Biological Diversity Advisory Committee

Climate Change & Invasive Species

A Review of Interactions

November 2006 Workshop Report




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Preamble

On 20 November 2006 the Biological Diversity Advisory Committee (BDAC), whose role it was to advise the then Australian Government Minister for the Environment and Heritage, held a one day workshop in Canberra on climate change and invasive species' impacts on biodiversity. Eight talks were given, followed by a session of free discussion. Most attendees were experts from government departments, universities, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and cooperative research centres (CRCs).

The various sections in this report are based upon topics discussed on the day, but they incorporate many additional findings drawn from recent research.

Two previous climate change workshops have been held by BDAC and reports produced (Howden et al. 2002; Hilbert et al. 2007). Tim Low was commissioned to produce this report.

Tm Low

Australian Institute of Marine Science

Michael Douglas

Issues of concern include fires fuelled by gamba grass (right), great skuas on Macquarie Island (top left) and white syndrome of coral (bottom left).

Summary

A major impact of climate change is likely to be a worsening of Australia's invasive species problems. Invasive pests, climate change and habitat loss are the three main threats to biodiversity in Australia (Australian Biosecurity Group 2005), and the role of invasive pests in the extinction of many species is well established (Low 1999, Johnson 2006).

When native species are killed or stressed by climate change they may often be replaced by invasive species (Dukes and Mooney 1999; Cox 2004; Zaveleta and Royval 2002). Native plants are especially susceptible to displacement by weeds, because the pool of weeds is very large (Groves et al. 2003), because many national parks are surrounded by weed-rich landscapes (Saunders et al. 1991), and because weeds often travel more effectively than native plants across the landscape (Sutherst et al. 2007).

The traits of species that make them invasive will often help them succeed under climate change (Sutherst et al. 2007). In Australia, as in Europe, new forest types may form that are largely composed of weeds and vigorous native species (Cox 2004; Walther 2000).

In cool marine benthic habitats, a similar shift to invasive species may occur. Some pathogens will benefit from higher temperatures that will also stress their hosts (Harvell et al. 2002).

Extreme events such as cyclones, floods, droughts and fires, predicted to occur more often or with greater severity (Intergovernmental Panel on Climate Change 2007b), will facilitate invasions by introduced species, as they have in the past (Trounce and Dellow 2007; Griffin et al. 1989). Many of Australia's worst weeds do well after floods, cyclones or fires, which create ideal conditions for their establishment.

Invasive species can exacerbate the impacts of climate change by harming biodiversity in advance of direct climatic impacts. For example, in central and South America, more than 70 frog species have been lost to a chytrid fungus (*Batrachochytrium dendrobatidis*), an invasive pathogen that causes epidemics during unusually warm years (La Marca et al. 2005; Pounds et al. 2006). White syndrome, a disease killing corals on the Great Barrier Reef, provides another example of organisms threatening biodiversity under climate change (Bruno et al. 2007; Hoff 2007). Pest problems that are seemingly worsened by climate change in Australia include fox predation on endangered mountain pygmy possums; rabbits, foxes and weeds invading the Australian Alps; rabbit damage on Macquarie Island; and weeds colonising Heard Island (Green and Pickering 2002; Scott and Bergstrom 2006; Shaw et al. 2005).

Of special concern are so called ‘transformer species’ that create positive feedback loops. Flammable pasture grasses have the potential to convert vast tracts of eucalypt woodland into treeless plains as they promote fire and in turn are promoted by fire (Bond and Midgley 1995; Brooks et al. 2004; Csurhes 2005; D'Antonio and Rossiter et al. 2003; Vitousek 1992). Vines that grow after cyclones also create a feedback loop. They retard regeneration, increasing the vulnerability of rainforests to future cyclone damage, the end result being more habitat for vines.

Some native species are expanding their geographic range under climate change, and some of these may become major threats. For example, in Tasmania a sea urchin (*Centrostephanus rodgersi*) from the mainland has eliminated vast kelp beds (Johnson et al. 2005). In the Australian Alps, colonising kookaburras threaten lizards, and wallabies reaching higher altitudes have the potential to eliminate herbfields. When native plants and animals migrate in response to climate change, the more successful colonisers may become invasive by suppressing other species.

Invasive species have received insufficient recognition in climate change discussions. Priorities for action include the removal of sleeper weeds and outlier weed populations, better management of flammable grasses, better preparation for extreme events such as cyclones, legislative control over weedy biofuel crops, and debate about conservation goals in a changing future.

Building ecosystem resilience should also be a priority. While it may be impossible to avert climate change or to eradicate invasive species, it may be possible to reduce other threats, such as pollution, salinity, livestock grazing, or over harvesting. Healthier ecosystems are usually more resistant to invasion.

Invasive Species

Invasive species are animals, plants, or other organisms that threaten biodiversity by behaving as predators, competitors, parasites or pathogens when they establish somewhere new. Foxes (*Vulpes vulpes*), starlings (*Sturnus vulgaris*) and prickly pear (*Opuntia stricta*) are well known examples in Australia. Many kinds of organism can become invasive when taken from one country or region to another. Australia has invasive fish, birds, snakes, spiders, centipedes, worms, sea squirts, starfish, molluscs, sponges, as well as fungi, bacteria, viruses, algae, mosses, ferns, and almost 3,000 invasive flowering plants (Low 1999).

Invasive species may come from any part of the world. Australia has earthworms from the Amazon, seaweeds from northern Asia, South African shrubs and lilies, and shellfish from New Zealand. Some species were introduced deliberately, such as sparrows, deer, and willows, and others have been accidental introductions, such as rats and some ants and snails.

Native species moved to a new area within Australia may also become invasive and damage local ecosystems. Examples of this phenomenon are koalas (*Phasolarctos cinereus*), which have been introduced to Kangaroo Island where they are defoliating trees and seriously damaging their own habitat, and Cootamundra wattle (*Acacia baileyana*) which has become a weed when grown outside of its natural range. As an added complexity, native species can become a problem within their usual range if they multiply in response to changes caused by people. In these situations natives within their usual range are sometimes termed invasive.

Invasive species can create serious problems, including damage to crops, harm to human health, and extinctions of wildlife. It is estimated that weeds cost Australia $4 billion each year (Sinden et al. 2004) and that red fire ants (*Solenopsis invicta*) could cost Australia $8.9 billion over the next 30 years if the $175 million effort to eradicate them is unsuccessful (Kompas and Che 2001).

Invasive species have caused more animal extinctions in Australia than any other factor (Australian Biosecurity Group 2005). Australia has lost 22 mammal species, and implicated in most of these extinctions are foxes, cats (*Felis catus*) and sometimes rabbits (*Oryctolagus cuniculus*) (Johnson 2006; Maxwell et al. 1996). Black rats (*Rattus rattus*) have eliminated five bird species on Lord Howe Island (Hutton 1990), and chytridiomycosis, a fungal disease, is held responsible for the extinction of seven frog species in recent decades (Laurence et al. 1996; McDonald et al. 2005).

Many more native species are currently are risk from invasive species. Rare marsupials, such as numbats (*Mymecobius fasciatus)* and bilbies (*Macrotis lagotis*), are threatened by foxes and cats; threatened plants are killed by the die back fungus, *Phytophthora cinnamomi*; and endemic red crabs (*Gecarcoidea natalis*) on Christmas Island have been eliminated in some areas by yellow crazy ants (*Anoplolepis gracilipes*).

Invasive species may also change ecosystem function and landscape structure. Some weeds may turn grasslands into shrublands, alter fire regimes, silt up streambeds, and change the shape of beach dunes (Low 1999). Water buffalo (*Bubalis bubalis*) turn freshwater lagoons into saline marshes (Skeat et al. 1996), camels (*Camelus dromedarius*) pollute waterholes, Asian mussels (*Musculista senhousia*) trap silt, and donkeys (*Equus asinus*) erode slopes (Low 1999).

The invasive species problem has increased, according to the Senate Report (2005), *Turning Back the Tide.* 'The rate of incursions has increased dramatically in more recent years,' it states, 'with the growth of international trade and travel leading to the importation of thousands of invasive weeds, pest animals and diseases.' Trade over the internet is contributing to the problem. The CSIRO estimates that Australia gains 20 new invasive species each year (Australian Biosecurity Group 2005). Very few of these will ever be eradicated (Low 1999).

Rowan Trebilco

Tim Low

Rabbits (Oryctolagus cuniculus) on Macquarie Island are benefiting from warmer temperatures, reduced impact of myxoma virus, and the removal of cats. Chicks of the light-mantled sooty albatross (Phoebetria palpebrata) (above) are not harmed directly by rabbits, but they are harmed indirectly if nest sites erode away. Erosion of overgrazed slopes (below) has become a major problem.

Climate Change

From 1910 to 2004, the average maximum temperature in Australia rose by 0.6ºC, and the average minimum temperature rose by 1.2ºC (Nicholls and Collins 2006b). Since 1979, all but four years have been warmer than average. Night time temperatures are increasing faster than daytime temperatures. The number of hot days has increased, and cold days and frosts have decreased (Nicholls and Collins 2006a). By the end of the century, global average air temperatures are expected to rise an additional 1.8°C – 4.0°C (Intergovernmental Panel on Climate Change 2007a).

In addition, in the colder regions of Australia snow cover, depth and duration has declined by 40 per cent since the 1960s (Osborne et al. 1998). Long term rainfall patterns are also changing. Since 1950 the north western two thirds of Australia have become wetter while southern and eastern areas have become drier (Smith 2004). These trends are predicted to continue, with central Northern Territory and northern New South Wales also becoming wetter (Suppiah et al. 2007).

The overall trends predict that Australia's weather will become more extreme, with an increasing incidence of intense rain, floods, tropical cyclones, storm surges, droughts and fires (Intergovernmental Panel on Climate Change 2007b). Droughts have already become hotter and more intense (Nicholls and Collins 2006a). While there is no clear trend towards more frequent tropical cyclones, there has been an increase in cyclones of high intensity (CSIRO 2007).

