Impacts of Global Change on Australian Temperate Forests

Howden, S.M. and Gorman J.T.

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Foreword

This report describes knowledge about the potential impacts of global change on Australian forests available at the time of the workshop in February 1998. It is a strategic contribution to the development of an understanding of global change impacts on forest systems and is part of a broader study addressing global change impacts on a range of managed ecosystems in Australia. The workshop was kindly supported by both the Australian Greenhouse Office and the Bureau of Rural Sciences. CSIRO Wildlife and Ecology provided rooms and facilities at Gungahlin, Canberra. We would like to thank the members of the steering committee (Dr Roger Gifford, Dr Miko Kirschbaum, Dr Richard Lucas, Dr Ross McMurtrie and Dr Joe Landsberg) who help develop the format and content of the workshop. We also thank the many participants who attended the workshop, many of whom travelled large distances to be there. We particularly appreciated the contributors of written papers and presentations. We thank Penny Reyenga (BRS) for her assistance during the workshop and in preparing this report.

All those at the workshop made valuable contributions. Their joint views defined the overall conclusions of the workshop. Any failure to capture the tone and diversity of these views in the workshop summary may be laid at the feet of the editors.

MH, JG.
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Introduction

Increases in atmospheric carbon dioxide are likely to impact on Australian ecosystems both directly (through physiological responses) and indirectly (through potential climate change). These changes along with other human-induced changes (i.e. ozone layer depletion, land-use changes) are termed global change.

Increasing concern about global change components has generated a diverse variety of research and lead to significant policy responses both internationally and within Australia. For example, the United Nations Convention on Climate Change and the Kyoto Protocol were developed in response to concerns about the potential impacts of climate change. However, even if the Kyoto Protocol is ratified and implemented, carbon dioxide levels will at least double in the 21st century with climate change appearing inevitable. This example highlights the need to understand the potential effects of global change on important ecosystems such as Australia’s forests, rangelands and crop lands.

To date, much of the information generated by global change research has yet to be integrated to investigate the likely impacts of global change on Australian temperate forests. Consequently CSIRO hosted a workshop in February 1998 to bring together researchers to compare results and approaches and to create an opportunity for interaction with policy makers, forest managers and funding providers.

The objectives of the workshop were to:

- *identify the driving factors associated with global change;*
- *assess the possible impacts of these factors and their interactions at different scales;*
- *assess uncertainties;*
- *identify possible adaptation options;*
- *examine ways to further progress assessment if necessary;*
- *develop links between the research community, resource management sector and policy sector to enhance capacity to deal with global change issues;*
- *identify additional research requirements and policy issues.*

The following sections of this document contain a summary of the workshop discussions along with copies of the workshop presentations. Only the presentations for which written papers were provided have been included, however, the content of other presentations have been incorporated into the workshop summary where possible.
Workshop Summary

There are well-documented changes already occurring in many of the fundamental factors that affect the productivity and biodiversity of Australian forests. These include climatic components which are known to strongly influence species distributions and productivity, atmospheric CO₂ levels which are known to affect productivity and UV-B levels which are known to impact on ecosystem processes. Information from a diverse array of systems, regions and processes provides a reasonably coherent and internally consistent picture of existing change that is broadly aligned with expectations of future impacts of human activities such as climate change. Changes in concentrations of CO₂ and other greenhouse gases, increase in UV-B and nitrogen cycling and alterations of landcover are demonstrably of human origin. The balance of evidence suggests that observed climate change is also largely caused by human activities.

Future increases in atmospheric CO₂ concentrations are almost certain notwithstanding the Kyoto Protocol negotiations, with current concentrations (360ppm) approximately doubling to 700ppm by the year 2100 in mid-range scenarios. Global warming in the range 0.5 to 3.8°C is likely as a consequence and regional warmings could be higher or lower than these figures. There is considerable uncertainty about the direction and magnitude of change in regional mean rainfall amounts but increases in rainfall intensity are expected.

These uncertainties in climate change and their interaction with CO₂ and other global change factors combined with the general lack of quantitative studies to date make it difficult to be quantitative about likely impacts.

Given the uncertainty, we adopt a subjective risk analysis approach in this summary based on quantitative studies where possible. This includes the probability of an event occurring; the resources that are at risk and their value; whether impacts were likely to be positive or negative; and whether it is possible to minimize or maximize that impact. These early estimates of the impact risks will be improved as global change estimates became more certain.

We summarise results of the workshop below following the general structure used in the workshop addressing biodiversity, productivity, carbon trading, hydrology and soils, pests and diseases, fire and UV-B increase. Information needs are then summarised.

Biodiversity

The rate of climate change expected over the next 100 years is unprecedented over the past 160,000 years.

Palaeoecological studies show that under past climate changes many species have been able to ‘track’ climate changes and to migrate, often by quite long ‘jumps’ to suitable sites. However, this is likely to be extremely difficult for many species due to the unprecedented likely rate of change, the fragmentation of the Australian landscape and the effects of introduced weeds, feral animals, pests and diseases reducing the suitability of habitat in dispersal sites.
Assessments of the existing climatic ranges of Australian *Eucalyptus* species indicate that many species occupy a very limited temperature range (e.g., 25% have a range of less than 1°C). Global warming of the extent expected over the next decades will result in many species having their entire population exposed to temperatures under which no individuals currently exist. There is some uncertainty as to the implications of this as species boundaries may not be the result of direct climatic limitations but may be due to competition or other factors. Furthermore, there is a theoretical expectation that the temperature optimum of plants with C3 pathways (includes all trees) may increase with increased CO2. Nevertheless, there is likely to be a reduction in fitness and abundance of these and other species in their current locations and, if migration is not successful, some species may become endangered or even extinct.

Such climate envelope studies (e.g., using CLIMEX) are one way to investigate potential requirements for changing ranges of species. However, existing climate limits may be related to the realised niche rather than the fundamental niche, leading to errors in extrapolation to climate change scenarios. Improved physiological data can more effectively identify the fundamental niche but considering Australia has a megadiverse biology, such work is unlikely to be comprehensively completed.

Different growth and phenological responses combined with different rates of migration and survival and different climatic envelopes will inevitably change the abundance and distribution of plant species, competitive relationships between these species, community structures, and possibly ecosystem function at any given location. There may be interactive effects through logging, recreational use, fire management and fragmentation.

Changes in temperature are also likely to affect fauna with an increase of 3°C resulting in almost 60% of the species studies in SE Australia losing 90-100% of their existing range although the forest species studies may tolerate such change more than those from other environs.

Changes in rainfall are also likely to affect species distributions. About 23% of Australian *Eucalyptus* species have ranges of mean annual rainfall that span less than 20% variation. Even though climatic tolerances might be larger than the climatic envelope they currently occupy, if even a moderate proportion of the present day boundaries reflect climatic tolerances, substantial changes in the forest flora can be expected with global change.

There appears to be considerable variation between species in ability to respond to CO2 increase. This could be a result of differences in photosynthetic acclimation. There may also be species-specific changes in phenology in response to CO2.

CO2 responses may also differ between locations with both more nutrient rich, warmer and drier sites likely to respond more to increased CO2 levels. In such sites, increased growth may lead to greater litter loads and hence risks from fire damage.

Higher CO2 is likely to reduce leaf nitrogen contents particularly in some locations where nutrient cycling is slowed. This is likely to have negative impacts on herbivores (some of which are seen as desirable such as koalas and some of which are perceived as
pests). The tourism industry is highly dependent on forests and forest animals (e.g., 75% of overseas tourists hope they will see a koala and 11% wouldn’t come if there was no unique wildlife) and so changes in abundance of sought-after fauna may have large economic impacts. The above effects on foliage quality may be increased if high CO₂ also slows soil nutrient cycling processes although this is likely to be species and situation dependent.

There is currently substantial clearing of native forest for plantations, agriculture or urban development and this will impact on biodiversity. Establishment of plantations has increased markedly over the past decade due to various economic and policy drivers and establishment rates may increase further if the Kyoto Protocol comes into force. The workshop participants thought that impacts from possible carbon trading regimes may be the most rapid and significant impact of global change on Australian forests and their component organisms.

Many of the above factors can interact, however, there is currently no framework for integrating these impacts. As an initial step towards this integration we provide below a subjective risk analysis. This analysis suggests a high likelihood of global change having a negative impact on biodiversity in Australian forests.

![Biodiversity Graph](image)

**Adaptations for minimising impacts of global change on biodiversity**

Given the likelihood of negative impacts of global change on biodiversity, there is a need to form adaptation strategies. These could include:

- Increase reserve areas and ensure that reserve design incorporates corridors or stepping stones to assist in migration of flora/fauna. One improvement over the existing situation would be to reduce fragmentation where possible. The role of on and off-reserve forested areas, corridors and biolinks in biodiversity conservation needs study and

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1 The diagram is based on the workshop papers and discussions. The component changes such as rainfall are plotted individually in terms of whether they are likely to increase or decrease biodiversity. The span of the lines indicates the likely range of possibilities of impact based on uncertainties in both the change itself as well as the impact this may have. These components are integrated to give an approximate probability distribution of impacts. This could be read in this case as: There is a high probability of, say, temperature change having a negative impact on biodiversity and virtually no probability of it having a positive impact. Overall there is a low probability of global change impacts on forest biodiversity being positive and a high probability of them being substantially negative. These results are of course location and time dependent but at least may provide a starting point for planning.
critical evaluation given the possible rates of change. Aiding migration by providing ‘stepping stones’ rather than corridors or assisted migration may be other options although raising their own issues such as competitive exclusion of existing species. An alternative viewpoint was that increasing reserve area would increase the pressure of use on remaining areas thus having counter productive effects on conservation.

- Ensure that there remains flexibility in reserve allocation as there are many areas of uncertainty concerning global change. Fixing boundaries of conservation areas based on current knowledge (such as in the current RFA process) may be problematic as species distributions may change in the near future and conservation boundaries may need to change with them. An alternative view was expressed that flexible reserve boundaries may shrink due to political/economic pressures. If fixed boundaries continue to be adopted, selection of areas with diverse age and species structure will aid adaptation.

- Maintain healthy forests with full spread of ages classes, structure and species composition.

- Focus on those species that have a narrow climatic envelope which are thus vulnerable to small climatic changes, by developing models and historical information on distributions (generalist species were thought to be less likely to be severely impacted upon by climate change). Analysis of dispersal mechanisms and ecology of these species could help establish management or recovery plans. There remained uncertainty as to whether there should be action to help move communities or assist them in persisting in existing locations. A key concern was that species may be more likely to be affected by migration of other species (either natural or assisted) than actual change in climate.

- Identify indicators for impacts and perhaps include them in an existing activity such as those for the Montreal Process Indicators. It was seen as imperative that the monitoring of indicators is carried out so at the very least we have some reasonable baseline data. There remain many issues to be resolved such as the scale of monitoring, whether to monitor species, functional groups or other groupings, species interactions, ecosystem processes or other indicators.

- Develop institutional processes so that change in the above indicators can be linked to global changes and acted upon to reduce impacts in a systematic way by including projections of future change. This requires an improved capacity to model global change impacts on forests. The current RFA processes don’t include consideration of global change.

- Recognise the roles, rights and responsibilities of Aboriginal people in conserving biodiversity.

- Provide information to the broader community as there is a lot of community interest and there is a need to work together on this issue.

In most of the above adaptations, there is a need to recognise the trade-offs in resourcing to conserve against global change impacts compared with other biodiversity threats. For example, it was suggested that removing funding from the current fox control programs could have an equally big impact on biodiversity as global change.
Productivity

Demand for softwood is increasing with expectations that it will provide about 75% of Australian forest products by 2020. Policies such as Plantations 2020 and those adapting to global change in response to the Kyoto Protocol are assisting plantation development, resulting in substantial expectations of land use change. The impacts of such changes on conservation trade-offs and provision of ecosystem services (eg water yield) needs to be assessed.

*Pinus radiata* is the major plantation softwood species in southern Australia. It can be grown in areas that are both phosphorus and water limited and is largely grown under conditions that are considerably warmer than where it is found naturally. The absence of pests, disease and competitors allows it to grow successfully across that wider range, but it is approaching its physiological limits and any further warming may cause production declines in northerly regions.

The possibility of an oversupply of softwoods over the next decades was raised as a result of increased supply both domestically and internationally. Any oversupply may 1) be exacerbated by global change possibly increasing productivity of some northern hemisphere forests as already appears to be happening or 2) damped by reduced production in tropical countries due to both management, policy and climate impacts. Improved marketing and end-use product development (eg more products to substitute for fossil-fuel intensive products such as steel and concrete) may be needed if significant oversupply appears likely.

Hardwood plantations are an increasingly significant component of the Australian forest industries. These species (largely *Eucalyptus*) are also tolerant of nutrient limitations and water stress but there are likely to be provenances that can tolerate warmer temperatures than currently exist. Identification and use of these genotypes could be an adaptation option.

Global supply and demand for hardwoods is likely to be volatile over the next decades. Global change may negatively impact on tropical hardwood supplies through climate change, increase in fire hazard and land use change, resulting in increased demand for Australian hardwoods.

CO₂ fertilization is likely to increase growth of both softwoods and hardwoods by up to 30% with doubling of CO₂, especially where trees are water limited but where soil fertility is adequate (eg karri forests). CO₂ response is likely to be lower (up to 16%) in nutrient limited conditions (eg ACT) and where soil moisture is not limiting (eg central-north Tasmania). However, the above growth estimates are based on short-term experimentation and it is uncertain whether such rates can be continued in the long term due to various acclimation processes and environmental feedbacks through nutrient cycling.

Where trees are not subject to water limitations, increased temperatures may expand the growing season of forests, particularly in southern Australia. However, higher temperatures will increase water use of forests, reducing productivity in some sites and partly offsetting the increases in productivity that arise through increased CO₂
concentrations. Increase in fire hazard may also be significant (see section on fires).

Reductions in rainfall or changes in seasonality that result in water limitations or prolongation of droughts would negatively affect production and seedling establishment. The establishment phase was seen as the most susceptible to climatic changes. Increases in rainfall are likely to have generally positive effects although in higher rainfall areas the relative magnitude of this will be smaller. The lack of directional rainfall change in scenarios limits projection of such effects.

There is an expectation that rainfall intensity will increase with climate change. More intense rainfall events would exacerbate soil erosion and pollution of streams during forestry operations making these operations more difficult and costly.

There remains uncertainty about the likelihood and degree of the above impacts and forest managers considered that in most cases there were higher priority issues to address with the limited resources available. Nevertheless, South Australia has established a monitoring program to inform them of significant changes so that they can take adaptive action. An unmistakable climate change signal was seen as necessary to instigate substantial change in operational management.

Adaptations to productivity change

In northerly locations, assess risks in locating new *P. radiata* or replanting harvested stands with this species and upgrade management of existing stands to reduce fire and pest/disease hazards.

Select provenances with higher temperature optima and maintain gene pool by collecting across regions for adapted species.

Develop forests with a rotation timestep of 15-20 years rather than 80-100 years to enable incremental adaptation and reduce risk of incorrect decisions.

Maintain nutrient status of forests and develop management options (eg thinning) suited to changed climates.

Establish new forests where soil depth is adequate for soil moisture buffering if drought spells increase.

Enhance capacity for erosion control.


**Carbon trading**

. The Kyoto Protocol, if it comes into force, commits Australia to legally-binding emission reduction targets.

. The possibility of forests acting as carbon sinks within an as-yet-unspecified carbon trading system means that the value in the forest estate is not just the existing production, ecosystem service and conservation values and this could be a strong investment driver. However, developing substantial carbon sinks (especially plantations) will have its own effects on agricultural landuse, biodiversity, environmental services (decreasing water supply down catchment, decreased environmental flows), fire regimes, soil processes (increasing acidity if pines planted) and supply/demand for wood and wood products. There is a need for projection of likely landuse change to ensure a balanced outcome and this will need socio-economic as well as biophysical analyses consisting of both data collection and modelling. An alternative approach to reduce emissions is to use biofuels to substitute for fossil fuels. The widespread establishment of such a landuse will have significant impacts on the above factors as well as the existing timber industry via competition.

. Global change is likely to impact on carbon storage rate and potential and this will need to be integrated into such studies. Furthermore, palaeoecological records and understanding of photosynthetic physiology suggests that increased CO₂ may enable forests to expand to lower rainfall areas providing soil and nutrient requirements are adequate.
There are several policies which could enhance carbon storage through native forest management and facilitating new forest establishment including those in the ‘Safeguarding the Future’ Environment Statement of 1997, the National Greenhouse Strategy, the Plantation 2020 policy and the Natural Heritage Trust. The effects of these policies need to be projected to the commitment period of 2008 to 2012 to reduce uncertainty as to the national ability to meet Kyoto targets. This uncertainty also relates to the scope of the Protocol but this should be resolved via the IPCC Special Report on Land Use, Land Use Change and Forestry and subsequent negotiations. The potential impacts of increases in forest areas on agriculture, environmental services (e.g., water yield) and biodiversity conservation need to be assessed in the light of this resolution and the policies and instruments that follow.

Comprehensive monitoring and verification of changes in greenhouse emissions relating to forest activities is a significant challenge which should be assisted through the National Carbon Accounting System, the new Cooperative Research Centre for Greenhouse Accounting, the National Greenhouse Gas Inventory and other activities such as the Greenhouse Challenge Vegetation Sinks Workbook. At the moment the capacity to model the impact of management on changes in carbon stocks in mixed forests, under land use change, with species changes and in soils (including charcoal) is assessed to be poor.

Hydrology and soils

Forest hydrology is very sensitive to changes in climate with slight changes being magnified when transferred to key variables of soil moisture, recharge and runoff. Changes in forest hydrology may influence nutrient cycles leading to additional impacts on growth in the long term.

Increased CO₂ tends to reduce stomatal apertures thus increasing water use efficiency. This can result in improved leaf water potentials resulting in higher leaf expansion rates and larger leaf areas. Consequently there may not be large changes in total water use at a catchment basis. However, there could be small increases in periods with adequate soil moisture which could increase rates of nutrient cycling, slightly increase subsoil drainage and increase forest growth periods. The net result could be the potential distribution of forests moves towards drier bioclimes. There may also be small increases in catchment water yields.

Increased CO₂ can reduce salinity impacts by lowering salt concentrations in leaves. However, increased recharge with increased CO₂ (particularly if rainfall increases) may
result in increases in salinisation risk.

Forest growth models linked to soil nutrient cycle models indicate that there will be significant growth response to increasing CO₂ levels (about 10-20% with doubled CO₂). However, this response will be mediated by nutrient availability with small responses if nitrogen and other nutrients limiting. Increased CO₂ will tend to decrease the water limitation thus increasing the area of forests which are likely to respond to nutrient additions.

 Increases in temperatures may have negative impacts on forests in northern Australia due to increases in evapotranspiration, pest attacks and fire frequencies. In parts of southern Australia where temperature currently limits growth, temperature increases may increase the length of the growing season. In both environments, increased temperature is likely to increase mineralisation of organic matter, leading to increased nutrient availability but this may be offset by reduced organic carbon levels, decreasing soil stability and water-holding capacity.

There is uncertainty about both direction and magnitude of changes in rainfall means. However, it is likely that changes in rainfall means will be amplified and the level of amplification will be greater in drier catchments. Changes in rainfall are unlikely to have significant impacts on soil moisture in wet catchments but are likely to also be amplified in dry catchments resulting in significant increases in drought frequency if rainfall decreases.

 Extreme climatic events, particularly high intensity rainfall events, are likely to increase, with this substantially increasing flood and erosion risk. There may also be an increase in frequency of El Niño events and possibly cyclone frequency which can have marked impacts on forests both directly and indirectly (eg through fires).

There remains uncertainty regarding the relative importance of the changes in mean rainfall vs extreme events.

There is a lack of good spatial soil, forest condition and other data which is needed to improve the usefulness of predictions.

**Adaptation options for hydrology and soils**

- Develop regional risk assessments addressing how major species may respond to changes in soil moisture, nutrients and other factors to select ‘best’ species type and rotation length.
- Focus on shorter rotations to maximise flexibility.
- Include global change impacts in catchment planning activities.
- Develop better data on soils, forest condition, management impacts.
- Improve capacity to model regional rainfall change in GCMs and to downscale these results.

We present no risk assessments as the uncertainty in the scenarios and processes and the variation in the values attached to these ecosystem services makes a coherent
generalisation of impacts unviable.

Pests and diseases

There is considerable difficulty in developing scenarios of pest and disease impacts on forests under global change due to uncertainties in the direction and magnitude of climate change, the relative magnitudes of change in climatic and other components (e.g. landuse change, CO₂ increase, nitrogen deposition), the stress levels from other disturbance events (e.g. fire), the proximal drivers of insect outbreaks and the lack of detailed studies to date. There is also likely to be variation in response due to specific environmental conditions and to individual species responses. For example, herbivory response in some tree species may result in negative feedback to pests through induced defenses, or through resource degradation. In other species, herbivory responses may result in positive feedback to pests through the replacement of lost foliage with younger tissue, but this is conditional on the growth conditions for the plant being adequate.

Pest organisms usually have high reproduction rates, short generation times and efficient dispersal mechanisms, which allow them to respond rapidly to changes in both weather and climate. Hence changes in pest abundance and distributions are likely to be one of the earlier and most significant impacts of climate change on Australian temperate forests as they have been found to be overseas. Impacts are not likely to be restricted to flora as fauna already stressed by other global change variables might be further impacted on by the effects of these disease/pests.

Elevated CO₂ impacts on disease will depend on the interactions between hosts, pathogens and the environment. Enhanced carbohydrate levels that can occur under higher CO₂ can promote the development of some pathogens such as rusts but inhibit others such as mildews. The effect on pests is variable, but slightly poorer dietary quality with high CO₂ (about 10% reduction in leaf N% with doubled CO₂) has been shown in some cases to be partly compensated for by insects through an increase in total intake, the net result being relatively minor. In other cases, there were more significant impacts through disruption of the relationship between the phenology of pests and their hosts.

Forests would have high potential for outbreaks if climatic conditions became more favourable for plant growth, responses were not restrained by resources and herbivorous insects and host plants had flexible growth curves and activity cues. In areas where global change increased the environmental stress on plants, sap-feeding insects may be favoured.

Relatively small increases in temperatures in cold and temperate environments may increase the periods favourable for growth and activity for plants, insects and their enemies and may result in new areas being exposed to colonisation by certain pest species. This could be particularly important if pest populations will be able to increase each spring from residual over-wintering populations, rather than being dependent on the arrival of immigrants each year. Overseas experience already shows that such changes in temperature effects can result in extremely large increases in forest damage. However, there will also be a number of pest species which need cool conditions and their ranges are likely to contract.
Rainfall changes are likely to be critical factors in determining impacts. Hot, moister conditions may benefit the dispersal of many diseases. In contrast, if rainfall becomes more variable or is reduced during the growing seasons, discontinuity of growth and variation in tissue quality may disrupt the life-cycle of pests.

Changes in wind patterns could deliver migratory pests to new areas which could have implications for natural ecosystems as well as biological control programs. However, current GCM projections do not provide clear indications of such changes.

Either the construction of corridors between areas of native vegetation to assist in species migration and maintenance of biodiversity or an increase in plantations as a consequence of a carbon trading system are likely to assist in the movement of pests and diseases across regions. Similarly, management can affect pest/disease risk through removal of understorey species which harbour predators, limiting spread of organisms such as *Phytophthora* through quarantining areas, introduction of vigorous exotic pasture species or weeds, or environmental degradation such as compacted or waterlogged soils which increase plant stress and thus susceptibility.

