changes for zooplankton in Queensland oceans is low it is supported by growing international evidence from time series data (Richardson *et al.* 2009c).

The ecosystems of coral reefs in Queensland's Great Barrier Reef will be transformed by mid to late this century due to increased coral bleaching (and associated mortality) and the insidious effects of ocean acidification (Anthony & Marshall 2009). Both soft and hard corals will occur in lower density, have slower growth rates and be more fragile (Anthony & Marshall 2009). Future reefs are likely to be dominated by fleshy macro algae and herbivorous fishes (Anthony & Marshall 2009). The effects of ocean acidification will leave reef ecosystems vulnerable to increased erosion and mortality due to storms (Munday *et al.* 2009a). The shallow and emergent parts of coral reefs will be smaller in extent and provide less of a buffer against ocean swells (Hoegh-Guldberg *et al.* 2007). The specific magnitude, species affected and distribution of these transformations is not yet known but there are medium-to-high levels of confidence that these changes will occur (Poloczanska et al. 2009). The greatest changes are likely to be in the inshore and southern Great Barrier Reef. Improvements in sustainable fishery management and in land use practices aimed at reducing sediment and nutrient in runoff will ameliorate the impact in the remainder of the Great Barrier Reef to some extent (Hoegh-Guldberg 2011).

Despite the generally bleak outlook for corals, there is increasing evidence of variability in the coral calcification response to acidification. Pandolfi et al. (2011) therefore propose an alternative view stating that "…*geographical variation in bleaching susceptibility and recovery, responses to past climate change, and potential rates of adaptation to rapid warming supports an alternative scenario in which reef degradation occurs with greater temporal and spatial heterogeneity than current projections suggest*". They conclude that to achieve a better level of confidence in projections of likely ecological responses an understanding is needed of past responses of corals to interacting factors such as acidification, temperature and nutrients. Insights into the biological and evolutionary costs and constraints of coral acclimation and adaptation to climate and ocean changes are also needed (Pandolfi et al. 2011). History and variability are not the only processes that complicate the prediction of acidification and warming effects on coral reefs. The interacting effects of multiple stressors and ecological changes, largely derived from human activities (i.e., terrestrial runoff, overfishing, and pollution) are also likely to influence the response of coral to climate and ocean changes. Recently, Anthony et al. (2011) modelled the likely responses of coral to different combinations of CO_2 and fishing pressure on herbivores and found that reefs subjected to overfishing and nutrient pollution are likely to be more vulnerable to acidification – that is, less resilient. They also conclude that under higher levels of CO_2, management of local-scale disturbances are critical factors in reef resistance to the effects of climate and ocean changes (Anthony et al. 2011).

Climate and ocean changes are likely to result in coral reefs that are less colourful. They will also have less substrate complexity and reduced biotic diversity (Hoegh-Guldberg, 2011). This means that the Great Barrier Reef will have lower attraction for diving tourists. Some areas will still have appeal due to features such as a high diversity of remaining biota, the occurrence of natural events like spawning aggregations or the presence of unique geological features (Mumby & Steneck 2011). As mentioned above, in relation to the effects of acidification (Pandolfi et al. 2011) corals are showing phenotypic resistance, local adaptations and acclimatisation to the harmful and lethal effects of climate and ocean changes (Anthony & Marshall 2009; Brown & Cossins 2011). Confidence in the likelihood of widespread direct adaptation occurring remains low because of a lack of knowledge about the mechanisms involved. Thermal damage, epigenetic mechanisms in acclimatisation, photo-protective defences of the symbiotic algae-coral relationship and the likelihood of more rapid increases in sea surface temperatures in the future are all imperfectly understood (Brown & Cossins 2011; Hoegh-Guldberg 2011). The study of these mechanisms is a focus of some current research programs (e.g., Pandolfi et al. 2011; Rodolfo-Metalpa et al. 2011).

Little is known about plant-animal assemblages inhabiting the soft-sediment inter-reef areas of Queensland or the deeper continental shelf and slopes. Even less is known about the vast and largely unexplored deeper pelagic and deep benthic ecosystems off the Queensland coast. How these ecosystems will be affected by climate and ocean changes is also not known.

Tropical coastal fish species are expected to expand their distributions southward as the East Australia Current causes increased sea surface temperatures further south (Munday et al. 2009b). By the mid-end of this century the diversity of reef fish species is expected to decline due to loss of coral habitats. However, large uncertainties exist due to poor understanding of ecological or physiological capacities of fish to adapt in situ to large environmental changes. For example, recent studies indicate that reef fish in the Great Barrier Reef are already showing local adaptation to the warming ocean by employing developmental plasticity (Donelson et al. 2011). The levels of confidence in the likelihood of these expected changes occurring are low-to-high (Munday et al. 2009b).

The southeast Queensland fish biota of temperate origin may be locally extirpated and replaced by those of tropical affinity (Booth et al. 2009). The fate of fish species that have a close dependency on coastal habitats will be linked to the local level of anthropogenic impacts (Munday et al. 2009b). These changes have medium-to-high levels of confidence. Changes for pelagic fish and shark species are less well known but likely to include southward shifts in spatial distributions. There is less certainty on population or species diversity-level impacts. Local tropical assemblages of pelagic fishes will change, in some cases expanding their range (e.g., tropical tunas moving further south) but others that are restricted to southern waters (e.g., sardine, blue mackerel and tailor) may have their ranges and abundance reduced (Hobday et al. 2009).

In the north catches of species subjected to commercial and recreational extraction (e.g., prawns, barramundi and mud crabs) may be adversely impacted by changes in summer rainfall patterns. Much of their life cycle and migration depend on monsoonal freshwater flushed into the sea (Abesamis & Russ 2010; Staples & Vance 1987). Sea level rise plus tidal and storm surges may also reduce the area of essential habitat for prawns and estuarine fish, particularly in the Gulf of Carpentaria. Declines are predicted for some mid-trophic level pelagic commercial species (e.g., jack mackerel) and its cool water prey (krill) (Last et al. 2011). Squid on the other hand, may grow faster, mature earlier and require more food resources (Hobday et al. 2008).

Mangrove forests and other intertidal wetlands on the coast may adapt to rising sea level and remain stable if the rate of vertical accretion of the soil surface of the wetland equals or exceeds the rate of sea level rise. Current elevation of mangroves and salt marshes, in southeast Queensland in particular, are keeping up with local rates of sea level rise. Accretion rates are variable but can be as high as 3.4 millimetres per year (mm/yr) at Cape Ferguson, (BoM 2010). In Moreton Bay, sandy areas in the eastern bay have the highest surface elevation gains in both mangrove and salt marsh (5.9 mm/yr and 1.9 mm/yr) while in the muddier western parts of the bay accretion rates are lower (1.4 mm/yr and -0.3 mm/yr in mangrove and salt marsh respectively) (Lovelock et al. 2010; Lovelock et al. 2009). With sea level rise, salt marsh and mangroves may invade freshwater ecosystems. Built structures on the landward edge of salt marshes will increase the impact of sea level rise on salt marshes because such structures will prevent landward movement of salt marshes and result in them being 'squeezed' between mangroves and the built environment. Salt marshes may retain their current land coverage where losses of seaward mangroves are low and if barriers to landward migration (topographic or built structures) are minimal (QCCCE 2011). On the other hand, expansion in mangrove communities will be associated with retraction of coastal sedge, grassland and woodland communities. There may be conservation gains for mangrove-dependent species, like the false water rat, but these gains will be tempered by other threats (diseases, pollution, and feral predation) and urban development (QCCCE 2011).

Mangroves and coastal wetlands have an important ecosystem services role in protecting coasts from storm and tsunami damage, storm and cyclone-related tidal surges. Rates of erosion of mangrove fringes, due to the impacts of storms and waves, are not known for southeast Queensland but rates in other settings are known to be 2-3metres per year. For tidal wetland ecosystems projected rates of change are expected with a medium level of confidence (Lovelock et al. 2010; Lovelock et al. 2009). The adaptive capacity of mangrove wetlands may be increased by high rainfall because it increases sediment inputs and enhances plant growth rates. If rainfall declines, the productivity, diversity and area of mangrove wetlands will decline. This could possibly result in increases in samphire and salt flats (Lovelock et al. 2010; Lovelock et al. 2009).

The expected ecological changes for seagrasses include decreased productivity as temperature increases, local losses and mortality due to decreased light associated with suspended sediments from increased storm disturbances, compositional shifts in the seagrass community favouring heat-tolerant taxa, decreased health and overall spatial extent, range expansion upshore and southward and reduced ecosystem services such as nurseries or supporting resources (fisheries) (Connolly 2009; Lovelock et al. 2009). These changes will vary locally and are related to interactions with habitat disruption and pollution. There is a good deal of information and knowledge on which to base a mid-to-high level of confidence in the occurrence of these expected changes (Connolly 2009).

Rising sea-surface temperature has been shown to alter the timing of seabird breeding. In addition food web changes impact on adult condition and breeding success because life histories of tropical species are strongly linked to food availability. Any long-term negative change in food supply can affect breeding success and may see local populations decline, collapse or migrate southward if suitable habitat exists. All these expected ecological changes have a low-to-medium level of confidence (Chambers et al. 2009).

The sex ratio of marine turtle hatchlings is determined by nest temperature during incubation. Higher temperatures produce more females. On Queensland beaches marine turtle hatchlings show increased female dominance in warm years (i.e., an increased ratio of females to males). As temperatures continue to warm in the future there may be such high levels of demographic bias that population viability becomes compromised. Offshore coral cay islands with white (therefore cooler) sandy beaches may become increasingly important in male production. Increased coastal flooding due to storm surges and/or higher wave run-up are likely as climate changes. This will increase egg mortality of green turtle populations at the rookeries of the northern Great Barrier Reef (Fuentes et al. 2010). There is medium-to-high level confidence that these expected ecological changes will occur (Fuentes et al. 2009). In spite of this level of confidence there is little direct evidence that climate and ocean changes are having a negative effect on sea turtles at present. Instead most concerns are related to the synergistic impacts of nesting habitat disruption, fishing and pollution-related mortality.

There is no evidence that Queensland's salt-water crocodiles are, or will be, affected by climate and ocean changes, so there is low confidence in any current assessment of expected ecological impacts. Similarly, there is low confidence that sea snakes are being affected by current climate change (Fuentes et al. 2009) but venomous jellyfish and stingers may extend their range southward (Richardson et al. 2009a).

3.4.4 Regional change

Specific regional change in Queensland's coastal-marine ecosystems is currently unclear. This is partly because of a lack of State-wide regional studies and associated data (e.g., for the Gulf of Carpentaria, Cape York, or the far north) but also because of variation in and paucity of observations and predictions. For this topic, key research challenges remain, for example, in the gathering of regional and localised climate (and ocean) information, in improving regional projections and in assessing regional and sector-based risk/vulnerability (DERM 2010a). In addition, the net effect of multiple environmental factors and its synergies with human uses introduces large uncertainties (e.g., Nellemann et al. 2008). It is clear that regional variation in environmental and ecological changes can be expected throughout Queensland. This is particularly true for the Great Barrier Reef, southern Gulf of Carpentaria, southeast of Queensland and Coral Sea regions. Known changes centre around limited understanding of ocean warming, acidification, currents and sea level rise that are the main environmental factors addressed here.

Ocean warming projections under the A1B and A1FI emissions scenarios (defined in Section 2.1.3) indicate that surface temperatures of the Great Barrier Reef and Coral Sea will increase throughout. By 2100 an average increase of more than 2°C can be expected (compare Figure 1a and Figure 5 in Section 2.1.2 and 2.1.3, respectively). While temperatures overall will be higher in the north, the greater net increase in temperatures will occur in the southeast. Regional variation in ocean acidification follows a similar pattern correlated with warming (compare Figure 1b and Figure 6 in Section 2.1.2 and 2.1.3, respectively). Overall, however, ocean acidification increases. Under the combined effects of temperature and acidification, the Great Barrier Reef and its pelagic ecosystems are expected to change significantly, both in structure (e.g., loss of reef habitats) and function (e.g., altered production and tropicalisation). The regions that are expected to experience the most change are the southern parts of the Great Barrier Reef and the waters off southeast Queensland.

Other major changes with regional variation are expected from sea level rise and its interplay with storm surges and coastal erosion (QCCCE 2011). A simple example drawn from data generated to support Queensland's Coastal Plan (Environment Planning 2011) shows the potential impact of a 0.8m sea level rise[6] on the coastal zone (see Appendix 3 in Bustamante et al. 2012). Low-lying tidal wetlands and estuarine system will be most affected and, for the extent of data currently available, areas near Gladstone and Gold Coast regions are particularly vulnerable (Figure 7) (also see Traill et al. 2011). Considerable change is also expected to occur in the southern Gulf of Carpentaria region due to its low vertical profile, the wide extent of its coastal zone and the interplay between flash floods, rivers and tidal wetlands (see Appendix 3 in Bustamante et al. 2012).

The southward expansion of the East Australia Current (shown in Figure 2) will extend tropical influences into south east Queensland with expected changes in biodiversity, population connectivity, ocean productivity and the distribution of pelagic species and their pelagic habitats (Figure 17). This southward shift has strong implications for biodiversity management, if implementation of conservation measures relies on fixed or planned conservation areas.

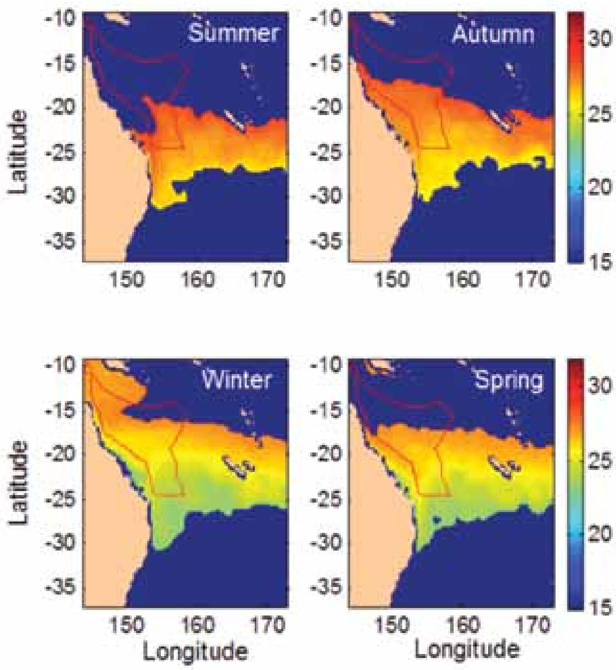


Figure 17: Projected future location of the present pelagic environment within the Coral Sea Conservation Zone (red line), a designated 'Area for Further Assessment'[7] (see Bustamante et al. 2012) as represented by sea surface temperature (colour bar), averaged for each season for the period 2063–2065 (Source: Hobday 2011).

[6] www.derm.qld.gov.au/coastalplan/coastalhazards.html

[7] Described in (Hobday 2011). Areas for Further Assessment (AFA) encompass representative examples of the range of biodiversity and ecosystems for developing marine protected area systems within a marine region.

Coastal development at Surfers Paradise: storm surge with high-rise development in the background and narrow coastal ecosystem buffers in the foreground (credit: Bruce Miller, CSIRO Marine and Atmospheric Research).

4. Ecosystem Services

Ecosystem services are the benefits provided to humans through the transformation of natural resources into a flow of goods and services. They are often grouped into four types: provisioning, regulating, cultural, and supporting. These services are derived from natural capital stocks of biodiversity and ecosystems. Natural capital stocks encompass the gradient from wild nature to managed systems (i.e., agro-ecosystems and monocultures).

Wild nature has been severely depleted globally, but losses are often offset by investment in manufactured and human capital. While some forms of natural capital are arguably substitutable, feedbacks from regulating and supporting services over the long-term may undermine the sustainability of substitutes and adversely affect living conditions.

Biodiversity provides the building blocks from which ecosystem services emerge. Biodiversity loss results in ecosystem function loss through the disruption of species interactions that facilitate energy transfer flows and recycling of matter. This has implications for ecosystem services. It is possible that losing biodiversity has consequences for ecosystem function that are significantly greater than previously anticipated.

In the context of a changing climate, where the timing, magnitude, and distribution of impacts are uncertain, and the possibility exists for rapid non-linear changes to ecosystem functioning, the importance of biodiversity will become critical. Ecosystems provide a range of services that can support successful adaptation to climate change in a wide range of Queensland sectors. These services can be drawn from all four categories of ecosystem service.

Here we recognise three broad types of 'adaptation services' provided by biodiversity: protection, where ecosystem structure provides the 'scaffolding' to help withstand climatic extremes; buffering, where ecosystem functioning provides resilience through substitutability to ensure services continue under a range of possible environments; and options, where diversity in ecosystem composition supports flexibility in decision making, particularly in how ecosystems are able to transform with climate change.

With climate change, such biodiversity adaptation services will have increasing value and importance to society, particularly where technological solutions cannot keep pace with the magnitude and rates of change expected under a >2°C warmer world. However, biodiversity will also be at risk from these changes and timely interventions will help ensure these services and other social and economic values continue to be available in the future.

The agricultural, forestry, fishery, tourism and other natural resource sectors are all important contributors to the character, viability and wellbeing of Queensland's economy and communities. These industries are reliant on the ecosystem goods and services provided by terrestrial, freshwater, coastal and marine ecosystems. In industries or economic sectors where the links between these ecosystem services (and their economic returns) and biodiversity are reasonably clear, such as tourism, then biodiversity tends to be conserved and appropriately managed.. Where this dependence of industry on biodiversity is less apparent, such as in intensively managed agro-ecosystems where new technologies increasingly make substitution of ecosystem services cheaper, biodiversity tends not to be a consideration.

By far the largest potential climate change impact on ecosystem services, and the one with the greatest uncertainty, will be the effect on freshwater supplies for consumptive and non-consumptive uses. Extraction of water for such uses will compete with environmental requirements for the maintenance of freshwater, estuarine and terrestrial ecosystems and the services they provide. This impact of climate change on freshwater provision will be closely followed by impacts on the type, quality or quantity of ecosystem services available to the tourism and rural sectors.

Private resource users are unlikely to act independently, or in a timely way, to conserve biodiversity because managing it today will incur upfront costs but the benefits to be gained are both delayed and uncertain. Market-based approaches are part of the solution to environmental problems. Strategies include: payments or offsets for conserving ecosystem services, taxes, charges and subsidies and promotion of the economic case for conservation through economic valuation and eco-labelling. However, context in achieving policy goals is important and no single policy is a panacea. The complex, uncertain and contentious nature of the issues involved, the existence of diverse and dynamic values and preferences, and the difficulties involved in changing institutions, require that a range of initiatives (i.e., including community-based and command-and-control approaches) be undertaken to promote effective responses of society to climate change (Section 4.3.2).

In this section we define ecosystems, and discuss the relationship between natural capital, ecosystem services and the Queensland economy. We consider the impact of climate change on ecosystem services and the importance of biodiversity as the provider of 'adaptation services'. An outline is provided of some of the institutional arrangements to facilitate climate adaptation responses. Supporting information is presented in Williams et al. (2012) and in the ecosystem services sections of the three ecological realm reports for terrestrial, freshwater aquatic, coastal and marine ecosystems (Bustamante et al. 2012; Kroon et al. 2012; Murphy et al. 2012).

4.1 Scope and definition

The world's ecosystems can be conceptualised as a form of capital asset (similar to manufactured and human capital) which, when properly managed, yields flows of goods such as food, fuel and fibre and services such as pollination, water purification, beauty, and genetic diversity that are important to human wellbeing (Daily et al. 2000). The Millennium Ecosystem Assessment categorised these ecosystem goods and services into four types: provisioning services, regulating services, cultural services that directly affect people and supporting services needed to maintain other services (Alcamo et al. 2003).

Knowledge and understanding of the nature of the links between ecosystem services and the natural systems that maintain them are essential to managing them effectively and ensuring their resilience, adaptive capacity and sustainability are preserved (Cowling et al. 2008; Wallace 2007). The 2005 Millennium Ecosystem Assessment demonstrated how the drivers of change in natural systems can affect human wellbeing. The majority of these drivers were found to be related to human activity. They include: land clearing, species introductions, technology use, agriculture, consumption and climate change (MEA 2005). While living standards have improved over the last half century through the productive use of ecosystem goods and services, many ecosystems have become degraded, potentially limiting future progress. Technological 'quick fixes' alone are not the solution. Instead, considerable change in the worldview and governance of societies are also urgently needed to reverse ecosystem degradation and meet development goals (MEA 2005; Ring et al. 2010).

The concept of nature as a stock of capital from which ecosystem services are produced and benefits derived is now common in environmental assessment reporting (e.g., DEWHA 2009a; EPA 2008) and is increasingly mentioned in strategies and policies about the conservation of biodiversity and the management of natural areas (e.g., DERM 2010a; NRMMC 2010; Steffen et al. 2009a).

A central aspect of mainstreaming ecosystem services is recognition of the integral link between human wellbeing, ecosystem condition and biodiversity, and the potential for intervention through policies, strategies and management at all levels of governance. In support of this mainstreaming objective, a new integrated framework for reporting on ecosystem services has been proposed which extends the traditional state-pressure-response framework commonly used in state of environment reporting (Burkhard & Müller 2008). This integrated framework, the DPSIR assessment framework (Kristensen 2004), enables the chain of causal links to be described, starting with '**D**riving forces' (economic sectors, human activities) through '**P**ressures' (emissions, waste, extraction) to 'States' (physical, chemical and biological) and '**I**mpacts' on ecosystems, and human health, eventually leading to management and policy '**R**esponses' (prioritisation, target setting, indicators) (e.g., Feld et al. 2010; Rounsevell et al. 2010). The DPSIR framework is being used in Australia as a structured basis for generating climate statements which relate mitigation responses to climate change drivers, and adaptation responses to the environmental pressures, states and impacts arising from climate change (Poloczanska et al. 2011).

The Millennium Ecosystem Assessment definition and classification of ecosystem services has been presented within a hybrid DPSIR assessment framework by the World Resources Institute to facilitate reporting on ecosystem service indicators (Figure 18). This hybrid framework expands on 'states' in DPSIR to distinguish ecosystem function, and ecosystem condition and biodiversity. Natural capital stocks are represented collectively by ecosystem functions, ecosystem condition and biodiversity from which ecosystem services flow. Natural capital stocks comprise all types of ecosystems including wild and domesticated forms of nature such as agro-ecosystems and monocultures.