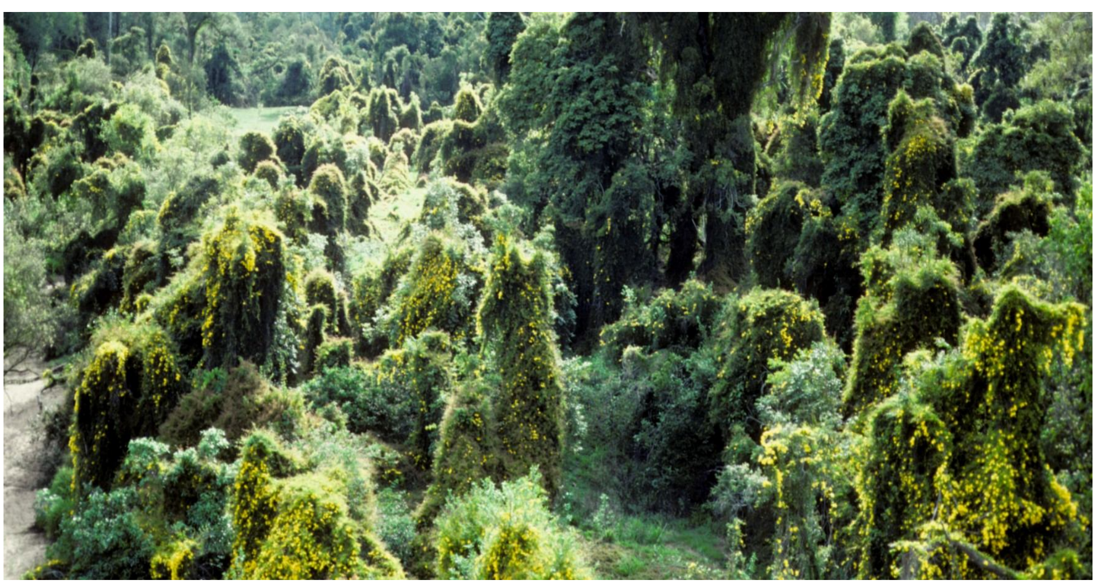
Most climatic changes have been driven by rising levels of greenhouse gases. Atmospheric carbon dioxide levels have increased from a pre-industrial value of about 280 parts per million (ppm) to 379 ppm in 2005 (Intergovernmental Panel on Climate Change 2007b), a level unprecedented in the past 420,000 years. Since 1750, carbon dioxide has risen by 35 per cent, methane by 151 per cent, nitrous oxide by 17 per cent, and tropospheric ozone by 36 per cent (ibid.).

Interactions

Climate change is expected to worsen the world's invasive species problems (Dukes and Mooney 1999), because ecosystems are more vulnerable to invasion when they are disturbed (Hobbs 1991; Hobbs and Huenneke 1992). Weeds and other pests often do better if there is disruption from fire, floods, logging, livestock grazing, or hydrological changes. As Mack et al. (2000) note, 'novel disturbances, or intensification of natural disturbances such as fire, have played a significant role in some of the largest biotic invasions'. Disturbance events create opportunities for invasive pests to take the place of natives. For example, droughts probably assisted rabbits to displace rufous hare wallabies (Lundie-Jenkins et al. 1993). Climate change has the potential to operate like a disturbance event by stressing populations (Sutherst et al.). As Zaveleta and Royval (2002) explain: 'climate change-associated diebacks of perennial vegetation communities – forests, woodlands, and shrublands – and accompanying disruption of faunal communities may provide new and widespread opportunities for disturbance-loving exotic species to colonize and spread'.

For many native species to survive in the future, they may have to relocate by spreading south, or perhaps into higher altitudes. But the speed at which species will be required to migrate could exceed those rates recorded in the past, when trees and other plants recolonised far northern latitudes after ice ages (Malcolm et al. 2002; Davis and Shaw 2001).

Tim Low



Weedy vines such as cat's claw creeper (Macfadyena unguis-cati) have very high growth rates, enabling them to recover faster than most native plants from disturbances such as floods

Mobile animals, notably birds, butterflies, dragonflies and marine species, are quickly relocating in response to recent climate change (Parmesan 2006; Hughes 2003; Chambers et al. 2005), but most native plants, and the less mobile animals, may be unable to migrate at the pace required by climatic changes. Many weeds and other pests can spread faster than native species because they are regularly transported by people (Sutherst et al. 2007; Lovejoy 2005a). Weeds often grow on roadsides where vehicles disperse them, leading Dukes and Mooney (1999) to conclude that 'roadside weeds should be some of the earliest species to shift their ranges as climates change'.

Tim Low

The Asian house gecko (Hemidactylus frenatus) is invading forests close to residential areas, where it may be displacing native geckoes. But in Australia as a whole introduced reptiles have only a limited capacity for invasion because the pool of species is very small.

A future scenario for the world's plant communities was presented by Cox (2004): 'because climatic zones are likely to shift faster than long-lived species can track through reproduction and dispersal, communities in disequilibrium may result, with conditions that indirectly favour weedy species, many of which are likely to be aliens.'

On the southern flanks of the Alps in northern Italy, climate change is favouring a shift from native deciduous trees to an evergreen forest made up of trees from other continents (including Australian wattles) (Walther 2000). 'This invasion has created a new forest type,' notes Cox (2004), 'which will provide a habitat for many exotic animals and microorganisms, and a new evolutionary stage for both native and exotic species.'

Replacement of natives by exotic plants is especially likely in Australia because many national parks and vegetation remnants are habitat islands surrounded by farmland in which introduced plants dominate. Weed spread from farmland into remnant vegetation is already a serious problem, exacerbated by nutrient inputs and fire events (Saunders et al, 1991). Australia has almost 3,000 weed species (Groves et al. 2003), representing all the functional types that constitute habitats (grasses and other ground covers, shrubs, vines, trees, aquatic plants). By contrast, introduced vertebrates such as frogs, reptiles and birds will not replace native species on a large scale because the pool of introduced species is very small. But large scale invasions by weeds can, on their own, profoundly alter ecosystems because nearly all animals on land ultimately depend on plants as primary producers.

In the marine environment, the waters of Tasmania and Victoria support a large and growing pool of invasive species (Hewitt et al. 2004; Edgar et al. 2005), and climate change here (plus sedimentation, nutrification and other impacts) may be facilitating the widespread replacement of natives by introduced species (Graham Edgar pers. comm.). Occhipinti-Ambrogi (2007) noted, in a global review, that '[a]nomalous temperature stress can cause mass mortalities in benthic organisms that result in empty niches for new colonisers'. Replacement of natives by invasive species will be one of the major impacts of climate change, but there will be others. These may include:

- changing relationships between predators, pathogens and prey (with either native or introduced species),
- changing fire regimes, and
- other climate harm to species already threatened by invasive species.

Climate change and invasive species have already combined to cause the first presumed climate change extinctions (Thomas et al. 2006). In Central and South America, a chytrid fungus is considered responsible for mass disappearances of harlequin frogs (*Atelopus* species) during unusually warm years (La Marca et al. 2005; Pounds et al. 2006) (see box). This serious example points to bioinvasion as one of the worst threats posed by climate change. Given that invasive species and climate change are considered two of the three main threats to biodiversity, the two operating together could be expected to produce extreme outcomes.

Despite this, assessments of climate change often fail to emphasise invasive species impacts. The Intergovernmental Panel on Climate Change report, *Climate Change and Biodiversity* (Gitay et al. 2002), runs to 77 pages, but invasive species rate only a few sentences, which fail to address most of the issues explored in this report. Note that not all pest impacts associated with climate change will be adverse – as explained in other sections, there will be some positive changes.

The following sections consider the impacts in more detail, focusing in turn on changing distributions and densities, rising carbon dioxide levels, extreme events, and fire. The final section looks at native invasive species.

FUNGUS & FROGS

Frogs are faring much worse from global changes than other vertebrates, with more than 400 species listed as 'critically endangered' by the Global Amphibian Assessment and many assumed to be extinct (Pounds et al. 2006). The disappearing species occur mainly in undisturbed forests where a pathogen is implicated.

Chytrid fungus (*Batrachochytrium dendrobatidis*) causes chytridiomycosis, a skin disease that under certain climatic conditions causes mass deaths. Listed by the Department of Environment and Water Resources as a key threatening process, it is considered responsible for the extinctions of seven rainforest frogs in Queensland (Laurence et al. 1996; McDonald et al. 2005) and more than 70 frogs in central and South America (Pounds et al. 2006). Mass die-offs have also occurred in North America and southern Europe.

Chytrid is very responsive to temperature, proving most active and harmful between 17 and 25ºC (Berger et al. 2004). It stops growing at 28 ºC and dies at 30 ºC. High summer temperatures may eliminate it from some areas. In Queensland and New South Wales, most chytrid infections and most frog deaths occur during winter (ibid; McDonald et al. 2005).

In the highlands of Central and South America, scores of harlequin frogs (*Atelopus* species), which are brightly coloured diurnal frogs, vanished in unusually warm years (La Marca et al. 2005; Pounds et al. 2006). At the altitudes where they vanished, climate change has increased evaporation and the air's capacity to hold water, leading to enhanced cloud cover. The cloud lowered daytime temperatures and raised night-time minima, creating an ideal climatic envelope for the disease (La Marca et al. 2005; Pounds et al. 2006).

The loss of more than 70 harlequin frog species represents the first mass extinction event attributed to climate change, although the proximal cause of death was an invasive organism. Climate Change is also implicated in recent chytrid epidemics among montane toads and salamanders in Peňelara National Park in Spain (Bosch et al. 2007) although no extinctions resulted.

Chytrid fungus should benefit from climate change in Tasmania, but not in Queensland, where temperatures in the mountains already fall within its optimal range. But if climate change produces long periods of cloudy weather, as occurred after cyclone Larry in 2006, the disease could benefit (Ross Alford pers. comm.)

The origin of chytrid fungus remains uncertain. A growing body of evidence implies that it is a pathogen that has spread recently around the world, possibly from Africa, but the failure to identify a source region for the fungus keeps open the possibility that it is a naturally widespread disease that has become more pathogenic under changed circumstances (Rachowicz et al. 2005).

In 2006 the Australian Government released a Threat Abatement Plan *(for infection of amphibians with chytrid fungus resulting in chytridiomycosis* (Department of Environment and Heritage 2006) to guide management of this disease.