### Adaptations to minimise impacts of pest and diseases

- Changes in quarantine resources to ensure stricter quarantine control to minimise entry of new pests and diseases into Australia.
- Where practicable, change silviculture practices away from monoculture to mixtures of species or mosaic blocks of different species. The point was made that no forest monocultures have previously collapsed, thus growers are unsure if this is a problem.
- Increase and/or maintain the genetic base of those species planted to reduce risk including more selection for resistance to known problems.
- Improve management to prevent trees getting stressed and develop techniques to identify when they are getting stressed.
- Research to determine which existing problems might increase with global changes.
- Identification of hazardous pests/weeds to focus control and monitoring.
- Funding research to better understand pest/host relationships in the context of global change to establish a basis for adaptation.
Establish monitoring program that will systematically enable impacts of climate and other factors to be interpreted so that management can flexibly adapt.

Assess whether forest corridors assist pest/disease migration and if so investigate management options.

Develop better impact scenario analyses to aid managers in planning.

**Fire**

Fire is an integral part of the ecology of many Australian forest communities and species have developed different strategies (eg ‘seeders’ vs ‘sprouters’) to compete successfully under prevailing regionally-variable fire regimes. Changes in fire regimes are highly likely to change the proportions of species with different strategies with possible repercussions on biodiversity and ecosystem functions such as hydrology.

The McArthur fire danger index commonly used in Australia is a function of fuel load, air temperature, relative humidity, wind speed and a drought factor based on rainfall and temperature. Whilst the index seems overly sensitive to some factors such as humidity and wind speed, it seems a reasonable indicator of fire intensity.

Values of this index increase under global change scenarios due to:

- increased fuel load expected under higher CO$_2$ levels due to increased growth, particularly if reductions in wood and litter nitrogen concentrations reduces decomposition rates. This is likely to make fires spread faster, be more intense and more difficult to control.

- increased temperature which will increase fuel dryness and reduce relative humidity (if other factors remain equal) although global circulation model results remain equivocal regarding humidity changes due to interplays between many factors such as evapotranspiration rates and rainfall. They are also uncertain about changes in wind speed. However, fire danger was assessed as unlikely to decrease with climate change unless the atmosphere becomes significantly moister and cloudier.

- reductions in rainfall may enhance the meteorological factors that drive fire danger index whilst increases in rainfall may increase the fuel load factor. The trade-off between these factors are uncertain and likely to differ between situations and climate change scenarios.

Fire danger index calculated from GCM results suggests an increase in fire danger across much of Australia with climate change.

Ignition frequencies are likely to increase through both increased human usage (and attitudinal changes) and suggested increased lightning strikes due to greater convective activity.
Increases in fire frequency and intensity may lead to the following impacts:

- greater demands on fire prevention and fighting services;
- decline in forest age and vigour due to changes in frequency of fires reducing soil nutrient status although this may be partly balanced by other global changes such as increased CO₂;
- slow changes in dominant composition due to altered fire regimes with shifts between the mix of ‘seeders’ and ‘sprouters’ which may ultimately threaten survival of some species;
- increased invasion of weedy species because of increased opportunity after fires;
- degradation of quality of forest products, wood values and soil degradation;
- loss of ecosystem services such as reduced water supply resulting from re-growth forests transpiring increased amounts of water after fire;
- changes in wildfire duration, intensity and frequency leading to impacts on prescribed burning regimes;
- forests may become a source of carbon dioxide and other emissions during the transition periods whilst composition and structure adapt to the new fire regime.

Increases in areas of forests due to existing drivers of land use change as well as possible new incentives for plantations associated with the Kyoto Protocol will mean increased opportunity for fires and increased economic losses from these.

**Forest fire danger**

 adapted to fire management

Given the likelihood of increased fire danger there is a need to develop adaptive strategies. These could include:

- a commitment to progressive adaptations to on-going change. These might include tracking changes in litter loads and meteorological variables to continuously adjust fuel reduction burning schedules; improving fire fighting capacities, increased use of long-term, seasonal and short term climate
forecasting, establishing monitoring systems including historical and current information baselines.

- funding to increase management flexibility particularly to experiment with a greater range of prescribed burning regimes and greater fire suppression flexibility.

- research to better forecast fire danger for specific forest types and to better understand the ecological impacts of changing fire regimes including identification of the species/groups most likely to be affected.

- improved (ie less uncertain) global change scenarios so that planning can be more effective.

**Ultraviolet Radiation**

- Chlorofluorocarbon and other halogenated gas emissions have depleted the Earths stratospheric ozone layer resulting in substantial increases (about 7.5% increase per decade) in damaging ultraviolet radiation over southern Australia. This trend is expected to continue over the next decades potentially doubling pre-1960s levels of UV-B exposure if it continues for another 40 years with even higher levels possible in southern Australia if the ‘Antarctic ozone hole’ continues to grow.

- Ultraviolet radiation damages DNA and membranes, reducing plant growth and affecting reproduction and phenology, with $C_3$ plants (eg trees) being more severely affected than $C_4$ plants (eg many forest weeds). Increases in CO$_2$ can offset some of these impacts in some cases.

- Increased ultraviolet radiation can reduce the growth response to CO$_2$.

- We present no risk assessment diagram as the impacts are consistently negative

**Other Issues**

There are a range of pertinent, ongoing social changes that can impact on our forests that were considered beyond the scope of this workshop but this does not imply lack of importance. These include particularly change in attitudes to the balance between conservation and production, increased arson risks in forests near urban areas, increased risk of introduction of new pathogen and/or weed species, impacts of genetic engineering, changes in demands from tourism and recreation and issues relating to Aboriginal occupation, tenure and use. Any or all of these will interact with global change issues.

**Next steps**

- the participants responded to several questions arising from the workshop. The questions and interpreted summaries of the responses are:
Can we translate current knowledge into action?

Uncertainties in current climate change scenarios strongly limited the willingness to take substantive management action by the forest managers and industry groups. Nevertheless, they saw value in assessing likely susceptibilities of forests given directional change in climate. This included the development of analytical capabilities such as models of forest response to fire and better capacity to link theory with management (eg issues such as biodiversity conservation, identification of critical thresholds for change). There was also general agreement that one concrete action that could be taken is the establishment of a monitoring program including long-term sites (such as those already established in South Australia) combined with remote sensing. Global change is but one of many issues that need to be managed.

Are there precedents to guide the level of uncertainty needed?

Forest managers and industry groups though that high levels of certainty of change were needed before management was likely to be altered due to the dominant effects of timber pricing. However, if the direction of change was clear then adaptation was likely. There remain problems in providing such directional change from current global climate models (particularly of rainfall) and better downscaling of global climate models remains a key need. Whilst there was general acceptance that climate was already changing, industry and forest managers did not feel a need to respond as at least the climate parts of these changes cannot yet fully be attributed to human activity. In contrast, conservationists were more willing to accept such changes as a motivation for altering management and tended to adopt a precautionary principle approach.

How will we know that global change is impacting on our forests?

Most participants viewed that theory, models, experimental evidence and experience were adequate to define likely impacts of foreseeable changes. These particularly included changes in vigour, forest type, condition, density and nutrition in areas near current climatic limits and changes in incidence of disturbance factors such as fire frequency and pest and disease attacks. A monitoring program with a combination of remote sensing techniques (including forthcoming satellite radar platforms), long-term sites and transects in likely sensitive locations and an expanded set of Montreal Process Indicators was suggested. Bioindicators (tree rings, sensitive species) have already proven to be effective global change monitoring tools in some locations.

Are we in a position to advise what level of resource to invest in monitoring and analysis for effective adaptive management?

The lack of directional impacts was seen as restricting the capacity to advise on this issue. Nevertheless, incorporation of appropriate indicators into the State-of-the-Environment and Montreal Process indicators was seen as a cost-effective pathway of providing some data. What data is collected needs to be compatible with existing analytical tools (eg models) to enable more effective interpretation. The precedent set by the planning of the South Australian monitoring sites suggests that it is sound management practice to establish such capacities.

Are the tools in place to do analyse global change impacts?
There are several quite advanced tools developed in Australia. These include CLIMEX, Bioclim, CENW and 3-PG. There is the capacity to integrate some of these with remote sensing information in quite sophisticated ways to investigate growth responses. However, there was a view that we need more complex ecological models (eg species replacement and competition models) to understand likely forest impacts and that the existing capabilities only address separate components of the issue. There was concern that we don’t yet have the understanding to also effectively aggregate these processes over spatial and temporal scales. If further analytical capability is developed it needs to be tied in with the monitoring processes described briefly above. Furthermore, a data and tool-sharing policy needs to be developed between different organisations to ensure maximum efficiency of expenditure and to place the debate of a common footing. Poor resource descriptions (eg soil information) seriously limits broadscale assessments.

*Is the R&D in place to adequately contribute to decisions relating to global change?*

Whilst there has been some progress developing some of the techniques and tools for addressing many of the issues relating to global change and Australian forests, much of this work remains inadequate to quantify nationally the possible impacts and define clearly management adaptation. The lack of capacity to quantify is epitomised by the use of qualitative rather than quantitative responses earlier in this summary. The inability to deliver goes through the R&D chain from climate change scenarios, to growth responses (including pest/disease impacts), species changes, management implications (eg fire management), biodiversity planning, industry planning, and carbon stock issues. Without addressing capabilities throughout this chain, there will continue to be stark limits in both the quality and timing of advice able to be provided to Australian governments, industry and the public. Overseas experience has already shown that global change impacts through increased pest/disease impacts and forest fire frequencies can occur rapidly and have large local, regional and national consequences. Preliminary analyses suggest that Australia can suffer similar impacts. There is thus a need to establish a medium-long-term, structured research and monitoring program. Australia is in the fortunate position of currently having some of the worlds pre-eminent workers in these fields. Development of a modest but well-designed R&D program is thus highly feasible. This will require communication between industry, researchers, governments and interested public organisations. The current relatively low priority placed on global change research by the forest industry and the key short term impacts most likely falling on biodiversity, bushfire risk and pest/disease risk suggests that initial impetus for such a program will most likely need to come from public funding. This report provides much of the information and a risk assessment procedure to guide development of such a program.
Current evidence of global change and its impacts

Howden, S.M.,1,2 Reyenga, P.J.2 and Gorman, J.T1
1. CSIRO Wildlife and Ecology, GPO Box 284, Canberra, ACT 2601.
2. Bureau of Resource Sciences, PO Box E11, Kingston, ACT 2604.

Introduction

The worlds ecosystems are being subjected to changes in atmospheric composition, climate and landuse, here referred to as global change. Management for the possible impacts of global change on Australian forests has to be made in the context of existing risks and risk management practices. In its simplest form, risk management requires assessment of both the likelihood of occurrence and the magnitude of impact. Changes in forest management practices will occur when the potential impacts of global change are seen as both likely and of sufficient magnitude to warrant action. In commercial forestry operations, an additional element for consideration is the immediacy of the changes as long-term impacts will be discounted following normal investment practice. In a recent national workshop on global change and Australian forests, participants persistently stated that substantial adaptive action was unlikely given the uncertain nature of the global change scenarios currently available. This view seemed to arise from a belief that global change was something that will happen only in the future and that it was largely a theoretical construct based upon the uncertain results of global climate models. However, there is substantial evidence that global changes of various types are already occurring and that some of these changes are already likely to be having an impact on Australian forests and other ecosystems. This paper outlines briefly the evidence for such changes in Australia and elsewhere and casts a broader net than just forestry issues. However, this is a limited review as an exhaustive compilation of relevant studies would take several volumes. Neither is it an assessment of the potential impacts of global change on ecosystems as these are dealt with elsewhere in detail (eg Watson et al. 1998). There is ongoing debate about the influence of human activities versus natural variability on some of the trends documented below and these viewpoints will be noted. However, in either case, continuation of these trends is likely to have impacts that require adaptation responses.

Atmospheric change

Human activities including the combustion of fossil fuels, deforestation, agriculture and industry have resulted in well-documented changes to the composition of the atmosphere (e.g. Manning et al. 1996). Gases which have increased in concentration include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and chlorofluorocarbons, all of which trap radiative energy, thus making the earth warmer than it would otherwise be. The current atmospheric CO₂ concentrations are about 30% higher than in pre-industrial times and are currently increasing by about 0.4% per year (Manning et al. 1996: Fig. 1) while methane (CH₄) and nitrous oxide (N₂O) have grown by about 145% and 15% respectively in the same timespan (IPCC 1996). Analyses with global climate models conclude consistently that the increasing concentrations of these gases has already had an influence on global climate (e.g. Cubasch et al. 1997, Rowntree 1998) and will result in further climate changes (e.g. Wilson and Hunt 1997) although there remains uncertainty as to the nature of these changes at regional levels. Increases in sulphate aerosols and particulates in the atmosphere are assessed as having offset some of the surface warming due to the accumulation of greenhouse gases.
Impacts of Global Change on Australian Temperate Forests

(eg Reader and Boer 1998, Saxena and Yu 1998) whilst accumulation of ozone in the troposphere (0-12km altitude) is likely to have resulted in additional surface warming (Bernsten et al. 1997). The observed climate change is consistent with the combination of greenhouse gas and aerosol forcing (eg Hegerl et al. 1997).

**Figure 1** Atmospheric CO$_2$ levels from ice cores (Etheridge and Wookey 1989, Etheridge et al. 1996, 1998, Morgan et al. 1997) and direct measurement from Mauna Loa (Keeling and Whorf 1998)

The observed increases in CO$_2$ levels in conjunction with temperature change may already be increasing plant productivity including forest productivity (Feng 1999) and Australian wheat yields (Nicholls 1997). Increasing CO$_2$ is also expected to increase the competitiveness of shrubs and trees (with the C$_3$ photosynthetic pathway) compared with warm season grasses (C$_4$ pathway) and the increasing dominance of these ‘woody weeds’ in many ecosystems is partly attributed to this (eg Polley et al. 1997) although changes in fire regimes and other factors are also likely to have a major influence (eg Archer et al. 1995)

The incidence of acid rain that has been so damaging to northern hemisphere forests and other ecosystems (e.g. Schulze et al. 1989) is much lower in Australia (Australian Environmental Council 1989) although there are regional and local variations in hazard; for example near power stations (Robinson et al. 1995).

**Temperature change**

There is evidence accumulating from a diverse array of sources that temperatures have been changing at both global and regional scales during the past century (e.g. IPCC 1996, Briffa et al. 1995, Pollack et al. 1998). This change appears to be continuing with global-averaged temperatures for both land and ocean during 1998 far exceeding all previously recorded temperatures (Figure 2). The global mean temperature was 0.66°C above the average based on
Figure 2  Global mean ocean and land surface temperature variations from a 1880-1997 baseline. (Jones et al. 1999).

the period 1880-1997, exceeding the old record (in 1997) by 0.15°C. Record land and sea surface temperatures were 1.02°C and 0.51°C above average, respectively. Global reconstructions of temperature records indicate that northern Hemisphere mean annual temperatures for three of the last eight years are warmer than any other year since at least 1400 (Mann et al. 1998) when this record began. This analysis is supported by sub-surface geothermal measurements (Pollack et al. 1998).

Minimum daily temperatures have tended to rise faster (about 0.15 °C per decade) than the maximum daily temperatures (about 0.07 °C per decade), which means that the day-night difference (the diurnal temperature range) has decreased in most places, by up to 0.12°C per decade (Kukla and Karl 1993, Salinger 1995, Zeng et al. 1997). There have been suggestions that variations in solar activity have been instrumental in these recorded warmings (e.g. Friis-Christensen and Lassen 1991) as well as changes in solar luminosity (Hoyt and Schatten 1997), decrease in volcanic stratospheric aerosols (Wu et al. 1990) and decreases in stratospheric ozone (Gates 1993). However, recent analyses (e.g. Hegerl et al. 1997, Cubasch et al. 1997, Rowntree 1998, Mann et al. 1998, Tol and de Vos 1998) suggest that whilst these factors have had an influence, changes in greenhouse gas concentrations are most likely to be responsible for a large component of the temperature changes observed during this century.

When corrected for volcanic and El Niño effects, temperatures in the troposphere (the lower 12 km of the atmosphere) have increased by about 0.1 °C per decade since 1958 (Allen et al. 1994, Jones 1994, Salinger et al. 1996). This is very similar to the recent estimate of 0.11 °C per decade derived from satellite-based microwave sensors for the period 1980-1996 (Prabhakara et al. 1998, Hansen et al. 1998) and the value of 0.093 °C per decade for the shorter period of 1979-93 (Jones 1994). There was in the past an apparent contradiction between the satellite-based data which appeared to show a cooling of the troposphere (e.g. Christy et al. 1995, 1998) with the surface data which showed a warming (eg Jones 1994). However, recent analyses which have allowed for orbital decays (Wentz and Schabel 1998)
and calibration factors on successive satellites (Prabhakara et al. 1998) appear to bring the satellite estimates into line with the surface measurements.

Recent warming trends have also been found in Australia using high-quality surface temperature records (Plummer et al. 1995, Torok and Nicholls 1996) and are supported by data from dendrochronological (tree ring) studies (e.g. Cook et al. 1991). Annual minimum temperatures have increased by 0.85 °C per century and maximum temperatures by 0.39 °C per century (Wright et al. 1996). These increases have not been spatially nor temporally uniform (Figures 3 and 4) with minimum temperatures increasing more in the north-east part of the continent and greater increases occurring in autumn, particularly in May (McKeon and Howden 1993, McKeon et al. 1998). Part of this autumn warming in the north-east may be related to recorded increases in sea surface temperatures in the Coral Sea (Salinger et al. 1996, Zheng et al. 1997) which appear to be resulting in increased incidence of coral bleaching in this region (Jones et al. 1997). Upper ocean temperatures have been increasing globally too (eg Fig. 2) with these changes from 1955 to 1996 being consistent with the increase in net radiative forcing arising from increased concentrations of both greenhouse gases and aerosols (White et al. 1998) although long term natural variability may be influencing temperatures too (eg Latif et al. 1997). Mean temperature increase of 1.1°C off the west coast of the USA over the past 22 years due to increased frequency of warm El Niño events has had a significant impact on coastal ecosystems with large declines in species richness and abundance, trophic structure and productivity (Holbrook et al. 1997; McGowan et al. 1998).

**Figures 3** Trends in mean annual minimum temperatures (°C per century) for Australia (Bureau of Meteorology).
The increased minimum temperatures recorded in Australia may be partly related to a 5% increase in cloud cover since 1910 (Jones 1991, Jones and Henderson-Sellers 1992). This trend is similar to that recorded globally (McGuffie and Henderson-Sellers 1994). The change in cloudiness appears to have resulted in significant decreases in solar radiation in both coastal and inland Queensland in autumn and winter and increases in vapour pressure in May (McKeon et al. 1998).

The trend to warmer temperatures appears to have already reduced frost frequency and duration (Stone et al. 1996) thus increasing Australian wheat yields (Nicholls 1997) and increased the frequency of heat stress in livestock (Howden and Turnpenny 1997, Howden et al. 1999). Warming trends in other continents also appear to be having impacts on ecological and other processes. For example, there has been pronounced warming in the period 1961-1990 over substantial areas in Alaska, northwestern Canada and northern Asia (Chapman and Walsh 1993, Hansen et al. 1994), which has reduced area of snow cover by about 10% and resulted in earlier snowmelt in spring (Groisman et al. 1994) leading to an earlier start to the growing season and increased seasonal plant growth (Keeling et al., 1996, Myneni et al., 1997). Tropical forests, in contrast, may be reducing growth due to increasing minimum temperatures leading to loss of carbon from these systems (Beardsley 1998). Global warming already appears to be affecting the lifecycles of forests insects, increasing damage to temperate and boreal forests (Fleming and Candau 1998, Mulvaney 1998). Warming in north America has also resulted in a substantial (~120km) northwards migration of the discontinuous permafrost zone (Kwong and Gan 1994, Halsey et al. 1995) with costly impacts on transport infrastructure (Pearce 1997).

Global and regional air temperature increases are closely linked with reductions in global glacial mass (Dyurgerov and Meier 1997b, Haeberli and Beniston 1998) although in some regions increased precipitation has increased glacial mass (Dowdeswell et al. 1997).
Increased air temperatures during the period 1961-90 have been associated with a marked reduction in global glacial mass with this contributing an average of 0.25mm/year to sea level rise (14 to 18% of the 100 year average sea level rise). The rate of glacial shrinkage has increased significantly since the mid 1980’s (Dyurgerov and Meier 1997a,b) with European glaciers losing 10-20% of their mass in this period (Haerberli and Beniston 1998). Glaciers in New Zealand are also showing substantial retreat (de Freitas 1988) whilst in the Antarctic there have been changes in ice flow rates (Bindschadler and Vornberger 1998) and retreats and break-up of large ice-shelves where they are close to the climatic limit (Doake and Vaughan 1991, Skvarca 1993, Vaughan and Lachlan-Cope 1996). These changes in ice shelf area and dynamics have been linked (Doake and Vaughan 1991) with the significant warming that has occurred at the edge of Antarctica and in the surrounding ocean (Jones 1995). There has also been a marked decline in Antarctic sea ice extent with a southerly migration (2.8° latitude) of the summer sea ice boundary between the mid 1950’s and 1970’s with some suggestion that this has already affected Antarctic marine productivity (de la Mare 1997).

Rainfall

Australian rainfall has increased slightly over the past century with part of the trend influenced by the period of heavy rainfalls in the mid-1970s (Lavery et al. 1997). The relationship between ENSO (El Niño Southern Oscillation) and rainfall amount has altered since the 1970s with higher rainfalls for any value of the SOI (Southern Oscillation Index) than would have previously been expected (Nicholls et al. 1996). Furthermore, it appears that the ENSO system itself is changing (Nicholls et al. 1997) with an apparent functional change in the mid 1970’s (Graham 1994) to increased frequency of El Niño events and fewer La Niña events. These have been assessed in the context of the historical record as being very unusual and unlikely to be accounted for solely by natural variability (Trenberth and Hoar 1996, 1997) although others (eg Mantua et al. 1997, Allan and D’Arrigo 1999) have a conflicting view that the recent persistent El Niño events could be part of long-term natural variability.

Tropical cyclones contribute a large part of the summer rainfall in many tropical areas but the number of tropical cyclones observed in the Australian region has declined since the start of reliable satellite observation (1969/70) reflecting the increased incidence of El Niño events (Nicholls et al. 1998).

Increases in rainfall intensity are an expected occurrence with global warming (e.g. Gordon et al. 1992) and studies document an increase in both heavy rain events and average rainfall over large areas of Australia from 1910-1990. The largest increases were along the east coast, particularly in New South Wales, but decreases evident in the south west of Western Australia and inland Queensland over this period (Suppiah and Hennessy 1996, 1998). In the summer half year, the all-Australian average rainfall (based on area weighted station data) increased by 14%, heavy rainfall increased by 10-20%, and the number of dry days decreased by 4% (Suppiah and Hennessy 1996, 1998). In the winter half-year, the changes were about half these figures. The trends in heavy rain events are partially but not totally explained by ENSO fluctuations over recent decades (Suppiah and Hennessy 1996, 1998).

Global trends in rainfall amounts and characteristics are more difficult to identify due to various discontinuities and biases in the records (Folland et al. 1992, Groisman and Legates 1995) however significant regional changes have been reported. For example, in the mainland USA, precipitation since 1970 continues to average 5 to 10% higher than during earlier
decades of this century with a increase in heavy rainfall events (Karl et al. 1995, Angel and Huff 1997, Dai et al. 1997) resulting in increased surface runoff (Groisman and Easterling 1994). There has also been a recent increase in atmospheric humidity in southern USA, apparently linked to changes in airflow in spring and autumn seasons (Lettenmaier et al. 1994). In southern Canada precipitation has increased by 13% over the past century and by up to 20% in northern Canada (Groisman and Easterling 1994). Significant trends towards decreased rainfall have been noted over western and central Amazon in recent years, while eastern parts have become wetter (de Paiva and Clarke 1995). In Europe, over the past 40 years there have been marked increases in precipitation in Scotland (Briffa et al. 1994) and western Spain (Onate Rubalcaba and Pou Royo 1995), decreases in rainfall over the Mediterranean basin (Piervitali et al. 1997) and increases in rainfall intensity over Switzerland (Rebetz et al. 1997). In China, average annual precipitation has decreased by 5% over the past 30 years, with the greatest decrease being in the summer season (Dai and Ding 1994). There remains difficulty in determining the component of these changes that is associated with short-term and long term natural variability and that arising from global change. However, many of the above changes are broadly consistent with results from global climate models which incorporate greenhouse gas and aerosol forcings.