Such an ecosystem services driven approach to biodiversity and natural areas conservation has in some cases been advocated and in others criticised because of the potential conflicts and tradeoffs that arise between competing intrinsic and utilitarian perspectives (e.g., Egoh et al. 2010; Faith et al. 2010; Perrings et al. 2010; Tallis et al. 2008). There are also inherent difficulties involved in determining and quantifying the relationships between natural capital and ecosystem services, and different human perspectives on value (e.g., Hearnshaw et al. 2005). Vira and Adams (2009) for example cautioned the use of proxy indicators of ecosystems services when developing mechanisms for biodiversity conservation, noting that flows of ecosystem services may be imperfectly related to stocks of natural capital and are poor surrogates for the complex web of relationships that characterise biodiversity (see also, Kremen 2005).

The clear benefit in adopting a natural capital approach (Kareiva et al. 2011) is that it facilitates the integration of ecosystem-oriented management within economic decision-making and development, areas that have traditionally focused on human and manufactured stocks of capital (e.g., Blignaut & Aronson 2008; Ring et al. 2010; Sukhdev et al. 2010). The benefit of integrating these forms of capital is that it forces society and decision makers to explicitly acknowledge the interdependencies between these stocks. It also emphasises the fact that choices between these stocks are being made based on implicit assumptions about their substitutability (Dasgupta & Mäler 2001; Maler et al. 2008). Importantly for biodiversity and ecosystem conservation, it forces society to explicitly decide which components of natural capital are suitable to be substituted with manufactured and human capital and which are not – based on their contributions to maintaining human wellbeing (Howarth 2007). The links and tradeoffs between natural, human and manufactured capital, and the subsequent feedbacks through regulation services (which may adversely affect living conditions) are poorly understood (Carpenter et al. 2009; Díaz et al. 2011; Fisher et al. 2011; O'Farrell et al. 2010), and depend on the values, beliefs and preferences of individuals and groups within societies (Abson & Termansen 2011; O'Brien & Wolf 2010). A natural capital approach to ecosystem management therefore involves cross-sectoral collaborations in developing conservation objectives (informed by the values and preferences of society which is underpinned by what is believed to be ethically defensible and representative) and is a mechanism for achieving collective action in managing natural resources.

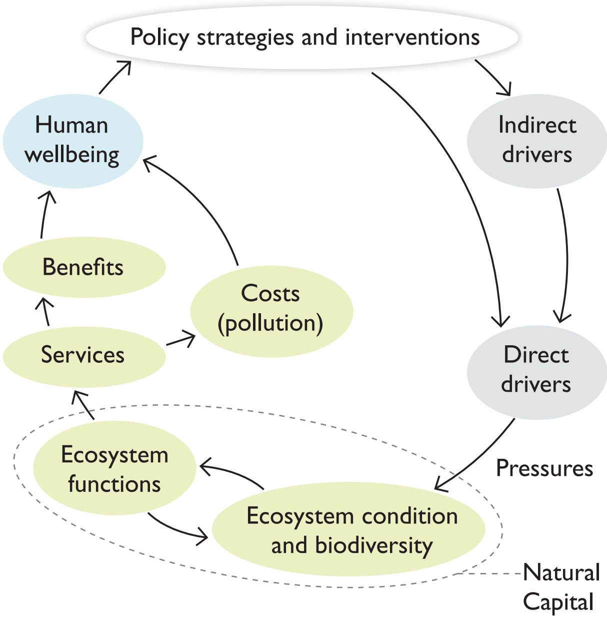


Figure 18: The hybrid DPSIR assessment framework used in the development of an ecosystem service indicators database by the World Resources Institute, http://www.esindicators.org/#frameworks, 2010. Here we included a surrounding box (dotted lines) to show the link between natural capital stock and ecosystems in this framework, and introduced a path that identifies costs (i.e., impacts) as well as the benefits. Natural capital stocks include wild nature, agro-ecosystems and monocultures.

4.2 Natural capital and ecosystem services in Queensland

In the previous section we identified the link between ecosystem services and the state of natural capital stocks (ecosystem function, structure and composition). While much is known about the effect of biodiversity loss on ecosystem function, uncertainties related to trophic interactions and feedbacks remain (Hooper et al. 2005). There is general scientific consensus that diversity among species provides insurance for stable supplies of ecosystem goods and services, especially in response to changing environmental conditions over long time periods (Hooper et al. 2005; Kahmen et al. 2005). This stability is believed to be related to the presence of functional traits and redundancies which allow substitution among species so that compensatory community responses are possible during periods of environmental fluctuation. These responses stabilise function and confer resilience and resistance to ecosystems (Chapin et al. 2000; Kremen 2005; Walker et al. 1999). While this is a central principle, it may not apply to all functional elements or all ecosystems. For example, a recent study of reef-fish systems found that each species uniquely contributes to overall ecosystem functioning. This means that the consequences of losing any one species are significantly greater than previously anticipated (Mora et al. 2011). A similar study for grassland ecosystems concluded that many species are needed to maintain multiple functions at multiple times and places (Isbell et al. 2011). While the mechanisms are still under investigation, it is clear that biodiversity is critical to the functioning, health and service provisioning of some ecosystems (Chapin et al. 2011; Duffy 2009; Ulgiati et al. 2011). In the many ecosystems where these links and relationships between biodiversity and ecosystem functioning, health and service provisioning remain unclear (or even non-existent under present climatic and environmental conditions), the role of biodiversity in providing redundancy and adaptive capacity to the functional and structural traits of ecosystems is likely to become increasingly important as the rate and magnitude of environmental variation and change increase (Isbell et al. 2011).

Ecosystem functions are the natural life-supporting procedures that facilitate energy transfer around food webs and perform the major processes of carbon, oxygen and nitrogen cycling (Traill et al. 2010; van der Putten et al. 2004). In many situations the supporting and regulating services of ecosystems that enable food and water provision, ensure climate regulation, and restore fertile soils depend on the health of the ecosystem functions and structure. Many of the provisioning services from ecosystems would collapse in the absence of the supporting and regulating services (de Groot et al. 2002; Hooper et al. 2005), but not necessarily in the absence of biodiversity. For example, nutrient cycling is a fundamental regulating service provided by well-functioning ecosystems without which food production would not be possible. Another regulating service provided by many ecosystems is climate regulation through the sequestration of CO_2 emissions in soil, vegetation and oceans. However, deforestation and the degradation of soils are leading to substantial emissions of CO_2 from these carbon stocks that are enhancing the greenhouse effect and contributing to climate change. (Buesseler et al. 2007; Korner 2000; Lal 2004; Melillo et al. 2011) (see Sections 3.1.2, 3.2.4 and 3.3.4). Without this sequestration and storage of CO_2, the CO_2 concentration in the atmosphere would be twice current levels and the extent of global warming (due to greenhouse gas forcing) would be much greater.

4.2.1 Overview of Queensland's natural capital and economic sectors

Considering the links between ecosystems (i.e., natural capital), ecosystem services and human wellbeing, Maynard et al.(2010) applied the concept of ecosystem services to southeast Queensland to map and prioritise areas for protection. Their ecosystem reporting categories expand on the Millennium Ecosystem Assessment classification (Alcamo et al. 2003) to match their more local scale of assessment. Maynard et al.(2010) further incorporated 19 ecosystem functions and 28 ecosystem services into their framework for southeast Queensland. Much of the framework is generally applicable to the whole of Queensland so we referred to this in developing a general summary of natural capital stocks, ecosystem services and their relationship to different sectors of the Queensland economy and society (see Table 4 in Williams et al. 2012). This overview, incorporating key government initiatives and responses from public websites and environment reporting (EPA 2008), demonstrates how the character, culture and economy of Queensland depends in large part on its natural capital. The identified links and dependencies between Queensland's economic sectors, its natural capital, and ecosystem services are briefly summarised below.

Natural and modified pastures and grazing

The extensive areas (over 80% of the state) of natural and modified pastures in which grazing is the main land use (Stone et al. 2008) are important ecosystems to the continued viability of the livestock industries in Queensland. These grazing regions occur predominantly in the western rangelands and savannas where rainfall is influenced by the El Nino Southern Oscillation and is highly variable (Risbey et al. 2009). The Delbessie Agreement, which governs activities on rural leasehold land, is based on 'duty of care' and prevention of land degradation (DERM 2009d). To avoid overgrazing and land degradation, stocking rates in these dryland regions are based on sophisticated modelling of pasture growth and short-term rainfall projections (Hassett et al. 2010). Grasses and trees often co-exist in a dynamic, competitive relationship determined by decadal patterns of rainfall. From the pastoralist perspective this increase in the ratio of trees and shrubs to grass is 'woody vegetation thickening' (Gifford & Howden 2001; Henry et al. 2002).

Pastoral properties generally cover large areas that span a vast range of climates, soil types and topography. Such variety may enable a portfolio approach to farm planning that can confer some economic resilience to external threats and pressures. Properties with little environmental variation may have limited options and low resilience to change. An assessment of the level of impact risk for the grazing industry due to climate change noted the detrimental effects and adverse impacts of industry adaptation on biodiversity (Cobon et al. 2009; McKeon et al. 2009). Cobon et al. (2009) identify the need for further research to identify the most vulnerable pastoral regions, to inform adaptation policy and to facilitate transitional change and training for land managers. Resilience of local economies in the most vulnerable regions could be improved by diversifying their farming systems to include complementary management of carbon, food, bio-energy and biodiversity.

Native forests for tourism, timber, bio-prospecting and biodiverse-carbon sequestration

Native forests in Queensland account for 30% of the land area (BRS 2009). Historically timber harvesting has supplied native hardwoods and softwoods for the building and construction industry. However, following decades of over-harvesting and extensive clearing of native forests and woodlands, increasingly strict clearing controls and codes of practice were enforced (Low & Mahendrarajah 2010). The forestry industry is now transitioning into plantations and developing manufactured wood products. Much of the remaining public forest estate is being transferred to conservation and recreation uses. Native forests in Queensland are presently highly valued for their supporting (e.g., biodiversity conservation), regulating (e.g., climate regulation) and cultural (e.g., recreation) ecosystem services. These services do not usually conflict with the need for clean water and wildlife habitat. Clearing exemptions under the *Vegetation Management Act 1999* are now only granted to enable activities such as the building of "necessary" infrastructure (DERM 2009e). Other minor uses such as beekeeping, bioprospecting and extractive industries (e.g., crushed rock and sands) are strictly controlled. While some of these industries do not depend on native forests, others, such as biodiscovery, depend on the existence and preservation of wild nature (Wildman 1999). For example, wild macadamia populations in remnant rainforests of southeast Queensland are important natural stocks of native plant breeding material to enhance the future adaptive range of domestic varieties (Hardner et al. 2009).

The provision of services from native forests remains vulnerable to the general impacts of climate change such as drought, rising temperatures, wildfire, disease and pathogens (DAFF 2009; Wilson & Turton 2011). Production forestry, however, operates in a highly variable climate and has a long history of adaptation based on field experience and scientific research regarding the requirements of different tree varieties. While this suggests that the Australian forestry industry may be well placed to manage climate change impacts (Wilson & Turton 2011) the projected rate of climate change may surpass the decades required to develop and distribute new tree varieties (see Hallegatte et al. 2011a; Stafford Smith et al. 2011; Steffen et al. 2009a).

The character of forest ecosystems may be substantially altered in response to changing climate as patterns of rainfall distribution and temperature conditions change (Section 3.2.4)(Murphy et al. 2012). Increased vulnerability of forests to climate change occurs if they are located in areas at the edge of their species' ranges; where there is little or no room for forest biota to migrate; or where there is high competition with other land uses (Murphy et al. 2011; Wilson & Turton 2012). A landscape-level adaptation pathway for forests might involve restoration between large areas of habitat. The goal of restoration may be to reinstate key functional species that provide habitat architecture for other species and facilitate natural establishment of plant-animal interactions. Such planting actions could be undertaken as part of an overall strategy of species translocation or assisted migration under climate change. The choice of species for environmental plantings should therefore be made within the same ethical and risk assessment framework as might be applied to threatened or vulnerable species (e.g., see Minteer & Collins 2010), or for management of potential native or alien invasive species (see Section 5).

Native vegetation management in Queensland

Intact (remnant) terrestrial native vegetation (including native pastures and forests, discussed above) makes up 80% of Queensland (Accad et al. 2008) and is principally managed under the *Vegetation Management Act 1999*. Vegetation contributes to local climate regulation (e.g., Gorgen et al. 2006; McAlpine et al. 2007) through greenhouse gas abatement (Henry et al. 2002), refreshes oxygen in the air, provides clean water and mitigates the adverse impact of natural hazards such as erosion and flooding (NRMMC 2010). The multiple regulation and mitigation services provided by native vegetation combined with the negative effects of degraded areas lead to the introduction of clearing controls through the *Vegetation Management Act 1999* and subsequent legislation to improve effectiveness (EDO 2010; McGrath 2007; Productivity Commission 2004). Other policy measures support vegetation condition assessment (Accad et al. 2010; Eyre et al. 2011) and improvement through regulation (DERM 2009f; Hassett et al. 2010) and incentives (e.g., Comerford & Binney 2006; Windle et al. 2009).

The potential of native vegetation to sequester carbon is of increasing interest as a way to offset greenhouse gas emissions and manage natural values (Eady et al. 2009; PCCC 2010; Queensland Government 2010). Opportunities for carbon accumulation associated with ecosystem recovery activities are also being investigated (DERM 2009b; Fensham & Guymer 2009; Witt et al. 2011) and may be an added incentive to maintaining or enhancing ecosystem function and services in some regions. Regrowth vegetation and woody plantations managed for carbon sequestration represent an important opportunity to link adaptation pathways for biodiversity and pollution mitigation. For example, monoculture plantations that have a long rotation period but that have been planted under current climate conditions may have reduced yield or performance as climate conditions become sub-optimal for those species (Wilson & Turton 2011). In contrast, biodiverse plantings (i.e., mixtures of compatible native species that partition and maximise the use of water, light and nutrient resources and provision of habitat for other species) are likely to be more robust and represent a risk-spreading strategy. While carbon markets provide strong incentives for 'carbon farming', there can be significant tradeoffs in the provision of other services, unless additional incentives are provided to ensure co-benefits (Stafford Smith et al. 2011).

Biodiversity for pollination-dependent industries

Biodiversity provides important pollinators, seed dispersers, and pest control agents on which agriculture and forestry depend. For example, the native lycid beetle, the flower wasp, and the halcid bee, all make important contributions to the pollination of macadamia (Blanche et al. 2002; Vithanage & Ironside 1986). Stingless bees, especially *Melipona* and *Trigona* spp., are known to be effective pollinators of at least nine crops and contribute to the pollination of about 60 other crop species (Heard 1999). Crop pollination by wild pollinators is an ecosystem service that is under-researched and under-valued in the tropics (Martins & Johnson 2009). It has been estimated that in most north Queensland rainforest communities, more than 80 percent of plant species are partly, or entirely, pollinated by insects (Armstrong & Irvine 1989). For example, tropical rainforest beetles in north Queensland are important native pollinators of custard apples in commercial orchards (Blanche & Cunningham 2005) and hawk months pollinate papaya (DPIF 2010; Morrisen 1995). Voracious insectivorous birds and mammals such as microbats are important biological control agents that help minimise the impact of pests on agricultural and forestry crops. They also limit disease vectors such as mosquitoes (Kunz et al. 2011; Whelan et al. 2008).

The capacity of native pollinators, seed dispersers and pest control agents to provide ecosystem services depends on the condition of their native habitat and its proximity to farmland. Such services can be maintained if the habitat requirements and foraging distances of the relevant species are understood and taken into account when planning mosaic farming landscapes (e.g., Keitt 2009; Martins & Johnson 2009).

Riparian and littoral habitats for flood protection, erosion control and water regulation

Riparian and littoral vegetation are special cases of native vegetation that occur at the complex interfaces between terrestrial and aquatic systems (freshwater and marine). Vegetation in these areas protect land from erosion; filter sediments, nutrients and pollutants; mitigate the effects of flooding and storm events; and provide supporting habitats for terrestrial and aquatic biodiversity (Brauman et al. 2007; DEWHA 2009b). For example, several functional traits of wetland forests, such as decomposability, growth form variety, growth form composition, and leaf area influence water purification through their effects on nutrient and sediment retention (de Bello et al. 2010). Riparian and littoral habitats are complex areas to manage and require a range of legislation and policies to regulate their management (DERM 2011d; Environment Planning 2011). The interfacing vegetation in these regions supports nursery and breeding habitat for fish and other animals. Recreational fishing is a favoured pastime of Queenslanders and so emphasis has been placed on managing fish populations and protecting fish breeding habitats (DEEDI 2009; DEEDI 2010; Derbyshire et al. 2007; Dixon et al. 2009). Buffers to mitigate the impacts of human development on wetland and riparian vegetation, and to maintain their ecosystem regulation and supporting functions, are recommended in a wide range of legislation and agreements (Deacon et al. 2011).

Freshwater ecosystems for tourism, flood protection, waste sinks and provision of supporting services

Queensland's wetlands are situated in all landscape types from the arid Lake Eyre Basin of inland Australia to the coastal catchments that flow into the Great Barrier Reef (see Section 3.3). Functioning wetlands provide water quality filters or sinks for nutrients; traps for sediment and other contaminants; nursery and breeding habitats for many marine and freshwater species (including commercially important fish and crustaceans); refuges for fauna and flora in times of drought; and sinks for mitigation of floodwaters and replenishment of groundwater (Kroon et al. 2012). In a review of the scientific literature pertaining to Queensland wetlands, Davis et al.(2007) emphasised the importance of these wetland functions in the provision of ecosystem services.

Water reservoirs are a major source of drinking water in Queensland. The management of these reservoirs has to take into account not only varying water levels but also the possibility that heat waves, stratification, rising surface water temperatures and other factors could result in cyanobacterial blooms (see Sections 3.3.2, and 3.3.4). The prediction of such blooms is a major issue for human health and ecosystem functioning (Leigh et al. 2010). Rivers and lakes have always been a resource for recreational activities like swimming, boating and fishing. Measures implemented to maintain rivers and lakes include fishways to bypass dams and weirs (Lawrence et al. 2010). Maintaining a healthy waterway results in many other economic, biodiversity and aesthetic benefits both within the river catchment and right down to the ocean (GBRMPA 2009). For this reason plans that aim to reduce sediment, nutrient and pesticide loads entering the Great Barrier Reef have been proposed for several catchments (e.g., Bohnet 2010; Brodie et al. 2012; Kroon & Brodie 2009).

Marine biodiversity for food, pharmaceuticals, tourism and cultural services

Queensland's marine biodiversity directly supplies ecosystem services such as food; income and leisure activities through commercial and recreational fisheries; and income and cultural services through marine tourism. Cultural values of iconic species such as dugong, turtles and grey nurse sharks, species that are often under threat from existing pressures, are difficult to quantify. The Great Barrier Reef region provides direct and indirect income from tourism; income, food and recreation from fisheries; income and health benefits from novel pharmaceuticals; coastal protection from storms and cyclones; and social wellbeing through its awe-inspiring beauty and recognition as a World Heritage Area (Bustamante et al. 2012). The Great Barrier Reef is the largest, and one of the best managed, reef systems in the world (Pandolfi et al. 2003). Effective management has contributed to its current good condition and resilience. Much of the fishing originally allowed in the area is now not permitted due to the recent rezoning of the Great Barrier Reef (GBRMPA 2003; GBRMPA 2004) and the Regional Adjustment Program (Gunn et al. 2010). Fisheries still permitted in the region (e.g., Queensland aquarium fish fishery) operate according to the best practice guidelines for their industry.

Coastal zones

The coastal zone is home to more than 85% of Queensland's human population, and has significant resources and environmental values that provide a foundation for the state's economic and social development (EPA 2008). Natural resource use activities include quarrying (sand, gravel, quarry rock and fill), commercial and recreational fishing, hunting by indigenous communities and collection of ornamental materials (Hurse et al. 2008). Many natural resources have been exploited in the past resulting in clearly observable declines in their quantity and quality (Daley et al. 2008). Consequently the values and issues for the coastal zone are now reflected in the State Coastal Management Plan (Environment Planning 2011) which defines how the region will be managed.

Climate adaptation by people

Recognising the need to anticipate the future, the Queensland Government developed a staged strategy comprising a diverse range of short, medium and long-term policies that move Queensland toward a low carbon future (Queensland Government 2007a; Queensland Government 2008). This strategy is complemented by the adaptation plan, 2007-2012 (Queensland Government 2007b) that outlines the next steps in the Queensland Government's response for managing the impacts of climate change. An update of the strategy was been brought forward following the 2011 flood events and an issues paper invites public input (Queensland Government 2011b).

Because so many of the State's social and economic activities are tied to the natural environment there is a need for more specific information to be collected about the effects of climate change on Queensland's natural environments and landscapes. This report makes a contribution toward a collective understanding of the impacts of climate change on biodiversity and ecosystem services in Queensland.

4.2.2 Linking biodiversity, ecosystem services and the Queensland economy

In the previous section, we demonstrate the link between biodiversity, natural capital and ecosystem services in Queensland. Where there is a clear link between biodiversity and the economic returns to an industry, or economic sector, biodiversity tends to be conserved and appropriately managed. A good example of this is tourism and its dependence on the natural integrity and ecological diversity of the Wet Tropics and Great Barrier Reef regions. Although, even the health and viability of the Great Barrier Reef is continually being challenged by cross-scale threats from on-land agricultural practices and from increasing shipping traffic to meet growing international trade in commodities. In many other industries and economic sectors (when considered in isolation from the environment and in the absence of climate change) this dependence of industry on biodiversity is not as strong and is less apparent. For example, many simplified agro-ecosystems comprising only a few kinds of crops, or livestock, currently perform extremely well (i.e., have been and continue to be profitable over extended periods) even though species diversity is low and ecosystem functions are few. A characteristic common to all of these resource-based industries is that many ecosystem services are amenable to substitution (for human and manufactured capital) through the development and adoption of new technologies (e.g., water treatment technology, fertiliser, genetically-modified crops) and infrastructure (e.g., roads, buildings, institutions).

To determine the economic (i.e., utilitarian and not intrinsic) value of an ecosystem service's contribution to a sector or community requires that three key assumptions about the meaning of value and the assignment of value to goods and services are met, namely that the ecosystem service's value can be ascribed (i.e., not intrinsic or held values), measured at the margin, and expressed in terms of exchange (Abson & Termansen 2011). This is clearly possible for 'wild-harvested' fish and aquaculture from the Great Barrier Reef – which have an estimated gross market value for the tonnes of annually harvested product of about $150 million and $50 million, respectively for 2005/6 (Access Economics, 2007) – for example, but is clearly not possible for the intrinsic, spiritual, cultural, and indirectly useful (e.g., supporting services) values derived from these services.