Distributions & Densities

As our climate progressively changes, the ranges and population densities of many invasive species may also change. A two degree rise in temperatures might see cane toads (*Bufo marinus*) reaching southern New South Wales (Sutherst et al. 1995), and prickly acacia (*Acacia nilotica)*, one of our worst weeds, invading vast areas of inland Australia (Kriticos et al. 2003c). If higher temperatures encourage farmers to switch from sheep to cattle (Howden et al. 2004), prickly acacia will be favoured, as cattle are better dispersers of their seeds.

Tim Low

The cane toad (Chaunus [Bufo] marinus) is one example of a pest species with a northerly distribution that can be expected to spread southwards as temperatures rise.

Melting glaciers have come to symbolise climate change, and on Heard Island, Australia's southernmost outpost, they are heralding invasion as well. Winter grass, a weed from Europe, is advancing there on deglaciated sites at more than 100 metres a year (Scott and Bergstrom 2006; Scott and Kirkpatrick 2005). It first appeared in the 1980s, highlighting how quickly invasive species can exploit change. This remote island was previously free of weeds.

Changes will occur in marine environments as well. The arrival of the European green crab (*Carcinus maenas*) in Tasmania after a run of unusually warm winters (1988 to 1991) may well be an instance of climate assisted dispersal (Thresher et al. 2003). This species was present in Victoria for almost a century before it spread south.

Aquarium fish released into streams could fare especially well from climate change because most species are from the tropics and likely to benefit from rising temperatures. Some invasive species have a presence in regions they cannot yet exploit because temperatures are too low. According to Sutherst et al. (2007), 'perennial weeds can sometimes persist as "sleeper" populations in marginally cold climates where they frequently fail to reproduce'. Alternatively, they may be confined to a particularly warm or moist site within a colder or drier region. 'Following climate warming,' Sutherst et al. (2007) explain, 'these established sleeper populations may form nascent foci for potentially rapid increase in abundance'. The sleepers could include garden plants growing in alpine ski resort gardens and around homesteads on farms.

Many wildlife pathogens will also benefit from climate change as warmer temperatures usually increase virulence by promoting growth, reproduction, and higher transmission rates (Harvell et al. 2002). In south eastern Australia the dieback fungus, *Phytophthora cinnamomi*, is expected to benefit from wet periods increasingly coinciding with warm soil temperatures (Chakraborty et al. 1998).

Shorter and milder winters in cool regions and hotter summers in the tropics will benefit many pathogens by stressing host species, thereby increasing their susceptibility (Harvell et al. 2002). Some of these changes will be desirable, for example if the pathogen is a biocontrol agent attacking a weed. Climate is known to have a profound influence on the biocontrol agents (mainly insects) that attack weeds such as lantana (*Lantana camara*) (Day et al. 2003). However, in cases like this, it is unclear what the net effect may be when droughts and rising atmospheric carbon dioxide are also taken into account. Changes will be complex, with weeds and pest animals interacting in many different ways.

In the Australian Alps, foxes, hares (*Lepus europaeus*), house mice (*Mus musculus*), feral horses (*Equus caballus*) and weeds have all increased their presence at higher altitudes (Green and Pickering 2002; Pickering et al. 2004). Foxes are preying more on endangered mountain pygmy possums (*Burramys parvus*) because their usual fare during early spring (bogong moths *Agrotis infusa*) are arriving later (Ken Green pers. comm.). This is compounded by the pygmy possums needing to forage more widely because they too depend upon the moths for food, thereby increasing their exposure to foxes. Broad toothed rats (*Mastacomys fuscus*) are also suffering more from fox attacks. As snow cover declines, they become easier for foxes to find. House mice are multiplying because grasses, and thus edible grass seeds, have increased after an intense fire in 2003 (Ken Green pers. comm.).

Rising temperatures will suit many weeds, with more than 160 invasive species in the Alps, but mainly at lower altitudes (Catherine Pickering pers. comm.). Weeds do especially well along roadsides, which serve as conduits to peaks. Pellet clover (*Trifolium ambiguum*), an intentional introduction, has spread rapidly in recent years after remaining largely dormant since the 1960s. This is probably due to it being favoured by the drier warmer conditions (ibid.). Some of the ski resort garden plants may become weedy as temperatures rise, as others have done in the past (Sainty et al. 1998).

One of our worst pests, the European rabbit, may benefit in very cold regions but lose habitat further inland (Scanlan et al. 2006). Having evolved in Spain and southern France under a Mediterranean climate of winter rainfall, its breeding cycle is triggered by shorter day lengths. In southern Europe this signals the approach of lush new plant growth (Cooke 1977), but most rain and new growth in the northern half of Australia comes in summer, a season when lactating female rabbits suffer heat stress and dehydration. Rabbits are predicted to retreat southwards and whole ecosystems will benefit because browsing rabbits prevent mulga and other dominant rangeland plants from regenerating (Lange and Graham 1983; Cooke 1987). Rabbits also sustain foxes and feral cats, which then attack native fauna, so climate change may reduce predation pressure in some places. Conversely, native birds of prey that now rely largely on rabbits as a food source (Baker-Gabb 1983) may suffer if they decline.

On subantarctic Macquarie Island, rabbits and rats are already benefiting from a milder climate. The survival rate of rabbit kittens born in winter has increased, not only because temperatures are higher but because there is less snow to melt to flood burrows (Justine Shaw, pers. comm.). The rabbits have also benefited from the removal of feral cats and reduced impact of myxoma virus. They are now removing so much vegetation that slopes are eroding and the island ecosystem is under threat. Black rats have colonised the high plateau where they now feed intensively on seeds of the large leaved silver daisy (*Pleurophyllum hookeri*) (Shaw et al. 2005). Rats were not recorded at an altitude of 280 metres previous to 2000.

The many interacting factors often make it difficult to predict the outcomes of climatic warming. For instance, it is difficult to predict the effect on the success of the bellyache bush (*Jatropha gossypifolia*), a major weed in the dry tropics. The bellyache bush invades wetter habitats faster than drier ones, but its seeds last six years in dry habitats compared with only three in wet habitats (Faiz Bebawi, pers. comm.).

Invasive species with short life cycles may evolve rapidly in new locations and escape previous climatic limits (Cox 2004; Sutherst et al. 2007). An example of this may be cane toads, which are spreading into both hotter and colder regions than they occupy in their native range in South America (Urban et al. 2007).

People will also change their distribution in response to climate changes, and this will influence pest invasions. Many millions of people could be displaced by climate changes (Dupont and Pearman 2006). Six of Asia's ten mega cities, including Jakarta, Mumbai and Bangkok, are perched on the coast where they are vulnerable to rising sea levels (ibid.). If climate refugees come to Australia, or if

Australian forces mediate disputes, the quarantine implications will be significant, because invasive species are known to spread with refugees and military equipment (Australian Quarantine and Inspection Service 2000; Sutherst 2000)

People may also respond to concerns about climate change by growing biofuel crops, some of which are very weedy (Raghu et al. 2006; Low and Booth 2007). The Queensland Government receives many enquiries from landholders wanting to grow jatropha (*Jatropha curcas*) (Faiz Bebawi pers. comm.), which is a significant weed (Randall 2004-7). In South Australia, giant reed (*Arundo donax*) is being trialled as a biofuel, although it has become invasive elsewhere in the world (Bell 1997; Milton 2004). Other potential biofuel plants which may pose a serious weed threat include castor oil bean (*Ricinis communis*), neem tree (*Azadirachta indica*) and reed canary grass (*Phalaris arundinacea*). Water shortages may also lead to the spread of aquatic pests such as tilapia (*Oreochromis mossambicus*) if water supplies are diverted over large distances.

Climate change adds to the threat that many native species face today from invasive species, even if the pest species gain no benefit from climate change. Several marsupials that disappeared from most of temperate Australia, where foxes are prolific, survive today in the north of their range, often on islands that lack feral predators. The bridled nailtail wallaby (*Onychogalea fraenata*)once ranged from north Queensland to the Murray River, but now survives only near Dingo in central Queensland where foxes are scarce (Strahan 1995). This population may be highly vulnerable to climate change, but any attempt to re-establish nailtails further south will be hindered by foxes unless there is intensive management. Other species in a similar situation include the bilby, golden bandicoot (*Isoodon auratus*), banded hare wallaby (*Lagostrophus fasciatus*) and rufous hare wallaby (*Lagorchestes hirsutus*).

As a different kind of example, water buffalo and climate change may be independently converting large tracts of freshwater wetlands into saltwater swamps (Mulrennan and Woodroffe 1998). Higher rainfall and rising sea levels may convert coastal plains along Northern Territory rivers into saline wetlands (Hughes 2003), and water buffalo achieve a similar end by creating swim channels that allow saltwater into freshwater lagoons, killing paperbarks (*Melaleuca* species), lotus lilies (*Nelumbo nucifera*) and wild rice (*Oryza meridionalis*), a staple food of magpie geese (Skeat et al. 1996). Saltwater has already penetrated up to 35 kilometres inland (Letts et al. 1979). Ironically, climate change will greatly disadvantage water buffalo if it converts the freshwater wetlands of the Alligator River Region into a saline system, as would be expected from a 1-2 metre rise in sea level (Hughes 2003). Climate change will of course disadvantage some pests. The northern Pacific seastar (*Asterius amurensis*), Asian kelp (*Undaria pinnatifida*), redfin perch (*Perca fluviatilis*), crack willow (*Salix fragilis*), and other cold climate species will have less habitat to exploit.

Extreme Events

The Intergovernmental Panel on Climate Change (2007b) predicts an increasing incidence of extreme events for Australia, and for the world. Its most recent summary of predictions for Australia includes ‘increases in the severity and frequency of storms and coastal flooding’ and ‘increased drought and fire’. Australia faces ‘major challenges from changes in extreme events’, yet Australia’s natural systems ‘have limited adaptive capacity’.

Extreme events such as cyclones, floods, droughts and fires provide many opportunities for pests, especially weeds, to spread. By killing or weakening native species over large areas, by aiding dispersal of pests, and often by providing a pulse of nutrients, they serve as major triggers for invasion. The escape of pest animals from captivity is sometimes facilitated by extreme events as well.