UV-B and ozone

The short wavelength portion of the ultraviolet range (UV-B; 290 nm to 320 nm) is damaging to both plants and animals (e.g. Rozema et al. 1997) and is strongly absorbed by ozone. Emission of chlorinated fluorocarbons and similar compounds has resulted in reductions in stratospheric ozone levels particularly around the poles in winter (e.g. Farman et al. 1985, Rex et al. 1997) resulting in increases in surface UV-B levels, with the Antarctic ‘ozone hole’ being of record size this year (Shanklin 1998). These increases in UV-B have been significant at latitudes greater than 35°S and range from about 7% per decade for Tasmanian latitudes to 3% per decade for the latitudes of more northerly regions in Australia (Herman et al. 1996). Similar trends of increasing UV-B are supported by data from NZ (Basher et al. 1994) and other regions (e.g. Blumthaler and Ambach 1990) although in polluted areas absorbing aerosols and high levels of tropospheric ozone tend to reduce surface UV-B levels (e.g. Bruhl and Crutzen 1989) although they have their own impacts as covered below.

Shindell et al. (1998) suggest a link between the observed increasing concentrations of greenhouse gases and the increased loss of polar stratospheric ozone. The mechanism they explored through global climate models is that higher concentrations of greenhouse gases increase the stability of the stratosphere and the polar vortices resulting in significantly colder lower stratospheric temperatures and thus greater ozone loss. Further research is required to explore the relationships between these two trends (Salawitch 1998).

Tropospheric ozone concentrations have tripled this century and are currently increasing by 0.25 ppb/year (Taylor et al. 1994) largely from fossil fuel combustion, some industrial activities and biomass burning. Ozone has negative impacts on photosynthesis at current concentrations and has been shown to reduce crop yields (Heck et al. 1988) the growth and disease status of some tree species and through this species composition as well as litter decompositional processes (McBride et al. 1975, James et al. 1980). Increases in ozone concentrations can also increase allergen contents of some common grasses (Masuch et al. 1997). In Australia, high levels of ozone are typically found near the major cities where
concentrations are correlated with increased human death rates (Simpson et al. 1997, Morgan et al. 1998)

Sea level

Global sea level has risen by between 10 and 25 cm over the past 100 years (Fig. 5; Peltier and Tushingham 1989, Barnett 1988 cited in Quayle and Karl 1996) with trends of 1.7 to 2.7 mm/year for Australia/NZ (Salinger et al. 1996) similar to the global estimated rate of 1.8 mm/year (Douglas 1991). This rise in sea level is a combination of thermal expansion due to observed temperature increases of the oceans (Church et al. 1991), glacial melting (Dyurgerov and Meier 1997a,b), groundwater extraction (Sahagian et al. 1994) and an uncertain component from changes in the Antarctic and Greenland ice caps (e.g. Zuo and Oerlemans 1997). Preliminary analyses of data from new satellite-based sensors indicate sea level rises of about 4 mm/year in the last few years, perhaps linked to ENSO behaviour (Nerem 1995).

![Sea level rise](image)

**Figure 5** General global sea level trends (1880-1986) relative to 1951-70 baseline period with a 5-year running mean (Barnett 1988 from Quayle and Karl 1996).

Nitrogen cycling and landuse change

Human activities have altered substantially the global nitrogen cycle, increasing both the availability and mobility of nitrogen with a large range of subsequent impacts (see Vitousek et al. 1997 for a comprehensive review). They assess that human activities over the past few decades have approximately doubled the rate of input of nitrogen into the terrestrial cycle and that this increasing trend is likely to continue. In the many environments where soil nitrogen is limiting, this may increase biomass accumulation (e.g. Hunt et al. 1988, Holland et al. 1997) although this can be at the expense of ecosystem diversity as nitrogen-responsive species dominate (e.g. Aerts and Berendse 1988). At the high levels of nitrogen deposition found in the northern hemisphere (often around 40-50 kg N/ha/year; Vitousek et al. 1997), the growth response declines, leading to the possibility of ‘nitrogen saturation’ (e.g. Aber 1992). However in Australia, the relatively low level of nitrogen inputs from the atmosphere (about 10kg N/ha/year: Baker and Attiwill 1987, Adams and Attiwill 1991) suggest that this is likely
to be limited to areas of native vegetation affected by agricultural or urban landuse (Granger et al. 1994). Nevertheless, in Australia increased nitrogen availability is implicated with tree dieback from increased herbivory (Landsberg 1990), increased weed invasion of forests (Granger et al. 1994) and stem deformity in Pinus radiata planted on previously improved pasture (Hopmans et al. 1995).

Increased nitrogen inputs also result in increased acidification of soils as nutrient cations such as calcium and magnesium bind to the nitrate which can be leached, resulting in accumulation of hydrogen ions and increased exchangeable manganese and aluminium (e.g. Williams 1980). For example, since 1950 forest soils in southern Sweden have halved their cation concentrations (Rosen et al. 1989). In Australia, landuse is probably a more significant contributor to increased acid loads than deposition (Robinson et al. 1995) and there is substantial evidence of increasing soil acidification following forest clearing and replanting (e.g. Prosser et al. 1993), under cropping systems (e.g. Coventry 1992, Dolling et al. 1994), in both temperate (e.g. Williams 1980) and tropical (e.g. Noble et al. 1997) improved pastures as well as in other agricultural and horticultural systems (Moody and Aitken 1997).

Trends in landuse change are also likely to have a significant impact on Australian forests. Prior to European settlement, an estimated 69 million hectares, or less than 10 per cent of Australia, was covered by forest (Resource Assessment Commission 1992). However, since European settlement, clearing mostly for farms and urban development has reduced the area of forest to approximately 41 million hectares (ABARE 1995). Forest clearing is still occurring although variable across States and regions, with the average annual tree clearing rate for Queensland (1991-1995) being 262,000 ha/year although subsequent regrowth occurs on an estimated 43% of this area (Queensland Department of Natural Resources 1997).

Plantations are becoming a more significant component of the Australian forest industries with the total area of plantations expanding by about 25,000 hectares a year since 1990. In contrast to earlier trends, this expansion is driven mainly by new plantings of eucalypt hardwoods grown mainly for the pulpwood market. Many of these plantings are occurring on farmed land supported by Federal and State government policies (Race and Curtis 1997) representing a significant change in landuse. Additional plantings are occurring to ameliorate land degradation problems such as erosion, waterlogging and salinity and there are further plantings associated with the establishment of carbon sinks to offset greenhouse emissions elsewhere. It is possible that the most immediate impact of global change on Australian forests will be through policies and activities relating to the implementation of the Kyoto protocol.

Summary

This brief review has outlined well-documented changes in many of the fundamental factors that affect the productivity and biodiversity of Australian forests and other ecosystems. These include climatic components which are known to strongly influence species distributions (e.g. Hughes et al. 1996, Austin et al. 1997) and productivity (e.g. Landsberg and Waring 1997), atmospheric CO₂ levels which are known to affect productivity (e.g. Curtis and Wang 1998), nitrogen accessions which are known to have a variety of growth and biodiversity impacts (e.g. Vitousek et al. 1997) and UV-B levels which are known to impact on ecosystem processes (e.g. Huttunen et al. 1998). The review has also drawn together information from a diverse array of systems, regions and processes that taken together provide a reasonably
coherent and internally consistent picture of existing change that is broadly aligned with theoretical expectations of future impacts of human activities. Many of the recorded changes can be definitively linked with human activities whilst in other cases these links, whilst suspected, remain to be definitively attributed and may be related to very long term variability. In either case, there does seem to be a strong case for assessing costs and benefits of adapting to these documented trends given that projections for human activities all point towards intensification rather than reduction.

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Climate change scenarios, impact thresholds and risk

Roger N. Jones
CSIRO DAR, Private Bag No.1, Aspendale Vic 3195, Australia.

Introduction

Global climate is a complex, adaptive system influenced by bio-physical relationships linking earth, ocean and atmosphere. Like most complex, adaptive systems climate is metastable, exhibiting aspects of both regular and chaotic behaviour. Over the last decade, the performance of global climate models (GCMs) has improved due to a more realistic and comprehensive representation of this regular behaviour. Better physics and higher resolution has also improved the representation of chaotic behaviour within GCMs.

Despite these advances, it is becoming clear that climate models will never be able to provide a singular prediction for future climate. Even if the pathways for greenhouse gas emissions were known, which they are not, there will always be a remaining threshold of uncertainty, giving a range of predictions rather than a single figure. There is no consensus amongst climate modellers about how close modelling is to reaching this threshold of uncertainty, how far current estimates can be reduced and what time-scale may be required for this to be achieved (cf. Mahlman, 1997).

The uncertainty within climate scenarios flows through to the prediction of impacts. If a single scenario is used to model a particular impact, the results may be fairly precise but are conditional on that single scenario, and are not representative of other futures. Conversely, if the major uncertainties are incorporated into a comprehensive, broad-ranging scenario (eg. CSIRO, 1996), when applied to impact analysis, the resulting range is too large to be of real use for planning or policy purposes.

In summarising the results of impact studies published to 1995, the Working Group II Second Assessment Report of the International Panel on Climate Change (IPCC, 1996b) concluded that many ecological and socio-economic systems were at risk from climate change. However, to date, research has not been able to provide the strategies needed to address the two major issues raised in the United Nations Framework Convention on Climate Change (UNFCCC) regarding climate change impacts, namely the issues of mitigation and adaptation:

1. Mitigation strategies aim to stabilise greenhouse gas concentrations in the atmosphere at levels preventing “dangerous” anthropogenic interference with the climate system.

2. Adaptation strategies recognise that some climate change is inevitable, and that some systems sensitive to climate will prove to be vulnerable, requiring adaptation measures.

As both of these strategies deal with the identification and avoidance of risk, a framework is needed to link climate change modelling and scenarios with levels of impacts, through the use of risk assessment. This paper describes an emerging framework that does this through the use of impact thresholds. It introduces a methodology for assessing risk to those thresholds under climate change, including the identification of “dangerous” climate change. An example, using a simple irrigation demand model, is used to show how the technique works. This methodology is also adaptive, as it can produce new estimates of risk by incorporating new or improved information. A possible direction for the assessment of forests under global change is suggested.
Climate change scenarios

Climate change scenarios provide the input into impact models. Although there are many different assumptions and levels of detail within various types of climate change scenario, their major uncertainties can be divided into three categories (see Figure 1):

1. **global climate sensitivity**; measured by the sensitivity of global climate models to greenhouse gas forcing
2. **emission scenarios**; influenced by economic activity, population growth and technology
3. **regional variability**; influenced by the chaotic behaviour of climate through spatial and temporal variations ranging from daily to multi-decadal time scales.

Scenarios of global warming that contain the first two types of uncertainty listed above have been prepared by the IPCC (1996a). These scenarios are presented as a range of possible temperatures, having an upper and lower limit, and sometimes a “best bet” option. On advice from the IPCC (1996a), they are assumed to have a uniform probability of occurrence. Regional variability may also be incorporated into scenarios to take account of temporal variations, or to incorporate a more realistic spatial distribution of climate change. Regional climate change scenarios for Australia that summarise the results from a number of different GCMs, and incorporate all three of the above uncertainties, are periodically prepared by the CSIRO (eg. CSIRO, 1996).

If the vertical integration of physical through to socio-economic impacts is sought, the incorporation of these broad ranges of uncertainty into the impact analysis will produce a very large range of possible impacts, termed as the *uncertainty explosion* (Henderson-Sellers, 1993; Figure 1).

The assumption that uniformity persists through all the steps of impact analysis is the most conservative assumption possible. However, if any of the steps are independent of each other, when multiplied together the resultant distribution will not be uniform but will instead be distributed about their average.

![Figure 1](image_url): Range of major uncertainties involved in impact modelling at a particular time, showing the uncertainty explosion caused when these ranges are multiplied to encompass the full range of future possibilities.
For instance, if the range for global warming in 2070 of 0.7–2.1°C (IPCC, 1996a) is multiplied by estimates for inland Australia of 1.0–1.8°C local warming per degree of global warming (CSIRO, 1996), the resultant range is 0.7–3.8°C. Assuming the independence of both these ranges, when they are sampled randomly and multiplied, the probability distribution they produce is not uniform but is peaked (Figure 2). Although the range expands as in Figure 1, the central values are far more probable than the extremes.

![Figure 2: Probability distribution of a regional scenario for temperature change in 2070 for inland Australia (CSIRO, 1996), showing the probability of occurrence for 5% increments within the total range of 0.7–3.8°C, based on Monte Carlo sampling. The component ranges are 0.7–2.1°C (global warming) and 1.0–1.8°C (local warming per degree global warming), sampled randomly and multiplied 5,000 times.](image)

This is a long-established technique that has been recognised and used in many fields such as economics, insurance and in gambling (Bernstein, 1996). Mostly, the technique applies statistical methods to historical data in order to forecast the probability of a particular set of outcomes.

For climate change, historical data is limited, so the input data is based on scenarios of greenhouse gas emissions, model studies of climate and reconstructions of past climates. For this method to work, several conditions must be met:

1. Scenarios must be independent if random sampling is to be used. If factors show dependence, this must be incorporated into the sampling method.
2. The full range of possibilities within a single scenario must be allowed for, as a truncated range will under-estimate risk
3. The major factors influencing the impact under analysis should be incorporated into the methodology wherever possible.

The application of this method to climate change scenarios is described in the section on risk.
Impact Thresholds

To assess risk, climate impacts are explored to determine appropriate thresholds. An impact threshold is a generic term for any threshold that can link an ecological or socio-economic impact to a climatic state or states.

Threshold events may signal a distinct change in conditions or a step on a scale that has been nominated as significant (ie. a benchmark). Examples of climatic thresholds are frost, snow and monsoon onset. Biophysical or environmental thresholds, represent a distinct change in conditions, such as the drying of a wetland, floods, breeding events etc. Operational thresholds are set by benchmarking a level of performance, eg., yield per area of a crop in weight, volume or gross income (Jones and Pittock, 1997). An example of an operational threshold is described in Campbell et al. (1997) where the identification of sustainable thresholds for grazed grassland systems under global change is recommended.

Critical thresholds are a special category, being assessed to determine the point at which the risk of an impact becomes “dangerous”. This assessment involves placing values on processes and/or outcomes. The assumptions behind such valuations should ideally be transparent and should be understood by all those affected. As impacts differ within sectors and regions, and may vary over time, critical thresholds for different activities and localities will not be reached at the same time or with the same rate of climate change. Climate scenarios can be used to determine when and where “dangerous” thresholds are reached in various sectors (Parry et al., 1996). This is then related back to rates of greenhouse gas emissions.

To show how the methodology described in this paper can be used, a simple irrigation demand model was constructed. Data from the Model Farm in Kerang, northern Victoria, was used to build a simple model estimating irrigation demand on a perennial pasture dominated by Trifolium repens (White Clover) and Lolium perenne (Perennial Ryegrass). This pasture is grazed by beef cattle with some hay produced every spring. The inputs are maximum temperature, rainfall and A Class pan evaporation from an official weather station situated on the property collected during 1990–96.

An earlier model estimating water-use during the irrigation seasons 1989–90 to 1995–96 showed that irrigation management during those years was remarkably consistent (Jones, 1997). Based on rainfall, pan evaporation data and irrigation water-use for those seasons, it estimated total water-use on the farm to within ±4%. Water-use on the Model Farm was also correlated with the total Cohuna Irrigation District consumption from 1976–96 and the combined Cohuna-Kerang District consumption from 1987–96 at 0.84 and 0.88 respectively. This shows that irrigation demand on the Model Farm is representative of irrigation demand at the district level.

A simple box-type irrigation demand model based on the relationships described by Boughton (1966) was constructed and run on a daily time-step. The model requires estimates of the field capacity of the soil, wilting point and threshold soil moisture for T. repens (the dominant summer-growing pasture plant). When soil moisture falls below a certain threshold level estimated for T. repens, irrigation is automatic and equivalent to 75mm rainfall. The model was calibrated using the 1995–96 season where irrigation volumes had been recorded for individual paddocks over the season. Initially, the model was run in four separate modules allowing for differences in soil- and pasture-types across the farm. A single paddock model was chosen to represent irrigation demand for the purposes of demonstration. This model was
based on the pasture and soil within the paddock containing the weather station.

Although the accuracy of the model was less than that achieved for the more empirical model used in Jones (1997), it was more physically realistic. Given the strong relationship between the earlier model, farm water-use and district water-use, this model was assumed to be adequate for the technique described here.

The context for the chosen threshold is the recent capping of irrigation allocations in Victoria (MWEC, 1997). During the 1970s and 1980s, most irrigation demand was met by allocations exceeding the nominal water right with the only exception being in the 1982–3 drought when restrictions were introduced. However, there was also a gradual increase in irrigation allocations basin-wide. This increase in demand is a principal reason for the setting of the cap for the Murray-Darling Basin, authorities having realised that such an increase was a threat to the overall health of the system (Cox and Baxter, 1996).

The irrigation cap is now set at 200% of the annual water right (G. Jones, pers. comm.). In most years, this cap will be achievable, but in years when demand is high and supply is low, this limit will not be met and farmers will have to adapt, eg. by watering fewer pastures or crops, destocking, adding supplementary feeding or by introducing more efficient irrigation systems.

An annual threshold for irrigation demand was set at 12 Mlha⁻¹. On the basis of past management, demand above that level would require some form of adaptive behaviour, as meeting that demand would exceed the farm cap. During dry years, a short-fall in irrigation supply may also mean that the 200% cap is not met. This cannot be factored into the current model, as it requires an estimation of runoff in the upper catchment and of the behaviour of the irrigation supply system. For the purposes of this exercise, it is assumed that supply will only fall short during those years when irrigation demand is high. Based on past irrigation figures, this is a reasonable assumption.

Daily maximum and minimum temperatures and rainfall from 1990–1996 were used as input to the LARS-WG weather generator (Racsko et al., 1991) to produce a 100-year series of artificial climate. Both rainfall and temperature were adequately reproduced for the purpose of this model. Evaporation was estimated by calculating regression relationships for individual months of daily evaporation against maximum temperature for the period 1990–1996, then using those regressions to estimate evaporation from the weather-generated maximum temperature. Evaporation regressed from temperature was substituted into the model for 1990–1996 and compared with the results produced with the A Class evaporation data. The results were identical, although this is partly due to the stochastic nature of the model which irrigates in 75 mm increments.

The figure of 12 Mlha⁻¹ provides a threshold above which some adaptation is required. For 100 years of weather-generated data based on the observed 1990–1996 climate data, this threshold is exceeded 5% of the time. This model therefore offers the following thresholds for further investigation:

- an annual threshold of 12Mlha⁻¹, whose frequency of exceedence can be estimated using a 100-year artificial record of climate
- a critical threshold where the frequency of irrigation demand above the annual threshold
exceeds the ability of the farmer to adapt, causing harm to that activity.

Risk

Having produced climate change scenarios and a model with a measurable threshold, the next step is to observe the behaviour of that threshold by forcing the model with the scenarios.

For current climate, the model simulates irrigation demand exceeding the annual threshold of 12 Mlha\(^{-1}\) in 5% of years. This is comparable with the estimate of Murray-Goulburn Water, the supplier of irrigation water to the region, that supply can be met in 97% of years (pers. comm.). The historical data suggests that these years will coincide. For the irrigator, this implies that only occasional adaptation measures will be required for current practices under the current climate.

The frequency of threshold exceedence was measured for scenarios of climate change at 10-year intervals from 2000–2100. Firstly, a sensitivity matrix was calculated for temperature increases ranging from 0–6.5°C and rainfall changes ranging from +30 to -30%. Evaporation was calculated from adjusted maximum temperature using the regression relationships described earlier. The resulting sensitivity matrix is shown in Figure 3 where the frequency of exceedence for the annual 12 Mlha\(^{-1}\) threshold ranges from a few percent to over 100%.

Figure 3: Sensitivity matrix showing the probability of exceedence of an annual threshold of 12 Mlha\(^{-1}\) for an irrigated pasture in Northern Victoria, relative to temperature and rainfall changes (see text).

Secondly, the upper and lower limits of temperature and rainfall scenarios for northern Victoria estimated from CSIRO (1996) were sampled to create non-uniform probabilities of occurrence as described above. For temperature, the two ranges sampled and multiplied were the global warming projections (IPCC, 1996a), encompassing the IPCC-estimated range of
climate sensitivity and the IS92a–f emission scenarios, and regional uncertainty expressed as local warming per degree of global warming (CSIRO, 1996; Table 1). The upper and lower limits of the change per degree range for summer and winter rainfall shown in Table 1 were multiplied by the randomly sampled global temperature. The adjusted summer and winter ranges were then randomly sampled also. They were averaged without weighting for summer/winter rainfall differences to estimate the annual changes shown in Figures 4 and 5.

Table 1: Upper and lower bounds for scenarios used in climate probability sampling. The temperature columns list the global range and the local range (the global range multiplied by the local change per degree of 1.0–1.8 °C). Rainfall lists the summer and winter ranges separately, which are produced by multiplying upper and lower ranges (% change per degree of global warming: -5%–10% for summer and -10–2.5 for winter) by global temperature.

<table>
<thead>
<tr>
<th>Year</th>
<th>Temperature (°C)</th>
<th>Rainfall (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global Low</td>
<td>Global High</td>
</tr>
<tr>
<td>2000</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>2010</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>2020</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>2030</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>2040</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>2050</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>2060</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td>2070</td>
<td>0.7</td>
<td>2.1</td>
</tr>
<tr>
<td>2080</td>
<td>0.8</td>
<td>2.5</td>
</tr>
<tr>
<td>2090</td>
<td>0.8</td>
<td>3.0</td>
</tr>
<tr>
<td>2100</td>
<td>0.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Scenarios were sampled randomly at 10-yearly intervals from 2000 to 2100, allowing a sampling density of 100 samples per gridpoint in matrices of up to 400 gridpoints. Cumulative probability plots were calculated from these matrices to show how the probability of climate change can be estimated when uniform distribution is no longer assumed throughout the whole process.

The cumulative probability plots in Figure 4 show, that rather than being a large rectangle of uniform probability, some outcomes are more likely than others. For instance, combinations of extreme changes in temperature and rainfall are unlikely. Figure 4 also shows that as the range becomes larger, the proportion of the scenario which has less than a 5% probability of occurrence also becomes larger.
Figure 4: Cumulative probability plots for climate change scenarios for 2030 and 2070 in northern Victoria based on CSIRO (1996). Temperature was sampled randomly within both the global and local ranges which were then multiplied. The upper and lower limits of the change per degree range for summer and winter rainfall shown in Table 1 were multiplied by the randomly sampled global temperature. The adjusted summer and winter ranges were then randomly sampled also. The probability plots were calculated by cumulatively adding percentage frequency in order from the most to the least likely for all gridpoints.
**Figure 5**: Cumulative probability plots for climate change scenarios and probability of exceedence of an annual irrigation threshold for 2030 and 2070 in northern Victoria. The cumulative probability plots are as shown in Figure 4 and the threshold exceedence plots are as shown in Figure 3.
The next step is to compare the probability of annual threshold exceedence with the cumulative probability plots for the climate scenarios in 10-yearly time-steps. This was carried out by measuring the probability of all climates falling below a certain threshold. Figure 5 shows that in 2030 the most likely outcome for the probability of annual threshold exceedence is in the 10–20% range, i.e. the annual threshold of 12 MLha\(^{-1}\) will be exceeded in 10–20% of years. In 2070, this range is much larger, extending up to 80%. A way to show this in more detail, is by using a threshold-probability chart (Figure 6).