4.2.3 Ecosystem services and climate change

In general, changes in the composition, structure and function of natural ecosystems, as a result of climate change, will directly affect the ecosystem services they provide. This has the potential to cause economic and amenity losses (Traill et al. 2010). In their review of terrestrial ecosystem change in Queensland, Murphy et al. (2012) developed a table relating different biodiversity responses to climate change and also (broadly) to the ecosystem services and sectors likely to be affected (see their Table 4). In Williams et al. (2012) examples of possible climate change pressures on ecosystem services and industry sectors in Queensland were given for three indicative sectors: the rangeland pastoral industry, nature-based tourism in the Wet Tropics, and Great Barrier Reef tourism and fishing (see their Table 7). Other links between biodiversity, natural capital and ecosystem services in Queensland and climate change impacts were described for terrestrial, freshwater aquatic and coastal and marine realms by Murphy et al. (2012); Kroon et al. (2012), and Bustamante et al. (2012), respectively.

By far the largest potential impact of climate change, and the one with the greatest uncertainty due to uncertainty in rainfall projections, will be on freshwater supplies for consumptive and non-consumptive uses. Demand for such supplies will compete with environmental requirements for the maintenance of freshwater, estuarine and many terrestrial ecosystems and the services they provide (Bustamante et al. 2012; Kroon et al. 2012; Murphy et al. 2012). Changes in consumptive uses of water and dependence on desalinisation technology to generate freshwater will be an additional social and economic expense, even if balanced by water use efficiency measures and permanent restrictions. The high cost of climate change impacts on water supplies will be closely followed by the costs of climate change on the tourism sector. Changes in the nature of ecosystems, exacerbated by seasonally unstable weather conditions and safety concerns, may lead to unmet visitor expectations. This could be offset by adaptation responses such as changes in tourism marketing strategies, diversification of tourism opportunities and an increasing focus on dry-season tourism ventures. Rural industries will also be affected by climate change (Stokes & Howden 2010; Stokes & Howden 2008) and farming could focus more on dryland activities and greater diversification in income generation activities. Adopting a flexible, risk-based approach, which includes remnant ecosystem protection and extensive environmental remediation integrated with biodiverse carbon-based farming, will provide a basis for future resurgence in locally sustainable agriculture ventures.

Because many ecosystems already have depleted biodiversity due to intensive land use and management practices, substantial time (i.e., decades to half-century or more) will be needed to restore them to a point of sufficient biodiversity that can confer benefits through services (Jones & Schmitz 2009). Therefore action to counter climate change, by improving biodiversity and ecosystem management, needs to start now (Pérez et al. 2011). Planned actions taken today, which are designed to reduce risk and build resilience in the future, require an initial investment that is often difficult to obtain because the benefits are uncertain as well as delayed (Füssel 2007). This is an appropriate context for government intervention to create institutions and set policies that help cover or minimise the upfront costs of such actions (Hepburn 2010).

The synthesis in this report provides a framework within which the individual interventions and regulations implemented by the Queensland Government (see Table 6 in Williams et al. 2012) could be coordinated to better achieve the high level goal of conserving biodiversity and building its resilience. This framework is based on the natural capital and ecosystem services perspectives that explicitly recognize the potential economic value of biodiversity and ecosystems; recognize society's values, preferences and attitudes to different forms of capital and their relative substitutability; reveal the increasing scarcity-values of natural capital due to the potential impacts of anthropogenic threats; and highlights the importance of new institutions to support conservation as a mainstream activity.

In previous parts of this report we presented the scientific evidence and projections showing the rapid, widespread and substantial changes in location, range, mean, or variability in factors that underpin the productive capacities of ecosystems. These factors include atmospheric temperatures, rainfall, ocean acidity and temperature, sea level rise, storm surge and pathogens. Climate change in excess of 2°C warming of the atmosphere will affect existing 'operating environments' of ecosystems and industries and these changes will likely exceed their capacities to resist and adapt. In this respect, biodiversity has a role in conferring resilience in ecosystems undergoing change. 'Resilience' is a complicated issue and difficult to quantify and value. It represents the capacity of an ecosystem undergoing disturbance to withstand, manage, adapt, acclimate, or navigate perturbations without the loss of ecosystem function, although the composition of species may change. In the next section we elaborate on this through the development of a new concept 'adaptation services', which emphasises the importance of biodiversity in coping with and adapting to climate-induced impacts. It is relevant to all resource-based economic activities in Queensland.

4.3 Biodiversity as the provider of adaptation services

The character of Queensland's economy depends largely on maintaining its stocks of natural capital. However, the historical approaches to managing many of these stocks – through intensification and specialisation of production methods based on input-intensive, low-diversity but high-yielding strains and varieties of animals and crops[8] – will be inappropriate for dealing with the predicted shifts in climatic zones, increases in temperature and rainfall variability, and increases in extreme events due to climate change. In the context of a changing climate, where the timing, magnitude, and distribution of impacts are uncertain, and the possibilities of rapid non-linear changes to ecosystem functioning exist, the importance of biodiversity will become critical. This is because biodiversity provides the building blocks that underpin the *composition*, *function* and *structure* of the ecosystems from which ecosystem services emerge. Of particular importance and relevance to climate-change adaptation are the 'adaptation services' that emerge from the presence of biodiversity, namely:

- ***protection:*** where ecosystem structure provides the 'scaffolding' to help withstand perturbations (such as extreme storm surges and neap tides) and reduces their negative consequences so that society can minimise impacts and the costs of building infrastructural defences (Hallegatte et al. 2011a; OECD 2008);
- ***buffering:*** where ecosystem functioning provides the resilience – through redundancy – that is needed to ensure ecosystem services continue to be provided under a range of possible environments[9] (Thompson et al. 2009; Walker & Salt 2006); and
- ***options:*** where diversity in ecosystem composition provides the flexibility in decision making (i.e., choices) particularly in how ecosystems are able and allowed to transform with climate change (Tisdell 2011a).

[8] The principle drivers of this trend are largely economic in origin and involve the broadening of markets from local areas to wider geographical areas, changes in production methods, and increased globalisation (i.e., trade), all of which lead to greater specialisation in economic production to exploit comparative economic advantages (see Myers 1981; Polasky et al. 2004; Tisdell 2003; Tisdell 2011b).

[9] This is equivalent to the "portfolio approach" to managing risk, typically used in various industries such as insurance, farming and finance.

These 'adaptation services' are a subset of all four categories of ecosystem services that specifically contribute to a wide range of sectors being able to successfully respond to environmental change, including climate change. The new concept of 'adaptation services' as an emergent property of biodiversity (constituents of species and ecosystems) is consistent with, but expands upon, the concept of 'ecosystem-based adaptation' that is increasingly being referred to in the climate adaptation literature (World Bank, 2010).

The adaptation services provided by biologically-diverse stocks of natural capital are currently under-recognised and under-valued. This has contributed to declines in biodiversity in many parts of coastal, terrestrial, and oceanic landscapes. As climate changes, the adaptation services provided by biodiversity will have increasing value and importance to society. For example, coastal littoral ecosystems and riparian vegetation are particularly important for the provision of protection services (as well as regulating and provisioning services). These ecosystems, however, are threatened by sea level rise and the human settlements along coastlines that prevent their landward migration (Traill et al. 2011). The loss of the protection services provided by these ecosystems requires their replacement by costly man-made defences to protect infrastructure from the expected increasingly vigorous coastal erosion processes and inundation. Such protection services will become even more important as costly technological solutions will not be able to keep pace with the magnitude, spatial extent, and rates of change in coastal erosion and inundation that are projected under a >2°C warmer world.

The available options for adapting Queensland's natural capital stocks (i.e., species and ecosystems as components of biodiversity) to climate change are presented below, followed by a brief discussion of the mechanisms and processes to facilitate actions by public and private agents to select and implement these options.

4.3.1 Adapting natural capital and ecosystem services to climate change

The options suitable for adapting to climate change depend on the type and state of natural capital stock. A list of the available options is provided in Table 2, grouped into four categories of natural capital stock (further details about the process and practices of adaptation for biodiversity and ecosystem management are provided in Section 5).

The identification, prioritisation and design of adaptation options will vary depending on the context and will need to be informed by: diagnostic approaches to probe the nature of problems and inform the changes required; the nature of the threats to the natural capital stocks; the types of stock affected (i.e., whether the natural capital stock is intensively managed monocultures, multi-species agro-ecosystems, or wild nature); the goals of society; the cost-effectiveness of each in achieving environmental outcomes; the environmental effectiveness of each option; the equity in the distribution of the benefits and costs of options; and the vulnerability of the stock (i.e., its exposure, sensitivity, adaptive capacity). Also, in the absence of mitigation, it will become increasingly likely that climate change may make adaptation impossible for some areas and types of natural capital. To avoid wasting scarce resources, these cases where adaptation is impossible need to be recognised early so that decisions to not intervene can be made.

Even though the science indicates that all sectors of the economy are likely to benefit in the future if they consider the 'adaptation services' of ecosystems in their resource-management decisions, it is unlikely that private landholders will adapt independently and begin managing

Table 2: Options for adapting natural capital stocks to climate change, grouped into four broad categories based on levels of modification and degradation.

Natural capital stock	Adaptation option
Wild nature	Intensify conservation efforts and, where possible, set aside neighbouring public, agricultural, or degraded areas for wild nature to migrate or transform into: a) naturally or b) facilitated through restoration efforts.
	Trans-locate iconic, keystone, and/or umbrella species.
	Collect and preserve genetic material in gene banks for possible future regeneration and release.
Multi-species agro-ecosystems	Increase the diversity of plants and animals being farmed.
	Farm a mix of ecosystem services (carbon, biodiversity, food, fuel and/or timber).
	Allow the systems to transform, naturally or through remediation, into wild nature.
Monocultures	Introduce new or modified species better able to cope under a wider range of expected possible conditions.
	Increase the diversity of plants and animals being farmed.
	Farm a mix of ecosystem services (carbon, biodiversity, food, fuel and/or timber).
Degraded natural and agricultural systems	Actively restore degraded natural capital stocks (irrespective of whether they are 'wild nature' or managed systems) through investments in remediation

for biodiversity, at least in a sufficiently timely manner, unless the intrinsic drivers motivating action are addressed (Greiner & Gregg 2011). As mentioned in Section 4.2.3, this is because landholders will likely incur upfront costs (in the form of time and effort to build understanding and new capabilities and forgone revenues) and because the benefits are not only delayed and uncertain but oftentimes they are experienced by others (i.e., public good). Additionally, the Queensland Government's responsibility to provide and manage environmental public goods (i.e., wild nature) will be tested under climate change due to the scale of the problem and the large increase in human and financial resources needed. There will be pressure to urgently build whole-of-community, whole-of-economy (i.e., public-private partnerships, environmental markets) and whole-of-government (i.e., cross-jurisdictional policies and interventions) understanding and responses. And these responses will need to be underpinned by redefined sets of objectives, evaluation approaches, and financing mechanism developed within participatory processes that allow for deliberation and negotiation and adaptively implemented and managed.

Since the private sector is unlikely to adapt independently in a timely way, and because the costs of adapting Queensland's natural capital stocks to climate change will exceed the Government's financial capabilities to do so, Government has a critical role to play in changing existing institutions. This could include a focus on explaining the value of biodiversity to the private sector, rewarding behaviour that preserves or enhances biodiversity and the provisioning of ecosystem services; and investigating opportunities for partnerships between government, non-government organisations, private industry and community groups to encourage adaptation initiatives. These three broad approaches to facilitating adaptation are discussed in Section 4.3.2, that follows.

4.3.2 Mechanisms and processes for implementing adaptation options

Three organisational approaches are generally proposed in the literature to solve the resource-access and resource-management problems that impede adaptation (see Ménard 2011 for an overview). These approaches include: 'command-and-control' where standards, charges, and management objectives are defined and enforced by public authorities; the creation of *market-based approaches* to allocate and regulate resource-use rights (e.g., taxes, 'payment for ecosystem services' schemes, insurance schemes, biodiversity offsets) (see Stavins 2003); and *collective actions* where financing, usage and monitoring of resources are done under cooperative or joint-venture arrangements such as self-organised local communities (see Ostrom 2005a) or public-private partnerships (see Agrawala & Fankhauser 2008).

The effectiveness of these modes of organisation depends on the institutional settings within which they are embedded and how well these 'match' the underlying dynamics of the ecological system[10] (Young et al. 2008). Different approaches are appropriate in different contexts. The institutional components required to underpin these organisational approaches involve (Ménard 2011): *legal regimes* that define the nature of the rights and the conditions of their transfer, and shape how players behave when undertaking transactions; *political regimes* required to establish legitimacy and define and implement enabling regulations; *bureaucracies* that design and implement rules; and *ideological regimes* underpinning the behaviours and perceptions of players when undertaking transactions.

A large body of literature exists in which the successes and failures of attempts to introduce regulations, markets or collective-action approaches are reported. Some of this literature is briefly summarised below. Lessons for Queensland are highlighted.

Market-based approaches

The introduction of market-based approaches is often proposed by economists as the solution to environmental problems (Stavins 2003). Examples of such approaches, and their possible use in Queensland to promote the protection and restoration of natural capital stocks, include:

- '*Payments for ecosystem services*' (PES) spanning a range of payment types (Shelley 2011) and a range of ecosystem services (e.g., water, carbon, biodiversity) (Kemkes et al. 2010; Whitten et al. 2009; Wunder et al. 2008). In this case, PES schemes that promote private resource owners and users to manage for a mix of ecosystem services might be considered (e.g., biodiverse and carbon rich systems that also provide food or fuel). The role of Government is to provide information and create the necessary organisational and institutional arrangements that facilitate potential (national and international) buyers and sellers of services in trading ecosystem services. In some cases, Government might consider participating as a buyer or seller of ecosystem services as one way of fulfilling its role as provider of public goods (i.e., instead of imposing environmental regulations and standards that are costly to enforce or investing in large-scale costly infrastructural and technological solutions);
- *Offsets* involving conservation activities are intended to compensate for the residual, unavoidable harm to the environment (e.g., biodiversity loss, carbon emissions and waste discharges) caused by development projects

[10] This is because it is the institutions that largely determine the transaction costs associated with establishing, allocating, and enforcing access or ownership rights (see Coase 1960).

(Grigg 2004; ten Kate et al. 2004). Importantly, ten Kate et al. (2004) emphasise that "*before developers contemplate offsets, they should have first sought to avoid and minimise harm [to biodiversity]*". Offsets are also referred to as 'biobanking' (e.g., see DECCW 2009). 'Offsets' can be designed and implemented in a variety of ways but essentially involve a development right or licence to pollute being granted with conditions that all unavoidable harm to natural and social stocks of capital are compensated to ensure no net loss. Consequently, offsets provide the Queensland government with a mechanism: a) to cost-effectively encourage companies to contribute to natural capital restoration and biodiversity conservation, often without the need for new legislation; b) to ensure development projects are planned in the context of sustainable development and counterbalanced by measures that secure the conservation of ecosystems and species; c) to secure more and better conservation and obtain additional funding to properly finance ecological corridors or strengthen networks of protected areas; and d) to ensure community amenity, livelihoods and cultural values are maintained or enhanced.

- ***Taxes, charges and subsidies*** to promote environmentally beneficial behaviours and outcomes. In this case, Government might consider: a) providing tax benefits for superannuation funds to invest in slow-growth, long-term indigenous plantations (Low et al. 2010) or to promote corporate donations to support the expansion of areas through protection and restoration activities; b) imposing charges on the private sector to discourage behaviours that degrade natural capital stocks (e.g., waste-discharge charges, a carbon tax); and c) ring-fencing revenues from corporate, pollution and/or resource-rent taxes (e.g., a variation of the resource-rent tax proposed in the Australian Government Future Tax System Review[11]) and carbon-finance schemes (e.g., carbon farming initiative, Commonwealth of Australia 2011); and the clean energy legislation package[12] to create environmental trust funds that ensure the finances are available today and in the future to fund programs that protect and restore natural capital stocks (e.g., through the Biodiversity Fund[13]).
- ***Building the economic case*** for conservation through the economic valuation of ecosystem services and biodiversity (Barbier 2011; IPCC 2007b; Liu et al. 2010a; Sukhdev et al. 2010; Turner et al. 2010). In this case, the Queensland government might consider: a) making it mandatory for corporations to annually account for and report on their net impact on wellbeing (using the Inclusive Wealth criterion, for example); b) making all development applications provide estimates of the long-term net effects on wellbeing (this will be particularly relevant for the granting of coal-seam gas extraction licenses); and c) actively pursuing the development of accounting metrics for building Queensland's regional environmental accounts (see Lange 2007; Wentworth Group 2010).
- ***Eco-labelling and enhanced consumer awareness***, to promote environmentally-enhancing and responsible practices of corporations. In this case, Government might use various forms of media to enhance the public's awareness about on-the-ground and financial contributions of private firms to conservation—ensuring the consistency, transparency, and integrity of the activities and environmental outcomes.

Experiences to date with market-based approaches have met with varying degrees of success (e.g., see Anthoff & Hahn 2010; Chhatre & Agrawal 2009; Corbera et al. 2009; Jack et al. 2008; Ring et al. 2010). Anthoff and Hahn (2010) and Jack et al. (2008), for example, review the literature on incentive-based approaches in terms of their performance at meeting criteria of environmental effectiveness, cost-effectiveness and (in the latter case) equity. In the former cases, they found that market-based approaches generally result in cost savings but often fall short of achieving meaningful environmental outcomes (i.e., low environmental effectiveness). They provide numerous reasons for this and suggest options for improvement which relate to better defining the scope of targets, better linking targets to economic benefits and costs and agent behaviour, and acknowledging the difficult political and policy processes within which targets are negotiated and revenues from regulatory approaches are distributed.

Jack et al. (2008) highlight the importance of context in achieving policy goals and emphasise that no single policy is a panacea. They also emphasise that simultaneously achieving environmental, economic and equity objectives is unlikely and that trade-offs can be identified and incorporated into the choice and design of options by assessing the correlations or relationships between the characteristics of resource users and the resource, the nature of the costs and benefits of providing goods and services, and management and policy feasibility. Corbera et al. (2009) highlight the importance of flexibility in procedural design and continuous institutional adaptation for the long-term effectiveness of PES schemes and find that the interplay between institutions is insufficiently considered by governments, users and researchers involved in PES schemes. Finally, two recent reviews report on the many controversies

[11] See, Australian Government Future Tax System Review http://taxreview.treasury.gov.au/content/Content.aspx?doc=html/home.htm

[12] See, the Clean Energy Legislation Package at: http://www.climatechange.gov.au/en/government/submissions/clean-energy-legislative-package.aspx

[13] See, the Biodiversity Fund at: http://www.cleanenergyfuture.gov.au/biodiversity-fund/

and challenges associated with the economic valuation of nature and its services (Liu et al. 2010b; Ring et al. 2010) and indicate that it is generally the case that economic valuation studies undertaken in isolation of institutional reforms will not lead to the substantial improvements in the rates and scale of adaptations that are required.

Collective-action approaches

Ostrom (2005b; 2007) provides examples of where collective-action approaches are more appropriate than market-based approaches for achieving a sustainable environment while also supporting resource-based economic activities (e.g., fish or timber harvesting). The principal advantage of such approaches over market-based approaches is that the rules and practices that define the rights of access can be enforced at lower cost, where this is a significant part of the costs of intervention. However, successful collective-action approaches require situations in which: a) communities have lived together for many generations and have developed deep roots, local leadership, norms of trustworthiness and reciprocity; b) communities have gained effective knowledge of the dynamics of the resource system they are using; and c) the biological attributes of natural resource upon which the community depends are amenable to the development of use rules and norms that can be cost-effectively monitored and (self) enforced. An important role for Governments in pursuing such approaches is to support and build the social and human capital required.

Other collective-action approaches involve Governments, corporations and/or conservation agencies working in partnership on adaptation responses of mutual concern and benefit. For example, improving the profitability of mixed farm enterprises while also helping to protect biodiversity as a corporate and community group collaboration (e.g., Grain and Graze Program 2008). Instances where such approaches are likely to succeed are where different parties bring complementary capabilities to the partnership that overcome the constraints faced by each individually and where all have opportunities to gain. In the context of adapting Queensland's natural capital stocks to climate change, the Queensland Government will be facing adaptation demands that are likely to far exceed their budgets and capabilities, and will therefore need to begin building the case and promoting opportunities for the private sector to partner with them in meeting the challenge (e.g., Agrawala & Fankhauser 2008; Hartwich et al. 2007).

The role of government

It is generally not feasible for government to adopt a 'command-and-control' approach to addressing environmental problems, irrespective of the scale. This is because of the substantial resistance likely from communities and other vested interests that will be negatively affected by proposed changes, the demands on limited government resources to manage and enforce the imposition of rules, the mismatch between the scale of the environmental problem and the jurisdictional boundaries, and the lack of sufficient local knowledge and understanding. The roles of government is best focused on facilitating the creation of a common understanding of the properties and dynamics of the social-ecological systems of concern, on determining the organisational arrangements that match, and on creating an enabling institutional environment through the introduction of regulations and the provisioning of resources that promote cost-effective transactions between organisations. In this regard, processes are critical in the design and implementation of new institutions. This is briefly covered next.

4.3.3 The importance of process

Due to the complex, uncertain and contentious nature of the issues involved, and the difficulties in changing institutions, it is important that initiatives undertaken to promote climate adaptation are implemented:

1. by expanding existing risk-management and decision-making processes to include ways of better characterising problems (Renn et al. 2011) and allowing opportunities to reframe objectives to reflect changing perspectives, values and beliefs based on learning (e.g., Pahl-Wostl 2009, on triple-loop learning);
2. by incorporating experts, stakeholders, and communities in communication and deliberation to ensure knowledge is co-produced to better respond to policy questions faced (Lane et al. 2004; Swanson et al. 2010). In this context, Corfee-Morlot et al. (2011) highlight the importance of 'boundary organisations' in facilitating local science-policy assessment;
3. by promoting linkages between local, state and federal levels and across formal and traditional knowledge systems (Berkes 2002; Næss et al. 2005; Smith & Stirling 2010); and finally,
4. through the creation of 'niches' at the local scale where innovative institutional ideas, policies, land uses and technologies can be tested/experimented with and refined into viable alternatives for scaling up (Heilmann 2008; Rotmans & Loorbach 2009) and incorporated into national policy-making, planning, and development processes.