Fire events are expected to become more frequent and/or extreme almost everywhere in Australia (Williams et al. 2001). This shift will be driven by a greater frequency of days of severe fire weather, which will promote larger or more intense fires. Climate trends already imply an increased fire risk, with declining rainfall in south eastern Australia, more severe droughts, and more extremely hot days (Hennessy et al. 2006). These changes have not, so far, led to markedly more fires, perhaps because of changing fire management and reduced rates of arson (ibid.).

This situation contrasts with North America, South America, Russia and southern Europe, where fire events are already more extreme. In the United States, for example, longer warmer summers have seen a fourfold increase in major wildfires and a six fold increase in areas burnt, compared to the period from 1970 to 1986, and large fires now burn on average for 37.1 days compared to a previous average of 7.5 days (Westerling et al. 2006). In mainland Australia, the number of days with a very high or extreme Forest Fire Danger Index rating are likely to increase by 4–25 per cent by 2020, and by 15–70 per cent by 2050, with the biggest increases further inland (Hennessy et al. 2005). The period during which it is safe to conduct prescribed burns may narrow. In Tasmania, fire risk is expected to remain largely unchanged because of higher humidity levels (ibid.).

While there are some climate change impacts that remain partly speculative, the role of extreme events in driving biological invasions is well established. For example, the New South Wales Department of Primary Industries has a fact sheet dedicated to ‘Weed strategies following drought, fire and flood’ that draws upon lessons already learned (Trounce and Dellow 2007):

'Because of their greater competitiveness, weed species readily invade bare areas of ground which have been denuded of vegetation. Drought, fire and even floods can create these conditions as they devastate existing ground cover, thereby removing all competition for light, nutrients, moisture and space. The devastation allows quick weed establishment when more favourable conditions arrive.'

Athel pine (*Tamarix aphylla)* is a prime example of a weed that spreads dramatically after an extreme event. This exotic tree, which is often planted around homesteads, was not rated a major weed in Australia until the exceptional wet year of 1974. Floods along the Finke River in central Australia felled many river red gums (*Eucalyptus camaldulensis*) allowing groves of athel pines to germinate in their place (Griffin et al. 1989; Humphries et al. 1991). Athel pine rates today as one of Australia's 20 worst weeds, a single event having brought it to be named as a Weed of National Significance.

Thirteen of the 20 Weeds of National Significance benefit at times from extreme events. Floods assist the spread and establishment of prickly acacia, parkinsonia (*Parkinsonia aculeata*), mimosa (*Mimosa pigra*), mesquite (*Prosopis* species), pond apple (*Annona glabra*), olive hymenachne (*Hymenachne amplexicaulis*), parthenium (*Parthenium hysterophyllus*), alligator weed (*Alternanthera philoxeroides*), salvinia (*Salvinia molesta*), willows (*Salix* species) and athel pine. Fire promotes gorse (*Ulex europeaus*), and lantana (*Lantana camara*) is recorded growing in place of trees killed by fire (Hobbs 1991; Sutherst 2000). Pond apple in particular depends upon unusual weather events to achieve maturity. Its seedlings germinate *en masse* inside north Queensland's rainforests but seldom mature unless light levels are increased by canopy damage.

Both by Tim Low

Mimosa (Mimosa pigra) and prickly acacia (Acacia nilotica) are Weeds of National Significance that multiply after floods.

Exotic fish are known to spread during cyclones and floods. The appearance of new exotic cichlid fish (Cichlidae) in the Ross River at Townsville is attributed by biologist Alan Webb to flooding events, the fish appearing after particularly wet years, evidently after spreading from outdoor ponds that overflowed during heavy rain (Low 1999). In another example, the very wet weather in 1974 is blamed for the spread of carp (*Cyprinus carpio*) in south eastern Australia. Floods that swamp vast areas can transport fish and other organisms from ponds, dams and breeding facilities into distant watercourses.

Australian weed experts often talk about 'sleepers' – weeds that remain relatively static in the landscape before suddenly multiplying (Groves 1999; Grice and Ainsworth 2003). Extreme events could sometimes be the trigger for such phase shifts. Human behaviour often changes during or after extreme events in ways that facilitate biological invasions. Farmers crippled by drought or floods are less likely to practise good pest control, clean ups after cyclones may unwittingly spread unwanted plants and pathogens, fire trucks entering national parks may do the same, and overgrazing, which promotes unpalatable weeds, occurs more often during drought.

The provision of drought fodder has promoted significant weed spread in the past, although controls have improved today. Thomas et al. (1984) found an average of 68,700 weed seeds per bale of hay provided during the 1980–81 drought, and Davidson (1985) noted widespread reports of infestations of many weeds after fodder movements during the 1983–84 drought. The agistment of livestock during droughts can also facilitate movement of weed seeds over large distances.

A particular concern today is that nurseries will respond to climate change by promoting new drought-hardy garden plants with high weed potential (CRC for Weed Management 2007). In 1996 Mexican feathergrass (*Nasella tenuissima*), a major weed, was imported into Australia and cultivated in large numbers as a drought resistant ornamental ground cover (Australian Biosecurity Group 2005). By 2004 it had become a weed and is now subject to eradication efforts. Most weeds that invade bushland are escaped garden plants (Groves et al. 2005; Low 1999; Groves 1998).

The following sections consider two categories of extreme event in more detail – cyclones and fire.

Both by Tim Low

Variegated thistle (Silybum marianum) and parthenium (Parthenium hysterophyllous) are examples of serious weeds with seeds that are spread in drought fodder.

Cyclones & Invasive Species

There is growing awareness in the United States that hurricanes (cyclones) play a major role in exotic invasions. In 1992, Hurricane Andrew in Florida destroyed research and breeding centres and much of Miami zoo, setting free thousands of animals, from baboons (*Papio* species) and orangutans (*Pongo pygmaeus*) to wallabies (*Macropus* species) and capybaras (*Hydrochoerus hydrochaeris*) (Goodnough 2004). One reptile dealer lost almost 10,000 geckoes, and Mannheimer Foundation, a private research institution, lost more than 2,000 monkeys (Harper 1992). Two years later many monkeys, parrots and lizards remained at large. The hurricane facilitated a population explosion in large feral iguanas (Cleary 2005). Hurricane Katrina in Mississippi has raised fears that many weeds will spread in its aftermath (Yager 2006). Hurricane Wilma spread citrus canker, a devastating orchard disease. The Asian tsunami in 2006 (similar in impact to a cyclonic surge) promoted serious weed invasion in coastal districts of Sri Lanka, facilitating prickly pear cactus (*Opuntia dillenii*) invasions in known nesting habitats of five species of threatened marine turtle (Bambaradeniya 2007).

In north Queensland, Cyclone Larry struck in March 2006, and the potential for weeds and animal pests to benefit was obvious in the aftermath. Cyclone Larry released more than 200 Canadian elk (*Cervus elaphus*), rusa (*Cervus timoriensis*), chital (*Axis axis*), fallow (*Dama dama*) and sambar deer (*Cervus unicolour*) from a farm at Babinda (Kaufman 2006). Many of these deer remain at large and are a serious concern to the Wet Tropics Management Authority because they browse rainforest vegetation (Ellen Weber pers. comm.). Had the cyclone struck further north it is possible that other exotic species could have been released from Mareeba Zoo. Exotic invertebrates may also invade areas after cyclone events. After Cyclone Larry, Cairns City Council imposed strict controls on residents whose properties were infested with yellow crazy ants, to ensure that ants were not transported when cyclone debris was removed.

Many seedlings of miconia (*Miconia calvescens*), a serious weed targeted for eradication, germinated in damaged rainforest around El Arish, near Tully, apparently responding to the heavy rainfall after the cyclone (Helen Murphy pers. comm.). Cyclone thrown trees impeded efforts to control this weed by blocking access tracks. Miconia spread from the property of a rare plant collector, and many other plants in collections pose very high weed risks, exacerbated by future cyclones. Siam weed (*Chromolaena odorata*) is another serious pest that may have spread during clean up operations.

At Curtain Fig National Park on the Atherton Tableland, Christmas vine (*Turbina corymbosa*), an ornamental plant from Latin America, smothered damaged trees after the cyclone, spreading inwards from the edge of the park following canopy loss (Gillanders 2007). Vines do especially well in forests disturbed by cyclones (or by logging). They often survive damaging events because their stems are flexible. In addition, their leaves make up more of their biomass than do leaves on trees, so vines have more photosynthetic potential (Schnitzer and Bongers 2002).

In Florida, vine diversity increased substantially following large scale hurricane damage, with exotic vines making up 34 per cent of the increased vine diversity. Horvitz (1998) concluded from this that: '[n]on-indigenous vines seemed to have a special role; not only could they compete with native vines, but they could also negatively affect the regeneration of other natives from a diverse array of sources including pre-established juveniles and resprouts from damaged adults'. If cyclones become more frequent and intense in the Wet Tropics, many exotic vines could benefit. By slowing down regeneration, these vines increase the vulnerability of rainforests to future cyclones, thus entrenching themselves.

Cyclone Larry was followed by another cyclone, Cyclone Monica, which reached the Northern Territory, destroying 7,000 square kilometres of woodlands and other habitats. Large areas are now at risk from invasion by exotic gamba grass (*Andropogon gayanus*) and mission grass (*Pennisetum polystachion*) (Garry Cook pers. comm.). Both grasses favour disturbed sites such as roadsides, and both grasses grow very close to sites where trees were uprooted. Mission grass has colonised sites damaged by cyclones in the past. Panton (1993) attributed a 60 per cent decline in monsoon rainforest near Darwin to mission grass invading damaged rainforests after three cyclones (in 1976, 1982 and 1984). It served as fuel for 'high intensity fires' that further damaged the rainforest. Grasslands dominated by mission grass resulted.

Extreme events provide many opportunities for preventative action. Protocols can be introduced to minimise the risk of species escaping during extreme events. Deer farms, zoos, quarantine facilities and fish breeding facilities can be designed to withstand cyclones and floods, and consideration could be given to what activities are appropriate in extreme event prone regions.

Fire & Invasive Species

Much of Australia's vegetation is highly flammable. Fires burn readily through open forests, woodlands, heathlands, grasslands and often (during dry seasons) through wetlands. Climate change will increase the intensity and incidence of fire, and certain weeds will benefit from these changes and reinforce them (Williams et al. 2001). Fire will also, in some situations, increase predation rates by exotic predators, by removing protective vegetation cover (Gill et al. 1999).