Figure 6 shows that in 2030, the climate (x-axis) has a 90% probability of exceeding the threshold (y-axis) in 10% of years. However, the 20% threshold is only likely to be exceeded in 5% of possible climates. In 2070, the situation has changed. The 20% threshold will be exceeded by 80% of possible climates, and there is a possibility that the annual threshold could be exceeded up to 60% of the time.

![Figure 6: Threshold-probability plot showing the relationship between the probability of threshold exceedence and the probability of climate moving beyond that threshold in 2030 and 2070.](image)

Having established a relationship between the probability of climate change and the probability of a threshold being met, or exceeded, the topic of risk needs to be engaged. Risk assessment needs to look at the threshold being modelled and to ask, at what level does this become dangerous? If we assume that at the point when the annual irrigation threshold of 12 MLha\(^{-1}\) is exceeded 50% of the time, that industry is unable to adapt to that level of demand, we have identified a critical threshold.

Figure 6 shows that in 2070 the critical threshold will be exceeded in 20% of possible climates. The next question that needs to be asked is, does that level of probability warrant concern? This requires the linking of thresholds and probability to degrees of risk through forecasting. This may be done in a rational framework, where risk is assigned numerically according to a given method (e.g. cost-benefit analysis, where cost is multiplied by probability to derive an index of risk). It also may be carried out by referring the problem back to the relevant stakeholders and using a combination of objective and subjective methods to derive
the risk attached to a critical threshold through consensus.

One way of viewing the problem is to look at how the critical threshold is affected over time. Table 2 shows its probability of exceedence in ten-year intervals from 2040–2100. This probability ranges from only 1% in 2040 to 63% by 2100. How do we refer this back to mitigation and adaptation strategies?

The degree of adaptation that may be required can be diagnosed by surveying the window between now and the time when the critical threshold begins to pose a risk. For example, the nominated critical threshold of 50% does not become significant until about 2070, indicating a large potential for adaptation. Figure 6 suggests that the frequency of the annual threshold of 12 Mlha\(^{-1}\) will have doubled or tripled from the current level of 5% by 2030. This suggests that some adaptation will be required by the coming generation of farmers.

Table 2: Probability of exceedence of the critical threshold of 50% over time.

<table>
<thead>
<tr>
<th>Year</th>
<th>Probability of exceedence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050</td>
<td>1%</td>
</tr>
<tr>
<td>2060</td>
<td>6%</td>
</tr>
<tr>
<td>2070</td>
<td>23%</td>
</tr>
<tr>
<td>2080</td>
<td>27%</td>
</tr>
<tr>
<td>2090</td>
<td>50%</td>
</tr>
<tr>
<td>2100</td>
<td>63%</td>
</tr>
</tbody>
</table>

By 2050, the second generation may be dealing with a situation where the annual threshold is being exceeded 30% of the time, requiring a much greater level of adaptation. The third generation, at about 2070, will be approaching the limit of adaptation (as assumed by this example) set by the critical threshold.

Mitigation can be carried out to reduced levels of greenhouse gas to avoid such critical thresholds. However, the pressure for mitigation will not come from one or two critical thresholds identified on a regional basis but from the integrated assessment of a number of sectors and regions. For that to be possible, methodologies such as that proposed here, need to be adopted and used widely.

Discussion

The model presented above is not intended for use in the forecasting of climate impacts on irrigation. For example, it ignores several factors that will impact on irrigation demand on the paddock scale, including:
- CO\(_2\) fertilisation, which will tend to increase productivity per unit of water supplied
- increased efficiency in water use due to higher CO\(_2\) may alleviate evaporative demand somewhat, however, the tendency of farmers to maximise production will still lead to increased transpiration accompanying temperature increases (Jones, 1997)
- evapotranspiration is not likely to maintain its current relationship with maximum temperature during climate change as is assumed here
- irrigation supply, which is also affected by climate, will limit demand in times of shortage.
To incorporate the above factors would require a coupled crop or pasture model with a soil-moisture model, explicit scenarios of evapotranspiration and a water-supply model. There are also short-comings in the use of a 7-year climate record to generate long sequences of artificial climate data. Improved sampling of historical climate data and weather-generated data from more than one random seed would also be required.

Likewise, the cumulative probability plots for rainfall and temperature shown in Figure 4 are only intended as examples. The conditions for sampling listed at the end of the section on climate scenarios have not fully been met. The results are also subject to the assumptions made in CSIRO (1996).

The purpose of this paper is to provide a framework that can move beyond the assessment of sensitivity and vulnerability of climate impacts to address the issues raised by the UNFCCC concerning mitigation and adaptation. While this framework shows how thresholds can be linked to climate in a probabilistic manner, further work is needed to develop this into a robust form of risk assessment.

Conclusion

Although the model used to illustrate the framework presented to this workshop is not a forest model, it was chosen because at a very simple level, many of the issues it faces are similar to those faced by forest modelling.

Forests will respond in a complex manner to changes in temperature, rainfall, evaporation, soil moisture and CO₂ content of the atmosphere. Framing this complexity within the large uncertainties posed by climate change scenarios is a very difficult task. The methodology presented here may allow some of that uncertainty to be managed by relating thresholds of forest impacts to climate scenarios, and also to include other elements of global change.

A possible threshold is the point where the positive effects of CO₂ fertilisation are counterbalanced by the negative impacts of temperature. For instance, by sampling temperature, rainfall and CO₂ concentrations for forest models at a series of locations and at different times, it may be possible to estimate when the probability of positive impacts on forest growth becomes outweighed by the probability of negative impacts.

The diagnosis of thresholds linked to scenarios of climate change allows risk to be attached to activities such as the emission of greenhouse gases. It can also show how wide the window for adaptation is likely to be. It is only by identifying risks within an uncertain future, albeit one of our own making, that we can hope to avoid them.

References


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Tree response to elevated CO₂ concentration in the short and longer terms

Roger M. Gifford
CSIRO Plant Industry, GPO Box 1600, Canberra, ACT 2601

Predicting the impact of the increasing atmospheric CO₂ concentration, interacting with its associated climatic changes, on forestry production requires, inter alia, quantitative knowledge of a) immediate responses of primary physiological processes to a step change in CO₂ concentration, b) the within-plant feedback responses (acclimations) that occur over time after such a step change, c) the within-ecosystem repercussions and feedbacks that are engendered by the primary whole plant changes. Several forest productivity models already attempt this. The further up the time- and space-scales the model goes, the more difficult it is to know how to represent and quantify the processes. Unfortunately the state of the science is such that it is still uncertain exactly what even all the primary responses are and their magnitudes.

Until recently it seemed clear that the stimulation of photosynthesis (and associated suppression of photorespiration) and reduced stomatal conductance were the primary direct responses of plants to elevated CO₂ concentration. In the background there have also been long standing strands of less consistent evidence that elevated CO₂ can suppress dark respiration (Amthor 1996). This aspect has become a major revitalised research thrust in the last few years. Additionally, certain morphological effects may also represent direct responses: CO₂ effects on a shortening of the cell cycle in grasses (Kinsman et al. 1997), and on apical development and flowering (Marc and Gifford 1984) may be independent of the photosynthesis, stomatal and respiratory effects, but the evidence has been too scant, and non-existent in trees, for models to include such effects to date.

The reasons for, or even the field-relevance of, acclimation of the three main primary processes (photosynthesis, respiration and stomatal conductance) is still far from resolved too. However, much of the research data relied upon for models deals not with immediate short term responses but with the responses after several weeks, months or years growing in elevated CO₂ concentration. As such, they represent the responses after within-plant acclimation has occurred. However to the extent that acclimation on that time-scale in the field has to do with interplant competition, not all feedbacks on those time scales are represented especially when the experiments are on spaced plants.

In a meta-analysis, i.e. statistical analysis of numerous reports in the literature of specific selected responses, Curtis (1996) drew some unexpected conclusions for trees. The analysis was for responses of 41 species of tree that had been described in the literature up to the middle of 1994. The time-scale of experiments reviewed ranged from 33 to 1095 days. There was considerable variation in the response to CO₂ of all attributes examined. Briefly, Curtis’ findings (in terms of mean responses across all species) were that for a doubling of atmospheric CO₂ concentration:

- Leaf net photosynthesis, averaged across all studies was stimulated by 50%. Some of the variation may have been due to duration of exposure to high CO₂, environmental stress, type of growth facility, or pot size. With respect to the magnitude of the doubled CO₂ response of leaf net photosynthesis:
  - exposure for more than 50d gave a lower % response than exposure for less than 50d
there was no further change in response through time beyond 50d exposure
- N-stress decreased the % response to CO₂
- water stress increased the % response to CO₂
- plants in open-topped chambers gave a larger response than those in greenhouses which gave larger responses than those in growth chambers
- Pot size was not important for the response of photosynthesis

- Stomatal conductance, averaged across all studies, was not significantly affected. However, stomatal conductance was significantly reduced in unstressed plants especially after >100d exposure. For stressed plants stomatal conductance was increased (but not statistically significantly) by high CO₂ concentration.
- Dark respiration was greatly reduced by growth in elevated CO₂ concentration
- Leaf nitrogen concentration was greatly reduced by elevated CO₂ concentration
- Specific leaf area was greatly reduced by growth under elevated CO₂ concentration

The unexpected conclusions from that meta-analysis were the non-response of stomatal conductance, the magnitude of the dark respiration suppression, and the stronger response in the field than in controlled environments. However the large quantitative spread of results is cause for concern. Clearly, if there is an enormous quantitative range of results, we not only have difficulty in believing the output of a formal meta-analysis as necessarily being correct, but we also have a problem with providing any sort of generalisations for parameterising models. Other than throwing up our hands in dismay, the only way forward is more of the traditional method of perceptive and discerning scrutiny of the individual experimental data, formulation of hypotheses to explain them, followed by new experiments intended to test those hypotheses. There have been several relevant papers published on trees since 1994 from which to further evaluate Curtis’ meta-analysis conclusions. Most such studies have been on Pinus spp. The thrust of that more recent “high CO₂” work is tending to support the conclusion of weak stomatal responses in trees and the existence of respiratory suppression. However, this reviewer suspects that these findings may not both withstand the test of subjective critical analysis as opposed to all-embracing objective statistical meta-analysis.

In addition there is work in progress on long term responses. The longest term study to date has been on Quercus ilex after 30 years of natural growth in high CO₂ concentration (average ~ 650ppm) near two CO₂ vent sites in Italy, matched with similar aged trees nearby in normal air (Hattenschwiler et al. 1997). After 30 years, the trees in the elevated CO₂ concentration had a 12% greater stem diameter. They also had equal recent ring widths which, given the larger diameter, represents an 11-12% increase in annual ring area in the latest years. The mean height of trees was also increased and, assuming there was no increase in wood density the results calculated out to represent a 33% increase in stem biomass. Given that the typical several-month growth response of C₃ plants to doubled CO₂ concentration has been found several times in “reviews of reviews” to be about 33%, this result supports Curtis’s finding that there is no further down-regulation after 50 days.

References


Abstract

There are four key impacts on Australia’s forests and forestry:

1. **Direct biological impacts.**

   Climate change over a century is likely make the climate over almost all of a species range unsuitable for that species. This shift in ecological niches will greatly affect the various communities of plants and animals in the forest. The rapidity of these changes also means that most species will not be able to cope with the change by natural migration.

   If forests grow either faster or more slowly, it will affect the domestic supply of wood. If regions become unsuitable for forestry, or if formerly unsuitable regions become suitable, it will greatly affect the location of mills, and the viability of local communities dependent on those industries.

2. **Economic impacts.**

   Changes in productivity of our forests will affect the supply of wood. This will be most dramatic if climatic changes were to lead to the death of established forests. There are no indications at this stage that this is likely to happen, but adverse changes in rainfall could lead to this.

   Globally, the largest impacts of climate change are likely to occur in boreal forests. This could greatly affect the supply of wood on the global market and, through that, the Australian industry. Warming could markedly increase the growth of boreal forests. However, this could be matched by less certain, but potentially more devastating, losses of wood through increased incidences of pests, disease and fire.

3. **Impacts on forests through managing the national carbon budget.**

   Following the Kyoto agreement, management of the biosphere is now considered a part of the national Greenhouse Gas Inventory for which individual countries take responsibility. It is likely that tree planting will be supported as a cost-effective means of reducing net carbon emissions. The logging of existing forests with high standing biomass may similarly be discouraged.

4. **The National Greenhouse Gas Inventory (NGGI).**

   The biospheric component of the NGGI is still very poorly quantified. Given the Kyoto agreement, better quantification has now become mandatory. What additional research and monitoring will be required to bring the NGGI to the standard required by international agreements?

**Introduction**
Climate change affects forests and forestry in many different ways. Trees are long-lived and are strongly affected by their environment. Hence, any climatic changes are likely to occur within the life time of trees already in the ground. These include important ecological stresses as the climate becomes increasingly unsuitable for trees at their current locations. Growth rates and forest health are also likely to be affected. We need to understand what is likely to happen, and, if possible, devise adaptive strategies.

Forestry requires a continuous supply of wood from stands within the vicinity of existing mills, and any reductions in growth rates threaten on-going supplies. Forestry is also a business that operates within a global economy. Hence, the Australian forest industry is affected not only by the effects on trees in Australia, but also by international developments. These could be beneficial or detrimental, and are inherently difficult to fully predict.

Of more immediate importance is the National Greenhouse Gas Inventory (NGGI). All countries are now beginning to compile annual national Greenhouse gas inventories. Compiling the biospheric component of these inventories is very difficult. Because of the international pressure to reduce net emissions of Greenhouse gases, it is likely that considerable future pressure will be placed on different industry sectors, including the forestry sector, to reduce their emissions and maintain existing sinks.

Any attempts to reduce net Greenhouse gas emissions from Australia is likely to also include measures to increase Greenhouse gas sinks, such as through the establishment of plantations. This is likely to create considerable opportunities for commercial plantations and non-commercial biosphere reserves.

**Biological Impacts in Australia**

Most species occupy ecological niches that are defined by narrow ranges of temperature, rainfall, soil type and other aspects of the environment. Species usually occupy niches that are restricted to only a few degrees in temperature. The narrowness of niches is largely due to competition from other species. Competing species may be more tolerant of warmer or colder conditions, or more resistant to certain pests or diseases that may thrive in colder or warmer or wetter or drier conditions. Only rarely does the environment exceed physiological tolerances of species.

Hence, it is likely that climate change will lead to significant ecological stresses as the climate for species in their existing habitats will become progressively less suitable and they are outcompeted by species better adapted to changed conditions. Species with better dispersal potential, broader ecological tolerances and more invasive growth habits are likely to become more prevalent at the expense of species with restricted dispersal, lower growth potential or simply more specific ecological requirements. This will not only affect the dominant tree species, but also the entire ecological community dependent on that habitat. There is considerable danger that species with currently restricted distributions might face local, and possibly complete, extinction during such rapidly changing climatic conditions (Kirschbaum *et al.* 1996).

Forests that are already established will generally be able to grow to maturity and be available for forest harvesting. Exceptions to that may be some stands of *Pinus radiata*. In Australia, *P. radiata* is largely grown under conditions that are considerably warmer than the species’
natural ecological niche. The absence of pests, diseases or competitors allows it to grow successful across that wider range, but it is approaching its physiological limits. Any further warming may cause it to exceed those limits in some regions.

Another exception may be related to pests, such as termites, or diseases, such as *Phytophthora cinnamomi*, that may become more prevalent under future conditions. Changed climatic conditions may make it possible for them to infect and devastate stands from where they are currently excluded by unsuitable climatic conditions.

Forest growth may not be greatly affected by climate change, as the largely detrimental effects of increasing temperature and the positive effect of increasing CO₂ concentration may partly compensate for each other. Depending on the nature of current limitations to growth and the relative rates of increase of CO₂ concentration and temperature, the balance of effects may be positive or negative, and may differ between regions.

Overall, it is not anticipated that wood supply will be drastically altered by climate change. However, some adaptive measures may nonetheless be warranted, such as using seed stock from slightly warmer locations whenever new forests are established, avoiding the establishment of new plantations in regions that are already supra-optimal for particular species.

**Economic Impacts**

The boreal forests in Eurasia and North America are likely to be the forests most strongly affected by climate change (Kirschbaum *et al.* 1996). These forests are also the source of most of the world’s wood. General warming is likely to greatly increase the growth potential of these forests, but there are also significant threats due to increased water stress and increasing incidence of pests, disease and fire.

It is not yet clear what the balance of effects will be. If tree growth in the boreal region is going to increase with minimal negative side effects, then the world wood market may become dominated even more by cheap supplies of wood from boreal forests, and the Australian industry may come under increasing cost pressure.

On the other hand, if impacts in the boreal region will be dominated by tree death, especially if caused by increased wild fire, supplies from boreal forests could diminish and create new opportunities for alternative wood suppliers to supply an increasing demand on the world market. Wood prices may then increase and enhance the profitability of the Australian industry.

A third possibility is that problems in the boreal region may outweigh the beneficial effects, but that standing wood is not lost, but can be extracted in salvage harvests. It could have the effect of flooding the global market for some decades with cheap wood before the inevitable exhaustion of these temporary supplies creates opportunities for the Australian industry in subsequent decades.

It is not yet possible to predict how changes in the boreal forests will affect wood supplies to the global market, but it does seem likely that climate change will have a significant effect on it. Impacts on the Australian forest industry may be more strongly affected by biological
impacts in other parts of the world than in Australia.

The National Greenhouse Gas Inventory

Of most immediate relevance in the climate change context is the annually compiled National Greenhouse Gas Inventory (NGGI). According to the latest NGGI, in 1995, 16.0 Mt C yr\(^{-1}\) was removed in forestry operations while 21.7 Mt C yr\(^{-1}\) new wood grew in the same period, making forests a putative sink of 5.7 Mt C yr\(^{-1}\) (NGGI 1997). The calculations of wood growth are still very uncertain and based on incomplete wood inventory information.

Furthermore, there are also methodological problems in relation to fire. Carbon loss from fire is not included in the inventory, yet reported average growth rates of forests are partly caused by the rebound effect of forests after a previous fire. It creates the anomalous situation where forests are treated as a carbon sink whereas in reality, they may be losing carbon.

The Greenhouse contribution of the forestry sector must be put on a much sounder basis. This would require greater disaggregation of forest types and age classes and age-dependent growth rates, and fire must be treated in a methodologically consistent manner.

Even with a more consistent approach, it is not clear how fire affects the forests’ overall carbon balance. Forests are routinely subject to hazard reduction burns. This is likely to affect the average carbon density of forests. Frequent low-intensity hazard reduction fires can prevent less frequent, but more destructive, high-intensity fires. This may allow the build-up of higher standing biomass. On the other hand, frequent fires cause on-going nutrient losses that may reduce long term forest growth.

There is also a small amount of charcoal formed during fires which constitutes a long-term carbon storage pool. It is also unclear whether soil organic matter may be changing in our forest. Soil organic matter amounts are affected by natural factors, such as increasing temperature and CO\(_2\) concentration and forest management, such as harvesting, site preparation and fertilisation. These effects have not yet been adequately quantified for the NGGI, but they are likely to be significant because they occur over large areas.

Tree Planting for Mitigation

As part of an attempt to limit emissions of Greenhouse gas emissions to 8% above 1990 levels, there is a developing push to increase carbon sinks by establishing new tree planting schemes. They come in essentially three categories: commercial and non-commercial plantations for carbon storage and biofuel plantations to substitute for fossil fuels.

Commercial plantations can sequester carbon very cost-effectively, as any profits from the eventual sale of wood can be offset against the costs of plantation establishment. Carbon may then be sequestered at virtually no cost to society. However, carbon storage is only temporary as carbon is eventually released upon wood utilisation. However, while carbon is stored in trees rather than the atmosphere, it does constitute an important benefit. The benefit could be increased if wood were used for long-lasting purposes, such as furniture or housing frames.

Non-commercial plantations could be set up as biosphere reserves or ‘Greenhouse parks’.
Costs of establishing those would have to be borne completely by public funds with no offsetting financial benefits. However, such plantations could have other environmental benefits, such as preservation of ecological diversity, prevention of salinisation or erosion, or for providing shelter for domestic stock. In Greenhouse terms, their benefit is in the indefinite storage of carbon.

Wood can also be substituted for fossil fuels. Wood can be used to generate energy either in domestic heaters or for commercial power generation, especially in remote communities. By replacing fossil fuels, energy can be generated in a renewable form that places no net load on the atmosphere.

These mitigative options create considerable opportunities for the forest industry by providing the impetus to expand commercial and non-commercial plantations across Australia. Energy plantation are not yet established to any significant extent in Australia. Fire wood for domestic heating is the only wood currently used as energy source, but it is not usually sourced from plantations.

**Conclusions**

Climate change is likely to affect forests and forestry in many different ways, including potential direct biological and indirect economic threats and opportunities. At this stage, we can only identify possible factors, but their quantification is still difficult. The assessment of overall impacts is even more difficult considering that biological threats in one country may become economic opportunities in another.

Because of the long time frame in forest growth, it is necessary to anticipate development long before they are likely to occur. Ecological stresses are likely to be the most serious threats, and plans should be developed now to assist natural populations to cope with it.

At the same time, even before the impacts of climate change begin to significantly affect the growth of trees across large parts of the world, the beginning efforts to curb the emissions of Greenhouse gases are having significant effects on the forest industry, creating both operational constraints and significant emerging opportunities.

**References**


The effect of climate change on forest growth in Australia

Miko U.F. Kirschbaum
CSIRO Forestry and Forest Products, PO Box E4008, Kingston ACT 2604, Australia

Abstract

The forest growth model, CenW, was run for the whole Australian continent based on the currently observed climate and with the inclusion of soils nutrient limitations. It was run for a generic eucalypt forest cover and for Pinus radiata. It was run under:

i) current conditions; and with

ii) 2xCO₂

iii) +3.0°C

iv) 2xCO₂ and +3.0°C

v) 2xCO₂ and +3.0°C - 20% rainfall

vi) 2xCO₂ and +3.0°C + 20% rainfall.

In response to doubling [CO₂], growth was simulated to be enhanced, with greatest responses in driest regions and smallest responses in cool and wet regions. Increasing temperature, was simulated to lead to slight growth enhancements in cool and nutrient-limited regions, but to be highly detrimental in water-limited regions.

In response to doubling [CO₂] and increasing temperature, growth of a generic forest was found to increase for most of the south, but to decrease in the north. There were complex further interactions, with growth increasing in some regions and decreasing in others. Responses were generally inversely related to the magnitude of temperature increases. There was also a strong sensitivity to changes in rainfall.

For P. radiata, growth responses were negative in most regions, dominated by the direct response to increasing temperature. Only some slight positive responses were possible in Tasmania and cooler higher-elevation sites in south-eastern Australia, but negative everywhere else.

Foliar nitrogen concentrations were predicted to increase in most regions, driven by enhanced rates of soil organic matter decomposition, and, especially in the far north of Australia, by decreasing productivity. Soil organic matter was generally predicted to be reduced because of enhanced decomposition rates. Surface litter was predicted to slightly increase in most of the south of Australia in line with increased biomass productivity, and to decrease in the north and marginal inland areas due to decreased biomass productivity and enhanced decomposition rates.