4.4 Conclusions

Queensland's culture and economy depend on the goods and services provided by its natural capital stocks. These stocks and services will be unavoidably affected by climate change and will impact on the wellbeing of individuals, communities and organisations across all economic sectors. The impacts of climate change will vary over space and time and across ecosystem type but will broadly involve: reductions in the reliability and quantity of rainfall runoff throughout Queensland reducing freshwater supplies to support ecosystem services such as pastures, crops, livestock and fish; increases in ocean temperature and acidity and shifts in ocean currents that will cause breeding habitats to shift and change in structure, function or composition and will disrupt and possibly undermine fisheries productivity and amenity values; and increases in magnitude and/or frequency of perturbations and disturbances such as storm surge, wind speeds, flooding and inundation events will increase pressure on coastal ecosystems and their protective values.

Where climate change causes declines in ecosystem services this will reduce the social, economic and cultural benefits and will require communities and businesses to reconsider, redefine and alter their dependencies, values, and preferences for natural capital stocks and reflect on issues of ethics and equity in relation to how ecosystem services are utilised. A critical component of this re-evaluation will be the conscious decision to resist inevitable change by either investing in technological and infrastructural substitutes for ecosystem services that incur permanent costs, or investing in maintaining and enhancing the resilience and adaptive capacity of ecosystems to ensure the sustained provisioning of ecosystem services (particularly those as yet unknown services (i.e., adaptation services) that will enable future adaptation). The latter option has been shown by The Economics of Ecosystems and Biodiversity study[14] to be consistently more cost and environmentally effective (European Communities 2008; Ibisch et al. 2010; Perrings 2010; Ramos et al. 2010; Ring et al. 2010; Sukhdev et al. 2010; ten Brink 2011).

The three adaptation services of protection, buffering and options that are provided by biodiversity but currently under-recognised and under-valued, will become increasingly important and valuable under climate change as ways of sustaining flows of valuable ecosystem services that avoid costly technological/infrastructural 'fixes'. Humankind has the capacity to adapt its management and use of natural capital and ecosystem services to climate change, but the complex, uncertain and insidious nature of climate change and its impacts on biodiversity makes the 'who, where, when and how' of adaptation unclear and contentious.

The public good nature of biodiversity means too little will be conserved if left to markets. Likewise, private players are unlikely to autonomously adapt their existing resource-use practices in a timely way to better manage and conserve biodiversity because the benefits of doing so are delayed and uncertain relative to the upfront and often large costs. Even though the resources required for managing climate-change impacts on ecosystems, biodiversity and ecosystem services will exceed government budgets and capabilities, the Queensland government has a critical role to play in ensuring these adaptation barriers are overcome. Practical responses and actions that can be undertaken to achieve biodiversity, ecosystems and ecosystem services outcomes are addressed in Section 5.

Stockman musters cattle on Belmont Station in central Queensland (credit: CSIRO Livestock Industries).

[14] TEEB – the Economics of Ecosystems and Biodiversity, see http://www.teebweb.org/

View over beach, Port Douglas, North Queensland (credit: Fiona Henderson, CSIRO Ecosystem Sciences, science image DA11404).

5. Adaptation principles and options

Evidence for climate change, and the inevitability of change continuing, is clear. Although adaptation to climate change is a new challenge for policy and natural resource management, some general principles (listed below) are emerging from the recent collective experience.

Climate change is complex. Effective adaptation options will require a coordinated plan of action developed collaboratively by stakeholders. Adaptation actions will need to account for varied and substantial changes in ecosystems by the end of this century.

How climate change will affect ecosystems is uncertain. To spread the risk of taking an ineffective adaptation action, alternative adaptation options may be explored and tested under different ecosystem change scenarios.

A paradigm shift in ecosystem management is needed because current approaches have not been sufficient to halt biodiversity declines. This management shift must include: (i) extending the focus to include ecosystem function and services rather than species in isolation, (ii) managing to improve landscape processes and functions, such as the provision of complex habitats, and (iii) planning adaptation actions covering longer time and larger spatial scales.

Rapid climate change is an added pressure on biodiversity, which is already being impacted by disturbances such as altered fire regimes, land use changes, invasive species, diseases and pathogens. To halt declining biodiversity, adaptation actions must manage all these pressures.

To develop adaptation management options, seven action themes have been identified for Queensland. These adaptation themes, listed below, need to be assessed and further developed by relevant Queensland Government agencies in the context of their existing programs.

1. To manage changes in species and ecosystems, reassess current biodiversity management objectives relative to longer and larger scales and the multiple ways in which biodiversity is experienced and valued by society.
2. To improve the provision of ecosystem goods and services, emphasise to society the values that biodiversity plays in the capacity of ecosystems to adapt to climate change.
3. To effectively reduce losses in biodiversity and ecosystem services, stress to society the need to significantly mitigate global greenhouse gas emissions and substantially increase biodiversity management effort.
4. To help natural resource managers improve biodiversity and ecosystem services, build their knowledge on the impacts of climate change and awareness of how to respond through their current programs.
5. To increase the likelihood of biodiversity adapting independently to climate change, develop options for reducing other disturbance pressures on biodiversity and manage conflicts with adaptation in other sectors, as they arise.
6. To build the adaptive capacity of biodiversity and ecosystems, develop plans to strategically manage the condition and connectivity of habitats across landscapes and assess the risk of actions that have long-term implications.
7. To sustain human and environmental uses of water under climate change, develop action plans to improve ecological and hydrological flows of water through landscapes.

Within each pathway, there are actions that can be implemented immediately, and others that can be undertaken later as more information becomes available. However, there are significant ecological knowledge gaps and social questions that need to be addressed as part of the process of adaptation.

To develop a set of adaptation principles and management options, in this section we build on our experiences with working with biodiversity managers in Australia and overseas and in review of the climate adaptation literature, including information presented in previous sections of this report (Bustamante et al. 2012; Ferrier et al. 2012; Kroon et al. 2012; Murphy et al. 2012; Williams et al. 2012). We discuss these adaptation principles, including how climate change is likely to affect biodiversity and related implications for policy, planning and management. We then present a framework for developing and assessing adaptation options, including criteria for evaluating priorities. Finally, we describe seven adaptation themes comprising sets of actions for further development by ecosystem managers and policymakers in Queensland. Adaptation options were considered these in terms of broad principles of management rather than in situ options that are highly contextualised. The latter require a different process of planning and consultation with practitioners, which was beyond the scope of this work.

5.1 Adaptation principles

5.1.1 Knowledge base

A wide range of options for adapting biodiversity management to the possible future impacts of climate change have been proposed in the scientific literature, and by policymakers and managers around the world (e.g., Dunlop & Brown 2008; Hagerman et al. 2010a; Heller & Zavaleta 2009; Lemieux & Scott 2011; Mawdsley et al. 2009; Steffen et al. 2009a). However, the science of climate change adaptation is relatively recent – there is limited collective experience of implementing and evaluating adaptation options. Knowledge about future impacts or potential opportunities are varied, as reviewed by Heller and Zavaleta (2009) and Hagerman et al. (2010a). Much of the work to date has focussed on a few types of impact and response, for example shifting species distributions (e.g., Huntley et al. 2010; Keith et al. 2008; Yates et al. 2010). There has been little systematic effort to address adaptation in the context of the full suite of potential ecological changes, levels of uncertainty, and the complexities that arise from existing management challenges. However, a number of principles are emerging such as how to deal with uncertainty under climate change (e.g., Hagerman et al. 2010a; Heller & Zavaleta 2009; Mawdsley et al. 2009). This section outlines some emerging principles of adaptation (Table 3). These principles have implications for designing policy and developing ecosystem management programs in Queensland.

Table 3: Emerging principles of adaptation for biodiversity management.

Principle	Issue	Policy Implications
Climate change is a complex phenomenon	The timing, duration and magnitude of climate change impacts are highly varied across the globe.	Policy and management responses need to apply to multiple aspects and scales of change, with urgency set by the timing, location, magnitude and of climate change impacts.
Uncertainty is inherent to climate change	Predicting the impacts of climate change is uncertain because of the many driving factors and delays in ecosystem responses and interactions at different scales.	Uncertainty in the causes and consequences of climate change means proposed policy designs will be contested, delaying implementation.
Beyond 2°C global warming	There is a high likelihood that the magnitude of climate change will significantly exceed a 2°C global average warming.	Adaptation action plans for biodiversity management may require new objectives and actions.
A shift in ecosystem management	With climate change current approaches to management have not halted biodiversity declines. Therefore, a shift in how ecosystems are managed will be required.	The goals and action plans for biodiversity management will require a stronger focus on ecosystem processes and functions.
Climate change in the context of other pressures on biodiversity	Climate change is one of many disturbance pressures affecting biodiversity, and all these pressures interact in complex ways.	Adaptation to climate change will need to be included in existing ecosystem management programs.
Adaptation by people and institutions	Much of the complexity of adapting to climate change arises from the human dimension of ecosystem management	Plans and policies on climate change adaptation will require collaborative and coordinated efforts by many different stakeholder groups.

5.1.2 The nature of climate change: scale of impacts and rate of change

Ecosystems and their species are facing substantial, long term and continuous change in many aspects of their physical and biotic environments, as distinct from one-off or temporary changes due to periodic disturbances such as fire, flood or storms. The directional change in environments arising from projected climate and ocean change (see Section 2) are likely to transform many ecosystems and lead to species extinctions (see Section 3).

As described in previous sections of this report, climate change alters ecosystems. These changes will be widespread in Queensland (Low 2011) and will affect biological responses at all levels of organisation – genes, individuals, populations, species, assemblages and ecosystems. Climate change is not a singular phenomenon. Therefore policy and management responses to just one aspect of climate change risks being ineffective at best and maladaptive at worst. Furthermore, future rates and the expected magnitude of climate and ocean changes are projected to be well beyond contemporary natural variation. The ecological consequences of climate change are already apparent in the form of behavioural responses such as the timing of migratory bird arrivals or departures. Other climate changes, often with unexpected consequences, are projected to increase over the course of this century. Adaptation planning should consider the likelihood of substantial changes to ecosystems.

5.1.3 Uncertainty in environmental change and ecological responses

Climate change is complex and involves many uncertain factors and processes, including delays in ecological responses, interactions between social and ecological subsystems, and interactions across scales (Wilby & Dessai 2010). Some climate change trends are well characterised, but many remain uncertain. Thus, uncertainty is inherent to climate change, and will affect how different adaptation options, strategies and management decisions are designed (Dunlop & Brown 2008; Hagerman et al. 2010a; Stafford Smith et al. 2011). For example, decision making may be delayed until information is improved and uncertainty is reduced. Scenario modelling may be used as a tool to clarify or reduce uncertainty.

5.1.4 Beyond 2°C global warming: adaptation pathways to transformation

There is a likelihood that the magnitude of climate change will significantly exceed that characterised by a global average warming of 2°C, sometimes regarded as 'safe' climate change (Hay 2011; Richardson et al. 2009d). Responding to greater climate change is fundamentally different from responding to change that is more-or-less within natural variation. Greater climate change will require *transformational changes* to policy and management, as opposed to *incremental changes* (Stafford Smith et al. 2011). Incremental adaptation aims to maintain existing activities and use existing technologies, whereas transformational adaptation requires new technologies and may entail major changes in management objectives and institutions. A switch from incremental responses to transformational responses may be appropriate in the future (Park et al. 2012).

Adaptation pathways are a useful tool for evaluating the policy, planning and implementation consequences of transformational management responses (Stafford Smith et al. 2011). Adaptation pathways, with staged decisions about options, can be developed to accommodate different climate projections and ecological change scenarios. For example, adaptation may initially involve relatively low risk, incremental, management decisions prior to more significant transformational management changes. Most critically, pathway planning aims to avoid making adaptation decisions that seem attractive in the near-term and appropriate for small changes (i.e., up to 2°C global warming) but are ineffective under greater change. This is particularly important for decisions with long lasting consequences. For example, as major urban infrastructure has a design life of at least 50 years, it may be sensible for new development to take into account the risk of high-end levels of climate change impacts. Ecological processes such as forest succession may take up to 100 years or more to provide suitable habitat for hollow-dwelling arboreal mammals and nesting birds (Steffen et al. 2009a; Vesk & Mac Nally 2006).

5.1.5 The need for a paradigm change in ecosystem management

The need for a paradigm change in how ecosystems are managed has been argued in the scientific literature (Geertsema et al. 2008; Sodhi & Ehrlich 2010; Watts 2008). These concerns are based on the observation that current approaches to management have not been sufficient to halt biodiversity decline (sCBD 2010). There is now a realisation that different actions will be required under climate change (e.g., Dunlop & Brown 2008; Hagerman et al. 2010b; Steffen et al. 2009b). Various proposed elements of a management shift have included a number of issues: the magnitude of investment; managing versus resisting change; managing significant loss; focussing on ecosystem services and landscapes processes and functions rather than species; expanding the responsibility to include business and community; and planning over longer time and larger geographic scales.

These changes are consistent with a transformational adaptation pathway with adjustments to the goals of biodiversity management and policy (Prober & Dunlop 2011). They include a focus on ecosystem function as a key strategy for designing actions (Bennett et al. 2009). The many different aspects of biodiversity that are valued by society, and how these values may change under climate change, are discussed in Section 5.2.

5.1.6 Climate change in the context of other pressures

Climate change is one of many pressures affecting ecosystems and their species. The interaction of climate change with disturbances such as changes in land use and invasion by exotic species, disease and pathogens results in 'threat syndromes' (see Section 3.1.2). There is significant ecological, economic and institutional risk in planning climate change adaptation actions without considering all pressures. Critically, the interacting effects of climate change with other stresses are likely to result in impacts that are much greater than a simple combination of the two effects (see Figure 19). To be most effective, adaptation to climate change is best initiated through existing environmental management programs across government, institutions and industry (discussed in more detail in Section 5.3.6).

5.1.7 Adaptation by people and institutions

Whereas the task of adapting biodiversity management to future climates has significant ecological dimensions, much of the complexity of adapting to climate change arises from the human dimension of ecosystem management (e.g., Howden et al. 2007). In Section 4.3.2, we outlined mechanisms and processes for implementing adaptation options. In Section 4.3.3 we described the importance

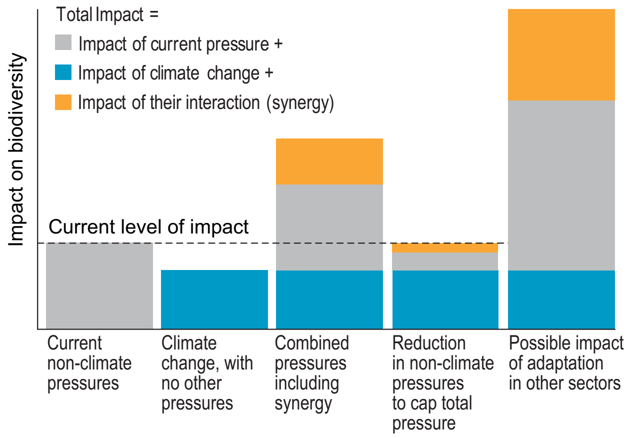


Figure 19: Scenarios of potential impact on biodiversity arising from non-climate pressures, climate change and their combined impact including the interaction between them. The fourth scenario shows the reduction in other pressures required to contain the total future impact at the current non-climate change level. The last scenario incorporates adaptation to climate change in other sectors leading to significant increases in pressure on biodiversity. The levels of impact shown are indicative, and unlikely to be easily quantified. Relative magnitudes of impacts due to other pressures, climate change and their synergy will vary considerably between ecosystems and regions, and between scenarios with different biodiversity values. See Section 5.1.6.

of process. But climate adaptation also needs to consider the range of different stakeholders, and to be implemented collaboratively across their organisations and institutions. Achievement of a coordinated response to climate change requires community participation.

5.2 Adaptation framework

5.2.1 Components of the framework

The complexity of climate change impacts is overwhelming. To aid understanding, a conceptual framework for identifying adaptation options is useful. It can help account for multiple biodiversity values, different types of ecological changes, losses of biodiversity, variable levels of uncertainty, and the combined effects of other disturbance pressures.

In this section we present a framework to help policymakers and managers evaluate and design adaptation options. This framework addresses two key issues that influence the effectiveness of adaptation responses: (i) uncertainty associated with different types of ecological responses to climate change, and (ii) the different aspects of biodiversity that are valued by society.

The framework builds on our past experiences. It represents a 'work-in-progress' because parts of the framework are based on a greater depth of knowledge than others. As knowledge improves, this framework can be further developed and adapted to suit the specific planning requirements of ecosystem managers and policymakers in Queensland.

The framework consists of five components (Figure 20):

- *Biodiversity outcomes:* the different dimensions of biodiversity that are experienced and valued by society, which are likely to be affected by climate change.
- *Management objectives:* those specific aims required to achieve positive biodiversity outcomes.
- *Ecological change scenarios:* those scenarios that are likely outcomes of climate change.
- *Adaptation options:* those management actions contributing to the positive biodiversity outcomes.
- *Priority analysis:* for exploring priorities for developing adaptation pathways.

Iterative refinement to this framework may include a sub-framework that explores changes to governance, institutions and organisational structures that currently reinforce inappropriate natural resource management practices that may contribute to the issue of biodiversity 'threat syndromes'.

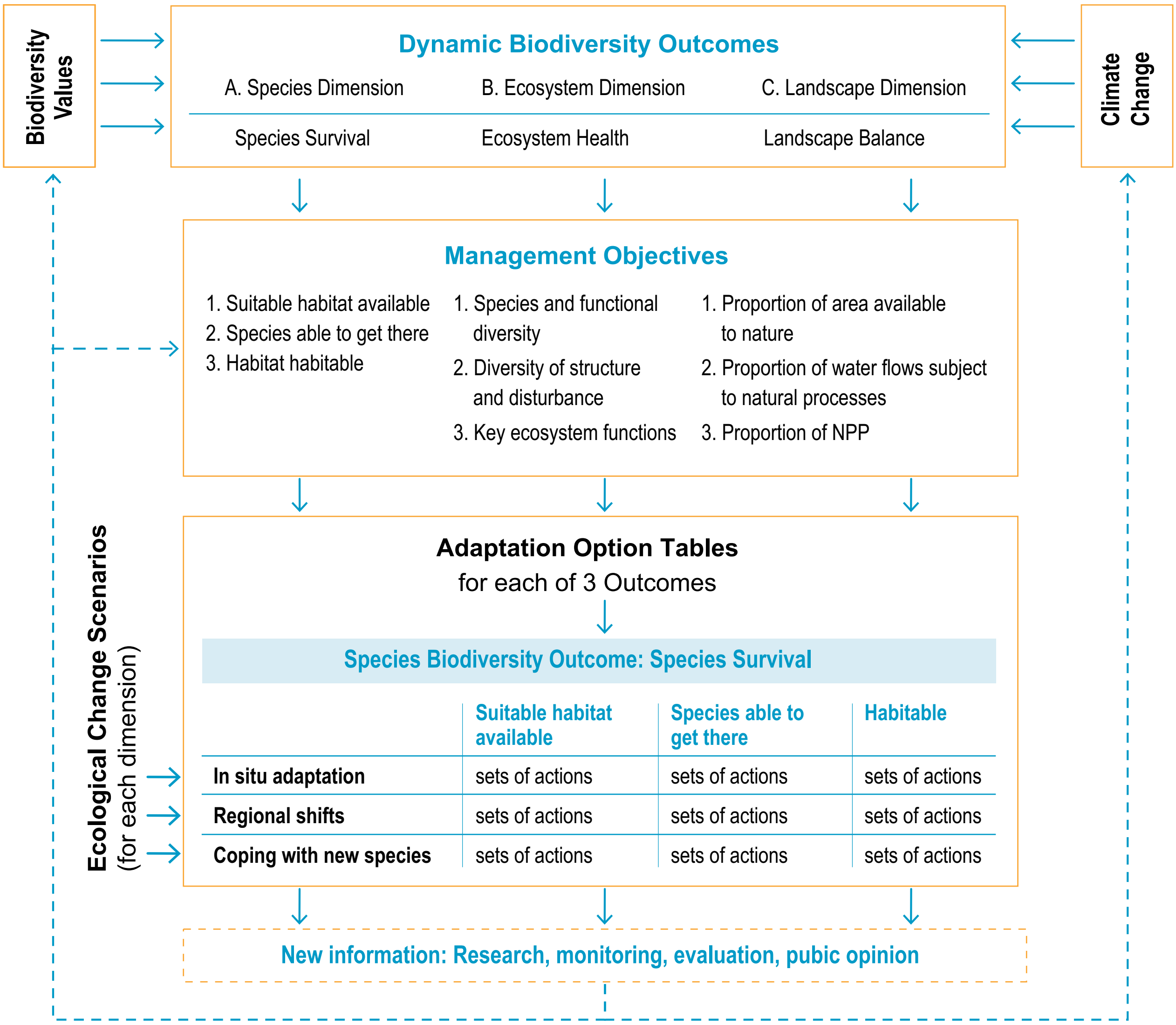


Figure 20: An Adaptation Framework illustrating a ***dynamic biodiversity outcome*** for each of three dimensions of biodiversity, with nested ***management objectives*** and corresponding sets of management actions that are effective under different ***ecological change scenarios***. (Actions matrix only shown for the species outcomes) (Dunlop *et al.* 2011). Individual management actions can then be prioritised and staged to be undertaken within an adaptation pathway.

5.2.2 Biodiversity outcomes and policy objectives

This part of the framework formalises the link between different aspects of biodiversity that are valued by society, how these values and preferences are considered in policy objectives, and how peoples' experiences and perception of these values will be affected by climate change.

How do people experience and value biodiversity?

Species and ecological communities have been the main focus of biodiversity conservation and its management. Species extinctions grab headlines. There are, however, many ecosystem services and other societal values associated with biodiversity and natural areas (Millennium Ecosystem Assessment 2005; Williams et al. 2012) (see Section 4). Here we define three very different ways people relate to, experience and value nature. We describe these respectively as species, ecosystem and landscape dimensions of biodiversity (Table 4). While there is an overlap in terminology, these three dimensions are quite distinct from scientific levels of biological organisation (i.e., genes, species, populations, communities, ecosystems, biomes). They are also independent of the scales at which management may be implemented, as management at one scale can affect outcomes on each dimension (Dunlop et al. 2011).