Australia can expect more extreme fires due to climate change producing more days of extremely high temperatures. Rainfall over much of the southeast and southwest may decline, increasing the risk of frequent and/or severe droughts. In northern Australia, where rainfall seems likely to rise, increased plant growth will increase fuel loads. Rising atmospheric carbon dioxide may also increase fuel loads by facilitating plant growth, where water and soil nutrients are not limiting. More frequent or severe droughts may increase litter fall and also increase fuel loads.

In the tropical savannas around Darwin, fires burn almost every year, while in alpine grasslands and heathlands almost a century may pass between fires. Fires burn mainly in winter and spring in northern Australia, and from summer to autumn in southern Australia. To understand fire triggers and impacts, northern and southern Australia are best considered separately.

In southern Australia the fire frequency may increase significantly due to climate change (Hennessy et al. 2005). More droughts and days of extreme fire risk can be expected and single fires will burn larger areas at shorter intervals. This scenario has begun to be observed in high country regions, for example fires in Kosciusko National Park and Alpine National Park in late 2006 burnt areas that had previously burnt in 2003. Fire intervals of a decade or less may become commonplace.

Fires harm most weeds, but some species benefit from their passage. These are usually plants that originate from regions of the world where fires are prevalent, such as southern Europe, South Africa, and the African savannah (Carr 1993). Fire adapted plants regenerate vigorously after fires, either resprouting from burnt stems and rootstocks or germinating in large numbers from seeds that have lain dormant or are those spread after a fire. Such weeds can compete successfully with native fire adapted plants because they grow without the army of enemies (insects, pathogens and browsing mammals) that control them in their natural habitats. A wide range of weeds in Australia show various adaptations to fire, including pine trees, geophytes, shrubs from Mediterranean regions (gorse, Spanish heath (*Erica lusitanica*) and brooms (*Cytisus* species) and grasses (Crane 2003; Humphries et al. 2002; Richardson 1998; Schwilk and Ackerly 2001),

The tropical savannah woodlands of northern Australia are characterised by grasses that grow thick and tall in the wet season before drying out in the harsh dry season. In northern Australia, pasture grasses that invade savannah woodlands are the 'fire weeds' of greatest concern (Douglas and Setterfield 2005; Kean and Price 2003). Having evolved in Africa under high grazing pressure from large mammals, these plants were imported into Australia because they produce more feed for cattle than native grasses. If they are not eaten they dry out, producing large fuel loads for fires. In 1992, biologists Carla D'Antonio and Peter Vitousek proposed that such grasses can change fire regimes via a 'grass-fire cycle' (D'Antonio and Vitousek 1992). Introduced grasses often grow taller and/or thicker than the native grasses they replace, not only producing more fuel for fires, but often more interconnected fuel. These grasses support fire, as it supports them (Bond and Midgley 1995; Low 2004). Grass fire cycles of invasion have been documented in Hawaii, North America, Central and South America, and Australia (Rossiter et al. 2003).

Michael Douglas

A Queensland Government risk assessment concluded that gamba grass (Andropogon gayanus) had the potential to 'transform Australia's eucalypt-dominated tropical woodlands into tree-free grasslands.'

In northern Australia, gamba grass (*Andropogon gayanus*) from Africa produces the most extreme fires. It is a pasture grass of limited value to the grazing industry that grows extremely tall, up to 4.75 metres, compared to 1-3 metres for the native grasses it replaces (Rossiter et al. 2003). It dries out later in the dry season and remains erect for longer, creating a taller, denser fuel load. Unlike native grasses, it can carry two fires in the one dry season (ibid.). Gamba grass fires are eight times as intense as native grass fires, with flames scorching the crowns of trees (Rossiter et al. 2003). Repeated gamba grass fires kill eucalypts, resulting in a complete habitat shift to an 'Africanised' grassland (Kean and Price 2003; Rossiter et al. 2003). Gamba grass poses an extreme threat to Australia's northern savannas (Csurhes 2005). According to Rossiter et al. (2003) it 'can clearly be described as a transformer species… with the potential to alter the community structure and the nutrient, water and carbon cycling processes over large areas of Australia's savanna ecosystems'.

In a Queensland Government risk assessment, Csurhes (2005) concluded that '[i]f large areas of northern Australia become dominated by gamba grass, the associated fire regime is predicted to transform Australia's eucalypt-dominated tropical woodlands into tree-free grasslands'. An increased fire risk through climate change, increases the prospect of this occurring. Such an outcome would accelerate climate change by releasing carbon stored in woody vegetation. Exotic cheatgrass (*Bromus tectorum*) in North America does this when it replaces shrublands after fire (Bradley et al. 2006). A precedent exists for grasses displacing trees over immense areas. The dramatic replacement of forests by savannah in Asia and Africa in the late Miocene has been attributed to climate change promoting grass fires (Beerling and Osborne 2006).

Gamba grass is very adaptable, colonising sandy soils and floodplain black soils, and although presently confined to the Darwin region and north Queensland, bioclimatic modelling shows it could establish as far west as Broome and as far south as northern New South Wales, even without climate change (Csurhes 2005). It can produce 77,000 seeds per square metre of ground compared with 50-6300 seeds for the native grasses it replaces (Flores et al. 2005).

The Northern Territory Government is establishing a tropical invasive grasses taskforce to better manage gamba grass and other flammable weedy species, which pose a threat to properties and houses as well as to biodiversity. The national taskforce will include representation from Queensland, Western Australia and the Australian Government.

Other fire promoting grasses of concern include mission grass (*Pennisetum polystachion*), buffel grass (*Cenchrus ciliaris*), molasses grass (*Melinus minutiflora*), green panic or guinea grass (*Panicum maximum*), and perennial veldgrass (*Ehrharta calycina*) (D'Antonio and Vitousek 1992; Brooks et al. 2004).

Mission grass produces fuel loads about four times greater than native grasses, with its flames reaching more than five metres high (Panton 1993). It also dries much later in the dry season, maintains an upright stature when dry, and can carry two fires in one dry season. As noted already, this grass destroys rainforest patches near Darwin by invading them after cyclones and then burning (ibid.). Mission grass has been listed as one of Australia's 18 top environmental weeds (Humphries et al. 1991).

Buffel grass is causing fire mediated invasions across much of inland Australia. According to Humphries et al. (1991) it 'dramatically increases the fuel load causing hotter, larger fires; thus increasing vegetation homogeneity and in all likelihood killing native plants such as [river red gum] *Eucalyptus camaldulensis*' Thick stands along gully lines convert watercourses from firebreaks into wicks which spread fire further (ibid.). Buffel grass has also been listed as one of Australia's 18 worst environmental weeds (ibid.). It aids the spread of parthenium (*Parthenium hysterophyllus*), a Weed of National Significance (Butler and Fairfax 2003). In the Kimberly region it spreads into vine thickets (rainforest patches) along tracks made by feral cattle, fuelling very hot fires that kill rainforest trees (Norris and Low 2005). It spreads fires that appear to pose the main threat to the endangered Slater's skink (*Egernia slateri*) (Pavey 2004). Serious concerns about buffel grass have been expressed by many biologists in Australia and in North America (Franks 2002; Fairfax and Fensham 2000; Butler and Fairfax 2003).

Other flammable weeds in Australia do not promote fire to the same extent as grasses do, although many of them will benefit from more fire under climate change. Gorse, as a Weed of National Significance, rates as the most invasive of these. Rees and Hill (2001) state that 'a single fire can allow the establishment of a stand that can persist for 30 years and the development of a substantial seed bank that could persist for even longer'. Too little is known about the role of fire, especially increased fire, in promoting flammable shrubby weeds such as brooms, Spanish heath and blue butterfly bush (*Psoralea pinnata*) in south eastern Australia.

Weeds can increase fire frequencies and intensities without themselves benefiting. Tropical vines that dry out in the dry season can act as wicks or ladders spreading flames from a grassy understorey to the crowns of monsoon forests which are then damaged. Rubber vine (*Cryptostegia odorata*) in north Queensland, and various vines near Darwin are implicated in this problem (Panton 1993). These vines appear not to benefit from fire, and indeed, controlled burns are used to control rubber vine. Some weeds, such as succulent prickly pears (*Opuntia* species) and dense shrubs, retard fire (Brooks et al. 2004). Thicket forming shrubs may shade out the grasses that so often fuel fire (Mack and D'Antonio 1998). On Northern Territory floodplains, mimosa (*Mimosa pigra*), rated one of Australia's Weeds of National Significance, is one of these (Braithwaite et al. 1989). Other shrubby weeds such as hyptis (*Hyptis suavelens*) and lantana (*Lantana camara*) suppress fire when green but carry it when dry. Many of the garden plants that invade bushland remnants on city edges are fire suppressing. Complete fire suppression is often undesirable because many native plants require periodic fires for regeneration. Fire suppressing weeds could ameliorate some impacts of an increasing fire risk under climate change, but only at the cost of invading native forests.

Fires raise other issues too such as exposing small mammals and birds to attacks by introduced predators over large areas due to removing vegetation. The numbat, which is highly vulnerable to predation by foxes and cats, apparently disappeared from arid Australia at a time when large fires reduced vegetation cover, rather than during times when foxes and cats colonised the outback (Friend 1990). On Mount Buller in Victoria, recent fires have forced cats and foxes into the habitat of the endangered mountain pygmy possum, increasing predation rates.

Another problem for the future will be pest invasions associated with fire breaks and fire control. If fires become a greater threat there will be more fire tracks and fire breaks cut in national parks, and these will serve as conduits for invasion by weeds and feral animals. Weed seeds have the potential to spread on fire trucks unless strict protocols are established.

Spanish heath (Erica lusitanica) and English broom (Cytisus scoparius) are two of several weedy shrubs in temperate Australia that recruit well after fires.

Rising Carbon Dioxide

Plants require carbon dioxide to photosynthesis. The rate at which they can perform this operation is often limited by carbon dioxide levels, so rising atmospheric CO2 has the potential to promote plant growth rates. Higher carbon dioxide also reduces stomatal conductance, which in turn reduces leaf transpiration (water loss), making plants more water efficient (Ghannoum et al. 2007; Eamus 1991; Farquhar 1997; Morison 1993). This in itself can promote growth when nutrients are not limiting.