Introduction

Forests in Australia are impacted by the simultaneous increase in temperature and [CO₂] as well as possible changes in rainfall. Plant growth is closely tied to changes in these climatic factors, but the responses interact in complex ways with current growth limitations, such as the degree of water and nutrient limitation, and the combination of climatic changes.

Various models have attempted to simulate the extent to which these interacting factors
control the response of tree growth to climate change. The approach here was to use a detailed forest growth model that explicitly includes all the various feed-back effects that affect tree growth. This allows the initial perturbation due to climate change to be modified through various plant and soil feed-back effects.

**Simulations**

Forest growth simulations were run for the whole Australian continent with the comprehensive forest growth model CenW. The model is a generic forest growth model that simulates the fluxes of carbon and water, the interception of solar radiation and the dynamics of nutrient cycling through trees and soil organic matter.

Photosynthetic carbon gain was modelled in dependence on light absorption, temperature, soil water status and foliar nitrogen concentration. It was assumed that 45% of gross photosynthesis is lost in respiration. Water use was calculated with the Penman-Monteith equation, with canopy resistance given by stomatal conductance, which, in turn, was linked to calculated carbon gain. Water was lost by transpiration, soil and canopy evaporation and gained by rainfall.

Nitrogen was added from a constant rate of atmospheric deposition and mineralisation during the decomposition of soil organic matter (see below). Decomposition rate was determined by temperature, soil water status and soil organic matter quality in a modified formulation based on the CENTURY model.

The nutrient cycle was closed through litter production by the shedding of roots, bark, branches and foliage. Litter was added to the organic matter pools from where carbon was eventually lost, with nitrogen becoming available again as inorganic mineral nitrogen.

CO₂ sensitivity of photosynthesis was calculated based on simplified form on the biochemically-based model of Farquhar and co-workers by assuming that photosynthesis is limited by RuBP regeneration capacity. Under those conditions, CO₂ sensitivity of photosynthesis is less than if it were assumed that photosynthesis is limited by Rubisco activity. Stomatal conductance was calculated based on the Ball/Berry formulation. Details of all calculations are given by Kirschbaum (1998a, b).

For each location, the model was run for 10 years, with new seedlings as starting condition. Mean monthly minimum and maximum temperatures, mean monthly radiation and mean monthly rainfall were obtained from ESOCLIM surfaces (McMahon et al. 1995).

In CenW, fertility is essentially determined by the complex interaction between the total amount of soil organic matter, the rate of organic matter decomposition, the relative amounts of organic carbon and nitrogen and the relative proportions in respective fractions. Soils information was based on the soils information contained in the Atlas of Australian Soils which has been digitised by NRIC (1991). The model was then run to find amounts of soil organic matter with which relative foliar nitrogen limitations were obtained that corresponded to a fertility estimate obtained for each soil type (J. Walcott, pers. comm.). These values were used as input for runs with present and future climates.

For addressing the effect of climate change, direct plant responses to temperature are very
important. For *P. radiata*, minimum, optimum and maximum growth was assumed to occur at mean monthly temperatures of 5°, 15° and 20°C. For runs with a generic forest, it was assumed that forests at their present location had optimally adapted to the conditions experienced there. At locations with extreme climates, optimum growth temperatures were restricted to be within the range of mean monthly temperatures between 10° and 30°C.

**Results and Discussion**

Fig. 1 shows simulated net primary production of a generic forest. Observed net primary production rates broadly correspond to the observed growth potential of native regrowth forests, with excellent growth in the high-rainfall parts along the east coast and parts of Victoria and Tasmania. In these regions, growth is principally determined by the extent of nutrient limitation. Good growth rates are also simulated for WA and across the north of the country where strongly seasonal rainfall restricts the growing season to only part of the year. Growth rates decrease markedly with decreasing rainfall towards the interior of the country, with about half of Australia only receiving rainfall for growth of less than 1 t ha⁻¹ yr⁻¹.

Fig. 2 shows net primary productivity of *P. radiata*. Observed growth is similar to that of a generic forest for the cooler southern parts of the continent, where the temperature response function assumed for *P. radiata* is reasonably close to that of an optimally adapted forest, but it falls off sharply towards the north because of supra-optimal temperatures.

In response to doubling \([\text{CO}_2]\), growth increased were observed across the whole country, but it varied greatly across regions. It was less than 10% in cool and moist regions, but increased with increasing temperature and aridity, with growth responses greater than 50% in the drier parts of WA and along the inland margin from SA to the NT.

In response to increasing temperature by 3.0°C, slight increases in growth were calculated for cooler and wetter regions, but most regions are likely to suffer growth reductions, especially where it is dry and warm. The negative responses in drier regions is due to increased evapotranspiration, and in the hottest regions, there are also direct responses to supra-optimal temperatures. Growth enhancements in cool and wet regions are mainly caused by stimulation of organic matter decomposition that makes more nitrogen available for tree growth. The response of *P. radiata* to increasing temperature is much more negative because *P. radiata* is already experiencing supra-optimal temperatures in much of its northern range.

Increasing \([\text{CO}_2]\) and temperature frequently interact with other environmental conditions in such a way that some environmental conditions in cooler and moister regions, or in wetter, elevated areas, may not be limiting. For example, warm and wet places with \([\text{CO}_2]\) increase might not experience the same growth enhancement as cooler and dryer places with the same increase in temperature.
predicted growth increases in the range of 25 to 50%. Growth responses were mainly negative in the north, and some marginal inland regions, with growth reductions by more than 50% in many regions. Responses were generally inversely related to the magnitude of temperature increases, and there was also a strong sensitivity to changes in rainfall.

For *P. radiata*, growth responses were largely negative, dominated by the direct response to increasing temperature. Some growth increases were possible in Tasmania and cooler higher-elevation sites in south-eastern Australia, but responses were negative along the drier interior sites and along the milder coast, and responses were very negative along the northern-most extent of the species’ possible range.

Under doubled [CO₂] and temperature increase by 3.0°C, foliar nitrogen concentrations were predicted to increase in most regions, driven by enhanced rates of soil organic matter decomposition, and, especially the far north of Australia, by decreasing productivity (data not shown). A few regions were predicted to have reduced foliar nitrogen concentrations, largely regions where increased productivity outpaced the increased nutrient supplying capacity of soils. Increasing foliar nitrogen concentration was one factor contributing to increases in net primary production.

The increased soil nutrient supply was caused by increased soil organic matter decomposition rates. This was also predicted to lead to reduction in soil organic matter in the range of 0 to 5 t ha⁻¹ (data not shown). Some areas had even greater losses of soil organic matter. These either occurred in the far north where growth was predicted to be decreased and in cooler regions where the sensitivity to organic matter decomposition was relatively high.

Surface litter was predicted to slightly increase in most of the southern parts of Australia in line with increased biomass productivity, and to decrease in the north and marginal inland areas (data not shown). These decreases were due to decreased biomass production and enhanced decomposition rates.

These simulations involve many complex interactions between carbon uptake, carbon allocation, nitrogen cycling, the utilisation of water and others. Each component of these complex interactions affects every other component. The climate has an initial direct effect on each component, but then also leads to feed-back effects which may be of greater ultimate importance than the initial effect itself. As these feed-back effects are an integral part of the overall system response, it is not appropriate to model system without their inclusion.

However, the range of possible interactions is such that the ultimate response is significantly affected by the exact way in which these feed-backs are modelled, or, whether, specific interactions are included at all. It is therefore not possible to make predictions about system responses with high confidence. Confidence is further reduced by uncertainty about the relative magnitudes of changes in temperature relative to changes in [CO₂], and whether there will be changes in rainfall.

Nonetheless, concern about climate change is ultimately focussed on concern about the impact of climate change, and providing an assessment based on our best understanding of the interaction between all relevant factors is essential. Overall, these simulations provide no cause for alarm in relation to the impacts of climate change on tree growth, with the positive effects of increasing [CO₂] and the largely negative effects of increasing temperature compensating each other. However, within this broad pattern there are significant effects on
individual species and specific regions. Adaptive managerial steps seem warranted where negative effects can be expected.

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Impacts of global change on Australian forests: modelling studies

Joe J. Landsberg
CSIRO Land and Water, Pye Laboratory, Canberra.

Introduction

As a basis for considering the use of models to evaluate the impacts of global change on Australian forests we need to be clear about the assumptions underlying our analyses, and our objectives. What are we trying to achieve? What will we regard as a satisfactory outcome of the exercise?

To deal with the assumptions first: let us accept, for the purposes of this discussion, that an accelerated rate of global climate change, attributable in large measure to human activity, is a reality, and that the main components of that change will be regional increases in temperature - and presumably atmospheric humidity - and changes in rainfall patterns. The uncertainties associated with these changes are so large, particularly when considered in relation to uncertainties in our ability to predict the effects of temperature and water balance (other than gross changes) on forest growth, that attempts to forecast the effects of changes in these variables fall into the category of speculative, hypothetical exercises, that may be of value for the purpose of ‘what if’ scenarios, but are not useful as serious exercises in prediction. But the most important, and inarguable, component of global climate change is the increase in atmospheric CO$_2$ concentrations, with all the implications that seems likely to have for plant growth. The changes in atmospheric CO$_2$ are relatively large, and can be assumed to be (more or less) spatially uniform. Their effects - at least on the growth of young plants - are reasonably predictable, so this variable deserves closer attention. However, the title of this workshop includes the words ‘global change’, not climate change, which implies consideration of other factors, namely (presumably) land use change. This has considerable implications for our objectives.

There seem to be three objectives that we need to consider (the priorities are a matter of individual agendas):

- we are concerned to predict the consequences, in a global context (cf Kyoto Protocol) of changes in the area of forest and woodlands in Australia, and in the state and condition of those forests. Modelling studies are obviously important in considering the impact of the changes in terms of carbon storage or release, but I doubt that detailed models are the right tools to use in analysing these impacts. The uncertainties in the basic information available about soils and climate, areas affected, and how they are affected, are so large that simple approximations may be the best we can do. The use of highly detailed models, requiring large numbers of parameter values and considerable information about the structure and condition of the plant community, may veil guesswork in a cloak of scientific respectability that leads, in the end, to loss of credibility. The main requirement in this area is for information about the rates, extent and type of the changes (clearance and a complete change in land use; fire in forests that will be allowed to regenerate; logging which will change the age structure and growth patterns of the forests?)

- we need to predict the effects of changes in forest area and condition on land
degradation, biodiversity, wood production and economic values. Again, modelling studies provide an important means of assessing the implications of various situations and scenarios. They may also be of immediate practical value in a political context, by providing tools that can be used to demonstrate the consequences of policies or management actions. To do this the models need to be scientifically well-founded and well enough calibrated to convince the sceptics. At large scales the problem remains one of information and reliable data, and only simple models are needed.

- we need to be able to predict the growth rates of managed forests and plantations, in particular areas where the conditions are well specified. This is not a problem that has much relevance to global change, except insofar as success in this area will contribute to our ability to make better estimates of the national carbon balance.

The statements above do not imply that complex, process-based (mechanistic) models have no place in assessing the impacts of global change on forests. Such models are important as a framework for developing our scientific knowledge and understanding, and as a means of ensuring that simple models are soundly based and consistent with process understanding, rather than simply empirical. The next part of this discussion is concerned with a simple model that could contribute to achieving the first two objectives outlined above, by providing good estimates of tree growth rates - and hence carbon sequestration and commercially useful information - over long periods for areas where conditions are reasonably well specified. The model is aimed specifically at the third objective.

The 3-PG model

The 3-PG model (Landsberg and Waring, 1997) calculates radiation absorption by forest canopies, hence Gross Primary Production (total CO₂ uptake) and Net Primary Production (NPP). NPP is partitioned to stems, roots and foliage and the model provides the time course of biomass production, stand carbon balance (excluding soil respiration, so it is not net ecosystem production) and the parameters of interest to production forestry (stem volume, stem diameters, basal area). It applies to homogeneous even-aged stands (not necessarily single species). 3-PG has been successfully tested against forest growth data from WA, Victoria, Tasmania, Queensland, New Zealand, Oregon and Brazil. The model is driven by weather data, works on a monthly time step and has been used to simulate the growth of forests up to several hundred years old. A version driven by satellite data (3-PG-S) provides information on the biomass production rates and monthly carbon dynamics of established forests. It allows monitoring of changes in forest growth rate over time.

The presentation at the workshop will include model test data.

Spatial variability and remote sensing

In the course of testing 3-PG, particularly in relation to forest growth over large areas, the importance of spatial variability became increasingly obvious. Natural forests, in particular, are not homogeneous, and this characteristic - which reflects the effects of forest management and exploitation as well as topography and soils - limits our ability to predict forest growth rates and to characterize the effects of changes in atmospheric CO₂ and climate on the carbon
balance and productivity of large areas of forest. The problem comes back to one of scaling and of what constitutes a homogeneous area in terms of the variables that affect forest growth? The simplest answer to this seems likely to come from remote sensing. Radiometers on satellites - such as the AVHRR instrument and the instruments on Landsat - or spectroradiometers mounted in aircraft, provide a ‘signature’ for forests that indicates the type and condition of the canopy, and hence reflects the situation in relation to soil fertility, moisture and previous treatment. Homogeneity can be defined in terms of uniformity (within specified limits) of the radiometric signature of forested areas, determined either manually or in terms of pixel statistics.

Remote sensing is not a cure-all panacea that will provide all the information we need to model forest growth; coupled with it we require good weather data, including information about variability, particularly in rainfall; good soils maps - a rare commodity in Australia - where they do exist at scales large enough to be useful the information provided seldom includes the essential data on soil physical properties and water holding capacity; and on-the-ground information about the forests. Remote sensing can be used to fill the soil water holding capacity gap, to some extent, by combining water use calculations with rainfall records and sequential observations to identify the point where the condition of forest canopies changes as a result of water stress. Remote sensing, surveys (using modern techniques) and mapping will all help to fill the gaps in information needed to achieve - or at least move towards achieving - the first two objectives outlined above. Using satellite measurements to drive a model such as 3-PG increases enormously the accuracy with which we can estimate forest growth and assess the probable impacts of changing conditions.

Conclusions

Models are an essential and important part of the toolkit for analysing the impact of global change on Australia’s forests, but their applicability is generally limited by our lack of knowledge about the forests themselves - their extent, age distribution, and condition, the soils they grow on and the characteristics of the weather to which they are subject. Models allow scenario analysis, and exploration of the ‘what if?’ questions. Research on the detailed physiology underlying forest growth, and the basic mechanisms of response to environmental change, must continue, but it may be better to use the detailed, short time step, models that encapsulate our knowledge of those processes to develop and evaluate simpler models, likely to be more widely used, than to use highly detailed models to make ill-founded analyses of real situations. Looking to the future, the scientific community would do well to press for more resources in high-quality mapping, surveys and continual (remote sensing) monitoring - which must include the establishment of procedures to archive and evaluate the data - rather than for more research on matters such as tree physiology and soil carbon cycles - however much more interesting and accessible to study these may be. There is also the problem of trying to extend the vision of politicians and funding agencies beyond the restricted horizons dictated by political expediency and economic myopia.
What are the likely implications of climate change for future forest production?

Assoc. Prof. Ross McMurtrie\(^1\) and NGAC Project Team\(^{1,2}\)

1. School of Biological Science, University of New South Wales, Sydney NSW 2052
2. CSIRO Forestry and Forest Products, PO Box E4008, Kingston ACT 2604

Introduction

Controlled experiments have consistently shown that, under optimal growing conditions, plant growth is greatly increased by elevated CO\(_2\) - the ‘CO\(_2\)-fertilisation effect’ (CFE). However, most native Australian forests are on sites where growth is limited by nutrients and/or water. Considerable uncertainty remains about the magnitude of the CFE under nutrient- and water-limited conditions. An emerging understanding is that the CFE is diminished under soil nutrient limitation, but is amplified under water limitation (e.g. Kirschbaum et al 1996a,b). This viewpoint is supported by results from several field experiments and from modelling studies.

What are the implications of this understanding for the productivity of Australian forests under climate change? What ecosystem factors are critical in determining responsiveness to rising CO\(_2\) and temperature? In this talk these questions will be addressed by applying the G'DAY forest ecosystem model to evaluate annual stemwood production of forests growing on sites of widely differing rainfall and fertility.

Experimental evidence on CO\(_2\) responsiveness of nutrient and water-limited forests

The CFE under nutrient limitation has been extensively studied using both experiments and models. In short-term, controlled-environment experiments, a large relative CFE is commonly observed even under severe nutrient limitation (e.g. Idso & Idso, 1994). In the longer-term, however, there is little evidence of a CFE in nutrient-limited natural environments. For example, in a long-term field experiment at an infertile wetland site in the Alaskan tundra, only a transient CFE was detected (Tissue & Oechel, 1987). In contrast, a large CFE was sustained over 6 years in a nutrient-rich temperate wetland in Maryland (Drake et al., 1996). Modelling studies have verified that, under nutrient limitation, the long-term CFE may be less than the short-term CFE (e.g. Comins & McMurtrie, 1993). This decrease in the CFE with time can be understood in terms of negative soil feedbacks: increased growth at elevated CO\(_2\) leads to enhanced nutrient immobilisation in biomass and soils, and hence to reduced availability of soil nutrients to support further growth.

Less is known about the CFE under water limitation, because few experiments have been conducted involving manipulations of both CO\(_2\) and soil moisture. However, the few published studies suggest that the short-term CFE is amplified under water limitation (e.g. Idso & Idso, 1994), as observed, for example, in an experiment involving free-air CO\(_2\)-enrichment (FACE) of wheat grown with plentiful water supply and 50% reduced water supply (Kimball et al., 1995), and in field experiments on Kansas tallgrass prairie (Owensby et al., 1996) and Californian Mediterranean grassland (Field et al., 1996). A physiological explanation of this amplification is suggested by the consistent experimental finding that water-use efficiency (WUE), defined as carbon uptake per unit water loss, increases at elevated CO\(_2\) (Morison, 1993). Experiments indicate that leaf-scale WUE (defined as net
photosynthesis / transpiration) increases approximately linearly with CO₂ concentration (Morison, 1993). Modelling studies have also predicted an enhanced CFE on dry sites (Ryan et al., 1996; Pan et al., 1997).

Application of G'DAY to nutrient- and water-limited forests

The above evidence from both experiments and models suggests that the CFE is enhanced under water limitation, but diminished under long-term nutrient limitation. However, it is difficult to extrapolate from this evidence to predict the combined effects of water and nutrient limitations. The objective of this talk is to analyse the long-term CFE when both water and nitrogen (N) are limiting, by using a model to integrate the interactions between the C, N and water cycles. Our approach is to evaluate the CFE for closed canopy, equilibrated forests using the G'DAY forest ecosystem model (Comins & McMurtrie, 1993; McMurtrie & Dewar, 1998). G'DAY is a forest ecosystem model that simulates the mechanisms of C and N cycling in the plant and soil. The plant is represented by 3 biomass pools (foliage, wood, root), and the soil by 4 litter pools and 3 soil organic matter (SOM) pools (called active, slow and passive SOM). The C-cycling model describes photosynthesis, allocation and senescence, and the decomposition of litter and SOM. The N-cycling model describes atmospheric N deposition, biological fixation, plant N uptake, allocation and retranslocation from senescing tissue, N release and immobilisation by decomposing litter and SOM, and gaseous N emission from soil.

G'DAY has been used to evaluate annual stem volume increment (∆V) for sites of widely differing annual rainfall (500 to 1250 mm) and fertilities, at two CO₂ concentrations (350 and 700 ppm), and for two temperatures (current and + 4°C). Across this rainfall and fertility range, modelled ∆V ranges from 10 to 23 m³ ha⁻¹ yr⁻¹ at current CO₂ concentrations, from 12 to 27 m³ ha⁻¹ yr⁻¹ at doubled CO₂, and from 15 to 31 m³ ha⁻¹ yr⁻¹ under rising CO₂ and temperature. The simulated response to increased CO₂ alone is least (+1 m³ ha⁻¹ yr⁻¹) on wet, infertile sites and is greatest (+9 m³ ha⁻¹ yr⁻¹) on fertile sites with intermediate rainfall (~800 mm per year); these results are consistent with the above experimental evidence on CO₂ responses under nutrient and water limitation. On the other hand when both CO₂ and T increase, the simulated response ranges from +4 m³ ha⁻¹ yr⁻¹ on wet, infertile sites to +15 m³ ha⁻¹ yr⁻¹ on fertile, intermediate rainfall sites. Rising temperature has a positive effect mainly because soil decomposition is enhanced, leading to increased nutrient availability - but this effect is countered by a negative effect on water-limited sites, because tree transpiration is enhanced leading to more rapid exhaustion of soil water resources.

These results will be used to discuss the consequences of rising CO₂ for wood yield of native forests in various regions of Australia. The results will be extended to discuss how altered rainfall and nutrient inputs are likely to affect production.

There are several uncertainties in the above analysis, including: (1) the issue of whether stomatal conductance declines at high CO₂, and consequences for the sensitivity of WUE to CO₂; (2) inadequately understood feedbacks between the nutrient and water cycles (e.g. what are the consequences for water balance if foliage mass increases at high CO₂?); and (3) differences in conclusions for forest sites where soil evaporation, under-storey evaporation, run-off and drainage are large components of forest water balance.
A conclusion from the above simulations is that there is not one unique sensitivity of plant productivity to increasing CO₂, but that the response is highly ecosystem specific, with responses likely to range from small to large positive responses in conditions where plants are strongly water-limited, but where other limitations play no significant role.

**Critical factors determining forest responsiveness to rising CO₂**

An NGAC-funded research project at UNSW and CSIRO Forestry and Forest Products has considered the broad issue of what determines ecosystem responsiveness to rising CO₂ and temperature (UNSW & CSIRO, 1997). We concluded that, in trying to assess the responsiveness of different ecosystems to increasing CO₂ and temperature, it is necessary to include considerations of all the feedback effects that interact with temperature and CO₂ in determining an ultimate growth response to an initial perturbation. There is not likely to be a general responsiveness of systems to increasing CO₂. Instead, the effect of increasing CO₂ on forest growth can differ substantially between forests due to interactions with a range of factors that affect nutrient supply. Some systems are likely to be highly responsive to increasing CO₂ while others are likely to be quite unresponsive.

The response of a particular forest to increasing CO₂ can only be predicted if the main factors controlling nutrient supply and growth in that forest are understood and incorporated into an assessment. There is a need to further refine our understanding of the factors that increase or reduce the CO₂ responsiveness of different sites, and then apply that understanding individually to different sites.

The understanding gained through our work has been summarised in Table 1. It compares the relative responsiveness of productivity to increasing CO₂ in ecosystems affected by different limitations and the responsiveness of different aspects of ecosystem function to increasing CO₂.

The greatest growth responses are to be expected under water-limited conditions as greatly enhanced water use efficiency in increased CO₂ can lead to the greatest growth stimulation. Under non water-limited conditions, growth responses are likely to be greater at higher than lower temperature because the CO₂ responsiveness of photosynthesis increases with increasing temperature.

Under nutrient limited conditions, growth responses are generally reduced, but not generally down to zero. This is true for both nitrogen- and phosphorus-limited conditions, with the extent of growth response depending on both the openness of the system with respect to nutrient fluxes and the time horizon. The least responsive systems are those with closed nutrient cycles, where the total amount of nutrients in the system does not change much irrespective of changes of the internal status of the system due to growth under increased CO₂ (Kirschbaum et al., 1998).