Table 4: Attributes of 'static' and 'dynamic' biodiversity outcomes associated with three dimensions of biodiversity that might be experienced and valued by people in different ways (adapted from Dunlop & Brown 2008). This table aims to facilitate a conversation about values and policy objectives under climate change. 'Static' outcomes are those that could be achieved with an unchanging biodiversity. 'Dynamic' outcomes are those that might be achievable as biodiversity changes in response to climate change.

Dimension of biodiversity	Attributes of biodiversity	
Entities valued by society, each at multiple scales	*'Static' outcomes* *Current policy objectives*	*'Dynamic' outcomes* *'Climate-ready' policy objectives*
Individual species and genes (fundamental units of biodiversity, including ecological communities)	Abundance, distribution and co-occurrence (community) (also population genetic diversity and demographic structure)	Existence of a species (surviving and evolving somewhere)
Ecosystem and habitat (quality, ecosystem processes, from patch on the ground to key ecological processes)	Ecosystem type (composition, structure and function; condition relative to type)	Ecosystem 'health' (key ecological processes, maintaining and/or cycling water, carbon, nutrients, soil, primary productivity, species diversity)
Land/river/sea-scapes (quantity; social-ecological system; degree of human domination; many ecosystem services; surrounds to continent)	The mixt of human uses and natural ecosystems	The balance of uses (the proportion of biodiversity appropriated by humans)

Species, including the genetic variation within them and their assemblages in ecological communities, are the fundamental units of biodiversity. Species are most frequently at the forefront of biodiversity policy and assessment (e.g., threatened species and ecological communities). Even when managing at the landscape scale the usual question is, 'What is the impact on species?'. In this framework (Table 4), the species dimension captures how a person may experience or relate to a particular species (e.g., bird watching or culturally important species) or ecological community.

The ecosystem dimension relates to the *quality* of nature at multiple scales and the landscape dimension relates to the *quantity* (Table 4). The ecosystem dimension represents the condition or health of the functioning ecological unit including key ecological processes. It is multi-scaled and may be represented by the condition of a patch of rainforest habitat, a wetland, or the ecosystem of an estuary. The ecosystem dimension reflects how biodiversity may be experienced, for example, when picnicking, swimming or bushwalking. While it is usual to think of condition in relation to natural ecosystems, the concept of health can apply to backyards, nature strips, fishponds or cotton crops, as well as regrowth, remnants, and habitat in protected areas (see Hearnshaw et al. 2005, for a discussion of ecosystem health concepts).

Landscapes refer to social-ecological systems comprising multiple ecosystems and human activities. Here, the land/river/sea-scape dimension captures the degree of human domination of nature from the scale of a person's local surroundings through to the continent and beyond. The landscape dimension captures how biodiversity may be appreciated from a hill-top, headland, aeroplane, or in iconic artworks. It also relates to the provision of many ecosystem services. Specific ecosystem services may depend on the presence of certain species or ecosystem processes but for many ecosystem services the quantity of service provided will be affected by the extent of human dominance of nature. For example, services such as hydrological regulation, carbon sequestration, timber harvesting or recreational fishing are all directly affected by the loss of habitat or biodiversity (see Section 4).

How will different values be affected by climate change?

Traditionally, in a 'static' world (without climate change), biodiversity outcomes would be described largely in terms of their identity or that of their components (middle column in Table 4). Current biodiversity policy and management objectives are often implemented in terms of maintaining these attributes. However, all of these attributes will almost inevitably change as climate change progresses. The third column suggests 'dynamic' biodiversity outcomes that are more fundamental and less likely to change as a result of climate change. These outcomes are implied at the highest levels in biodiversity policy. But, they may not be articulated in legislation and implemented in management plans. For example, the general term 'ecosystem resilience' is often cited as an objective under climate change, but the definition used in many strategy documents refers to "*retain[ing] essentially the same function, structure, identity, and feedbacks*" (Walker et al. 2004). Such aspirations may be infeasible in the medium term[15]. Resilience can, however, be applied to different aspects of biodiversity. The framework in Table 4 is an attempt to be specific in the application of the resilience concept.

'Dynamic' biodiversity outcomes under climate change

Table 4 considers potential 'climate-ready' policy objectives because it articulates which biodiversity outcomes management might seek to preserve (third column) as other attributes change in response to climate change (second column). Whereas many biodiversity programs focus on species outcomes, for example, threatened species recovery and investment in threatened ecological communities[16], other programs are oriented towards ecosystem and landscape outcomes (e.g., Great Barrier Reef water quality program[17], cessation of broad-scale land clearing[18], and the 'healthy working river' goal for the Murray-Darling system[19]). In addition to highlighting the difference between static and dynamic outcomes for biodiversity, Table 4 enables more explicit consideration of values derived from experiencing the ecosystem and landscape dimensions of biodiversity.

By focussing on 'climate-ready' biodiversity policy objectives in Table 4, the following 'dynamic' biodiversity outcomes can be expressed:

- **Species** *survive* (extinction avoided) while their abundance, distribution and assemblages change with climate change.
- The *health* of **ecosystems** is maintained as their composition, structure and function change with climate change.
- The *balance* between natural and human dominated processes is maintained across whole **landscapes**, while the types of ecosystem and human uses change with climate change.

These objectives are expressed specifically *in relation to the impacts of climate change*. When considering the impacts of other pressures, it may be desirable to increase the health of an ecosystem or decrease the human domination of a landscape. This is because the values associated with different biodiversity outcomes depend on the preferences of society which are essentially informed by, or underpinned by, what people feel or believe to be ethically defensible and representative. Therefore, if equity is considered to be important by a society then this will be reflected in their preference for biodiversity initiatives that lead to equitable outcomes and so these will have a higher value.

Dealing with contentious issues

It is important to recognise that these biodiversity outcomes cannot be solely determined by 'objective' science, but will be contentious due to individuals, communities, and businesses having very different values, preferences and perspectives. These perspectives are underpinned by fundamental and often deeply-held values, worldviews and beliefs. Strongly-held belief systems further compound the challenges of defining and agreeing on a set of biodiversity outcomes, especially given the complexity and uncertainty associated with climate change and how biodiversity will respond to those changes and how society will be affected in turn.

In such situations of uncertainty, ambiguity and equivocality, deriving what is considered to be a socially acceptable set of biodiversity outcomes can only be achieved through cycles of interpretation, explanation, interactive discussion, negotiation and social ratification (Zack 2007). Science can facilitate the political process by identifying and quantifying the distribution of benefits and costs. The political process then addresses the ethical and equity issues, for example, by taxing or charging those who benefit (or who cause the damage) and by providing compensation payments to those who lose out.

These notions are particularly important to the concept of landscape outcomes, which refers to a 'balance between nature and human-use' of ecosystems services. The appropriate balance or relative proportion of use may not just depend on scientific principles of sustainability and harvest quotas, but may depend on what a society deems to be acceptable, which changes over time, and particularly under shifting baselines as will be the case with climate change (Browne & McPhail 2011).

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[15] In many situations, including the draft Queensland Biodiversity Strategy (DERM 2010a) and the Australian Biodiversity Conservation Strategy (NRMMC 2010), this definition is used to describe the response of an ecosystem to a *disturbance or temporary pressure*. While this is a feasible aspiration under climate change, in itself it provides little guidance about what levels of change might be "acceptable" or not *under climate change*, and it leaves open the inference that "preservation of identity" is the long term objective as well as the short term objective.

[16] Recovery and conservation plans in Queensland, http://www.derm.qld.gov.au/wildlife-ecosystems/wildlife/threatened_plants_and_animals/recovery_conservation_plans.html

[17] Reef water quality protection plan, http://www.reefplan.qld.gov.au/about/rwqpp.shtm

[18] Vegetation management in Queensland, http://www.derm.qld.gov.au/vegetation/index.html

[19] Murray-Darling system, http://www.mdba.gov.au/programs/tlm

5.2.3 Management objectives

Here we describe key management objectives that might usefully contribute to the 'dynamic' biodiversity outcomes (Table 5), which are described in Section 5.2.2. The links between each objective and outcome are illustrated in our framework (Figure 20). Three management objectives are defined for each of the three biodiversity outcomes. Whereas the management objectives listed for 'species survival' reflect current conservation practice and trends, the proposed objectives for 'ecosystem health' and 'landscape balance' are based on management experiences. Management actions that potentially arise from these objectives are assessed in Section 5.2.5.

The *ecosystem health* objectives outlined in Table 5 can be applied at multiple scales, from the habitat patch to the regional ecosystem. Acceptable levels (or ranges) of each of these ecosystem requirements may need to be varied adaptively under future climates (Hobday 2011). The current *landscape balance* may not be desirable (e.g., unsustainable fisheries, over-allocated river waters) and the appropriate management objective may be to alter the balance (cf. Table 5).

5.2.4 Ecological change scenarios

In Section 3 we described how climate change leads to many different types of ecological changes in Queensland (seee also, Low 2011). We noted that climate change interacts with other factors such as environmental heterogeneity and biogeographic history. The net outcome of these changes will affect how people experience and value biodiversity across the species, ecosystem and landscape dimensions (Table 4). Some trajectories of change are better characterised than others. For example, the anticipated transition from a hard-coral dominated reef to soft-coral and macro-algal dominated ecosystems on the Great Barrier Reef (see Section 3.4). However, uncertainties surround the detail of such change (e.g., Pandolfi et al. 2011). Much of this uncertainty cannot be dealt with probabilistically and is potentially challenging for planning (Dessai & Hulme 2004). To address the inherent uncertainty in adaptation planning for climate change, we merged individual ecological change processes into a few scenarios (Table 6), which are linked to a manageable set of biodiversity outcomes (Dunlop & Brown 2008).

Uncertainty surrounds which scenario might dominate, which ecological phenomena might result in greater loss of biodiversity, and which processes might be readily managed to reduce that loss. By exploring these scenarios, planners can develop flexible management approaches that are effective for a range of possible futures under climate change (robust strategies). They will also know when and where specific interventions might be required. This will help them design monitoring programs to determine which management options will likely be most effective. There are critical links between each scenario, its biodiversity outcome and management objectives (Figure 20). Three ecological change scenarios are defined for each of the three dimensions of biodiversity value. These scenarios are combined with management objectives to provide

Table 5: Key management objectives that might usefully contribute to the 'dynamic' biodiversity outcomes.

What is needed ...	Management objective
...for species to survive under climate change, while abundance, distribution and assemblages change?	• Habitat of a suitable type must be available. This is a combination of the area of available habitat and the environmental and climatic conditions (i.e., the fundamental niche). • Species must be able to get to the habitat that is suitable for them; this could be: in situ, near-by or along broad climatic gradients. • Habitat must be habitable: conditions must be suitable for individuals to establish, grow and reproduce (i.e., the realised niche); this is a function of other species, ecological processes, disturbance regimes, and other human pressures.
...to maintain ecosystem health as ecosystems change under climate change, while ecosystem composition, structure and function change?	• Healthy ecosystems require a sufficient number of species including a diversity of species functional types, and a diversity of species within each functional type. • A diversity of structural species types and a diversity of disturbance histories provide habitat for multiple species and species requiring a mixture of habitat types. • Healthy ecosystems retain and cycle water, nutrients and carbon, and maintain net primary productivity.
...to maintain landscape balance under climate change, while the types of ecosystem and human uses change?	• The proportion of the area occupied by natural processes and human dominated processes is appropriate and maintained for that landscape. • Proportion of river and wetland flow regimes subject to natural processes is appropriate and maintained for that landscape. • Proportion of net primary productivity appropriated by people is appropriate and maintained for that landscape.

a structured framework for defining adaptation options (see Section 5.2.5). A schematic of the tabulation process is shown for the species biodiversity outcome in Figure 20. The descriptions in Table 6 identify specific types of ecological change and indicate how this change might lead to a loss of identified values for each biodiversity outcome.

5.2.5 Adaptation options framework

The adaptation options framework aims to identify which individual management actions might contribute to particular management objectives under specified ecological change scenarios (e.g., see the schematic for species outcomes in Figure 20). The tables developed for each of the dimensions—species, ecosystems and landscapes—provide a statement of the desired biodiversity outcome; columns for each management objective that contribute to achieving the biodiversity outcome; rows for each ecological change scenario; and cells for specific sets of actions to achieve the management objective for a particular ecological change scenario.

Worked examples of these tables with an initial set of climate adaptation actions (options) for biodiversity management are presented in Tables 7 to 9. These tables are based on an initial synthesis of current knowledge (Bustamante et al. 2012; Kroon et al. 2012; Murphy et al. 2012; Williams et al. 2012). This adaptation options analysis identifies how individual management actions may contribute to the different management outcomes and objectives under a range of ecological change scenarios. Many of these actions are nested in nature; that is, one action often naturally follows another. Implementation of this part of the adaptation framework is exploratory – the actual choice of actions depends on the relative value of different outcomes which is ultimately a social choice, informed by science (e.g., see Bozeman 2003), and the effectiveness of different actions will depend on local ecological and management contexts. As natural resource managers become more aware of the implications of climate change and develop new adaptation options, these could be added to the respective table, or they can be used to refine the description of possible actions. This initial compilation of adaptation options indicates that individual actions will vary in their effectiveness.

The widest range of actions relate to species survival (Dunlop et al. 2011), followed by maintaining landscape balance. Maintaining ecosystem health, which is linked to the provision of many ecosystem services, had the fewest available management options identified. This is an area for future refinement. Adaptation actions ranged from on-the-ground management to cross-sector institutional

Table 6: Scenarios for assessing different types of ecological change.

Scenarios for assessing ...	Types of ecological change and impacts
species outcomes	• ***In situ adaptation.*** Species either unaffected, cope, adapt in situ, adapt locally (within their existing distributions), evolve; possibly with reduced abundance and range. • **Regional shifts.** Species disperse and establish at new sites matching their regional bioclimatic habitat; possibly declining in areas of pre-climate change distribution. • ***Coping with new species.*** Species colonise from elsewhere, some altering habitat and species interactions, altering the realised niche of resident species; possibly contributing to reductions in the abundance and range of resident species.
ecosystem outcomes	• ***Change in composition.*** Loss of species and establishment of new species; potentially reducing local species richness and diversity; structure and function may or may not change significantly. • ***Change in structure.*** Changes in the relative abundance or dominance of species lead to change in habitat structure; potentially resulting in a simplification of habitat; may or may not include changes in composition and function. • ***Change in function.*** Changes (loss) in net primary productivity for example as a consequence of change in function due to changes in environmental potential or abundance of producer species and food-web interactions; productivity possibly below its potential.
landscape outcomes	• ***Change in type of ecosystems and land/sea uses.*** Changes in land, water, and sea uses and changes in types and functioning of ecosystem; but not necessarily the net balance; potentially including loss of particular ecosystems or services. • ***Intensification of land/sea use.*** Less hospitable matrix for species and ecosystems as land uses intensify and agro-ecosystems expand; may happen rapidly in response to technology and climate adaptation opportunities; likely to include loss and degradation of supporting habitat for species and ecosystems. • ***Expansion of land/sea use.*** Potentially more hospitable matrix and reduction in extent and intensity of land, water, and sea uses; in response to decreased productivity of fisheries, grazing, cropping systems, etc; reduced water availability; potentially leading to increased habitat availability for native biodiversity, but land abandonment may be preceded by degradation.

responses. Actions applicable to maintaining landscape balance had more cross–sector implications. For example, as ecosystems and the services they provide change, the ensuing economic impacts on affected industries may need managing through structural adjustments. While such actions involve complex tradeoffs between sector interests that are challenging to implement, they will be more effective over the long term because landscape outcomes enable positive species and ecosystem outcomes.

Many actions addressed more than one management objective and were assessed to be effective across a range of scenarios. The most robust actions improved ecosystem condition by managing disturbance regimes (such as fire frequency and intensity and invasive species). Some actions were only effective when a specific scenario was important. For example, those actions contributing to habitat connectivity aided regional shifts in species distributions. Similarly, some actions were only beneficial for one of the outcomes (species, ecosystem or landscape), whereas others were relevant to two or more outcomes.

By far the most robust and widely applicable actions were those ensuring the availability of habitats for a rich biodiversity. Reducing the impact of disturbance pressures on habitats was also important. The actual choice of sets of actions, however, will depend on the relative value of different outcomes.

Table 7: Adaptation options for Species Biodiversity Outcome.

Species Biodiversity Outcome: "Maintain species survival (persistence); while abundance, distribution and assemblages change"			
	Management objectives		
Ecological change scenarios (any one could drive loss)	1. Suitable habitat available (fundamental niche)	2. Species able to get there (dispersal)	3. Habitable (establish, grow, reproduce) (realised niche)
In situ adaptation Species remain in the same geographical locations by: • being unaffected by climate change • coping with climate change • adapting genetically • adapting phenotypically • changing micro-niche or • behaviours to avoid climate change	Protect large areas of terrestrial and marine habitat • Expand effective areas of habitat by softening the off-reserve matrix and enabling local connectivity through protecting fragments, restoration, perennial vegetation, reducing barriers in rivers and flood plains • Maintain areas for multiple populations with isolation (insurance) and genetic exchange (evolution) • Maintain hotspots of evolutionary heritage/ palaeoecology refuges and existing climate refuges • Protect diverse areas and gradients to provide habitat heterogeneity at local and regional scales • Maintain habitat diversity provided by appropriate regimes of disturbance and diversity of time-since disturbance • Maintain complexity of riparian and aquatic habitats, and floodplain inundation • Maintain large scale refuges, mountains, lakes and large wetlands • Maintain free flowing rivers and ensure adequate flow regimes in modified systems	(NB: Only local dispersal needed for this scenario) • Protect areas with a diversity of habitats, including variable landscapes and gradients • Where appropriate, protect and enhance local connectivity through protecting fragments, restoration, perennial vegetation, reducing barriers in rivers and flood plains	Reduce other pressures • Limit other species arriving* by limiting connectivity, avoiding translocation, controlling new arrivals • But facilitate genetic exchange to enable local adaptation • Manage habitat variability, fire regimes, refuges, productive areas, periodic flooding to enable protection and recovery from disturbance • Monitor habitability where management can improve it • Modify habitat to enable survival (nesting, feed, mowing, fire, flooding, etc) for selected species • Ex situ conservation as safety net

+ By "protect" we mean make available for native biodiversity – this is done currently via a wide range of management approaches both on and off reserves.

* Other species arriving may have a negative impact on persistence of species in situ through competition, predation, etc.

Table 7 continued ...

Species Biodiversity Outcome: "Maintain species survival (persistence); while abundance, distribution and assemblages change"			
	Management objectives		
Ecological change scenarios (any one could drive loss)	1. Suitable habitat available (fundamental niche)	2. Species able to get there (dispersal)	3. Habitable (establish, grow, reproduce) (realised niche)
Regional shifts Species disperse and establish to match their regional bioclimatic habitat, and decline in their current distribution.	Protect geographically dispersed habitat to span environmental gradients and maximise diversity of habitats at regional scale • Large scale restoration in extensively modified areas to create habitat in connectivity gaps and increase regional habitat diversity • Protect a maximum diversity of environments and habitats at regional and state scales • Protect and create areas of suitable habitat for target species • Protect hotspots of evolutionary heritage/ palaeoecology refuges from colonisation by common species	• (NB: Dispersal needs vary considerably; no one "optimal destination"; some species won't disperse fast enough regardless of habitat availability.) • Some species will disperse readily: no special dispersal requirements • Some species will need stepping stones: fill gaps through habitat protection and restoration • Some species need local connectivity for transit between stepping stones (especially in aquatic environments): maintain and enhance stepping stones and habitat in the matrix; maintain river courses and ensure periodic flooding; strategic removal of some dams, weirs, levees where evidence indicates value to species. • Some species need contiguous suitable habitat: protect existing habitat corridors, enhance and restore habitat corridors • Some need assisted dispersal (due to lack of habitat or dispersal speed): translocate targeted iconic, vulnerable or ecosystem-engineer species • Maintain populations of seed dispersers, undertake mass assisted seed dispersal (especially for broad-scale restoration) • Maintain regional species turnover to avoid homogenisation	Reduce other pressures • Manage the presence of facilitating species • Increase establishment opportunities by increasing disturbance mosaic diversity • Protect multiple areas of suitable habitat for selected species to spread risks associated with disturbance and other ecological dynamics • Monitor habitability where management can improve it • Modify habitat to enable survival (nesting, feed, mowing, fire, flooding, etc) for selected species • Encourage genetic exchange (process of evolution) (e.g., vigorous new hybrids hybridisation of keystone taxa such as eucalypts and acacias to create supporting habitat for other species) • Ex situ conservation as safety net
Coping with new species Other species colonise from elsewhere, altering habitat and species interactions, altering the realised niche of resident species.	As for "*In situ adaptation*", with extra emphasis on: • Maintain areas for multiple populations with isolation (insurance) and genetic exchange (evolution) • Protect diverse areas and gradients to provide habitat heterogeneity at local and regional scales • Maintain complexity of riparian and aquatic habitats	• (NB: Local dispersal only needed for this scenario) • Protect areas with a diversity of habitats, including variable landscapes and gradients	As for "*In situ adaptation*", with extra emphasis on: • Limit other species arriving* by limiting connectivity, avoiding translocation, controlling new arrivals • Monitor habitability where management can improve it • Modify habitat to enable survival (nesting, feed, mowing, fire, flooding, etc) for selected species

+ By "protect" we mean make available for native biodiversity – this is done currently via a wide range of management approaches both on and off reserves.

* Other species arriving may have a negative impact on persistence of species in situ through competition, predation, etc.

Table 8: Adaptation options for Ecosystems Biodiversity Outcome.