The levels of carbon dioxide required by plants depends on their method of photosynthesis. Most plants use the C3 photosynthetic pathway, the original process for storing the sun's energy that evolved hundreds of millions of years ago when atmospheric carbon dioxide levels were extremely high. But carbon dioxide levels have declined since then as plants have increased the oxygen content of the atmosphere, and the C3 process is now less efficient because the enzyme that fixes carbon dioxide inside plants does not discriminate between CO2 and oxygen (Osborne and Beerling 2006). Burning fossil fuels improves C3 photosynthetic efficiency by increasing atmospheric carbon dioxide levels.

C4 photosynthesis is an evolutionary innovation in which carbon dioxide is concentrated at an early stage of the photosynthetic process. C4 plants can grow faster and use water more efficiently than their C3 equivalents, but they are damaged by chilling and do not grow in cold climates. About 3-4 per cent of the world's flowering plants use C4 photosynthesis, and most of them are grasses (4,500 species) or sedges (1,500) (Sage 2004). C4 grasses dominate tropical and subtropical Australia, making up more than 90 per cent of the understorey in more than 50 per cent of the continent. In southern Australia the understorey is dominated by C3 grasses and herbs.

Some of Australia's most invasive introduced plants are C4 grasses, but most weeds are C3 plants. Rising carbon dioxide will increasingly shape competition between weeds and native plants, and between different types of weeds. Many weeds are fast growing C3 plants that will grow even faster under rising CO2 (Poorter and Navas 2003; Dukes 2000). Nitrogen fixing weeds, such as brooms, gorse and acacias stand to benefit especially, because their capacity to grow faster will not be constrained in infertile soils by soil nitrogen, although it may be limited by soil phosphorus (Thomas et al. 2007; Poorter and Navas 2003).

Rising carbon dioxide levels will allow many weeds to increase their range. Prickly acacia and rubber vine, by increasing their water efficiency under carbon dioxide fertilisation, should greatly expand their ranges in dry areas of Australia (Kriticos et al. 2003b). Carbon dioxide will assist native plants to increase their ranges as well, but as noted earlier, weeds are often the first to exploit new opportunities. Prickly acacia and mesquite (*Prosopis* species) can benefit quickly because their seeds travel with transported cattle, which excrete them intact.

Where C3 and C4 plants grow together their interactions may be complex. Where weedy C4 grasses such as buffel grass (*Cenchrus ciliaris*) grow within eucalypt and acacia woodlands, the wet years should favour the native trees, but dry years, by promoting fire, should favour the grasses. However, higher carbon dioxide levels should also help tree saplings recover quickly after burns (Bond and Midgley 2000). Higher carbon dioxide could decrease the fire frequency if trees grow thickly enough to suppress fire promoting grasses, but fire risk will rise during drought because carbon dioxide increases plant biomass, resulting in more leaf litter and other fuel for fires.

Both by Tim Low

Gorse (Ulex europaeus) is a highly invasive weed which, because it is a nitrogen-fixing legume, could benefit more from carbon dioxide fertilisation than most weeds. But because it is adapted to a cool climate it may suffer from rising temperatures.

Rising carbon dioxide will also shift the balance between weeds and their herbivores and pathogens because plants grown at high carbon dioxide levels produce foliage with a higher carbon : nitrogen ratio (Ziska and Runion 2007). As nitrogen is often the limiting nutrient in a herbivore's diet, lower nitrogen foliage will be less nutritious (Bezemer and Jones 1998). In addition, carbon enriched plants can produce more carbon based defensive compounds which will make them less attractive to herbivores.

Herbivorous insects are thus predicted to decline under rising carbon dioxide levels, although experiments do not always support this (Johns and Hughes 2002; Coviella and Trumble 1999; Zvereva and Kozlov 2006). Free-air CO2 enrichment studies, which are more realistic than laboratory experiments, only show small reductions in leaf nitrogen (Ainsworth and Long 2005). In an Australian laboratory study, the leaf mining moth (*Dialectica scalariella)*, a biological control agent for Paterson's curse, fared very poorly under high carbon dioxide and raised temperatures (Johns and Hughes 2002). It appeared to develop too quickly to meet its nitrogen needs. In contrast, lantana beetles (*Octotoma* species) did well on lantana plants grown under higher temperatures and increased carbon dioxide (Johns et al. 2003). A different kind of biological control agent, rubber vine rust (*Maravalia cryptostegiae*), was found to produce more spores at higher carbon dioxide levels, suggesting it may become more effective (Chakraborty et al. 1998).

Rising carbon dioxide significantly reduces the effectiveness of glyphosate, the main chemical used to control environmental weeds in Australia (Ziska and Runion 2007; Ziska et al. 2004; Ziska and Goins 2006).

All by Tim Low

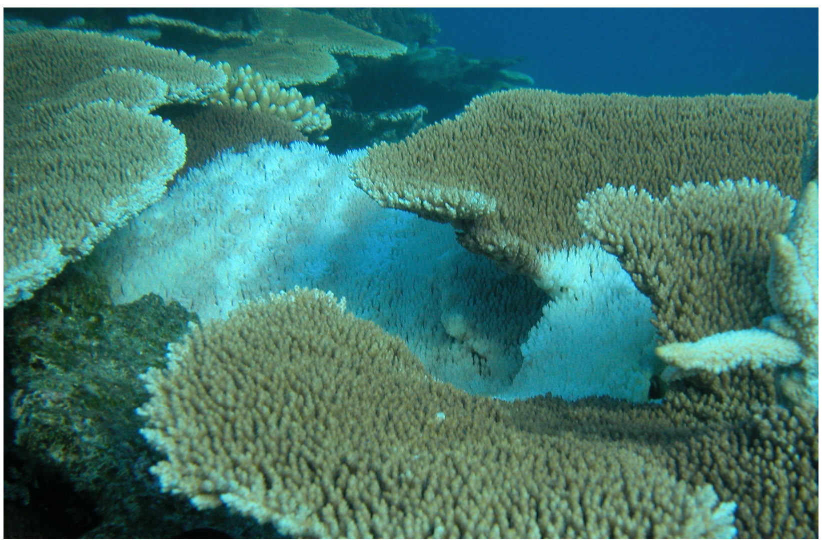
Climate change will affect the success of biocontrol agents on weeds, including lantana beetles (Octotoma scabripennis) (top), rubber vine rust (Maravalia cryptostegiae) (below) and moths that attack Paterson's curse (Echium plantagineum) (at right).

Predicting the precise impact of rising carbon dioxide on invasive pests is made difficult by the interplay of many factors. A recent field study in Tasmania found that, contrary to predictions, a C4 native grass fared better than both a C3 native grass and two C3 herbaceous weeds when temperatures and carbon dioxide levels were increased. This was apparently because of lowered seed production and germination rates in the C3 species (Williams et al. 2007). Although rising carbon dioxide can be expected to exacerbate weed problems, it is predicted that not all weeds will benefit. More free-air CO2 enrichment experiments are needed in the field over long time periods, to see if the conclusions reached in laboratory experiments hold true under more natural conditions.

Native Species as Problems

A changing climate will inevitably benefit some native species, but their success will sometimes come at a cost to other native species. The most significant changes identified so far have occurred in Tasmanian waters, where a strengthening of the warm East Australian Current has allowed marine species from mainland waters to colonise Tasmania. These include 16 species of fish, zooplankton, dinoflagellates, and an invasive sea urchin (*Centrostephanus rodgersi*) (see box). The urchin is posing a major threat to biodiversity by creating vast barrens where kelp beds once flourished (Johnson et al. 2005).

Australian Institute of Marine Science



Corals on the Great Barrier Reef are dying from white syndrome, which is not the same as coral bleaching.

A dinoflagellate, *Noctiluca scintillans*, which first appeared in 1994, has become an abundant consumer of microalgae that periodically forms immense blooms, commonly referred to as 'red tides' (Albinsson 2005). In Tasmania the number of blooms rose between 2001 and 2004 and blooms also appeared further south (Susan Blackburn pers. comm.). *Noctiluca* has been associated with massive fish kills overseas. Another significant problem for marine life is white syndrome, an emerging disease or group of diseases that is killing corals on the Great Barrier Reef during periods of high water temperatures (Bruno et al. 2007). This syndrome is not considered to be an introduction from elsewhere, but rather an example of temperature stress increasing susceptibility to pathogens. It is not the same as coral bleaching, but may have a similar potential to convert diverse coral reefs into 'underwater wastelands' (Hoff 2007).

The Australian Alps is another region where changes are raising concerns. Kookaburras (*Dacelo novaeguineae*) are hunting at higher altitudes than before, preying on alpine skinks (Ken Green, pers. comm.). Most skinks lay eggs, but alpine species are live-bearers, resulting in pregnant females spending long periods basking to promote incubation. Predation by kookaburras may reduce their numbers dramatically. With less snow, swamp wallabies (*Wallabia bicolor*) and red necked wallabies (*Macropus rufogriseus*) are reaching higher altitudes, placing alpine herbfields at risk (Ken Green pers. comm.).

Tasmania's alpine zone lacks expansive herbfields, apparently because of grazing pressure by red necked wallabies. The herbfields on the mainland, having developed in isolation from wallabies, could now disappear. Broad toothed rats will probably suffer increased competition from native swamp rats (*Rattus lutreolus*), which should benefit from the higher temperatures (Green et al. 2008).

On Macquarie Island, great skuas (*Catharacta skua*), a large predatory bird, are multiplying on a diet of rabbits, and they now attack Antarctic prions (*Pachyptila desolata*) and other petrels nesting on the island (Garnett and Crowley 2000). Further south, in the Australian Antarctic Territory, increasing snowfall from 1980 to 1996 (linked to climate change), produced large persistent snowdrifts at sites that were previously bare. Southern giant petrels (*Macronectes giganteus*) began crash landing on snow on previously inaccessible cliffs where Antarctic petrels (*Thalassoica antarctica*) bred, preying on them, resulting in almost complete breeding failure (Van Franeker et al. 2001).