This is further affected by the flexibility of the C:N ratios in the soil or wood (Kirschbaum et al., 1994; McMurtrie & Comins, 1996). Systems with fixed amounts of nutrients in the system and with inflexible C:N ratios cannot change the carbon store in the system and are therefore unresponsive to increasing CO₂ whereas systems with flexible C:N ratios can operate at increased C:N ratio in higher CO₂, which gives scope for some responsiveness to CO₂.
In comparing the response of different aspects of ecosystem function, we concluded that soil carbon storage is most likely to increase in response to increasing CO$_2$, whereas total biomass productivity is less likely to show a lasting increase because an increase in soil carbon through its immobilisation of nitrogen is one likely reason for the absence of a growth response. A growth response itself should express itself more fully in total biomass production and less so in above ground production as lower nutrient concentration in plants is likely to drive allocation shifts towards below-ground components.

**Table 1:** Notional responsiveness to increasing CO$_2$ (UNSW & CSIRO, 1997). Numbers of asterisks correspond to different magnitude of responses. The upper 10 items refer to the response of plant productivity under different limitations, and the final three items compare the response of three aspects of ecosystem functions.

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Responses of carbon and nutrient cycling in Australian forest soils to global change

Partap Khanna, Miko Kirschbaum and John Raison
CSIRO Forestry and Forest Products, P.O. Box E4008, Kingston 2604

Abstract

The impact of global change on the turnover and pools of C and nutrients in forest soils can result from both direct effects of temperature and moisture on soil biology, and indirectly via changes in forest growth and the amount and quality of litter inputs to the soil system (biological impacts). But the most significant impacts on soils are invariably associated with forest management practices (harvesting, fire, soil disturbance, slash management) or land use changes (especially clearing and cultivation).

Any increase in temperature associated with global change is expected to increase mineralisation of soil organic matter (SOM) and increase nutrient turnover with consequent stimulation of ecosystem productivity. Temperature changes are expected to affect forest systems more in temperate than tropical zones, and changes in rainfall will have most effect in drier areas. Increases in atmospheric CO2 concentrations are unlikely to have a direct effect on soil microbial biomass or activity, but changes may occur indirectly via increases in C:N and lignin:N ratios in plant litter.

Any change in soil organic C will affect soil structure e.g., the stability of soil aggregates, and thus the water holding and nutrient supply characteristics of forest soils. A degrading soil will lose C initially from less protected sites (active soil C fraction) and thereby release nutrients (N and P), the fate of which will depend whether there are vegetation sinks. Further loss of soil C will occur from more slowly decomposing SOM from highly protected intra-aggregate sites. During soil C sequestration, SOM is initially retained in less protected sites, and it takes a long time before SOM becomes highly protected in intra-aggregates. Together with C, nutrients are also sequestered. Most Australian soils are deficient in P, and this limits both biological N fixation and plant growth generally. Atmospheric inputs of limiting nutrients are also generally low. Thus, nutrient availability can be a major constraint to C sequestration in Australian forest soils. Managed forests (plantations or regrowth) are likely to show greater changes in nutrient cycling processes and stand productivity in response to elevated CO2 on changing climate than relatively undisturbed forests.

The frequency and intensity of forest fires may alter with climate change. In addition to the direct loss of SOM and nutrients during fires, and their consequent effect on the productivity of regrowth, changes in soils may have long-term consequences for SOM storage following fires.

Different feedback mechanisms involving nutrient cycling, C balance and global change will determine the direction and extent of soil change. Four types of land use are explored to show these feedbacks. Nutrient-related interactions affecting C-sequestration in forest soils and the effects of global change on them will be described with the help of a generalised theoretical model.
Introduction

Global change is a broad term encompassing increase in the atmospheric CO$_2$ and other greenhouse gases, depletion of the ozone, altered climate and changes in land use. Such changes are expected to alter many processes in forest ecosystems. Of special significance in this context are changes associated with soil C and related nutrient transfer and turnover processes. Both the production and decomposition of soil organic matter may undergo substantial changes in the long term. Soil processes can also be affected in a major way by forest management practices, and by changes in land use patterns.

Soils under temperate forests and the ranges of C, N and P in soils

Gifford et al (1992) estimated that there are 24.4 M ha of temperate forests in Australia. Data compiled by the RAC (1992) for States with temperate forests sum up to 22.5 M ha of native forest and about 0.7 M ha of plantations. The Montreal Process first approximation report (1997) gives values of 28.6 M ha of open eucalypt forest and 1.0 M ha for plantations in Australia. Some of the open eucalypt forest is expected to lie in the non-temperate zone. Thus an area of about 25 M ha of temperate forest in Australia seems reasonable. In addition, there are large areas of open woodland in the temperate and tropical zones.

By assuming a soil to plant carbon ratio of 0.8, Gifford et al (1992) calculated, based on the above-ground plant biomass, that there are some 1.7 G t of soil C in temperate forests of Australia at an average of about 71 t of C ha$^{-1}$. On the world scale, Schlesinger (1977) calculated an average value of 118 t C ha$^{-1}$ for temperate forests. A similar value (120 t ha$^{-1}$) was used for soils under both tropical and temperate closed forests in workbook 4.1 prepared for the NGGIC (1996). The total pool of C is thus large and varies markedly spatially.

Impacts of climate change on forest soils

The direct effect of CO$_2$ increase on some soil processes is expected to be small e.g., effects on the population and activity of microorganisms, but its indirect effect through changes in forest productivity, organic matter decomposition, change the availability and cycling of nutrients and possibly litter quality (C:N ratio) will be more significant. Such interactions are highly complex with many feedbacks so that a model is required to describe and simulate them.

The effect of temperature change is more direct and may greatly stimulate organic matter decomposition and through that forest productivity and nutrient cycling processes. For example, in forests with biological N-fixers an increase in productivity may increase N-fixation when other nutrients such as P are non-limiting, but when P becomes limiting, N-fixation may be reduced. Under severe P and S limitation, the expected positive forest growth response to elevated CO$_2$ may be constrained (Kirschbaum et al. 1998).

As an example, simulations using the CenW model (Kirschbaum, CSIRO Forestry and Forest Products) in a nitrogen-limited Pinus radiata stand over 40 years with a 3°C increase in temperature and a doubling of CO$_2$ concentration show:

1. High CO$_2$ increased NPP (direct response of photosynthesis), but an increase in temperature slightly decreased NPP (as a complex result of a number of several processes...
- higher respiration, higher water use) despite an increase in N availability).

2. Soil organic matter increased with an increase in CO$_2$. The resistant pool increased most due to the declining quality of litter. SOM decreased with an increase in temperature. Both the active and resistant pools of SOM were affected but the active pool was reduced by more than one third of the initial value. Kirschbaum (submitted) showed that a one degree change in temperature will significantly reduce soil C in temperate areas when the seasonal amplitude in annual temperature is small. Change in temperature will have less effect on soils from warmer areas and from those where seasonal amplitudes are large.

3. Mineral N in the soil decreased with elevated CO$_2$ but increased with increasing temperature.

4. Litter on the forest floor decreased with an increase in temperature but increased with elevated CO$_2$, both by more than 40% over 40 years compared with current conditions. These changes in litter mass could directly influence the frequency and intensity of forest fires.

**Forest fires and climate change**

It is well documented that biomass burning can be a significant source of the Greenhouse gases - nitrous oxide (N$_2$O), methane (CH$_4$), and volatile organic compounds. In addition some essential plant nutrients (N, P, S, K) are lost during fire. The amount of nutrients lost depends on the fire regime (fire frequency and intensity). A decrease in nutrients can affect productivity and decomposition processes - for example a decrease at sites already limited by P can further decrease productivity, reduce biological N-fixation, reduce litter quality and thus decomposition rate. Postburn changes in soil microbial processes can enhance rates of trace gas emissions. It is however uncertain whether forest fires will increase or decrease due to climate change.

Depending upon the intensity and frequency of fire some biomass C is converted into charcoal which is considered to have a very long life. Kuhlbusch and Crutzen (1995) have estimated the global black carbon formation to be 50-270 Mt yr$^{-1}$. Skjemstad et al. (1996) observed that 30% of the C in four Australian surface soils was charcoal in nature. The value for the deeper soil layers is expected to be much lower. Knowledge of fire history and of erosion/deposition rates are needed to interpret soil charcoal data. Moreover, a significant fraction of the black ash produced after fire is organic C, the stability of which is not known. Sequestration of C in charcoal is generally only a small fraction of the total C in forest soils.

**Impacts of land use on forest soils**

A number of land use practices are contributing to changes in pools and fluxes of C in Australia. Of significance was the clearing of forest and woodland vegetation for agricultural use and plantations in the past. Land clearing has been much reduced in recent years but still persists particularly for woodlands on private lands. The NGGIC estimated that annual total emissions associated with land clearing accounted for 107 Mt CO$_2$-equivalent (29 Mt C) out of which 14.5 Mt C stemmed from changes in the soil (SOM + roots), indicating the importance of soil C changes.
Four type of land use need be considered.

1. **Conversion of mature forest or woodland to regrowth/plantations or pasture/cropland**

   There is wide variation in the C content of mature native forest or woodland depending upon species, forest structure, soils and climate. The above ground biomass (tree, understorey and litter) of mature eucalypt forests can vary from 65 t C/ha for *E. signata* on sand at Stradbroke Island to 350 t C/ha for *E. regnans* in Gippsland (Turner and Lambert 1996). Carbon in the forest floor can vary from 4 to 22 t C/ha. In the poorest quality forests there may be little wood harvested, but even in the better quality forests much debris is left on the site and often burned. In a mixed species eucalypt forest at Maramingo in East Gippsland, Hopmans et. al. (1993) measured, after recovery of 50 t C ha\(^{-1}\) of wood, about 122 t C ha\(^{-1}\) remained in woody biomass. For three forest types in the Eden woodchip area, Turner and Lambert (1986) estimated 203 to 229 t C ha\(^{-1}\) in total aboveground biomass out of which about 50 t C ha\(^{-1}\) was removed in harvest. Management of the slash is thus an important issue affecting C budgets (emission rates and C retention) for such forests. Changes in aboveground biomass will be discussed by other participants.

When mature forests are converted to regrowth forests there will be at least initially a decline in soil C levels (Raison et al 1993), but information on long-term changes is lacking. Data on soil C change following conversion of native forest to plantation is also slight and insufficient to draw any clear conclusion. The effect of clearing of woodland on soil C storage depends very much on subsequent land use. Cultivation invariably leads to major declines. Conversion to pasture may or may not result in major changes depending upon the productivity of the pasture and the soil conditions. There are different views in literature and specific studies are required under a range of Australian conditions.

2. **Management of regrowth forests**

   Very little data are available on the impacts on soils of management of regrowth. It is expected that the degree of soil disturbance would increase with increasing intensification of forest management (prescribed burning, thinning, clearfelling, slash burning). Again studies are needed.

3. **Management of plantations**

   Little experimental data exists. Losses of soil C resulting from site disturbance may be replenished by inputs from the fast growing forest. Productivity is tending to increase with greater silvicultural inputs. Studies on podzolised sands show that soil C is highly dynamic and is sensitive to management operations which influence organic C inputs, decomposition or both. Most harvesting and site preparation operations result in the loss of the labile carbon pool which represents about 30 percent of total carbon. This pool can be buffered by residue retention and weeds during the period before significant litter input from the new crop occurs at which time the pool begins to be replenished. Long-term reductions in soil C occur when there are losses from the recalcitrant pool of soil C. This can occur on scalped sites or in association with high intensity fires.

4. **Conversion of grasslands to plantations**

   Depending upon the type of pasture (improved and productive or poor), soil organic carbon may initially decline with plantation establishment (soil cultivation, weed control), the decrease may be permanent depending on the fate of other nutrients (N and P) or may be offset by increases in the litter layer and coarse roots.
C sequestration by forests

Many factors determine net C sequestration at a site. Site history is very important for subsequent soil change, and it may take many years to approach a new equilibrium. Soil change can be a major factor affecting overall budgets, but is often ignored by those advocating forests as major future C sinks. More detailed analysis is required focusing on:

- the potential of a site to accumulate organic soil C, determined by climate and soil type.
- soil organic C storage that could be achieved by practical soil management, and
- the actual soil C levels occurring under current operational forestry.

Every unit of soil C sequestration will also sequester nutrients. The impact of this on important ecosystem processes must be considered, as well as the cost and impacts of adding nutrients with the objective of enhancing the storage of soil C.

Methodology for assessment of soil C in forests requires re-examination. The amount of C in the forest floor and coarse roots can be significant. Coarse root C is generally estimated from allometric relationships with stem basal area. Following harvest, C contained in the forest floor and killed coarse roots can be gradually transferred to the soil C pool. Often methods used to measure soil C capture an unknown and temporally varying portion of C derived from these sources. All pools, including charcoal and calcite, need to be accounted for.
Impacts of global change on biodiversity in Australian temperate forests

Jann Williams
Charles Sturt University, PO Box 789, Albury NSW 2640

Introduction

This is a summary of a discussion paper examining relationships between the conservation of biological diversity and global change in temperate forests in southern Australia. I consider the potential impacts of global change on biodiversity, discuss possible adaptations to these impacts and outline some future directions for research, environmental decision making and education within the current policy/planning frameworks of Australian governments. Uncertainties and risks associated with global change are considered significant and are also addressed. Further details on this presentation and topic can be obtained by contacting the author at the above email and will be included in the full workshop proceedings.

Definitions

Forests

The focus of this paper is temperate forests in southern Australia. This encompasses open and closed forests dominated by eucalypts, cool and warm temperate rainforests dominated by species such as Nothofagus, and forests with Callitris species as a component (Groves 1994). Plantations and agroforestry are also of relevance and may be particularly affected by climate change. Forests and woodlands merge throughout temperate Australia and the following discussion can be applied to woodlands as well.

Biodiversity

The Global Biodiversity Assessment (GBA) (Heywood 1995) defined biodiversity as: "the variability among living organisms from all sources and the ecological systems of which they are part; this includes diversity within species, between species and of ecosystems."

For temperate forests, biodiversity encompasses organisms as different as the bacteria that fix nitrogen in the roots of some plants to Eucalyptus regnans - the tallest flowering plant in the world; from macroinvertebrates in forest streams to the lichens that grow in tree canopies. Biodiversity however is more than just a list of species - it provides many of the ecosystem services essential to human-kind.

The GBA emphasised the need to understand the cycles of interactions that take place between biodiversity and human society - hence widening the scope of discussions on biodiversity so as to include the human dimension.

Global Change

This workshop broadly defines global change as a combination of potential climate change and other human-induced changes such as ozone layer depletion and land-use changes. Dale (1997) argued that the direct ecological effects on terrestrial biodiversity of land-use and climate change are dominated by the nature of land-use, at least over the period of a few decades. Given that the nature of global change may be strongly influenced by land-use, then
these practices set the stage on which many climate alterations will act.

Also of relevance is the working definition of global change used in the strategic plan for research on managed forests within the Global Change and Terrestrial Ecosystem component of IGBP (Linder et al. 1996). This definition focused on the impacts of elevated levels of atmospheric CO₂, as well as climate related affects such as changes in the amount and distribution of precipitation.

Australia’s biodiversity

From a global perspective, Australia's biological diversity is significant and has many unique attributes and a high level of endemism (Williams et al. 1994). Given the continent's evolutionary history, the level of endemism is not surprising, but it is important for policy because it places a notable stewardship responsibility on Australia. This responsibility is amplified because, of the twelve recognised 'mega-diversity' countries of the world, Australia is the only developed nation and is well placed to conserve biodiversity and manage its resources on an ecologically sustainable basis.

The biota of temperate forests are part of this stewardship responsibility. This is illustrated by the suite of arboreal marsupials that is principally found in temperate forests and whose occurrence is strongly dependent on the availability of food and tree hollows for nest sites (Pausas et al. 1997). The recently discovered moth that appears reliant on the availability of the scats of the Koala in which to deposit its eggs is another example of the interdependencies found in temperate forests.

While the status of taxonomic knowledge in temperate forests in southern Australia compares favourably with other developed nations, major gaps in knowledge remain. Also of serious concern is the massive deficiency in knowledge of the distribution, abundance, interactions and functional roles of the vast majority of forest biota. Combined with on-going threatening processes and uncertainties, these gaps in knowledge hinder moves to sustainable management.

The policy/planning framework

It is salutary to remember that biodiversity and other sustainability problems like “greenhouse” and population-environment linkages are complex and unprecedented (Dovers and Williams, in press). The policy framework associated with biodiversity conservation is a useful example of this situation.

The Convention on Biological Diversity (CBD), of which Australia is a signatory, establishes a framework of general obligations that Parties are to elaborate in more detail at the national level. Most of the Conventions’ obligations allow Parties some flexibility in implementation, recognising that conditions of biodiversity conservation and loss may vary widely.

The National Strategy for the Conservation of Australia’s Biodiversity (Commonwealth of Australia 1996) fulfils the requirement of Article 6 of the CBD; to establish a national policy. This is the central component of biodiversity policy in Australia, but overall the policy setting currently comprises some two hundred schemes, strategies, policies and programs. For
example, both Victoria and NSW, where temperate forests occur, have just recently released policy strategies to manage biodiversity.

Factors affecting biodiversity

A host of factors can be important in determining the nature, composition and function of ecosystems, and the distribution, abundance, population dynamics and evolution of species. The evolutionary history of landscapes and evolutionary ecology of species sets the stage. Then factors such as the availability of key resources (e.g. soil type and its affect on moisture and nutrient availability on plant performance), disturbance regimes, competition, predation, and dispersal ability become important for different biota. Resources necessary for the survival and reproduction of species may be patchily distributed in space (e.g. across the landscape), and time (e.g. between breeding cycles and dispersal phases of young). Complex interactions affecting the structure, function and resilience of ecosystems are increasingly demonstrated between biota in temperate forests (e.g. between fungi, ground-dwelling marsupials, fire and eucalypts). The maintenance of biodiversity under global change requires a significantly enhanced understanding of such interactions.

Climate affects the distribution and abundance of biota and biodiversity, especially at the regional scale. Palaeological evidence shows that the distribution of temperate forests has changed considerably over time, most recently during the last glaciation around 10,000 years ago. A critical difference now is the highly modified landscapes that influence the ability of ecosystems and species to respond to changed conditions, and constrain options for management (e.g. restoration). The current rate of environmental change is also of concern. Elevated levels of atmospheric CO₂ may also affect the response of species to changes in temperature and precipitation.

The potential impacts of global change on biodiversity

The Australasian chapter of the IPCC Regional Impacts Special Report (Basher et al. 1998) concluded that there is ample evidence for significant potential impacts of climate change on Australia’s biota. Alterations in soil characteristics, water and nutrient cycling, plant productivity, species interactions (competition, predation, parasitism, etc.) and the composition and function of ecosystems were identified as highly likely responses to increases in atmospheric CO₂ concentration and shifts in temperature, and rainfall regimes. Impacts on biodiversity are also likely to be exacerbated by the secondary effects of climate change such as changes in the occurrence of wildfire and insect outbreaks.

A number of techniques are used to examine the potential impact of global change on biodiversity. Because of the uncertainties and complexities involved, a number of these approaches have a strong technical, modelling component.

Bioclimatic modelling, where the current climatic envelope of a species is examined using different climate change scenarios, has been a widely used approach in Australia. For example, Brereton et al. (1995) used predictive models for bioclimatic ranges to examine the potential effect of enhanced greenhouse climate change on the distribution of 42 species of fauna in south-eastern Australia. In their analysis, forest species appeared to be less affected by climate change, which the authors felt might reflect the large altitudinal range of forest
habitats in south-east Australia. Only two of the eleven forest species studied disappeared under a temperature rise of 3 degrees, both of which had very restricted ranges. Hughes et al. (1996) also used this approach to examine the distribution of eucalypt species under climate change and noted quite large displacements in the range of some species.

These types of studies recognise that climate is only one of the factors that may affect the distribution and abundance of species, and that the current climatic range is not necessarily indicative of the potential climate in which species can occur. In some instances, changed levels of atmospheric CO$_2$ are also likely to influence the ability of species to respond to altered climatic regimes. This possibility has not generally been accounted for in climatic models.

The bioclimatic modelling approach generally focuses on the response of individual species to climate change. Another class of models, which has a more dynamic component, is the JABOWA/FORET type forest gap simulation models (Pausas et al. 1997). The utility of this approach and the ability of these models to obtain accurate predictions under climate change scenarios is discussed by Austin et al. (1997).

Experimentation in the laboratory and field is also used to examine the potential response of species to global change. These generally focus on the response of individual plant species to elevated levels of CO$_2$, although a series of FACE (free-air CO2 enrichment) experiments have been used overseas to examine ecosystem level responses (Mooney and Koch 1994). Studies such as those that examine the impact of human land-use (i.e. fragmentation) and the impact of weed species on natural ecosystems also add to our understanding of global change.

**Possible adaptations to impacts**

In the recent IPCC Regional Impacts Special Report, the primary human adaptation option in Australasia was seen to be changes in land-use management, such as changed forestry practices and control of pests and weeds (Basher et al. 1998). Active manipulation of species was not seen as being generally feasible, except for rare and endangered species or commercially valuable systems. For example, irrigation may be necessary for commercial forestry operations if soil moisture availability becomes limiting to growth. Climatic and ecological research, monitoring and prediction were seen as a necessary foundation to any adaptive response (Basher et al. 1997). Research into the human dimensions of adaptive management is also essential, including the capacity of current institutions and institutional arrangements to support learning and adaptation (Dovers et al. 1996).

Management prescriptions to address future global change options in natural areas generally fall into five categories: selection of more than one conservation reserve for each important community type; selection of reserves that provide habitat diversity; management for buffer-zone flexibility; management for landscape connectivity and management for habitat maintenance (Halpin 1997). Because of the lack of experimental field testing, these options have been largely intuitive, based primarily on assumptions of future landscape needs. It would seem essential that future questions about biodiversity protection under global change shift from highly conceptual arguments to specific management proposals. This must occur in forests managed primarily for nature conservation as well as those identified for production forestry.
In Australia, considerable attention has been directed to the criteria and indicators developed for the conservation and sustainable management of temperate forests through the Montreal Process (Commonwealth of Australia 1997a). While originally intended to assess progress towards sustainable management at the national level, these indicators have been adopted and modified at the regional level in Australia (Commonwealth of Australia 1997b), principally through the on-going Regional Forest Agreement process.

Criterion 1 of the Montreal Process criteria and indicators relates to the conservation of biological diversity, focusing on indicators of ecosystem, species and genetic diversity. At the national level, Criterion 5 addresses the maintenance of forest contribution to global carbon cycles. There is, however, only one indicator that specifically addresses the ability to predict impacts of climate change on forests. This indicator is not considered relevant at the regional level and, therefore, limits the effectiveness of this approach to measure climate change impacts. Effective monitoring of such impacts is an essential component of moves towards the sustainable management of temperate forest ecosystems.

Future directions

The Sustainable Biosphere Initiative of the Ecological Society of America has identified biodiversity, global change and sustainable ecosystems as priority areas. It addresses these areas on three fronts, a useful framework which this paper follows.

Research

Several ecological research areas have been identified by Halpin (1997) if progress is to be made on responding to global change and establishing scientifically-based strategies to conserve biological diversity. These are put forward as a starting point for discussion in the context of temperate forest ecosystems in Australia:

- well-defined sensitivity tests are needed of ecosystem responses at the forest site or sub-regional scale;
- analysis of the fundamental physiological tolerances, competitive interactions and dispersal mechanisms of key species are required to better understand the potential response of existing ecosystems to change;
- analysis of changes in local disturbance regimes (i.e. storm, fire, drought, pests) are required to understand and predict rapid changes in ecosystem properties and stability;
- analysis of the interaction between landscape fragmentation and the mobility and dynamics of populations are needed to better characterise current and future ecosystem controls;
- it seems appropriate to critically evaluate suggested management interventions both in terms of ecological viability and likely benefit-costs.

The final point is a critical one given the resource constraints felt by most land managers. Research on these topics is also likely to be most productive if linked to and/or complemented by interdisciplinary studies of land-use and the effects of climate change.