Ecosystems Biodiversity outcome: "Maintain habitat and ecosystem 'health', while ecosystem composition, structure and function change"			
	Management objectives		
Ecological change scenarios (any one could drive loss)	**1. Maintain species richness, functional diversity and redundancy**	**2. Maintain a diversity of structure, and mosaic of disturbance history**	**3. Maintain functioning: water, nutrient, carbon cycling; maintain net primary productivity**
Change in composition Loss of species and establishment of new species; habitat structure may or may not change significantly.	Ensure many species available by protecting a diversity of habitats, large areas and local connectivity • Maintain connectivity between regions • Maintain habitat diversity at site scale through managing disturbance and key species • Introduce species of "missing" functional types • Minimise other pressures • Manage disturbance and exploitation affecting vulnerable functional types • Encourage hybridisation • Maintain habitat and geophysical complexity	Manage disturbance regimes at site scale • Ensure appropriate diversity of disturbance regimes at regional scale	Reduce other pressures including physical disturbance to biota, soil, water courses • Monitor and manage grazers and other consumer species • Monitor and manage disturbance regimes • Monitor and facilitate or control key species that mediate ecosystem process ("ecological transformers"), both native and alien, (e.g., gamba grass in savannas; buffel grass in arid zone, macro-algae in reef habitats) • Introduce species of "missing" functional types
Change in structure Changes in the relative abundance of species, leads to change in habitat structure; likely to lead changes in composition.	Protect large areas and a diversity of habitats at local and regional scales, and maintain local connectivity • Maintain habitat diversity at site scale through managing disturbance and key species • Manage disturbance and exploitation affecting vulnerable structural types	As above • Provide artificial habitat structure: fallen timber, snags, reefs	As above
Change in function Change (loss) in productivity	Protect refuges: areas of high productivity (both permanently and seasonally) and local connectivity • Maintain habitat diversity at site scale through managing disturbance and key species • Introduce species of "missing" functional types • Minimise other pressures, especially disturbance and exploitation affecting vulnerable functional types.	Reduce frequency and intensity of "destructive" disturbance (fire, grazing) • Increase frequency of productive disturbance (floodplain inundation) • Manage grazing and human impact after natural disturbance • Provide artificial habitat structure: fallen timber, snags, reefs	As above, especially • Manage disturbance and grazing to maintain soil cover, producer species, carbon incorporation • Maintain environmental flows and flooding

** All of these need to be relative to some moving benchmark nominally reflecting something in equilibrium with the climate as it shifts.

Table 9: Adaptation options for Landscapes Biodiversity Outcome.

<table>
<tr><th colspan="4">Landscapes Biodiversity Outcome: "Maintain landscape balance, while the types of ecosystem and human uses change". Continued provision of ecosystem services: water, pasture biomass, fisheries production, pollination & pest control, etc</th></tr>
<tr><th></th><th colspan="3">Management objectives</th></tr>
<tr><th>Ecological change scenarios (any one could drive loss)</th><th>1. Proportion of area (intensity weighted) occupied by people and nature maintained</th><th>2. Proportion of water flows and regimes subject to natural processes maintained</th><th>3. Proportion of net primary productivity / biomass appropriated by people maintained</th></tr>
<tr><td>Change in type of ecosystems and land/sea uses

Changes in land, water, sea uses and changes in types and functioning of ecosystem (but not necessarily the net balance of natural and human domination).</td><td>Ensure changes in productivity of land and land uses does not lead to unplanned expansion of land use or external impacts (e.g., avoid increased area logged or increased logging intensity resulting from reduced tree growth)
• Allow space for landward migration of coastal vegetation
• Accommodate and facilitate (don't resist) changes in ecosystem types to new states, where desirable
• Adaptively manage recreation and other uses of natural ecosystems as their capacity to absorb impacts changes</td><td>Ensure impacts on water resources of land use change are factored into land management.
• In managed systems, ensure reductions in water availability, due to climate change, do not disproportionately affect environmental flows and the regimes of variation.</td><td>Changes in ecosystems may affect the ability of people to harvest biomass, e.g., reduced growth, woody thickening, altered palatability, change in fish community compositions, size, distribution and behaviour.
• Ensure harvest practices (fisheries, timber, grazing) accommodate potential changes in productivity
• Ensure adaptation in harvesting industries do not increase proportional impacts through maintaining harvest targets.
• Structural adjustment / economic impacts on affected industries may need managing.</td></tr>
<tr><td>Intensification of land/sea use

Less hospitable matrix and expansion of land use; may happen rapidly in response to technology and climate opportunities, may be unanticipated.</td><td>Develop mechanisms (e.g., regulation, incentives, off-sets) to manage land use changes resulting from sector adaptation. Proactive mechanisms, while opportunity costs are low, may be more efficient ahead of demand for land use change.
• Identify where intensification and expansion of land use may occur.
• Monitor anticipated changes, and establish early warning of unanticipated land use changes.
• Protect paddock trees and habitat fragments;
• Off-set losses of matrix habitat with set-aside and restoration to provide local connectivity, increase effective habitat areas, and maintain habitat diversity.
• Identify where regions of human population and settlement growth are likely to occur under climate change (e.g., coastal displacement, "hot-climate" refugees) and assess effects on species, ecosystems and landscapes.</td><td>Ensure impacts on water resources of land use change are anticipated and factored into land management.
• Ensure water extraction accommodates uncertainty, reduced availability, and increased environmental needs.
• For example, ensure near-term expansion of irrigation and industrial and urban uses are planned within long-term future water resource capacity.
• Manage impacts on groundwater
• Where extractions expand, consider triaging allocations to wetlands to ensure some survive.
• Protect free flowing river systems, ensuring development is within capacity of currently modified systems.</td><td>Ensure expansion and intensification is managed and off-sets used to ensure total appropriation is within acceptable limits.
• Monitor impacts of increased intensity as ecosystems change.</td></tr>
</table>

Table 9 continued ...

Landscapes Biodiversity Outcome: "Maintain landscape balance, while the types of ecosystem and human uses change". Continued provision of ecosystem services: water, pasture biomass, fisheries production, pollination & pest control, etc			
	Management objectives		
Ecological change scenarios (any one could drive loss)	1. Proportion of area (intensity weighted) occupied by people and nature maintained	2. Proportion of water flows and regimes subject to natural processes maintained	3. Proportion of net primary productivity / biomass appropriated by people maintained
Extensification of land/sea use Decreased productivity of fisheries, grazing, cropping systems, and reduced water availability lead to reduced intensity of human activities and potentially more hospitable matrix and greater availability of habitat .	Actively manage reductions in land use intensity (incentives, structural adjustment) to ensure the transitions lead, rather than lag, decreases in productivity to ensure ecosystems are not degraded before or during the transition. • Enable ecosystem recovery and restoration as land use transitions occur.	Actively manage reductions in land use intensity (incentives, structural adjustment) to ensure the transitions lead rather than lag decreases in productivity to ensure ecosystems are not degraded before or during the transition. • Decommission weirs, levees, dams or use them for managing environmental flows.	Ensure reductions in harvest (fisheries, timber, grazing) lead reductions in productivity to minimise over exploitation. • Ensure reductions in activity in one location / fishery do not lead to over-exploitation elsewhere. • Structural adjustment / economic impacts on affected industries may need managing.

Aerial view of tropical rainforest adjoining the Barron River near Cairns, northern Queensland. 2000 (credit: Gregory Heath, CSIRO Land and Water).

5.2.6 Managing risk with different types of decision: priority analysis framework

Uncertainty is pervasive to climate change (see Section 5.1.3) but planning and management can accommodate different types of uncertainty (Stafford Smith et al. 2011). In some cases the direction of change is certain, but the magnitude of change may be less certain. In other cases the direction of change is uncertain and unexpected impacts are likely to occur with substantial consequences. Therefore, climate adaptation planning needs to consider the possibility that most uncertainties are unlikely to be resolved by the time decisions need to be made (e.g., Dunlop & Brown 2008; Gordon et al. 2003; Imhoff & Bounoua 2006; Levin 2010; Vitousek et al. 1986). A wide range of different decision-making strategies are available for adapting planning and management to climate change. These include reactive, proactive, robust, and risk-spreading strategies, which are affected by uncertainty in different ways (Dunlop et al. 2011).

Adaptation pathways are a mechanism for addressing *transformational changes* to policy and management (see 5.1.4). This may include revising policy objectives and developing new management strategies that build capacity of individuals and institutions and reduce the risks of making big decisions in the face of uncertainty (Stafford Smith et al. 2011). A simple adaptation pathway could involve systematically assessing how climate change affects the feasibility of achieving current management and policy objectives. Strategies robust to climate change uncertainties are retained, whereas new strategies are developed for adaptation pathways that are sensitive to uncertainties (Adger et al. 2005; Dunlop & Brown 2008; Levin 2010; Stafford Smith et al. 2011).

Adaptation pathways are intended to reveal maladaptive actions – decisions that are ineffective because they do not account for the risks of climate change (Stafford Smith et al. 2011). Adaptation pathways need to be robust over a range of different climate change scenarios.

To help determine priorities for implementing adaptation pathways, we provide a priority analysis framework based on a series of questions (Table 10). The focus of these questions is on risks of making *proactive* decisions when dealing with *uncertainty, perverse outcomes* and *institutional barriers*, especially when decisions have a *long timeframe*. These questions were derived from issues highlighted in the climate adaptation literature and from our own experience working with agencies in Australia and globally (Adger et al. 2005; Levin 2010; Stafford Smith et al. 2011; Wilby & Dessai 2010). Priorities are affected by the values seen as most important to protect and maintain, such as the ecosystem services presented in Section 4 (e.g., see Figure 21). For particular regions, ecological modelling can provide guidance on priorities (Box 2).

Table 10: A priority analysis framework, which uses a set of questions to guide the choice of adaptation pathways.

Uncertainty

- What environmental, social or institutional factors most critically affect the outcome of the decision?
- What is the nature of the uncertainty?
- Is the decision sensitive to the magnitude of climate change?
- What information is required to make the decision and when will it be available and with sufficient accuracy?

Decision lifetime

- How long would action take to plan, implement and have an effect?
- Does the decision have to be made proactively?
- Can the decision be made after change in the critical driving factor has been observed?
- Is the impact reversible?
- Can the action be delayed, and if so at what cost?

Environmental effectiveness

- What is the likelihood of success?
- Is once-off or continual management required, and is this management facilitating change or resisting it?
- Can you choose when to and not to apply the management (Triage)?
- Is there a risk of perverse ecological outcomes or trade-offs with other values?

Can management be implemented within existing programs – not assessed in this implementation

- Does the management require new policy objectives or enabling legislation?
- Does the management required additional information or resources?

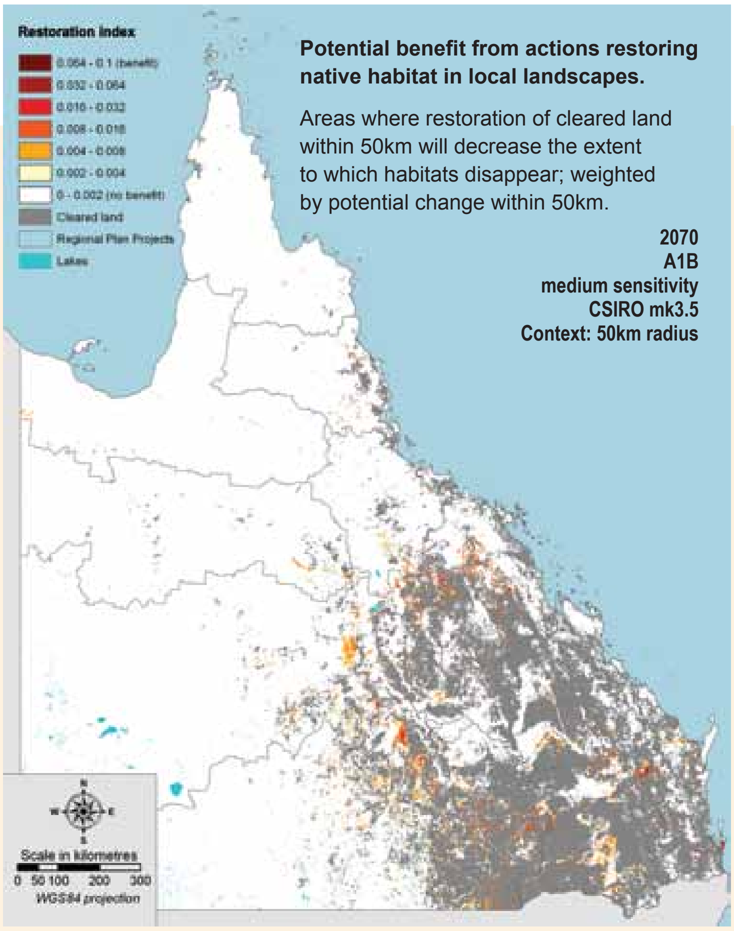
Equity and cost effectiveness

- How will the benefits and costs of change be distributed – socially, spatially and temporally?
- Will social acceptance of the biodiversity objectives and management actions change with time?
- What are the relative risks, costs and benefits of the proposed action to human wellbeing?
- What other critical social-ecological factors exist that may influence the adaptation pathway?

Figure 21: Intact littoral vegetation helps to protect coasts from erosion. Casuarina on beach, North Queensland (credit: CSIRO science image, EM0484).

Box 2: An illustrated example of how projections of spatial environmental change might be used to help identify priority areas for different types of adaptation management.

Ecological modelling, such as that described in Section 2.2, could potentially play a role in identifying parts of the State where most environmental benefit is expected to result from implementation of different types of adaptation management. To illustrate this potential, two new 'adaptation indices' were developed and trialled as part of the current study. These indices were derived from the GDM-based analyses described in Section 2.2, and further detail on their derivation and interpretation is provided in Ferrier et al. (2012). The first index aims to assess the potential benefit of adaptation management actions restoring cleared or degraded native habitat in local landscapes; for example, activities enhancing the extent, condition and local (short-distance) connectivity of native vegetation (see Figure 22 for an example of this first index). The second index aims to assess the potential benefit of adaptation management actions aimed at enhancing, or assisting, long-distance migration / colonisation; for example, actions such as establishment of large-scale (long-distance) habitat corridors, or assisted colonisation (translocation) (see Figure 23 for an example of this second index). These examples are included here merely to illustrate potential for the future development and application of ecological modelling to help identify priority areas for further integrated assessment (i.e., including social and economic criteria) and potential adaptation management. Rigorous implementation of this approach was beyond the scope of the current study.



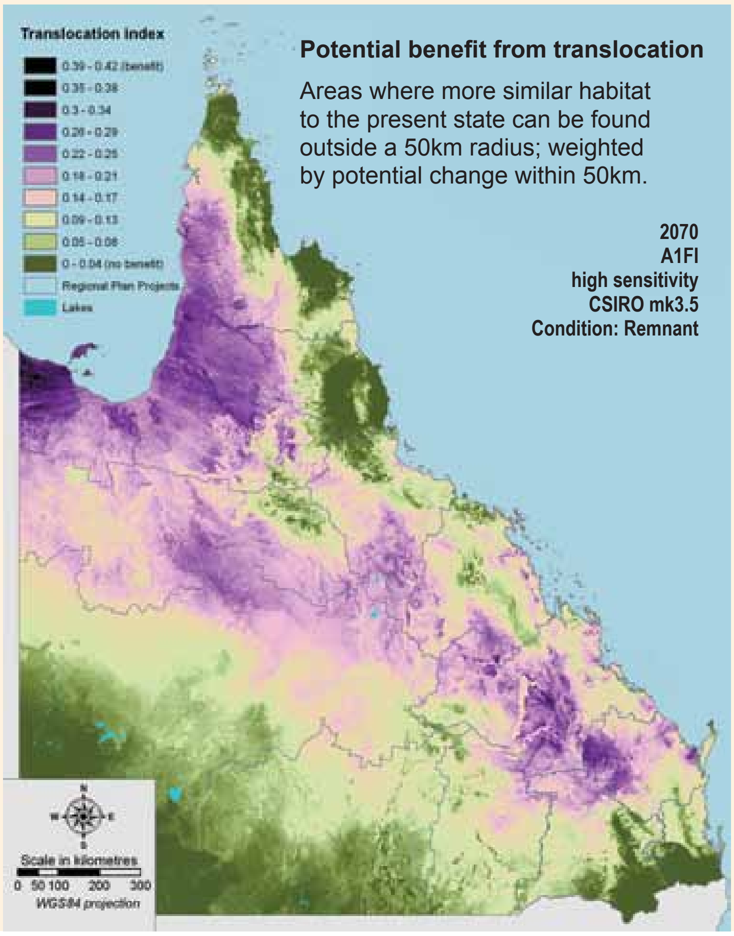


Figure 22: Index of potential benefit of adaptation management actions restoring cleared or degraded native habitat in local landscapes for the 2070 A1B scenario; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). This index has been derived using only those grid-cells with uncleared (extant) native vegetation (remnant regional ecosystems, version 6.0). This is a trial approach to identifying areas of remnant native vegetation that are likely to benefit most from restoration of cleared land in the surrounding landscape (50km radius). These areas are depicted in orange and red on the map, with cleared land shown in grey. See Ferrier et al. (2012) for details on the derivation of this index. Note: This map is based only on projected changes in environmental conditions; realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation, &etc.).

Figure 23: Index of potential benefit of adaptation management actions enhancing, or assisting, long-distance migration / colonisation for the A1FI 2070 scenario; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). This index has been derived using only those grid-cells with uncleared (extant) native vegetation (remnant regional ecosystems, version 6.0). This is a trial approach to identifying areas likely to benefit from actions such as enhancement of broad-scaled (long-distance) habitat connectivity, or assisted colonisation. See Ferrier et al. (2012) for details on the derivation of this index. Green areas are those which are likely to benefit least from such actions, while pink areas are those likely to benefit most. Note: This map is based only on projected changes in environmental conditions; realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation, &etc.).

5.3 A set of themes for developing adaptation pathways

5.3.1 Introduction and purpose

In this section we describe a series of adaptation options, which are organised into themes defining adaptation actions. These themes address key issues emerging from an analysis of climate change impacts on Queensland's terrestrial, aquatic and marine ecosystems (see Dunlop et al. 2011 for details). The aim is to effectively reduce biodiversity loss under climate change with adaptive management actions.

To further develop these adaptation pathways, Queensland Government agencies can use their regional ecological and management knowledge, within the context of their existing biodiversity management programs. At implementation scales, local governments and regional Natural Resource Management groups are likely to be critical to the design and delivery of effective climate adaptation policy because of their ability to tailor projects to local conditions and social contexts, thereby harnessing the intrinsic motivation of farmers to contribute to biodiversity management on their properties (Greiner & Gregg 2011).

5.3.2 Develop new biodiversity policy objectives

There is widespread recognition that current biodiversity policy objectives may not adequately accommodate the magnitude and nature of future ecological change (e.g., Dunlop & Brown 2008; Dunlop et al. 2011; Hagerman et al. 2010b; Steffen et al. 2009b). While these objectives can readily be summarized as 'managing change to minimise loss' or 'building resilience', there are significant challenges in revising policy objectives. In Table 4, we described a set of biodiversity outcomes that explicitly depart from a static perspective on biodiversity. Our aim was to accommodate the dynamic nature of species, ecosystems and landscapes under climate change. These 'dynamic' outcomes were presented to help progress research and debate into 'climate-ready' policy objectives (see Section 5.2.2). These objectives focused less on threatened species and more on maintaining ecosystem health and the evolutionary potential of the Australian biota (Prober & Dunlop 2011).

Any revision to the core objectives of biodiversity policy is likely to have implications for many management programs. For example, biodiversity investment depends critically on the 'objective function' (outcome) against which alternative investments are judged. Revision of policy objectives will alter the objective function of management. While current biodiversity objectives are likely to remain effective in the near future, ecosystem management decisions typically have long lifetimes. Decisions made on the basis of current 'static' objectives may be less effective as biodiversity responds to climate change through this century. Therefore, developing new biodiversity objectives could be judged as a policy development activity. The draft Queensland Biodiversity Strategy (DERM 2010a) has begun this process.

As well as ecological issues, there are significant social and institutional dimensions to any reassessment of objectives. Revised or new objectives potentially affect many stakeholders and the process of building consensus around new objectives may take a decade or more. Hence, there is some urgency to start considering future policy objectives by promoting debate among stakeholders (Dunlop et al. 2011; Hagerman et al. 2010a; Steffen et al. 2009a).

Key steps in revising biodiversity policy objectives to address climate change include:

1. assessing the impact of climate change on the desired outcomes of existing investment programs using a broad range of climate and ecological change scenarios;
2. assessing the impact of climate change on other biodiversity outcomes (e.g., ecosystem services) that might be valued by society but not explicitly identified in existing programs;
3. scoping which ecological outcomes might be feasible for different regions and settings in Queensland, such as by using scenario analyses to define how the benefits and costs may be distributed in future – socially, spatially and temporally;
4. undertaking widespread stakeholder consultation on how stakeholders value biodiversity and their motivations for retaining or enhancing biodiversity;
5. understanding which sectors of society have a sense of responsibility for preventing biodiversity losses (see Section 5.3.5);
6. assessing the feasibility of developing 'climate-ready' biodiversity policy objectives, management outcomes and investment programs (Section 5.2.2); and, finally,
7. developing new policy tools, biodiversity measures, conservation targets, and monitoring and evaluation programs to support implementation.

It is likely that such 'climate-ready' biodiversity objectives, policies and management actions will only be implementable under very different institutional and organisational arrangements.

5.3.3 Recognise and value biodiversity 'adaptation services'

In the context of a changing climate, where the timing, magnitude, and distribution of impacts are uncertain, the importance of biodiversity will become critical. This is because biodiversity provides the building blocks that underpin the composition, function, and structure of ecosystems, and their services. The services provided by biodiversity are currently under-valued. Biodiversity will become increasingly important under climate change, especially if technological solutions cannot keep pace with a >2°C warmer world (see Section 4.3).

Adaptation services are a subset of ecosystem services. They represent those services that have allowed successful adaptation to environmental change, where climate change is only one type of change (Williams et al. 2012). This new concept of 'adaptation services' expands the concept of 'ecosystem-based adaptation' that is increasingly referred to in the climate adaptation literature (The World Bank 2010).

Providing adaptation services will cost because protecting, restoring and managing biodiversity is expensive. Benefits are often delayed and uncertain. Supporting adaptation services means:

1. Providing public support, research and development, and communication and monitoring.
2. Making the goals and objectives of biodiversity management policies sensitive to climate change.
3. Introducing regulations that promote cost-effective interactions between private and public markets, and the implementation of cooperative activities that contribute to the preservation, management, restoration, and enhancement of biodiversity and ecosystem services.
4. Providing risk-based approaches to designing adaptation pathways.

5.3.4 Accommodate the likelihood of high levels of future loss

Because the future changes in Queensland's ecosystems are likely to be substantial and rapid, losses of biodiversity are currently impossible to estimate with any degree of accuracy. Without sustained reductions in global greenhouse gas emissions, there will continue to be significant extinctions of species (Leadley et al. 2010; Millennium Ecosystem Assessment 2005; sCBD 2010; Thomas et al. 2004). Historically, biodiversity policy and management aimed to prevent all forms of loss, but in reality investments have been towards the most-valued species or ecosystems. More recently, investment priorities have focussed on efficiency (e.g., Queensland's 'Back on Track' program[20]) by aiming to achieve the greatest reduction in risk per dollar. This means not investing in species that are highly threatened if they have little chance of recovery (so called 'conservation triage' – Bottrill et al. 2008; Hobbs & Kristjanson 2003).