Many examples of native species creating problems have been noted overseas. Especially serious are mass insect attacks on trees. North American spruce beetles (*Dendroctonus rufipennis*) have killed many millions of trees in a region stretching from Alaska to Utah, a problem linked to 'record-setting warming weather' which allowed the beetles to complete their lifecycle in one year instead of two. Logan et al. (2003) concluded that '[t]he extent of this blight was unprecedented, and may have resulted in a shift from spruce to grasslands in parts of Alaska'. The mountain pine beetle (*Dendroctonus ponderosae*), now more abundant with warmer weather, is spreading a damaging rust (*Cronartium ribicola*) that infects American conifers. This beetle will probably spread north and put at risk high elevation pine stands of great ecological importance (Parmesan 2006).

In Europe, pine processionary caterpillars (*Thaumetopoea pityocampa*) are attacking relict stands of Scots Pine (*Pinus sylvestris*) in locations that were previously too cold for the caterpillars. In Japan, mass oak death is attributed to beetles spreading a fungal pathogen further north (Hódar and Zamora 2004; Kamata et al. 2002). Mass deaths of trees from rising temperatures can be expected in the future, but insects are proving a more immediate threat in the northern hemisphere.

In Australia, climate change may be contributing to problems arising after native organisms were transported south by human activity (Low 2002). In northern

Tasmania, platypuses (*Ornithorhynchus anatinus*) are dying from *Mucor amphibiorum*, a fungal pathogen that has spread south from the mainland (Connolly et al. 1997). In southern Queensland, pandanus planthoppers (*Jamella australiae*) from north Queensland, accidentally brought south on nursery stock, have killed many thousands of pandanus trees (*Pandanus tectorius*) along beaches (Smith and Smith 2000b; Smith and Smith 2000a).

All by J. Connolly & M. Nowakowski

The fungus Mucor amphibiorum, which causes large ulcers on platypuses, is one of many invasive organisms to have spread south in recent years. Native to mainland Australia, it was first recorded in Tasmania in 1982, perhaps having arrived on frogs that travelled with fresh produce. Infected platypuses can die from secondary infection and a loss of temperature control, but only in Tasmania are platypuses harmed by this pathogen.

In the same region umbrella trees (*Schefflera actinophylla*) are escaping from gardens to become major environmental weeds (Low 2002). Umbrella trees are native as far south as mid eastern Queensland, and under climate change could be expected to colonise southern Queensland 'naturally'. Upon escaping from gardens however, they often form monocultures that suppress other plants, which seldom happens in their native range. In each situation a newcomer appears to have overwhelmed local native species, something that may happen often in future. Migrating species will sometimes leave their natural enemies behind and then proliferate unchecked (Sutherst et al. 2007).

Vegetation shifts could create many dilemmas. Plants responding to climate change will migrate across the landscape at different speeds (Overpeck et al. 2005). Those that arrive first may swamp in situ ecosystems and inhibit later arrivals – thus behaving like weeds. Sweet pittosporum (*Pittosporum undulatum*) invasion around Sydney may provide an analogy for this. Pittosporum is one of several local rainforest trees invading eucalypt forest in response to nutrient enrichment and fire suppression (Rose and Fairweather 1997). Because it dominates the process, ecologists talk about 'pittosporum invasion' rather than 'rainforest colonisation' (Low 2002). It is usually considered a serious weed, but not by everyone (Spafford Jacob and Randall 2006). Climate change may deliver many outcomes like this, with introduced weeds part of the equation. As Cox (2004) and Malcolm et al. (2002) say, climate change will favour 'weedy' species – only some of which will be introduced.

Reserve managers will have to decide if a newly dominating native plant requires management as a problem. Overabundant native plants, responding to different human impacts, already suppress diversity in many reserves (see Low 2002 for examples). The question managers should ask is whether such plants facilitate or inhibit biodiversity.

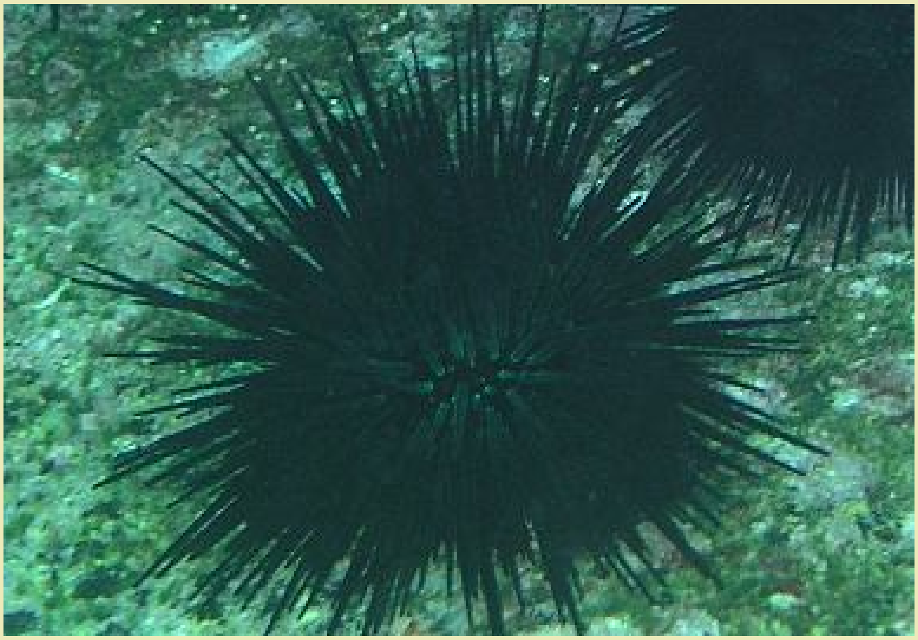
The vine *Merremia peltata* is one native species for which control could be justified in the future. It 'strangles' tropical rainforests damaged by cyclones, inhibiting their recovery and suppressing biodiversity. At Mission Beach the vine has been slowing regeneration since Cyclone Winifred struck in 1988 and will multiply if cyclones strike more often (David Bender pers. comm.). Like the fire promoting pasture grasses, it creates a positive feedback loop, with vine draped forests suffering more from cyclone damage, reinforcing vine dominance. Exotic vines contribute to this cycle as well.

The translocation of native species to avert their extinction may create similar problems, by driving out other species by predation or competition, or by introducing parasites or disease (McLachlan et al. 2006). As the Intergovernmental Panel on Climate Change (Gitay et al. 2002) warns: '[m]oving species to adapt to the changing climate zones is fraught with scientific uncertainties. The consequences of invasive organisms cannot be predicted; many surprises would be expected'.

Other issues to consider are outbreaks of native insects and pathogens hastening the death of trees, and toxic algal blooms killing native fish in drought affected waterways (Sutherst et al. 2007). The point made by Howden et al. (2003) should be heeded: '[m]any species are likely to be negatively affected by changes to mean temperature, rainfall, CO_2 concentration and disturbance regimes, and we may naturally tend to focus impact (and adaptation) assessments on those species. The greatest community and ecosystem impacts may, however, come from those species that are favoured by changed conditions or disturbance and interact with other species (for instance, competitors, predators, invasive weeds, etc.). Such species could be native or exotic.'

URCHIN BARRENS IN TASMANIA

Scott Ling



The formation of barrens by the sea urchin (*Centrostephanus rodgersi*) in Tasmania represents one of the most vivid and complete examples of 'downstream' impacts of climate change on marine systems world wide.

The urchin is one of many species conveyed southwards from New South Wales waters by a strengthening of the warm East Australian Current. After appearing in Bass Strait in the late 1960s or early 1970s it was found off the Tasmanian mainland in 1978, and now occurs along the east and south coasts, appearing recently in southwest Tasmania.

This urchin overgrazes seaweeds, converting highly diverse and productive seaweed beds into 'barrens' habitat largely devoid of seaweeds and the benthic invertebrates that occur in healthy seaweed beds (Johnson et al. 2005). In the Kent group of islands in Bass Strait about half of the nearshore shallow reef is now urchin barrens. On the east coast of Tasmania, patches of barrens habitat are now scattered over most of the east coast, with the potential to cover about 50 per cent off nearshore reefs, as they do currently in New South Wales and the Kent Group.

Barrens are a problem for three reasons. First, they represent a massive loss of biodiversity, and about a 100-fold reduction in primary production. Second, they cannot support commercial fisheries for abalone and rock lobster which, in Tasmania, have a combined annual value of about $150 million (before processing). Third, when sea urchins overgraze seaweeds they do not starve, but switch to a diet of benthic microalgae, encrusting algae, drift plants and benthic invertebrates. Accordingly, they can maintain populations in barrens habitat, and thus the barrens condition, indefinitely. Moreover, the density of sea urchins necessary to maintain barrens is much less than the density necessary to create them in the first place, so removal needs to achieve very low densities to effect recovery of seaweeds. Thus, removing sufficient urchins to facilitate recovery is extremely difficult.

The sea urchin has a negative impact on black-lip abalone, Tasmania's most lucrative fishery, in healthy seaweed beds not yet showing any signs of destructive grazing by sea urchins. When urchins establish in seaweed beds, abalone grow more slowly and produce smaller gonads, and change their behaviour by avoiding exposed microhabitats and becoming more cryptic.

While it seems clear that the arrival of *C. rodgersii* in Tasmania was driven by climate change affecting large scale ocean dynamics, overfishing of rock lobsters – the principal predators of sea urchins - has enabled urchin populations to build to the point where barrens can form. The Tasmanian government, abalone and rock lobster fisheries, and researchers are presently working together to investigate means of increasing the density of large rock lobsters in seaweed beds to minimize the risk of further barrens formation. This may require significant changes to lobster fishery management in Tasmania.

- Craig Johnson, University of Tasmania

Scott Ling

Recommendations

1) Reduce Climate Impacts

Invasive pests add more urgency to the need to reduce global emissions. Because climate change scenarios rarely take full account of invasive pests, they underestimate the risks to the future.

2) Increase Awareness about Invasive Species

Invasive species should be recognised as a major component of the climate change problem. They warrant more publicity, research focus, policy development, and funding for prevention and control. Biologists have focused attention on native species likely to go extinct under climate change, but not on what will replace them. People need to be shown, not just images of melting glaciers, but vistas of weed forests and urchin barrens.

Species that warrant a special focus include pasture plants that promote fire and garden plants that replace keystone native species. Peak grazing groups, pasture agronomists and the nursery industry should be engaged in dialogue. The Australian Government has a key role to play in bringing parties together to improve understanding. Garden plants with a history of weediness should be identified as such with nursery labels under a mandatory labelling scheme. Australians asking 'How can I help fight climate change?' should be told that removing weedy garden plants from gardens and nearby bushland will help.