Education

By providing information that links climate change and land-use, scientists can assist policy makers, stakeholders and the general public reduce the impacts of global change on biodiversity (Dale 1997). This should help define what climate change would mean in an ecological, social, health, political and economic sense and how society in general can
contribute to biodiversity conservation.

Environmental Decision Making

Many approaches and techniques to address the uncertainty inherent in management of biodiversity have been proposed or tested (Dovers and Williams, in press). Any or even all of these cannot be relied on to provide incontestable policy or management recommendations - subjective and political decisions will remain at the end of the day. Hence one important question is how to structure investigations and debate so as to best use available knowledge while still acknowledging underlying uncertainty. This is a point equally relevant to scientists and policy makers, and clearly directs our attention to the nature of policy processes and institutions to enable informed, flexible, precautionary approaches.

Conclusion

The complex and overarching nature of global change emphasises the need for interdisciplinary research and to explicitly incorporate human land-use when applying ecological applications and models. Specific management proposals are required which meet the management objectives for temperate forests in Australia, while also addressing global change. In the case of biodiversity conservation, land managers work within a complex policy and legislative framework. This brings important responsibilities and obligations that are likely to be even more challenging under a changing climate.

References


URL: http://www.environment.gov.au/air/climate/clim_change/eco (the report is only available on the internet)
Impacts of global change on Australian forests: fire

Ian R. Noble
Research School of Biological Sciences, Australian National University, Canberra 0200

With the exception of the wet tropical forests, fire has been an integral part of Australian forests throughout much of their evolution. Fire frequencies vary from once every 2 to 3 years in woodlands and savannas to only once per century or longer in some cool temperate forests. Most Australian forest species are well adapted to either persisting through a fire or re-establishing soon after.

Fire regime

The impact of fires on forests may be summarised in terms of the fire regime. The fire regime includes the frequency of fires, their intensity, the season of burning and their size and patchiness. Each of these components may be influenced by global change but the net outcome of changes in climate and human actions is extremely difficult to forecast.

In the 1960's McArthur developed a quantitative index of fire hazard. This was expressed as the fire danger index (FDI), and published as a meter in 1966 (McArthur 1966, 1967). Gill et al (1987) confirmed McArthur's assertion that the FDI is related to the probability of a fire occurring and many other studies have shown that the index is related to the behaviour of a free running fire. McArthur's approach paralleled similar developments in North America, but differed significantly in detail. Most Australian workers have concluded that McArthur's forest fire danger index remains the best tool for summarising fire hazard and behaviour in Australian forests. A series of variants have been developed and Noble et al (1980) expressed McArthur's original meter in equations. The FDI is a function of a drought index, temperature, humidity and wind velocity, while fuel load also affects fire spread and intensity.

Several studies have examined the equations in relation to projected climate changes (Beer et al 1988; Beer & Williams 1995). They concluded that the FDI is likely to increase slightly under most climate change scenarios. However, FDI is most sensitive to changes in relative humidity - a variable poorly forecast by GCMs. This sensitivity arises from the strong effects of relative humidity on fuel moisture that in turn dominates fire behaviour in McArthur's model. Researchers elsewhere do not find such a strong sensitivity. Simplifications of the equations of Noble et al (1980) show the relationship:

\[
\text{Intensity} = 0.83 \times \text{Fuel}^2 \times \text{Drought} \times \exp \left( \frac{\text{Temperature} - \text{Humidity} + 0.7 \times \text{Velocity}}{30} \right)
\]

where
- Intensity is kW m\(^{-1}\);
- Fuel load in t ha\(^{-1}\);
- Drought is a drought index scaled between 0 (wet) and 10 (dry);
- Temperature in °C;
- Humidity %;
- Wind velocity in km hr\(^{-1}\).

The implication is that 1% decrease in humidity is equivalent to a 1°C temperature rise or an
increase of 0.7 km hr\(^{-1}\) in wind velocity.

The distribution of rainfall is also critical in calculating the Drought index and thus FDI. FDI is linearly dependent on the drought factor, which is a very complex relationship in the meters, but is basically a soil dryness index. This index is greatly affected by recent rains, temperature (probably a surrogate for evaporative demand) and annual rainfall. Higher summer rainfall will mean more, and possibly longer, periods of moist fuel - ie low FDI. But this depends on temporal distribution (and amount) of rainfall events. Current GCMs can provide little guidance here.

In conclusion, there will probably be an increase in FDI under climate change. FDI is unlikely decrease - unless the atmosphere becomes is moister and cloudier.

**Fire fuels**

The next important variable is the amount of fuel available to a fire (this is mainly forest floor litter and twigs, and fine twigs on shrubs). The rate of spread of a fire is directly proportional to the FDI and the amount of fuel. Its intensity, measured as heat output per metre of flame front per second, is proportional to the rate of spread and the fuel load (ie on the square of the fuel load). Thus, fuel load is a critical variable.

Again, it is difficult to forecast the change in fuel load under global change scenarios. Fuel load is a balance between inputs from litter fall and outputs through litter decomposition and fires. If changed climate and CO\(_2\) concentrations lead to increased production of leaf, fine twigs and bark, litter fall may be expected to increase. The most common rate limiting factors for litter decomposition are warmth, moisture and nutrients (expressed as the C:N ratio). In most parts of Australia moisture is far more of a limit than temperature. Again, we have the problem that GCM outputs are not yet adequate to make confident forecasts about the moisture conditions in the litter layer.

There has been a lot of interest in changes to the C:N ratio under global change. There is good evidence that C:N increases in living tissue (ie changed conditions lead to more photosynthate being fixed but N remains limiting), but this does not always translate into higher C:N in the litter. A higher C:N ratio is likely to reduce the effectiveness of litter fauna in the decomposition process. Also structural variation in litter (eg lignin content) is an important factor in determining decomposition rates and appears to sensitive to global change parameters.

In summary, litter loads are more likely to increase than to decrease. Higher litter loads would enhance the effect of the factors summarised in the higher FDI and thus make fires more intense and more difficult to control.

**Ignition**

A final factor (or should it be the first!) is ignition sources. Human action and lightning are the main sources of ignition with human action dominating in most parts of Australia. Gill et al (1987) showed that in Victoria far more fires occurred on Sunday (even those attributed to
lightning) than midweek indicating the importance of human leisure activities in fire ignitions. Again, one must conclude that these are likely to increase in the future.

Thus, although there are many uncertainties, the balance of evidence suggests that under global change, fires will be more frequent. They may be more intense and difficult to control, although in some areas increased frequency may limit the accumulation of higher fuel loads. Also, human action may modify this outcome. Greater effort in fire prevention (especially via prescribed burning) and suppression may reduce fire frequency. However, reliance on suppression alone, usually leads to the build up of fuels and the inevitable, extremely intense fire.

Impact on forests

Will more frequent and intense fires have a significant impact on forests? In some cases maybe not. In many eucalypt forests most damage from fires occurs in relatively intense fires that burn or scorch all of the canopy. There is little direct evidence that mortality and stem death vary greatly with fire intensity. Strasser et al. (1996) found that mortality and stem death were most directly related to tree size (trees with larger dbh had a higher probability of dying, probably because of accumulated damage from previous fires) and a vigour index based on the potential height for a given dbh compared with actual height. Thus, more intense fires may not translate immediately into more mortality, but more frequent fires could lead to a faster accumulation of damage (eg fire scars which act as an entry point for subsequent fires) and loss of vigour.

There have been many descriptions of the relationship between fire regime and vegetation composition. In eucalypt forest there is usually little direct change in composition of the tree species as a result of a fire. After a brief period dominated by fire-weeds, followed by acacias or other shrubs, the site usually returns to the previously dominant eucalypts. In most eucalypt communities this occurs quickly since tree mortality is low and recovery of full crown foliage is quick (2 to 5 years). In others (e.g. *E. regnans* ie Mountain Ash forests) recovery is mainly from seed and is thus slower (decades).

Tasmanian wet sclerophyll forests show a more complicated successional dynamic and there is the possibility that there may be a positive feedback whereby increasing fire frequency due to global change effects leads to increased cover by flammable communities so leading to further increases in fire frequency (Noble & Gitay 1996). However, the time scale for these phenomena is measured in centuries rather than decades.

Fire frequency would have to change dramatically to lead to significant composition changes via mortality. However, recruitment patterns could change. Fire creates opportunities for recruitment and composition of the new cohort of recruits will depend on temperature and moisture regimes in some cases. How quickly composition might change also depends on the availability of seeds of better-adapted species and this may be a limit to rapid change. In the past, forest communities have achieved rates of dispersal across landscapes of several kilometres per year. However, this is a rate achieved over centuries or millennia and is probably made up of a series of long distance jumps followed by local establishment over the next century or so (Pitelka et al. 1997). These rates were also achieved in landscapes that had not yet been fragmented by human agricultural and urban activities. Composition change in many forests will be patchy and slow over human lifespans.
It is unlikely that increased fire frequency will increase forest productivity in Australia. There are a few studies showing a period of more rapid growth in the few years of reduced competition and increased nutrient availability after a fire (see Whelan 1995 for a review). However, increased frequency and intensity of fires may lead to significant nutrient loss both through volatilisation during the fire and from erosional losses over the subsequent months. Commercial productivity is likely to be harmed through loss of trees and damage to timber quality.

The effects of global change on biomass and carbon sequestration in forests will attract considerable attention in the post Kyoto context. Again there is no consensus on the net effect of global change processes. In a recent review Mooney et al (1998) noted that while tree seedlings responded to elevated CO₂ by more rapid carbon accumulation, there was some evidence that this might not always be translated to mature plants. The effect of fire per se under global change is likely to be to reduce sequestration. Increased fire frequency is likely to maintain lower average fuel loads, although again this will be a balance between two opposing, and uncertain, effects (greater litter fall versus more frequent consumption in fires). I emphasise that these conclusions apply to Australian forests and in particular to eucalypt forests. In other regions of the world, changed fire regimes could be a major factor in bringing about major shifts in ecosystem composition and possibly significant transient releases of carbon to the atmosphere.

The effect of fire under global change on other ecosystem services is also highly speculative. More frequent and intense fires will change the hydrological characteristics of catchments sometimes leading to more run-off but increased erosion and poorer water quality. Changed fire regimes will put many species at greater risk of local extinction, although there will always be a few that will benefit. Increased fire frequency is likely to offer more opportunities for weeds and pest animals to invade.

**Certainty/Significance Matrix**

I would put none of these impacts in the High certainty/High significance quadrant. The effect of global change on fire regimes is too uncertain. However, taking the most likely outcome - ie an increase in fire frequency or, more precisely, an increase in the frequency of intense fires then I suggest that the following impacts are the most likely and significant:

- more demand on fire fighting services,
- decline in forest vigour and mean age of individuals accompanied by a slow change in forest composition in some areas,
- some loss of productivity (both biological and timber products),
- a degrading of ecosystem services (eg increased erosion, nutrient loss), increased weed invasion, and some increased threat to biodiversity.

These impacts refer to native forests. In plantations, anticipatory action such as selection for species and provenances suited to warmer climates and greater attention to fire hazard, would avoid most negative effects. Even within native forests, increased attention to whole landscape management leading to the protection or creation of refuges and connecting corridors, an the sensible application of prescribed burning and fire management barriers could minimise the significant effects arising from the effect of global change on fire regimes.
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**Impacts of global change on pests, diseases and weeds in Australian temperate forests**

R.W. Sutherst¹ and R.B. Floyd²

CSIRO Entomology

¹Long Pocket Laboratories, PMB No 3, Indooroopilly, Queensland 4068
²GPO Box 1700, Canberra, ACT 2601

**Introduction**

Global change drivers include a number of different factors that can act independently or together to adversely affect the health of trees, or less commonly, may confer an advantage. The commonly accepted drivers are climate change including atmospheric composition, land use and land cover. Other important trends in the global environment need to be taken into account, especially the increasing velocity of world trade with its associated tolerance of greater risks of dissemination of exotic insects, diseases and weeds that have the potential to become pests.

In this paper we consider the potential impacts of a number of drivers that affect forests and rural woodlands, through their effects on the incidence and severity of pests, diseases and weeds. These effects will be illustrated by examples.

**Climate change**

Climate plays a mediating role on tree health, with trees stressed by drought or water-logging becoming vulnerable to attack by insects and diseases (Landsberg and Wylie 1983). With the distributions of many tree species apparently being limited by their climatic requirements, a change in the climate will inevitably affect those populations near the marginally suitable edges of their distributions. That will lead to a long-term shift in the species’ occurrence in Australia.

Several species of native defoliating insects respond to the health of trees and produce positive feedback loops that lead to tree dieback. While not usually classified as pests in undisturbed systems, such species have the potential to change greatly in status under certain climate change scenarios. Forest dieback events involving defoliating insects appear to be driven by extreme climatic events, at least in the New England area. Impact assessments need to take into account the likely changes in both frequency and intensity of such events under climate change. Sutherst *et al.* (1997) estimated the socio-economic cost of dieback in rural woodlands in the New England area and investigated how the incidence and severity of dieback events may be affected by climate change. The CLIMEX model (Sutherst *et al.* 1995) was used to develop a species-specific Ecoclimatic Index of the climatic requirements of five eucalypt species by inferring those needs from their observed geographical distributions. The risk of dieback was then correlated with the CLIMEX indices. The results were used to develop a Dieback Index with which to investigate the likely incidence of dieback under a range of climate change scenarios. The costs of dieback were estimated using approaches including interviews with graziers and experts, a survey of the literature and an economic model. The results were consistent with a triggering effect of excessive rainfall causing stress to trees in fragmented rural woodlands which were then defoliated by insects severely enough in successive years to kill the trees. Given the contrasting rainfall scenarios provided by the
CSIRO coupled and slab global circulation models the range of potential outcomes was extremely wide. Any increase in rainfall would be expected to increase the frequency and severity of dieback events and the estimated increase in costs of climate change would be substantial. Reduced rainfall is likely to be beneficial by reducing dieback and possibly increasing regeneration rates in dry years when competition from grasses is less severe.

Australia’s forests are vulnerable to invasion from a number of destructive species of insects, weeds and plant diseases. A serious concern to managers of native forests in South-west Australia (Shearer and Tippett 1989), Victoria (Marks and Smith 1991) and the other States is the widespread and very damaging root rot fungus, *Phytophthora cinnamomi*, which is moved mainly by human activity. The fungus attacks a wide range of native species of vegetation. This contrasts with its more benign behaviour in South Africa, which suggests that it may be under biological control there (Scott 1995). Given the pathogen’s increased propagation under higher temperatures and rainfall, it is likely to extend its damaging effects in both intensity and distribution when associated with an increased frequency of extreme rainfall events (Sutherst 1995), or average warming as shown for Europe using the CLIMEX model (Brasier and Scott 1994).

Several native insects have become significant pests in eucalypt plantations in Australia. One of the important pests of *Eucalyptus globulus* plantations is the geometrid moth, *Mnesampela privata* (autumn gum moth), which is known to feed on at least 27 species of eucalypts (Neumann and Collett, 1997). The CLIMEX model was used to examine the effects of climate change on the interaction between *M. privata* and its preferred host plant, *E. globulus*. The geographic distribution of the moth was defined using the records presented in McQuillan (1985) and augmented by records from various forest insect collections. The distribution of *E. globulus globulus* was described in Brooker and Kleinig (1990). Currently, the distribution of *E. globulus* is entirely within the distribution of *M. privata*. Under a climate change scenario of 0.1°C warming / degree of latitude, the overlap of the distribution of the two species would persist but be restricted by the distribution of *E. g. globulus* to the extreme south-eastern part of Tasmania. The stress from a changing climate is likely to have downstream effects on the trees’ ability to resist insect attack from species such as *M. privata*.

Successful regeneration of eucalypts is an episodic event in much of temperate Australia and it appears to be driven, either directly or indirectly, by climate. Successful recruitment has been observed to occur in only one year in a five to ten year period. The timing and amount of rainfall appears to be critical to seedling survival or it may indirectly affect survival through its effects on competing vegetation in different seasons. Other changed environmental conditions affecting regeneration include the introduction of vigorous exotic pasture species, heavy grazing of livestock and high densities of weeds growing under eucalypt woodlands. The CLIMEX model has the potential to infer, from field observations of variable regeneration rates in different years, the types of season that have high regeneration rates. Coupled with the improving skills in developing medium term seasonal forecasts, it should be possible to improve the cost-effectiveness of regeneration efforts.

Increasing concentrations of atmospheric CO₂ change the carbon/nitrogen ratios in plants. One effect of nitrogen dilution is that the plant tissues become less nutritious for herbivorous insects that are seen either as pests or playing a vital role in nutrient cycling. Detailed responses are expected to vary greatly with the taxonomic group of insect involved and results on insects have shown this to be true (Watt *et al.* 1995).
Land Use and Land Cover

The effects of changing land use on the vitality of eucalypts has been studied at length and reviewed recently by Farrow and Floyd (1995). Intense grazing has been shown to affect the health and recruitment potential of remnant woodland eucalypts. Tree health can be affected by livestock removing bark from rough-barked eucalypts, compacting soil that results in water-logging, removal of the under storey that shelters predators of defoliating insects and the accumulation of nitrogen under trees used as camp sites by livestock. Nitrogen accumulation can have an indirect negative effect on the health of trees by increasing the nitrogen content of foliage, which makes it more attractive and nutritious for insect herbivores. Recruitment of new plants under trees in a heavily grazed environment can be reduced by the compaction of soil, high densities of weeds following seed dispersal by livestock, bare ground forming a suitable seed bed for weeds and the direct browsing and trampling damage done by livestock. Eucalypts in grazed woodlands in much of rural Australia have not been able to reproduce successfully for decades resulting in senescing populations of eucalypts with no younger recruits.

Runoff from cropping that carries defoliants, fertilisers and pesticides into the environment is likely to contribute towards tree dieback of rural woodlands along riverbanks. The very severe pest problems in crops such as vegetables and cotton makes these crops particularly threatening to adjacent riverine woodlands containing species such as river red gum (Eucalyptus camaldulensis).

The increase in commercial plantations of eucalypts in several regions of temperate Australia has resulted in large areas of monocultures (for example, 80,000 ha of Eucalyptus globulus in south-west Western Australia). Several regions have experienced increased insect pest problems as the total area planted has increased. The total area planted in a region may comprise a large number of relatively small plantings placed at various distances from other plantations or remnant native vegetation. These spatial patterns and characteristics such as plantation size, shape and distance from the nearest remnant vegetation, as well as the characteristics of the remnant vegetation itself, are likely to affect the population dynamics and impact of natural enemies on herbivorous insect pests.

Salination in rural Australia is a widespread problem that can radically alter land use and vegetation cover. It is estimated that 4 million ha of land has been affected by human-induced or secondary salination (Williamson 1990). The sub-lethal effects of salinity on remnant trees has been related to increased susceptibility to insect attack (Landsberg and Wylie 1983). The linkage between tree stress and susceptibility to insect attack is not always apparent but is sometimes caused by the elevated nitrogen level in foliage of stressed trees (Landsberg and Wylie 1983).

Invasive species

The recent introduction into Australia of the western flower thrips (Frankliniella occidentalis), which has a very wide host range in North America, highlights the dangers that face our native Eucalyptus spp. Other major forest tree pests such as the Asian gypsy moth (Lymantria dispar) pose even greater threats as pressure from accelerating global trade increases. Similar threats exist from the spread of established exotic weeds such as lippia (Phyla canescens) and Lantana spp, as well as new exotic weeds such as Siam weed (Chromolaena odorata). There is an increasing awareness of the dangers of translocation of
plants and the advantages of treating outlying populations of advancing species before they become established (Pitelka et al. 1997).

Conclusions

Australia’s temperate forests face a range of threats associated with pests, diseases and weeds under global change. Disturbance associated with increased traffic and the spread of cropping areas all accelerate invasions by these noxious species. If Australia is to respond effectively to these changes it needs to develop a national approach, using generic risk assessment and management tools (Sutherst et al. 1996; Maywald et al. 1997) and exploiting the increases in efficiency of regeneration promised by improved seasonal forecasting skills (Hammer & Nicholls, 1996).

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The impact of global climate change on forestry in South Australia.

Robert Boardman
Forestry SA. GPO Box 2284 Adelaide 5001

Background

Forest renewal is the cornerstone of forestry
Impacts from a change in climate acting from the times seed was collected can be positive, neutral or negative between sites. The degree of impact depends on the genetic breadth in the seed sources available and is partly revealed in the next stage of forest renewal.

Forestry management theory is often stated to be based on principles of sustained yield of a renewable natural resource. Neither term, however is the key to forestry practices. The basic feature of the theory being applied is the length of the renewal cycle, often called the rotation, or sometimes, called the cutting cycle.

Sustained Yield
Sustained yield managed forests have cycle lengths based upon the culmination mean annual increment (in wood volume or monetary value) and employs silviculture to fully utilize stand productivity. Application of that forest theory reached its zenith in mid 20th century. The SA State government was one of the world’s leading protagonists in plantation management with almost classic textbook use of the theory applied to the regulation of radiata pine harvests and regeneration. It was. The Woods & Forests Department, now ForestrySA, was the earliest publicly-managed forestry agency in the former British Empire to grow plantations, certainly the oldest in the S. Hemisphere to do so (Lewis, 1975) The estate was managed for sustained yield of wood until the advent of environmental sustained development (ESD) in the 1980s (Boardman, 1987).

Switch to ESD
Since the mid-1980s, the focus in SA has been able to switch emphasis to the sustained yield of the forest resources rather than on products alone. There has been a long-term regional research programme aimed at optimal use and re-use of resources that dates from the late-1960s. It grew out of necessity from remedial work into a reduction in productivity of second rotations but has expanded in the light of very favourable results obtained. The research programme has attempted to assess the natural resources and to identify the critical limitations among these. A regional cooperative research programme between industry and latterly the CSIRO, 60 years old this year, has addressed practices which influence the long-term trends in nutrient and organic matter recycling and the application of nutrient supplements where feasible. The major products in SA forestry after wood have been public recreation opportunities and water yields. Water quality is now being added as a management objective.

Current systems
Two strongly contrasting forest management systems are adopted in SA.
• In plantations a regular cycle and moderate rotation length is adopted for intensive culture of radiata pine (P. radiata). It is currently 37 years, and was only reduced from 45 years in 1993. A shorter cycle, probably from 10 to 15 years, is foreseen with southern blue gum (E. globulus). Both species are subject to refinement through selective breeding.
• In contrast, management of native forest reserves (including forest and woodland in Parks)
has been benign protection without an explicit regeneration cycle. The renewal issue has only recently been addressed. This has reached the stage of determining how not to jeopardize their perpetuation, eg. Through inappropriate burning temperatures.

Prime importance of rotation length
Dawning recognition that forest renewal cycles, or rotation lengths, will need to be more variable to manage optimally a widening variety of forest-based resources. This need is there regardless of management systems now adopted and in addition to changes required to meet reasonably probable impacts of climate change. Forest managers would like to be reasonably assured about the direction of change and likelihood of a change occurrence need be no more stringent than about 2:1.

Under ESD, the overall aim in a forest estate will be to manage for an objective aimed at an appropriate level of net primary production (NPP). The aim will be a desirable balance between new biomass laid down as net exploitable productivity (NEP), long-term stemwood increment or net biomass productivity (NBP) through desirable rates of respiration and decay able to produce high quality dead organic matter. This will be attained largely through management of leaf area indices (LAI) by silviculture. That focus will not only be likely to deliver good commercial results but also optimal nutrient recycling and environmental economics.

The Place of Climate Change; one among many
Climate change, in this context, will be just one factor among several, involved in the ultimate aim on carbon management. Hence, climate change will become just one factor upon which the basis of forest management theory will be questioned in future. There are several facets:

• adaptation to public desires and physical needs of the forest biome can be foreseen as an ongoing process in the next century.