However, little attention has been given to the strategic implications of massive extinctions. We are not predicting such losses but highlight the need for strategies that consider the possibility and identify response options. The Draft Queensland Biodiversity Strategy (DERM 2010a), for example, goes beyond considerations of threatened species and identifies common species that may need to be managed in the future also. However, the strategy also presents a vision for preserving all species: 'every species matters', 'no additional species being classified as threatened', 'net increase in the health of degraded ecosystems' (DERM 2010a).

Developing strategies to reduce the likelihood of substantial biodiversity loss in the face of climate change involves:

1. Accommodating loss by accepting that 'no loss' targets are infeasible and that minimising loss may require different types of biodiversity management such as social and institutional dimensions.
2. Mitigating emissions to reduce global climate change may be the most effective way of avoiding high biodiversity losses in Queensland.
3. Allocating greater resources to biodiversity management.
4. Adapting biodiversity managements to existing land management programs to improve effectiveness and efficiency.

Each of these actions can be incrementally and proactively improved as more information becomes available. Waiting until the consequences arising from delayed action have occurred will result in inefficiencies, perceived policy failure and biodiversity losses that could have been avoided.

Other critical issues to consider, but not included here, are actions that deal with the rate and on-going nature of climate and ecosystem change, including institutional arrangements and the adaptive capacity of natural resource managers (to be consistent with new policy objectives, Section 5.3.2). Some of these issues are outlined in the next section where they relate to mainstreaming of climate adaptation across natural resource institutions and sectors.

[20] Back on track species prioritization framework, http://www.derm.qld.gov.au/wildlife-ecosystems/wildlife/back_on_track_species_prioritisation_framework/index.html

5.3.5 Mainstreaming: whose role and responsibility is it to adapt

As biodiversity management agencies around Australia undertake the process of responding to the future impacts of climate change, a number of questions arise, such as how should adaptation be addressed and who is responsible? Four factors are relevant to this question.

- First, responding to climate change is likely to affect many biodiversity policies and existing management programs.
- Second, much of the innovation, skills, knowledge and resources to develop adaptation responses lay within the community of people currently managing biodiversity.
- Third, almost all management actions undertaken to address climate change will either build on or intersect with existing management programs.
- Fourth, to be effective, and to be adopted, adaptation strategies should compliment local institutional and ecological contexts (Howden et al. 2007; Prober & Dunlop 2011).

Together, these four factors point to an imperative to 'mainstream' climate adaptation into the core business of existing ecosystem management policies, plans and programs. Mainstreaming does, however, need facilitating. It is unreasonable to expect existing agencies to readily absorb the massive task of minimising losses in the face of much greater climate change pressures (Boer 2010). The experience of agencies around Australia and globally indicates that responding to climate change is not easy – it is a 'journey' to increase our understanding of climate change (e.g., Lemieux et al. 2011).

Successful mainstreaming climate adaptation will depend on building awareness of the implications of climate change for different biodiversity values. This awareness will be shared within and between agencies, and between the public and private sectors. Three key steps that could be implemented incrementally include:

1. Building awareness of how climate change will affect biodiversity and what needs to be done about it.
2. Reassessing the objectives of biodiversity management by considering the full spectrum of ecological responses to climate change.
3. Assessing which adaptation strategies will be most effective to manage biodiversity under climate change.

It is also important to acknowledge that in many cases current institutional structures may not be the most effective arrangement for climate adaptation if global warming exceeds 'safe' levels. Although we have emphasised the need to work within existing arrangements, to be effective over the long-term, adaptation may also require new institutional and organisational structures.

5.3.6 Reducing other pressures

Most reviews of adaptation options stress the importance of managing the all disturbance pressures that act on biodiversity, including climate change (Driscoll et al. 2011; Dunlop & Brown 2008; Steffen et al. 2009a). There are three significant reasons for this:

- First, in some situations the most feasible way to reduce the total pressure on biodiversity will be to mitigate some of the impacts of climate change by reducing other pressures.
- Second, in many situations the combined impact of climate change and other pressures will be more than the sum of the separate impacts.
- Third, because climate change affects sectors such as agriculture, forestry, fisheries, fire management, coastal development, flood risk, and urban horticulture, these impacts will also increased pressure on biodiversity.

Managing other pressures is a low risk ('no-regrets' or 'robust') strategy because it provides benefits to stakeholders in addition to those provided by biodiversity management climate change. Hence,

1. there is economic logic to increasing investing in reducing other pressures as an adaptation option.

To successfully manage climate change adaptation in other sectors, such as agriculture, forestry and fisheries, it may be necessary to -

2. strategically avoid biodiversity adaptation actions that threaten livelihoods.

There are low cost opportunities to improve biodiversity outcomes through adaptation in other sectors. For example, switching to biodiversity friendly land uses, such as carbon farming and water-harvesting, makes biodiversity offsets a key component of a licence to operate (e.g., see Bekessy et al. 2010). Thus,

3. managing adaptation in other sectors needs to be done proactively, before irreversible ecological impacts arise, and before opportunity costs become prohibitive.

Alien invasive species (weeds and pests) are a pervasive 'other pressure' responsible for losses in biodiversity (e.g., sCBD 2010). Climate change driven alterations to the abundance and distribution of species, and interactions between species poses a number of challenges for future management of invasive species. The distribution of some known problem species are likely to expand and it may be possible to anticipate some of these changes (e.g., Kriticos et al. 2003; Kriticos et al. 2005; Martin et al. 2010; Webber & Scott 2012). Substantial threats could also come from alien species that are not currently considered to be a potential problem (Webber & Scott 2012).

Climate change may reduce resistance to invasion in some ecosystems. For proactive biodiversity management to be effective -

4. monitoring the establishment of invasive species and rapid risk assessments are required.
5. Guidelines are also needed for dealing with conflicts that might arise from shifts in the distribution of native species that are beneficial for some species or ecosystem services but detrimental to others (Dunlop & Brown 2008; Minteer & Collins 2010).

5.3.7 Managing habitat

Managing, protecting, and rehabilitating habitat on public and private land and in marine environments is an important aspect of natural resource management. There has been significant discussion in the literature about how habitat management might need to be adapted in response to climate change (e.g., Dunlop & Brown 2008; Heller & Zavaleta 2009; Mawdsley et al. 2009). This has mostly focussed on habitat requirements to increase the survival of species in landscapes and seascapes. Much less attention has been given to managing habitat for resilient ecosystem or landscape outcomes. The core characteristics of managing habitat can be simplified to area, spatial arrangement (connectivity and isolation), and ecosystem health (condition). These characteristics intersect variously with species, ecosystem and landscape outcomes (Table 4).

A number of studies highlight the primary importance of maintaining or increasing the area and variety of habitat types (e.g., Dunlop & Brown 2008; Hagerman et al. 2010a; Heller & Zavaleta 2009; Hodgson et al. 2009; Lemieux & Scott 2011; Low 2011; Mackey et al. 2008; Mawdsley et al. 2009; Steffen et al. 2009a). The National Reserve System in Australia is based primarily on the representation of habitat types (NRMMC 2005). Recent analyses have demonstrated that while environments are likely to change significantly, obtaining 'representativeness' of environment types in the National Reserve System (NRS) is a robust strategy for adaptation under climate change (Dunlop et al. 2011; Ferrier et al. 2010). It has been acknowledged that some refinement of principles and practices are needed to achieve 'comprehensiveness' 'adequacy' and 'representativeness' (CAR) in the NRS (DERM 2010b; Dunlop & Brown 2008; National Reserve System Task Group 2009).

Additional factors for managing species persistence include connectivity (enabling species to disperse to new areas of suitable habitat), and the habitability or condition of habitat (ensuring species can establish, survive and reproduce). These factors are not independent because local connectivity and habitat condition also influence the 'effective area' of habitat available to species. Considerable monitoring at landscape scales will be required to determine how much habitat is adequate for the protection of species, and at what point investing in connectivity and condition becomes more important than protecting additional areas of habitat.

The high degree of novel and disappearing environments suggests that as climates continue to change, species are likely to be responding (some declining and others thriving) in environments that are very different to current environments. This highlights that the notion of species migrating to track the shifting of their preferred environmental conditions is too simplistic. Some species may have the greatest chance of persisting locally; whereas others will survive by dispersing along regional climatic gradients. For some species, translocation may be the only chance for their establishment in a suitable habitat but such actions may have unwanted outcomes (McLachlan et al. 2007; Ricciardi & Simberloff 2009; Thomas 2011; Webber & Scott 2012; Webber et al. 2011; Weeks et al. 2011). Ethical considerations, ecological research and modelling can usefully inform policy and actions related to facilitation of species movements (e.g., see Hagerman et al. 2010b; Hoffmann & Sgro 2011; Lawler 2009; McLachlan et al. 2007; Minteer & Collins 2010) (see also, Box 2).

Habitat restoration can provide new habitat for species, enhance connectivity, manage hydrology, and sequester carbon. There is increasing awareness of the need to consider future climate change in the choice of species for restoration. The emergence of 'carbon farming' and carbon markets (Commonwealth of Australia 2011; Garnaut 2011) has been identified as a potential driver of significant landscape change, including reducing emissions from late-season wildfires and sequestering carbon through tree planting (Wentworth Group 2009). Such programs, if carefully designed, could deliver both emission benefits and contribute to reducing the vulnerability of biodiversity to climate change (Bekessy et al. 2010; Bradstock & Williams 2009).

It is likely that as climate change continues, many species will persist longer in certain parts of the landscape—so called refugia. Examples of refugia include gorges, mountain tops, shallow aquifers, lakes and deep lagoons. Local-scale variations in geology, topography, soils, hydrology and habitat structure also provide some buffering from climate change (Ashcroft 2010; Keppel et al. 2012; Shoo et al. 2011). Areas with less human pressures and more intact habitat also provide refuges for the persistence of species (DERM 2010a). Consideration of managing connectivity appropriately to allow dispersal but protect such refugia will be important.

Managing habitat to support species persistence therefore includes:

1. Identifying and protecting refugia.
2. Identifying which new areas best complement existing reserves.
3. Enhancing habitat connectivity to allow species to disperse to new habitats.
4. Managing habitat condition to maximise the potential for species to survive.
5. Developing tools or principles to evaluate the risk of controversial biodiversity management programs such as triage and translocation.
6. Restoring biodiversity by techniques such as plantings to take advantage of short-term establishment opportunities (i.e., during La Nina events).
7. Determining which areas of the landscape are likely to require rehabilitation actions earlier than others.

5.3.8 Water availability

Freshwater ecosystems integrate and concentrate a number of ecological functions. The availability of freshwater in soil, aquifers, rivers and wetlands is a significant factor in the productivity of both terrestrial and aquatic ecosystems (Sections 3.2 and 0). Water availability also influences dispersal and establishment by invasive species (Lonsdale 1993; Low 2008). The amount of moisture in fuels also affects the rate of spread of fire (Bradstock 2010; Section 3.2; Williams et al. 2009). Terrestrial runoff from catchments to coasts also influences the productivity and resilience of marine ecosystems including mangrove, seagrass and coral communities. The flow of water through landscapes is expected to be a major driver of ecological change, and reductions will likely lead to loss of biodiversity and ecosystem services in many ecosystems.

Changes to patterns of rainfall and runoff (combined with increasing rates of evaporation) may continue to involve rainfall declines in some populated coastal regions and increases in northern and inland regions (CSIRO & BoM 2007a; CSIRO & BoM 2010). The intensity of these perturbations, combined with human resource use pressures, may lead to the collapse of aquatic and freshwater-dependent ecosystems that are already under stress (Section 3.3). Because of the impact of altered rainfall patterns on stream flow and environmental water availability, and associated extended droughts and occasional extreme flood events, a range of landscape management principles have been suggested (Boer 2010; Kroon et al. 2012; Pittock & Finlayson 2011). These include: maintaining natural variability of flows associated with seasonality, droughts and floods; maintaining recharge into and discharge from groundwater systems; protecting groundwater dependent ecosystems; reducing sediment and nutrient inputs to rivers and wetlands; managing vegetation to maintain surface flow interception; reducing flashiness of catchments; and reducing habitat modification in and adjacent to aquatic systems.

In many aquatic systems substantial changes are likely in the occurrence and abundance of species and the nature of the ecosystems (Section 3.3). It may therefore be necessary to revise management objectives to accommodate change, especially where listed species and ecological communities are affected (cf. Section 5.3.2). This may have implications for the implementation of state legislation or policy and for obligations under international agreements (e.g., signatories are expected to manage their Ramsar Convention sites to maintain their 'ecological character'[21]).

Four adaptation concerns are:

Protect existing environmental flows and landscape water availability by increasing the emphasis on providing urban, industrial, mining and agricultural water services from within existing water diversions and infrastructure. This would see water-use efficiency as the default water supply management option rather than increased diversions. Protection of environmental water could also include an emphasis on preventing groundwater and surface water pollution, and managing nutrient and sediment runoff from human activities. Protecting and restoring parts of the landscape that have more reliable water availability for terrestrial biodiversity is an important climate adaptation option (Kroon et al. 2012; Murphy et al. 2012). These areas include gullies, seeps and shallow groundwater reservoirs that act as temporary or permanent refuges for a wide range of biodiversity by providing reliable access to food and water resources, and so enable persistence as the climate changes (James et al. 1999; Ritchie & Bolitho 2008).

Protect coastal ecosystems at the interface between human activities and environmental pressures. These pressures include sea-level rise, development and climate change impacts in catchments, coastal development associated with population growth, and infrastructure developments related to adaptation in the coastal zone (Traill et al. 2011).

[21] "Ecological character is the combination of the ecosystem components, processes, benefits and services that characterise the wetland at a given point in time (Ramsar Convention 2005a, Resolution IX.1 Annex A). Changes to the ecological character of the wetland outside natural variations may signal that uses of the site or externally derived impacts on the site are unsustainable and may lead to the degradation of natural processes, and thus the ultimate breakdown of the ecological, biological and hydrological functioning of the wetland (Ramsar Convention 1996, Resolution VI.1)." (DEWHA 2008a).

Approaches are needed to protect coastal ecosystems by minimising peak flows and nutrient loads during storm events; by reducing other human impacts on coastal ecosystems; by providing adequate space for future landward movement of coastal ecosystems; and by increasing the use of ecosystems as 'green infrastructure' to protect land and infrastructure from flooding and sea-level rise.

Protecting free flowing rivers because they are not affected by infrastructure, and important habitats for aquatic biodiversity. They are also likely to be much more resilient to the impacts of climate change than modified systems. They also provide refuges for biodiversity in surrounding catchments.

Restore and protect riparian zones because they mediating flows and provide carbon and nutrient inputs to aquatic systems (Lovett & Price 2006; Pusey & Arthington 2003). They also provide habitat and biological productivity and resources for terrestrial species especially during drought (e.g., Mac Nally et al. 2009). Under climate change intact riparian ecosystems have the potential to help buffer the impacts of reduced flows and increasing temperatures, provide refuge for terrestrial species, and provide habitat connectivity across landscapes and regions.

Some issues to consider when managing water availability:

1. Greater certainty and resolution in regional climate models will help clarify the timing, magnitude and directionality of change in rainfall patterns, seasonally, annually and decadally, because rainfall effectiveness affects freshwater storages in ecosystems, groundwater and surface reservoirs.
2. The role of freshwater systems as refuges for biodiversity under climate change.
3. Freshwater resources may become highly contested under climate change, and require greater mediation of decisions affecting the security for both human and environmental supplies.
4. The coastal zone and catchments of free flowing rivers require integrated management to protect aquatic, riparian and littoral ecosystems, to enhance their capacity for carbon storage in landscapes, to build catchment-scale networks of habitat connectivity, and to secure scarce water resources.

5.4 Ecological (and economic) modelling of adaptation scenarios

Ecological (and economic) modelling can assist with targeting adaptation actions by testing adaptation pathways. Ferrier et al. (2012) for example, includes a bioregional analysis of the potential adaptation options shown in Figure 22 and Figure 23. Applied to Queensland environments, these experimental indices aim to provide an indication of the potential value that could be derived through further refinement and application of this general approach. For example, it would appear that the Mitchell Grass Downs and the Gulf Plains represent 'hotspots' of initial concern and opportunities for positive action. In contrast, places that may be prospects for the retention or persistence of regional biodiversity through autonomous adaptation are the New England Tablelands and the adjacent Nandewar bioregions.

We envisage spatial biodiversity forecasts being used as information (social and economic) to support the development of regional and state-wide biodiversity conservation plans. These plans are best integrated with other land use plans (Ferrier & Wintle 2009).

A framework would also assist in the process of identifying key species of interest for adaptation planning under climate change. In addition to vulnerable and iconic species, which may be of interest for translocation, other species may be important as ecosystem 'transformers' or engineers. These species are selected to provide architecture for new habitats (e.g., trees, shrubs, corals). They also contribute to ecological functions (e.g., cycling of energy and nutrients, balancing trophic structures, contributing missing pollinators). This framework may also include the in situ management of native species, such as macadamia, which are critical to industry adaptation under climate change.

5.5 Conclusions

The four parts of the adaptation framework outlined in Section 5.2 and described in more detail by Dunlop et al. (2011) is designed to encourage solution seeking in a more integrated way by allowing the reader to examine linkages across scales and issues simultaneously. The priority analysis described in Section 5.2.6 (see Table 10), which forms part of this framework, has been developed as a draft for refinement and implementation through Queensland government programs.

From this, it becomes possible to outline a series of adaption pathways that address a broad set of adaption themes. Within each pathway, there are actions that can be implemented rapidly, and others that can be undertaken later as more information becomes available. However, there are significant ecological knowledge gaps and social questions that need to be addressed as part of the the process of adaptation. These are outlined in Section 6.1.

New housing developments in north Queensland coastal plains. Careful planning of future land-use and landscape management options is important for: maintaining productivity; improving water quality; sustaining healthy ecosystems and communities; and protecting the reef (credit: CSIRO Sustainable Ecosystems, 2007).

6. Concluding findings

There is little doubt that observed and projected climate and ecological changes warrant urgent revision of existing policies and approaches for managing ecosystems, biodiversity and natural resources. Questions and ambiguities remain, however, regarding which policy changes are needed; which management options are appropriate; how these should be designed; what data, information and knowledge are necessary and sufficient; and when these changes ought to be completed and actions implemented.

These issues were identified and discussed in the 'adaptation principles' (presented in Section 5.1) that describe the problems and challenges faced by natural resource managers in Queensland. Key 'adaptation themes' for Queensland were proposed in Section 5.3 to highlight the areas (themes) where proactive policies would likely facilitate adaptation management and where efforts might best be focused.

Finally, barriers to effective adaptation, in the form of critical gaps in data, information, knowledge and capacity were identified and discussed (below in Section 6.1). These were categorised according to the key outcomes to be achieved in order to realise the shift in paradigm for biodiversity policy and management to be effective.

Queensland has already made substantial progress in managing the pressures of development on biodiversity and natural resources and in developing adaptation strategies and initiatives that begin to address the known adverse effects of climate change. Future adaptation actions will be more productive if supported by critical monitoring and evaluation within an active adaptive management framework.

6.1 Information and knowledge gaps

There are many uncertainties about how species and ecosystems will respond to uncertain climate change and other pressures in the future. Given these uncertainties, the range of research and management topics required for increasing human and natural capacity to respond successfully to climate change has been documented for Australia following consultation (e.g., Hilbert et al. 2007; Hughes et al. 2010) and in scientific reviews (e.g., Cobon et al. 2009; Morton et al. 2009). In the adaptation themes described in Section 5.3 we emphasised the need for robust and no-regret policies and management strategies. These have inherent low risk and enable planning and implementation of climate change adaptation strategies to start without the need to wait for new information (Dessai et al. 2008; Wilby & Dessai 2010). However, there are various gaps in information, knowledge and understanding which potentially affect the design and implementation of adaptation actions.

These knowledge gaps relate to questions of how climate will change and impact on ecological processes, how species and ecosystems will respond to change, the varied way in which biodiversity is valued by society, and the extent to which human responses will be effective in managing and adapting to this change. Some answers to these questions could be provided by one-off research programs that collate and analyse existing information over a relatively short time frame (~2 years). In addition, concerted efforts to reconstruct and integrate extant and historical information, complemented by new data collected by ecological observation and experimentation, would also be beneficial for adaptation planning. Such comprehensive research would require more time (10-15 years) but result in a better understanding of ecosystem process and function, as well as of human capacity to manipulate responses through management. Ongoing monitoring and research can improve the quality of information used to periodically adjust management guidelines if these guidelines are sufficiently flexible and have response timeframes commensurate with the processes being managed.

Below we discuss a range of knowledge gaps and explain how they may affect ecosystem management decisions.

6.1.1 Policy objectives

Revising biodiversity policy objectives to better accommodate the possible impacts of climate change, and the uncertainty of these impacts, can be informed by an understanding of:

- how species, habitats, land-, river- and sea-scapes and ecosystem processes might change and what the implications of this will be for current policy objectives and for the variety of aspects of biodiversity that are valued by society (e.g., see Moss et al. 2010; Pereira et al. 2010);
- how an appreciation of expected biophysical and ecological changes might affect individual and community perceptions and preferences for different aspects of biodiversity and ecosystem services (e.g., see Stoeckl et al. 2011; Sutton & Tobin 2011); and
- social and political awareness of, and responses to, changes in biodiversity and ecosystem services and of the uncertainty and vulnerability of these to changing climates. This could be developed through narratives that describe socio-economic and ecological differences among sectors of society, the dimensions along which societies and economies evolve over time, and changing vulnerability patterns (as outlined by Hallegatte et al. 2011b).