3) Reduce Invasive Pest Impacts

Climate change adds more urgency to the need to prevent and control pest invasions.

To the extent that decisions about pest management don't take into account worsening problems under climate change, they underestimate the scale of response required. More should be invested in pest prevention and control. Funding for quarantine work should increase to reflect the growing pest threat to Australia posed by the main drivers of world change – globalisation and climate change.

Many recommendations to improve Australia's responses to the pest threat have been offered in recent years (Agtrans Research 2005; Senate Committee on the

Environment Communications Information Technology and the Arts 2005; Australian Biosecurity Group 2005; Groves et al. 2005; Sutherst et al. 2007).

Australia's capacity to identify invasive species is diminishing, due to declining funding for taxonomy, a trend that should be reversed by increasing funding and providing more career security.

The inability of quarantine officers to detect certain invasive species during border inspections (Whittington and Chong 2007; Stanaway et al. 2001) justifies a much greater focus on pre-border and post-border quarantine (ibid.), as practised increasingly in New Zealand (Nendick et al. 2006). As part of this, the Urban Hazard Site Surveillance Program, which surveys high-risk sites near ports, should be expanded in scope. As Stanaway et al. (2001) advocate, Australian companies need to play a strategic role in pest risk management, as they do in fire ant zones in Brisbane. A more cohesive framework for pest management is also needed (Australian Biosecurity Group 2005). Australia has a Vertebrate Pests Committee, a National Introduced Marine Pest Coordination Group, and an Australian Weeds Committee, but nothing dedicated to insect pests. State and federal laws on pests needs better harmonisation (ibid.), and a national list of invasive plants should be produced (Spafford Jacob and Randall 2006).

At the state level, more should be done to control pests that have the potential to compound the impacts of climate change. For example, water buffalo and rising sea levels are both converting Northern Territory floodplains into saline swamps, and although sea level rise may be impossible to prevent, control of water buffalo is practical and warranted (Norris and Low 2005).

3a) Remove 'Sleepers' and Leading Edge Outliers

Small outlying populations of pests, as yet unable to multiply because temperatures are too low, should be eradicated. Examples include prickly acacia stands in northern New South Wales that do not yet produce regular seed (Kriticos et al. 2003c), small infestations of orange hawkweed in alpine Tasmania and Victoria (Kriticos et al. 2006), garden plants in alpine ski resorts (Pickering et al. 2004), and various cacti in South Australia (Darren Kriticos pers. comm.).

The other sleepers to target are species that could multiply dramatically after extreme events such as cyclones, floods and fires. These include athel pines around outback homesteads (Groves et al. 2005), which are spread by floods, and unusual ornamental plants such as Asian gingers, vines and palms grown in the Wet Tropics, where cyclones pose a concern. The Queensland Government has a list of many plants invasive in the Wet Tropics that are potential candidates for eradication (S. Csurhes pers. comm.), but funding for assessment and control is inadequate. The Wet Tropics Management Authority does not presently invest in control of emerging weeds.

A national program to identify and remove climate change sleepers that threaten biodiversity would be very cost effective. A program to remove sleepers that threaten agriculture is already underway, although it does not have a climate change focus (Cunningham et al. 2006). The limited funding invested to date on the removal of sleeper weeds does not reflect the large potential benefits to the nation.

3b) Control Invasive Flammable Grasses

Flammable grasses may represent the single most serious category of introduced invasive species identified by this report, because they can destroy native vegetation over immense areas via a positive feedback loop, which would worsen under climate change. Australia needs a national strategy to coordinate management of these and other flammable grasses. One goal should be to ensure that flammable grasses are not introduced to manage land suffering from salinity, and another goal should be to prevent further plantings of gamba grass and to remove outlying infestations. Legislative controls over pasture plants are a state responsibility, but the Australian Government has a role to play in co-ordinating actions across states and territories.

3c) Institute controls over Biofuel Crops

Plants proposed as biofuel crops are often hardy, low maintenance plants of untested economic value but posing a high weed risk, such as jatropha (*Jatropha curcas*) and giant reed (*Arundo donax*). Controls should be imposed over the cultivation of such plants. These two species are presently prohibited in some states but not others. The Australian government should take a leadership role by disseminating information, coordinating policy responses, and supporting research initiatives to develop environmentally responsible biofuel systems.

4) Incorporate Climate Change into Pest Management

Pest managers need to pay more heed to climate change in pest planning. When risk assessments are undertaken, climate change is seldom explicitly considered. When it is considered, the focus is usually on changing temperatures and rainfall, and not on an increasing frequency of extreme events.

Models for analysing the impact of climate change on pests have been developed (Sutherst et al. 2007, 1996, Kriticos et al. 2003a; 2003b; 2003c). They are being applied to 45 target weeds in a *Defeating the Weeds Menace* project (John Scott, pers. comm.), and to various weeds of concern in New South Wales (Gallagher et al. 2006). These systems do not always consider every variable, such as changing fire regimes and increases in other extreme events, though more detailed analytical systems that consider fire and climate variability have been developed (Kriticos et al. 2003a).

5) Build Ecosystem Resilience

Ecosystems and species face many threats, and biodiversity loss often results from multiple threats operating together. While it may be impossible to avert climate change or to eradicate invasive species, it may be possible to ameliorate other contributing threats, such as pollution, salinity, livestock grazing, nutrification, or over harvesting. Healthier ecosystems are usually more resistant to invasion.

For example, Tasmania is losing kelp beds to an invasive sea urchin, but only because fishermen have removed too many of the lobsters that prey on urchins. Rebuilding stocks of large rock lobsters will increase ecosystem resilience to the sea urchins and reduce risk of further barrens formation. In the Australian Alps, the threat posed by weeds under climate change could be reduced by minimising road and track weed populations (Scherrer and Pickering 2001; Bear et al. 2006). In grazed native pastures, weed invasion can be reduced by keeping stocking rates low.

6) Prepare for Extreme Events

Policy frameworks are needed that anticipate the invasive risks posed by cyclones, floods and other extreme events. Scenario planning could be used to predict the outcomes of different events on different regions. The planning activities should consider which actions have the potential to promote invasions after extreme events, and generate plans to mitigate the risks. Emergency plans for cyclones and floods should include protocols for preventing the spread of weed seeds and other invasive organisms during rescue and clean up operations. Fire crews should also practice pest hygiene, especially when operating in national parks.

In cyclone and flood prone zones, protocols should apply to the design and management of deer farms, zoos, aviaries, quarantine facilities, research laboratories and fish breeding facilities, to minimise the risk of escapes. Ideally, zoos would not be built in cyclone prone regions and exotic fish farms would not be located on floodplains. In the north Queensland cyclone zone, where plant collectors living close to Wet Tropics rainforests grow vast numbers of unusual species of high weed potential, major investment in education and controls is needed.

7) Conduct Strategic Research

There is a need for more research into the interactions between climate change and invasive species. More needs to be known about the interactions between carbon dioxide and C_3 and C_4 plants, fire, soil nutrients, and herbivorous insects and pathogens. Hilbert et al. (2007) list research recommendations, and others could be suggested, for example, the potential of flammable shrubs (gorse, brooms, Spanish heath) to respond to a much higher fire risk in south eastern Australia. A study of native invasive plants, causing problems today because of non climatic impacts (Low 2002), may offer insights into invasion processes under future climate change.

8) Reassess Conservation Values

Native species that benefit from climate change may create conceptual dilemmas if they threaten other native species (Hannah et al. 2005). There could be calls to cull kookaburras and wallabies in Kosciuszko National Park to save lizards and herbfields. If native species threaten biodiversity after they relocate, or after translocation, managers will need to respond coherently. Overabundant or translocated koalas, kangaroos, possums, birds and plants have created dilemmas in recent years unrelated to climate change, raising many of the issues that need to be considered (Low 2002).

Debate is needed about the guiding principles for a world in which conservation is no longer about saving existing ecosystems but about preserving biodiversity by facilitating change.

Workshop Presentations

Professor Lesley Hughes
Department of Biological Sciences, Macquarie University
'Direct and indirect potential impacts of climate change on pest species.'

Dr Dick Williams
CSIRO Sustainable Ecosystems *and*
Dr Ross Bradstock (not presenting)
Director, Centre for Environmental Risk Management of Bushfires, University of Wollongong
'Climate change, fire regimes and Australian landscapes.'

Mr Tim Low
Biological Diversity Advisory Committee (2005-07)
'Disturbance & stress.'

Professor Jann Conroy
Pro Vice-Chancellor (Research), University of Western Sydney *and*
Dr Oula Ghannoum (not presenting)
Research Fellow, Centre for Plant & Food Sciences, University of Western Sydney
'Will rising atmospheric CO_2 concentrations favour invasive species over natives in Australia's rangelands?'

Dr Jo Luck
Statewide Leader, Bacteriology & Virology, Plant Health, Victorian Department of Primary Industries
'Impacts of climate change on pests and diseases of plants.'

Dr Darren Kriticos
Group Leader, Forest Biosecurity and Protection, Ensis – the joint forces of CSIRO and SCION
'Climate change and future species distributions: some implications for biodiversity conservation.'

Dr Ken Green
Alpine Ecologist, Snowy Mountains Region, National Parks and Wildlife Service, *and*
Associate Professor Catherine Pickering
School of Environmental and Applied Sciences, Griffith University
'Emerging climate related threats of pests and weeds in the Australian Alps.'

Professor Craig Johnson
School of Zoology and Tasmanian Aquaculture and Fisheries Institute, University of Tasmania
'Climate change cascades: Shifts in oceanography, species' ranges and marine community dynamics in eastern Australia.'

Workshop Participants

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Dr Doug Bardsley	Department of Water, Land and Biodiversity Conservation (SA)
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Dr Liz Dovey	Department of Environment and Heritage – Australian Greenhouse Office
Mr Michael Dunlop	CSIRO Sustainable Ecosystems
Dr Kris French	University of Wollongong
Ms Rachael Gallagher	Macquarie University
Mr Alistair Graham	Biological Diversity Advisory Committee
Assoc Prof Ken Green	National Parks and Wildlife Services
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