6.1.2 Institutional factors

The way that responses to climate change are designed and implemented can be based on:

- Developing an understanding of how adaptation actions can be incorporated into existing government programs and private management strategies. This includes assessing the implications of revised objectives (as above), estimating the costs and benefits of adaptation options, assessing the distribution among different stakeholder groups of the costs and benefits of adaptation actions, and determining how responsibilities might be shared between the private and public sector.
- Identifying necessary adjustments to existing programs and when new incentives, policy tools and institutional arrangements may be needed to achieve future ecosystem objectives in the context of other socio-economic drivers of change.
- An understanding of how policies, strategies, trends, path-dependent developments and practices in other sectors of the economy (urban planning, mining, water and energy utilities, transport) are likely to affect biodiversity and ecosystem adaptation efforts. Demographic and cultural changes also need to be taken into account.
- The way policy designs can best accommodate uncertainties associated with impacts, responses of biodiversity and social acceptability.
- Which incentive-based mechanisms are likely to be cost effective and acceptable to business and society in achieving desired environmental outcomes, and in which circumstances might these apply? Examples of a range of mechanisms and processes for implementing adaptation options were outlined in Section 4.3.2.

Development of adaptation responses through agencies, the non-government sector and private land managers can be facilitated by:

- Having a better understanding of the range of ecological changes that might occur and the implications of these changes for management in different regions.
- Greater awareness of different options for achieving adaptation objectives and the opportunity to share experiences between managers in different agencies and regions.
- Formal and informal engagement through participation processes and by facilitating stakeholder interactions between national, state, regional and local government agencies in meeting the 'planning of adaptation process'. Early involvement makes for greater acceptance of the outcomes and, more importantly, greater uptake of the implementation of adaptive strategies and actions.

Design of strategies and prioritisation of biodiversity investment under climate change will be enabled by:

- an understanding of the relative benefits of directing management toward species, locations (habitats) or ecological processes; and
- the development of decision support tools and mechanisms that ensure allocation of effort is robust in the face of uncertainty regarding the magnitude and types of ecological change. For example, by ensuring that effort is not automatically directed to the most vulnerable values.

6.1.3 Managing habitat for species

Habitat is managed through a range of natural resource and conservation programs including terrestrial and marine protected areas, formal incentive programs and resource access and use rights. The strategy of targeting a variety of habitat or environment types is robust under climate change; however, it can be complemented by other strategies which require:

- an understanding of the relative importance of biodiversity persistence compared to regional shifts in species distributions (e.g., see Sommer et al. 2010). This includes knowledge that accounts for the range of likely mechanisms of biological response (e.g., resistance, resilience, acclimatisation, genetic adaptation, local movement); and
- an understanding of how the principle of reducing threats enables species persistence through mechanisms such as habitat suitability or condition, refuges, and connectivity. Current ecological knowledge and theory provides some insights about the mechanisms of biodiversity persistence (e.g., see Dawson et al. 2011); but
- additional empirical information about how species actually respond (e.g., physiological, demographic, developmental, genetic) in different situations is needed, along with historic data analysis, new observation and experimentation (e.g., see Lavergne et al. 2010).

The movement of genes and individuals is an important ecological process that is likely to be a significant part of population-level ecological responses to climate change (Hoffmann & Sgro 2011). However, this process operates at many scales and there are significant gaps in the information required to design and implement programs to enable species movements and their independent adaptation. Ways to improve this situation including gaining:

- an understanding of the genetic basis of mechanisms allowing species to adapt locally to rapid climate change, and investigation of how evolutionary genetic considerations and goals could help shape particular management actions and guide adaptation strategies (e.g., translocation – Weeks et al. 2011);

- an understanding of the relative importance of access to suitable habitat locally, suitable habitat in different regions, habitat for temporary refuge from disturbances, or to areas providing resources such as food, water, shelter and breeding habitat;
- an understanding of the process of dispersal and the ecological requirement of different functional groups of species in terrestrial, aquatic and marine ecosystems;
- assessment of the relative importance of destination habitats and connectivity through contiguous habitat, the role of stepping stones or hospitable matrix in enabling rapid long-distance dispersal, and the relative importance of range-shifting populations and the dispersal of genes between populations and related species (that may give rise to hybrids better adapted to changing environmental conditions); and
- assessment of the physiological and ecological adaptive capacity of species and taxa to respond successfully through phenotypic plasticity to novel environments and habitats, as well as the nature of potential novel communities and biological assemblages.

Persistence in specific types of habitat, or refuges, is likely to be a key ecological response to climate change. But as for connectivity, this is a process that occurs at many spatial and temporal scales, and there are gaps in the information base for informing local implementation of adaptation actions. These include an understanding of:

- the scale and type of refuge and the nature of local buffering that might enable species to persist and the relative importance and duration of such refuges (e.g., see Dobrowski 2011). This applies particularly to locations that are 'islands' of cooler habitat (e.g., mountain tops and gullies, riparian and coastal ecosystems, wetland and groundwater-dependent ecosystems) (e.g., see Shoo et al. 2010). Species may persist in such refuges as the climate continues to change and aridity increases (e.g., see Graham et al. 2010);
- the role of refuges and environmental heterogeneity in the presence of climatic variability and extremes (fires, storms, droughts, floods) that may generate widespread and severe disturbances; or indeed refuges from human impacts (habitat fragmentation, degradation and isolation, presence of invasive alien species) that might otherwise decrease natural adaptive capacity (e.g., see Ashcroft 2010);
- how refuges are accessed and used, including how connected they need to be to a species' usual habitat, and how they are distributed across the landscape (e.g., see Sheldon et al. 2010);
- the type and nature of species that currently occupy a particular class of refuge (e.g., see Bell et al. 2010) and whether increasing connectivity or using these places as destinations for translocation or management action may do more harm than good (e.g., see McIntyre 2011; Minteer & Collins 2010; Pusey et al. 2006; Thomas 2011; Webber et al. 2011);
- the role of expected impacts on habitat-forming species such as corals, sea grass, mangroves, salt marsh grasses and oysters. Planktonic life stages of many resident and endemic species have absolute requirements for these habitats, so altering the structure or function of particular surfaces will reduce the capacity for them to settle and establish (e.g., see Cheung et al. 2009; Wernberg et al. 2011). Coral bleaching and subsequent mortality, as a result of rising water temperatures and ocean acidification, is already reducing the richness and density of coral reef fishes and other coral-dependent organisms (see Section 3.4.3) (and see Pandolfi et al. 2011; Wild et al. 2011).Spatial environmental heterogeneity often generates habitat diversity which is an important factor in enabling a variety of biodiversity and ecological responses to climate change. Environmental heterogeneity through its correlation with biodiversity patterns also underpins conservation theory and practice. There are gaps in our understanding of how to most effectively use habitat diversity in supporting the persistence of species under climate change; including:
- the importance of environmental heterogeneity (locally and regionally) in providing buffering from the full range of climate variability and change;
- the role of environmental heterogeneity at local, regional and larger scales in providing habitat somewhere for a wide range of species;
- how the patchiness of suitable habitats may change under different climatic regimes modified by environmental heterogeneity (e.g., in rugged terrain) and isolate populations; and
- the role of fire as a key deriver of environmental heterogeneity and determinant of some landscape refugia, and how fire might be managed differently under climate change and in different biogeographical contexts (e.g. see Section 3.2).

There are key gaps in knowledge about the ecological effectiveness of each of these dimensions of habitat as the climate continues to change. However, using current knowledge and new information (as it becomes available), spatial environmental and ecological modelling can assist the identification of areas where habitat protection and restoration may be more effective.

6.1.4 Ecosystems

Policymakers and managers will be faced with new challenges as a result of changes in the composition, structure and function of ecosystems change in response to climate change. However, there are key gaps in the knowledge required to make significant decisions about managing ecosystems. A greater depth of understanding is needed on how to:

- manage ecosystems transforming from one type to another (including novel ecosystems);
- characterise and manage ecosystem health as ecosystem type changes (including managing the risk of rapid degradation or collapse);
- use ecosystem changes, resulting from climate change, to improve the health of terrestrial, aquatic and coastal ecosystems that have been affected by human impacts.
- increase understanding of the way in which environmental variation, due to climate and ocean change, impacts on the productivity of entire ecosystems. (For example, the distribution, abundance, phenology and productivity of phytoplankton communities are changing in response to warming, acidifying, and stratifying oceans. Primary production has decreased by 6% worldwide since the 1980s. This continuing trend could cascade through marine trophic levels) (e.g., see Hoegh-Guldberg & Bruno 2010); and
- understand the potential for development of large-scale synergisms (or antagonisms) that affect key ecosystem functions. (For example, increased mass coral bleaching plus reduced calcification (as a result of acidification) are combining with the increased sediments, nutrients and pollution inputs from disturbed coastlines, to reduce the ability of these ecosystems to recover from natural and anthropogenic disturbances. One of these anthropogenic disturbances is overfishing that, by itself, can dramatically alter food web dynamics (e.g., see Halpern et al. 2008; Hoegh-Guldberg & Bruno 2010).

Long-term ecological monitoring networks can help promote a 'bottom-up' understanding of ecosystem processes. A network of monitoring sites has been established throughout Australia, which builds on the past efforts of individuals and institutions. The National Collaborative Research Infrastructure Strategy[22] provides for the maintenance and expansion of monitoring sites in Australia; part of a global network of research sites and satellite observatories.

6.1.5 Threats

Queensland ecosystems are currently affected by a range of threats. Under climate change many species and ecosystems will become more sensitive to these threats and many threats are likely to change. Knowledge needed to make decisions about managing these processes include an understanding of:

- how threats interact with climate change to affect species and ecosystems in different regions;
- how to assess the desirability of colonisation of new native and alien species. This includes assessing the risks from natural dispersal and colonisation, accidental dispersal, and dispersal enabled by managing connectivity or translocation; assessing the relative risk of spread from known potentially undesirable species, species thought to be benign or unknown species; and assessing the likely utility of attempting to predict the effects of responding to invasion risk with proactive intervention, early warning and rapid response, or general resilience-building; and
- how key threats may change, especially including those from adaptation in cropping, grazing, forestry, fishery, water resources and other sectors. This includes assessing when, and how, it might be most effective and efficient to manage change in these sectors.

6.1.6 Restoration and conservation

Ecosystem restoration may enhance species and ecosystem adaptation to climate change in many landscapes affected by human activities. Significant ecosystem restoration could be enabled by the emerging carbon economy or by other specifically restoration-focused incentive programs (e.g., environmental stewardships). However, there are significant uncertainties regarding how and where this might be done for greatest adaptation benefit. Key information required relates to:

- how carbon-sequestration, and other incentive-based projects, can be managed to effectively and efficiently ensure that they also provide future habitat for biodiversity;
- an understanding of the potential for native ecosystems in the marine, aquatic and terrestrial realms to be managed to sequester and store carbon;
- how to guide and prioritize climate adaptation investment to conserve biodiversity within realistic economic and social constraints. This includes studies that combine ecological predictions with economic considerations in a decision framework that would support complex choices about different adaptation options and pathways toward incremental or transformative change under severe uncertainty (whole of system analysis); and

[22] http://ncris.innovation.gov.au/pages/default.aspx

- novel ways to promote restoration (in addition to the carbon market) such as payment for ecosystem services and restoration that leads to increased water provisioning; the granting of biodiversity offsets (Alongi 2011; Wertz-Kanounnikoff et al. 2011); or 'restoration as a license to do business'.

Flexible, alternative mechanisms for financing ecosystem restoration and management need to be considered because of predicted tradeoffs between carbon and food, carbon and water, and carbon and biodiversity.

A final a key issue is:

- which criteria will be used to evaluate restoration options? Will the choice be based purely on cost-effectiveness? If so, what outcome measure do we use to compare the cost per unit outcomes of different restoration options?

6.1.7 Understanding

Policy development and ecosystem management are underpinned by scientific understanding of how species and ecosystems will respond to climate change. Key actions to improve that understanding include:

- determining how projections of spatial environmental change (niche modelling, macro-ecological modelling, modelling of environmental disturbance regimes) might translate into robust predictions about ecological change; and what reliable implications for policy and management can be drawn from these spatial predictions about environmental change (for example see Box 2);
- extending ecological modelling of environmental change to aquatic and marine ecosystems;
- assessing how human disturbance, species interaction and climatic variability interact with projected environmental change to affect ecological outcomes; in particular this can help to focus management directly at other pressures (including adaptation in other sectors) as well as to the direct impacts of climate change;
- assessing possible transition pathways and characterising ecosystems as they transform (e.g., like the model of wetland transitions under see level rise by Traill et al. 2011); this applies particularly to monitoring and evaluating ecosystem function and condition (health); and
- identifying individual and community preferences and values for different aspects of biodiversity and ecosystems; particularly under expectations of substantial climate change.

Ecological modelling using existing data and understanding is a useful tool for exploring future environmental and ecological change and the implication of management responses. For example, in Box 1, we provided a narrative to show how specific ecosystem scenarios could help managers identify where they may expect pressures from future invasive species to come from, and where they might expect some of the species under their management may need to move to in future. However, new empirical information is also required across a wide variety of terrestrial, aquatic and marine ecosystems, including information about:

- the sensitivity of ecosystems to change (including changes in hydrology and stream flow) species interactions, diseases and pathogens, population responses, fire dynamics and ecological connectivity. Some of this knowledge can be obtained from analysis of historical and time series data or from future monitoring of ecological responses to climatic variability and to human impacts;
- how changes to ecosystems actually affect different ecosystem services; and
- 'thresholds of potential concern' and how these can be picked up early to enable timely proactive responses. This requires monitoring of certain key variables in systems to detect changes in patterns that give warning of impending thresholds.

6.1.8 Detection and Attribution

Much of Queensland's response to climate-induced ecosystem change rests on our ability to detect and to attribute current and predicted climate and ocean changes, and determine how they differ from anthropogenic impacts on ecological changes. Detection involves demonstrating that climate has changed in some defined statistical sense while attribution is the process of establishing the most likely causes for a detected change with some level of confidence.

As the climate continues to change observations of ecological change will increase. Such ecological changes may be direct or indirect consequences of the accompanying environmental change. Dedicated field and experimental studies are key elements to support detection and attribution of such ecological impacts and changes. These will also inform levels of uncertainty in projections of change and impact assessment. Of critical importance are 'one-stop-shop' information warehouses such as Queensland's *CoastInfo*[23], *The Long Paddock*[24], *WetlandInfo*[25] with links to information at the national level such *OzClim*[26], *climate change in Australia*[27] and *OzCoast*[28]. Processes that synthesise current knowledge like the *Marine Report Card* (Poloczanska et al. 2009) are also key elements for the detection and attribution of climate and ocean changes.

23 http://www.derm.qld.gov.au/coastinfo/index.html

24 http://www.longpaddock.qld.gov.au/

25 http://www.epa.qld.gov.au/wetlandinfo/site/index.html

26 http://www.csiro.au/ozclim/home.do

27 http://climatechangeinaustralia.com.au/

28 http://www.ozcoasts.gov.au/

Citizen science and community observer networks provided through *Birds Australia*[29], the *Atlas of Living Australia*[30] and *ClimateWatch*[31], for example, also have important roles to play in the detection and attribution of ecological change events. For example, *ClimateWatch* – Australia's national phenological network (Donnelly et al. 2010) records information about changes in the timing of seasonal onset of flowering or the arrival and departure of migratory species. Such community observer networks could provide information about change that would help resolve challenging management decisions, such as when to regard the appearance of a vagrant species as a natural consequence of climate change (for which establishment could be facilitated) or whether the species may be damaging (and establishment is best resisted).

While scientific monitoring and experimentation can provide the knowledge base for detecting climate change and attribute the cause of ecosystem change for specific cases, community and social networks have the capacity to rapidly gather information about a wider range of phenomena across more locations. Over time, the two sources of information (scientific- and community-based) could provide complementary evidence around which to plan adaptation actions. They could also provide an early warning system of impending 'thresholds of potential concern'. This knowledge can be accrued by:

- encouraging community networks to improve the robustness of observations and records by implementing data and information management structures and training programs; and
- promoting wide-spread sharing of scientific data, including recovery of historical research data from precarious storage in archives and their meta-analysis (note. the Terrestrial Ecology Research Network[32] is implementing plans and strategies toward achieving this latter objective).

6.2 Summary and conclusions

There is little doubt that observed and projected climate and ecological changes warrant urgent change to existing policies and approaches to managing ecosystems, biodiversity and ecosystem services. This is because the magnitude and rates of climate and ecological changes over diverse geographical areas and bioregions are already detectable and projected to be substantial in the future (Sections 2, 3 and 4) and because Queensland's economy, social wellbeing and cultural identity are all heavily dependent on its natural capital stocks and ecosystem services (Section 4.2).

Questions and ambiguities remain, however, on how to respond: what policy changes are needed; what management options are appropriate; how should these be designed; what data, information and knowledge are necessary and sufficient; and by when do these changes need to be completed and actions implemented? Confounding the search for, and agreement on, answers to these questions are the many uncertainties about how climate will change and impact on ecological processes, how species and ecosystems will respond to change, how climate change will interact with other drivers of change, how effective responses will be at managing and adapting to change, and the diverse preferences and values of individuals, communities and businesses for the different dimensions of biodiversity and ecosystem services (Sections 2, 3, 4 and 5.1 and 5.2.2). The complexities involved mean that certain aspects will remain unpredictable no matter how much information, data and knowledge are available (Sections 4 and 5.2.2).

These issues were identified and discussed in the 'adaptation principles' presented in Section 5.1. They encapsulate the problems and challenges faced by natural resource managers in Queensland. In light of these, the calls for a paradigm shift in biodiversity management were re-emphasised but it was recognised that little agreement exists in the scientific and policy communities on what this might entail. Does it merely involve an increase in investment (of all kinds) or are more fundamental changes needed? An adaptation framework was proposed in Section 5.2 to provide a systematic and structured way for policymakers, managers and scientists to identify, design and evaluate appropriate adaptation responses. Such responses need to account for the multiple dimensions of biodiversity value, the different types of ecological change, the potential for considerable loss of biodiversity, variable levels of uncertainty, and the combined effects of other pressures that constrain adaptive responses to climate change.

The 'adaptation framework' addresses two key issues that influence the effectiveness of climate adaptation responses. These issues involve the different aspects of biodiversity that are valued by society and the uncertainty associated with different types of ecological responses to climate change. The former is addressed by: a) defining three ways people relate to, experience and value nature—described as species, ecosystem and landscape dimensions of biodiversity; b) identifying the various attributes of each dimension under 'static' and 'dynamic' conditions (Section 5.2.2); and c) suggesting key management objectives that might usefully contribute to 'dynamic' biodiversity outcomes in response to climate change. The latter is addressed using 'ecological change scenarios' that are linked to a manageable set of biodiversity outcomes and management objectives for each dimension of biodiversity. The 'adaptation framework' then emphasises the importance of identifying and developing no-regret options and strategies that spread risks, are robust

29 http://www.birdsaustralia.com.au/

30 http://www.ala.org.au/

31 http://www.climatewatch.org.au/

32 Australia's Terrestrial Ecosystem Research Network, http://www.tern.org.au

to different possible futures, are sufficiently flexible to be changed if and when there is a need, and consider the potential for transformational change. The development of alternative 'adaptation pathways' has been suggested as an approach for decision making in such contexts (Stafford Smith et al. 2011). We identified a set of adaptation themes as a basis for developing adaptation pathways by ecosystem managers and policymakers in Queensland (Section 5.3). These pathways may be best informed and implemented within active adaptive management framework.

The identification, design and implementation of adaptation pathways and options can only be achieved if the necessary processes, governance arrangements, capacity and capabilities (including monitoring, collection and collation of data and information) are available. These are necessary in order to diagnose problems, quantify and manage risk, constrain the complexity of systems dynamics, contextualise uncertainty, elicit human preferences for biodiversity values that inform policy and management objectives, and make reliable projections of possible futures. Key 'adaptation themes' (Section 3) were proposed to highlight the areas (themes) where changes would be most beneficial and where efforts might best be focused.

Finally, barriers to effective adaptation, in the form of critical gaps in data, information, knowledge and capacity were identified and discussed (Section 6.1). These were categorised according to key outcomes to be achieved in order to realise a paradigm shift in biodiversity policy and management. A paradigm shift may be a prerequisite to ensuring biodiversity, ecosystems and ecosystem services have the resilience, adaptive capacity and opportunity to respond successfully to global environmental change.

In conclusion, future natural resource management can be guided by a set of adaption pathways that address important and urgent climate change adaption themes, developed by relevant Queensland Government agencies in the context of their existing programs. Within each of these pathways, actions that can be implemented in the short term need to be identified as well as others that can be undertaken when more information becomes available. Developing and implementing these pathways will involve filling a range of ecological information gaps. There are also a series of critical questions, related to how society values different aspects of biodiversity, which need to be addressed. These questions concern the magnitude of biodiversity and ecosystem loss that is acceptable and how much society is prepared to pay to reduce that loss.

In the short term, to facilitate adaptation planning, a framework would assist the identification and prioritisation of key species. These being species that are important to the maintenance of ecological process and ecosystem function under climate change, that have heritage values or that provide future industry with options. Ecological and economic modelling also have important roles to play in assisting the process of targeting adaptation actions, testing adaptation pathways and designing landscapes to maximise the co-benefits of carbon farming and other ecosystem service values.

Queensland has already made substantial progress in managing the pressures of development on biodiversity and natural resources and in developing adaptation strategies and initiatives that begin to address the known adverse effects of climate change (e.g., DERM 2010a; DERM 2010b; Queensland Government 2011b; QCCCE 2011; Queensland Government 2007b; Queensland Government 2008; Whitfield et al. 2010). Future adaptation actions will therefore be more productive if supported by critical monitoring and evaluation within an active adaptive management framework. Scenario analyses, together with ecological and economic modelling, can provide guidance about areas in which adaptation actions will be most cost-effective given the likely responses to, and timing of, climate change. These activities, combined with the practical knowledge and operational experience of natural resource managers, will facilitate the development, and iterative improvement, of flexible adaptation pathways that account for the critical aspects of risk and uncertainty involved in managing species and ecosystems under climate change.

A rainbow hangs on the mist at Wallaman Falls, west of Ingham in north-eastern Queensland. These spectacular waterfalls are the highest in Australia. Such places will continue to provide cooler buffered environments for the species they support (credit: Paul Peter, CSIRO Land and Water, science image BU6790).

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The Queensland Government commissioned this synthesis of climate change impacts and adaptation options for terrestrial, freshwater aquatic, coastal and marine biodiversity, its ecosystems and the services they provide. The information presented here represents a synthesis of the scientific evidence assembled in seven background reports.

Williams KJ, Crimp S (2012) 'Queensland's biodiversity under climate change: an overview of climate change in Queensland.' (CSIRO Climate Adaptation Flagship Working Paper No. 12A.)

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These reports can be downloaded from the CSIRO website:
www.csiro.au/resources/CAF-working-papers.html