• the magnitude and direction of the impacts will see manager’s hands either forced or massaged. A reasonable indication of direction of change and probability of significant effect from climate change will be necessary to trigger an anticipatory management response. Forest managers have to be adept at setting objectives which optimize the benefits as a whole from the forest estate under their care for they have to live with their mistakes.

• if the focus is to shift more towards sustainably-managed forest ecosystems (of which plantations are only a much-simplified form) it should be recognized that the only place to do it is in disturbed forest lands, historically more or less affected by human activity, part of which has been obviously commercial.

Prognosis - the Impacts:

What are the impacts likely to be in SA, and where are they likely to fit into the list of priorities affecting forest management?

SA has been divided into two sub-regions in the light of climate change, which separates the areas (A) north of a line passing just above Kangaroo Island (Lat. 35°30’S) from those south (B) (Climate Change Group, 1992, 1996).
• Changes anticipated from modelling the climate change scenario which still prevails from the late 1980s, are more drastic and significant for vegetation in sub-region A than in B.

• The principal climatic impact in sub-region A is a reduction in annual rainfall. This, however, turns out to be less than ±2%. Of itself this is insufficient to cause any forest manager to react. However this masks a radically changed monthly distribution of rain and a marked rise in evapotranspiration. This translates into shorter growing seasons estimated from almost nil to minus-34% of a year in sub-region A. The northern boundary of the growing season isoclines on Eyre Peninsula, for example are due to shift about 70 km southwards by the end of the 21st C (French, 1987, 1989; Reiners, 1989; Boardman, 1994).

• Sub-region B: a contrast appeared in sub-region B when working from the 1992 scenario which has been resolved in the 1996 version. A northern sector (B¹) is also likely to show shorter growing seasons of similar magnitude to A (-9 to -33%). In contrast, the rest of sub-region B (B²) is unlikely to have a diminution in total rainfall and the extension of adequate rains into the late Spring and Summer with additional warmth is likely to extend the duration of the growing season for forests and woodlands. The extent of gain in growing season is from +2 to +23%. The 1996 prognoses fit closely with the original ones first reported by the writer in 1989 and confirmed in 1992.

These changes in length of growing season are potentially significant for land managers and a careful tally of year-by-year seasons is feasible and long-term trends should become apparent. (Figure 1 and 2.)

Some basic concepts

Botanic form
Application of horticultural or silvicultural practices can mean that introduction of both indigenous species beyond their endemic zones and exotic species, can both establish and survive beyond apparent natural boundaries, particularly edaphic ones.

Growth stage
• Compared to annual crops, forests have a similar vulnerability to annual crops (and weeds) when in the stand establishment stage, especially germination and seedling establishment. Their robustness at this state comes from the natural selection of favourable genetic traits by the weather prevailing; it has little to do with climate in a strict sense.

• Once well established, forests have a robustness greater than annual crops. They are always vulnerable in the short term to extreme climatic perturbations, more so if their range is near to the species climatic and edaphic limits. They possess several strategies linked to their ability to survive and acclimatise to long-term trends.
• Biomass and yield are accumulated over many years and fluctuate in response to annual variations. Most SA perennial species are among those classed as dendro-climatologically sensitive. They have the ability to tolerate frequent unfavourable growing conditions which may persist for several years at a stretch in the semi-arid zone.

Pathways
The first impacts to become apparent are likely to be governed by stress-responsive metabolic pathways under the influence of physiological processes.
• A discussion of the metabolic factors causing tree death or the formation of narrow growth rings showed that conditions both prior to, and during the growing season, occurred normally in SA (Boardman, 1994). This was illustrated by the additive combination of two models of influences for narrow growth rings. In most forest regions, one or the other set of conditions, prior or current, tends to predominate. In addition, the cambium and its activity can be demonstrated to be mediated genetically in the ageing process (Boardman, 1984). The genetics related to the ageing of trees has escaped attention at the workshop.

Drought
• Palaeo-ecological studies suggest that tree species in SA are probably better acclimatized to drought than any other single stress and that they are adapted to manage their respiratory loads. The level of any dormant evolutionary tolerance of stress factors can reveal a potential for adaptation which we have no way of assessing. Stress impacts are likely to occur in a pattern not seen hitherto. Reasonable probability of their nature and direction will be needed to initiate a managerial response.

• There is a downside to this adaptation in that growth rates of weeds and non-endemic tree species suggests that the endemic species are survivors of previously harsher climates (Boardman, 1986). Some appear unable to respond to more favourable climate or habitats with enhanced growth or even crown development. Canopy density has a profound impact on stand microclimate.

Microclimate
• There are marked differences in the microclimate between native stands and plantations of native hardwoods - and even more of exotic conifer species within a climate zone. A trend can be discerned towards more mesic, temperate conditions in this sequence. The whole question of microclimate passed unnoticed by the workshop until mentioned in an observation by Andrew Maclean after the previous Regional Review. Yet these are a vital aspect of the regeneration phase in species life cycles, probably the second most vulnerable stage in a species life cycle.

• Human activities can alter microclimates significantly in change scenarios of many kinds:

• Vegetation clearance has a drastic impact on ecosystem energy flows which is strongly shown by changes in microclimate.

• Grazing and selection felling of trees by agrarian users may be more insidious and attritiative. Periodic burning and the grazing, especially by "ovine and bovine" element (if we include sheep, goats and all manner of deer including giraffe in this epithet) can be less drastic in rate but more permanent in a laissez-faire social environment.
• Reminder that emphasis on the creation of a favourable microclimate is a feature of all the well-developed "silvicultural systems" used in the deliberate renewal of forest stands (Troup, 1926; Matthews, 1989). These range from clear-felling to uneven-aged residual stands (continuous-cover systems). A broad range has been adopted world-wide. The creation of a suitable microclimate is much more demanding where the general climate is less favourable for the renewal of the species. Forestry professionals are good at creating suitable microclimates for the so-called ‘regeneration niche’.

• Even where there has been a minor level of human disturbance in SA, the understorey species in the most productive mature, native open forest are shared in common with the mallee, and occur in woodland formations on soils of similar texture. The range of average growing season length this represents is from 2 months to more than 8 months. It is apparent that the dominant trees in the more productive ecosystems extract the greater part of the plant available water supply over a wide range of latitude.

• In essence the dominant trees produce, or the understorey species respond to a soil moisture supply equivalent to a ‘natural’ growing season of 2 months, typical for understorey in the least productive woodlands typically, the drier parts of the mallee. That becomes the least common denominator for them, and also includes "casual" seedling regeneration of overstorey species.

**Fecundity, the Crux**

• The most vulnerable part of the renewal cycle has to be the ability of a species to produce the means to propagate itself. First need is to obtain the necessary propagule (allowing for genetic engineering) with adaptive capacity. It appears as the crux for a species to continue to replenish itself. The alternative is doom. As has been said of the mule - a being “without pride of ancestry or hope of posterity”.

• Consequently, the mature tree, rather than the understorey, becomes the focus. The principal features most vulnerable to climate change are those affecting flowering, seed formation and ripening, and not those driving stemwood increment (important as that is as a precursor).

• “Foresters have to remember that trees only grow the way they do to be sexy” (pers. comm. Prof. Emeritus W.J. ‘Bill’ Libby, University of California at Berkeley.).

• Stress tolerance is critically associated with the ability to produce flowers and seed. The fertilizer effect of enhanced CO₂ concentrations (CFE) may result in additional dry matter production but drastically reduce fecundity, as recently reported for cotton (Reddy *et al*, 1997). As we heard at the workshop, the CFE effect may not be very significant in mature trees.

• Location of seed orchards: In the case of radiata pine, the low altitude and maritime climate found in the extreme south of SA and north of Tasmania, has been the most productive for seed orchards. Managerially speaking, if the climate shift is as anticipated, and despite a longer growing season, it is likely that plant available water supplies will merit a transfer entirely to Tasmania, like SA sub-region B², likely to show only temperate changes. The genetic constitution of radiata pine, for example, is planned
with a 10-year generation cycle by the Southern Tree breeding Association (STBA), so the adaptation of planting stock should be manageable within this strategy.

- Conservation in seed banks: In the broader scene, this was another aspect not discussed at this workshop. *Species conservation in seed banks and how to manage their refreshment from mature plants*, will also call for a sharp focus on considerations of this kind.

- Progeny and provenance testing: The second crucial area concerns germination of seed and capacity of seedlings to survive in the long-term. The smart thing here will be to test progeny on a wide spread of sites, especially warmer ones with a less definite rainy season. It needs pointing out that finding current site analogues to the GCC scenarios for field testing is quite difficult, even when the region can be identified. Apart from anything else, genotype x climatic environment interactions are proving to be elusive.

**Temperature - additional warmth**

- Consensus appears to be that vegetative growth will be enhanced by the increase in temperature and that CFE impacts are already being experienced, through increases in the size of leaves, including length and number of needle leaves.

- As the maps of growing season in Figure 1 shows, many SA woodland species are already close to their climatic limits at the dry, warm end.

- The net result of a greater amount of dry matter attributable to a carbon-fertilizer effect (CFE) is also considered likely to be found with probability > 2:1.

**Growing season changes**

- Maps of average growing season length in SA for the present era and under a postulated Climate Change scenario were first published in 1988 and have been revised several times based on a more intensive network of meteorological stations in Figures 1 and 2.

- These have been based on the De Martonne Drought Index (DI). It had been found to correlate closely with the output of the Waite model, $0.54E^{0.75}$ determining top soil 100 mm with adequate soil moisture (Prescott, 1949) and monthly averages based on more complex models (Byram Keech DI and later the Mount Soil Dryness Index) used in daily fire hazard rating in SA forest areas.

**Productivity changes in SA using the CVP approach:**

An advantage of the De Martonne DI has been its use in Paterson’s Climate-Vegetation Productivity (CVP) model (1956, 1959, 1962; Pardé, 1958) for forest stands. It is calibrated against tree productivity on favourable sites, those with sites with optimal soil depth, adequate fertility and adequate soil aeration, averaged over species. Hence, the model offered an opportunity to relate changes in growing season, temperature and rainfall patterns to changes in forest productivity. The method is described in an appendix.

**Results**

The results are shown using the NBP component, ie. as stemwood biomass productivity in
Figures 3 and 4, and the change over the next century, in Figure 5. Stemwood biomass is the component most closely linked to carbon sequestration.

**Shift**
In simple terms, the climate in SA is due for a shift southwards, or compression in a north-south axis, east of the Flinders Ranges, in sub-region A. The climate of the better-favoured “settled areas” of SA are likely to shift to the equivalent of eastern central NSW, say, east of Dubbo without much of the benefit provided by altitude in the Great Dividing Range.

**Reduction in average monthly rainfall**
We see a need to react now to the potential effect of lower average rainfall per month on local plant available water supplies. This is likely to over-ride the apparent shift in sub-region A. Lower average monthly rainfall, warmer months and postulated extension of the growing season, in the case of the sub-humid climate zone sites of sub-region B² is suited to vigorous native forest and commercial forestry.
Overall, this implies that more water will be consumed ‘on the run’ and less will be available
for deep percolation and even less for drainage to low-lying drainage basins. Hence, we see that monitoring the cumulative drainage and seasonal movement in groundwater will be a sensitive indicator of climate change trends. However, it is not likely to lead land-managers into precipitate action.

- The likely result will be a narrowing of the range in productivity. There will a stronger clustering about the mean productivity through restriction of extreme sites by attrition in each of the current ecosystems across a region.
- Dislocation of the natural drainage patterns, already severely disturbed in the SE region of SA coastal plains by drainage networks, will affect native wetlands and wet heaths, and the highest productive commercial plantations, provoking major ecological disturbance in ecosystems sensitive to prolonged changes in plant available water regimes.

**Disturbance induced as a result of climate change**

- Disturbance has significant stress impacts on forest ecosystems.
- The most marked disturbance affecting whole regions will be experienced in the semi-arid zones in sub-region A of SA. The impact of climatically-induced disturbance on forest and woodland cover (all of which in SA is classed as “open” formations).
- Changes in growing season length were used to assess the likely impact on long-lived species in tree dominated ecosystems, based on their current distribution (Boardman, 1994). The 87 species were divided into four groups, namely, those species -
  a) subject to major reduction on distribution ...............24 spp.
  b) threatened with some site loss but less frequent ..........18 spp.
  c) for which a gain or loss was not clear ....................17 spp.
  d) likely to gain a major opportunity for colonization ...28 spp.
- Among 40 *Eucalyptus* spp recognized, and these include ones likely to be utilized in plantations, 24 species across all major sub-genera appeared in groups 'a' and 'b'. Only five *Eucalyptus* species appeared to gain a colonization opportunity, group 'd'.

**Impact: Potential for afforestation in SA.**

The area of land capable of sustaining high productivity crops of commercial species is strictly limited to about 0.05% of the area of SA, located in the sub-humid climate zones. This area is found in the Lower SE region and most of the remainder in the Central (Mt. Lofty Ranges) region. Three isolated pockets of land enjoying enhanced orographic rain occur in the Mid-north at altitudes above 500 m ASL. Plantations currently occupy less than 200 000 ha in these favourable parts.

The provisions of the Native Vegetation Clearance Act make afforestation of all but tracts of cleared land almost impossible. In many cases parcels of land best-suited to pine plantations, at least, were not cleared for agriculture as they were too infertile. The Act makes it not feasible to include such land in afforestation proposals when included in property.

Plantations of small size have been planted on cleared land in the semi-arid zone where the average annual rainfall is currently below 550 mm and above 325 mm; no plantations were found located with average rainfall less than that figure (Boardman et al, 1992). The prospects for afforestation in a rainfall zone between 200 and 300 mm isolhuyets without
supplementary irrigation are discussed in Boardman (1994). Woodland formations in this zone appear naturally until an isohyet of about 275 mm is reached. At sites receiving less average rainfall, run-on or drainage water appeared to be features able to supplement average plant available water to reach the equivalent of 300 mm gross rainfall, at least.

The prospects of utilizing effluent, drainage from irrigated horticulture or artesian water of suitable quality and abundance, to irrigate plantations of trees across the State of SA were discussed by Boardman (1991).

Climate and Growth

The first interest is in the potential to gain in productivity from global climate change resulting from the enhanced Greenhouse gas (GHG) emissions. Estimates were made of the changes in productivity of SA radiata pine plantations under global climate change, utilizing the estimates of magnitude provided by Booth and MacMurtrie (1988) under three situation: extra warmth and changes to rainfall but no increase in ambient CO₂ concentrations; with a doubling of CO₂ concentrations to accompany the climate changes; and these with an added gain from a CO₂ fertilizer effect (Boardman, 1989, Tables 7.4.7 through 7.4.9).

• Briefly, the greatest gains in each region were +7; +13 and +17 m³/ha/year of stemwood respectively (based on an average current yield class of 24 m³/ha/year for sites conforming to the CVP assumptions).
• There is the possibility that the northern 'limit' of acceptable commercial plantations will expand, in principle, by one degree of latitude where rainfall is > 550 mm.

NB. These estimates will need to be revised with the insights which were described by Prof. Ross McMurtrie at the workshop yesterday.

A second issue bears consideration in the context of this meeting, and has a bearing on the assessment of "carbon taxes", considered below. This is with regard to the very 'fluid' nature of stimulation of tree growth during the juvenile period and the long-term impact that this has on productivity, as has been demonstrated in SA (Boardman, 1984, Keeves, 1966). It has been transformed by emphasis placed upon what N.B. Lewis (W&FD, 1966) termed plantation “getaway”. A recent paper from New Zealand (Mason et al, 1997) has attempted to model this phase in plantation development. Modification of a ‘basal area index’ (Ig) model for juvenile ages of Pinus radiata by Boardman and Archer (1984) had a similar origin. The concept is encapsulated by the “deviation-amplifying mutual causes processes” first described by Maruyama (1963).

Afforestation:

Afforestation is being promoted actively in the context of the Vision 2020 with emphasis on plantations. It also has potential to provide significant numbers of additional trees to increase the capital investment in CO₂ sequestration and so provide Carbon Tax offsets.

In SA for several decades, the expansion of the plantation estate has been well under 1%. This represents a situation in which competition from alternative land uses has been strong and remained high.

• High productivity Land: Since the 1950s, all land acquired for pine and most for southern blue gum afforestation has been purchased on the open market. This includes the State government which has done so under economic constraints based on value for alternative
land uses which had to be less than for commercial plantations. Consequently, value per ha. has been the arbiter and land suitable for commercial forests has been restricted to the limited areas of temperate climate and high rainfall (by SA standards!).

- In the period since the first global climate change conferences in the late 1980s, competition against commercial forestry agencies for such land has increased markedly, particularly for vines and horticulture crops. This almost certainly includes an insurance-type offset against climate change on their part.

- Land suitable for irrigated plantations comes into this category. The potential is high in remote areas with low population in latitudes equivalent to Iran and Iraq which are distant from ports and centres of population. [Bagdad and Oodnadatta are at similar latitudes from the equator. Oodnadatta was the site of the earliest profitable SA Forest Reserve - Delget Noir variety date palms were planted there in the 1880s (Lewis, 1975)]. It is also relatively high in the 400-600 mm zone north-west of Naracoorte in the SE, but there are already conflicts over the rationing and allocation of the water resources. Surface groundwater salinity is also a problem. The area able to utilize the potential effluent and drainage water available from settled areas is only several thousand ha. (Boardman, 1991).

- Moderate to Low productivity Land: There is a much more accessible area of land, and probably it could become available, if afforestation agencies were prepared to accept the growth rates accepted in Boreal zone of the northern hemisphere and in the latitudes above 45°N. In general these are a quarter or less than average for radiata pine and southern blue gum.

  - We should think carefully about how a fibre-based industry option should be based. We could well follow the example of SA cereal-growers and be prepared to accept lower productivity which can be compensated for by adopting an estate suitably scaled up in size. This view places economic emphasis on consideration of an annual gross harvest. It shifts the current narrow paradigm for plantations with their demand on high yield and short rotations to a much broader perspective. It comes down to the fact that, industrially-speaking, for perennial species the harvest is essentially "biomass" or "raw fibre". For example, the SA State government pine estate with an annual harvest of around 16000 m³, half comes from the 2000 ha of high productivity land reafforested annually. On moderate to low productivity land this same volume could be produced from around 10 000 ha renewed annually. This offers some hope of afforestation in the drier areas of SA.

  - By afforesting an additional estate of, say, 500 000 ha, a significant amount of additional anthropogenic CO₂ will be removed from the atmospheric reservoir

  - The field inventory studies by Kiddle et al (1987) and supplemented by Boardman et al (1992) in the semi-arid zone of SA provides some indications of the productivity that can be expected from use of native species of trees in this zone.

  - The range of species potentially suitable to grow in the broad rainfall and edaphic zones found there was also considered. The opportunities and constraints appear in Figure 3, and Figures 4 and 5 taken together.

There were several pleas against planting large areas with currently popular radiata pine and southern blue gum. For those seeking an ecologically-robust alternative the large scale planting of the site of the City of Monarto, proposed near Murray Bridge in the early 1970s is one of Australia’s best-kept secrets. This site saw a large proportion of 150 km² planted with a suite of species endemic to the site. The SE Freeway traverses part of this and its impact can be readily appreciated.
**Impact: Carbon tax**

*Capacity for offsets or trade-offs in SA:*
An social impact of climate change which will affect SA is a proposed Carbon Tax and the likelihood that assets in the form of sequestration of CO$_2$ will be available to offset liabilities mostly derived from anthropologically-derived respiration (decay) and fossil energy consumption. Insofar as the amount of sequestration will need to be assessable for tax purposes, the measurement and monitoring of net sequestration will be necessary. The trends arising from a change from a stable climate to an enhanced greenhouse one will be more than likely to affect growth rates of trees eligible for offsets. The SA position is that the National Greenhouse Gas Inventory (NGGI) is too crude and broadscale to be suitable. On the other hand, the suggestion of assessment at the property level of the Greenhouse Challenge Group, whilst at an appropriate scale, requires considerable care in selection of what parts should be monitored and when monitoring should take place, at least for the initial measurement of young stands. The position of the State government is that the range of practices, ownerships and productivity being achieved is so broad that the complexity virtually forbids use of any method currently available. Further research into an equitable and robust method of assessment is essential. The contrast with coin and monetary valuation of assets is, in its view, enormous.

**Impact: Conservation of Native Ecosystems.**

There has been no significant addition to the options suggested by Greenwood & Boardman, (1989). The Native Vegetation Clearance Act has been revised to strengthen its preservation provisions and to positively protect roadside native vegetation. There is still a need to put into practice possibly the best suggestion, namely to prepare gene banks of climatically-threatened species and provide, in local government planning, for integrated migration routes southwards.

Only the Native Forest Management Plans for land in declared Forest Reserves contain provisions for renewal of forest ecosystems, and the planning for sustainable management of them is in its infancy.

**Adaptive measures:**

Adaptive measures already considered, or have been explored in SA, show that the scope is limited by uncertainty about direction of change and the rate of change time-frames. Only one project has been adopted so far.

- **Establishment of a gene pool of adaptive genes.** For each of the 5 major subgenera of *Eucalyptus*, 3 species have been selected among native forest species
  - which represent the current sub-humid, Mediterranean climate, in SA (collected in SA).
  - those representative of a climate change to an extended rainfall season and longer growing season without increase in temperature (from Central Victoria).
  - those representative of both a warmer climate and growing season extended into
summer (from mid-Eastern NSW).

- These were establishment as plantation in 1993 in randomly mixed plots at normal and wide spacing.
- Planted in an agroforestry format in 1993 as 13-tree groups for selection of the strongest and best formed individual as soon as evident to simulate a park-like savanna woodland.

- **A Suite of climate-sensitive Bio-indicator species.** A second approach was planned but has not been executed. In this a suite of 9 ‘indicator’ species representing the range of climate change anticipated from current distribution are planted periodically at sites expected to show the maximum rate of change locally. This provides a biologically-sensitive array of species with the opportunity not only to measure growth rates but also to assess the two primary stand renewal processes noticed above: indicator species fecundity and indicator species ability to establish themselves.

- A Forest Reserve at Whyte-Yarcowie has been set aside. It is located on the eastern flanks of the Flinders Ranges in a zone where the climate change impact is ‘concertina-ed’ over a short distance. This is where “Goyder’s Line” is likely to move westwards more rapidly than elsewhere.

- The design has been based on the Bradford-Hutt (silvicultural) system and the same suite in original thinking, was to be established at 5-year intervals. This was when the scenario was given an expected time line of 50 years. Continuity of unwavering purpose is another factor seen as important. At the time of planning (1989) the SA State forests organization had enjoyed a continuity of almost 115 years. Draastic reorganization of government agencies and downsizing of staff since then have changed all that through dilution of technical expertise. Extension of the scenario beyond a century has raised, in consequence, greater concerns about managerial supervision, diligence and continuity of resolve to maintain the integrity of this approach. Nevertheless, regional interest in the project has increased recently and reactivation is being considered as this site of special scientific interest.

References


Climate Impact Group. (1992). Climate change scenarios for the Australian Region. CSIRO Division of Atmospheric research, Mordialloc, Vic.


**Appendix**

**Productivity changes in SA using the CVP approach:**
**Method**

- Becking (1962) included conversion to dry matter in place of stem volume (Weck, 1957) and modifications related to use of a minimum temperature limit. Becking related stemwood biomass to net biomass (net primary production, NPP) of forest with an assumption of 0.55NPP contributed to stemwood. This estimate has been demonstrated from site productivity sampling and modelling to apply to the kinds of favourable sites represented by the CVP index by Paterson in temperate climate zones (e.g. Battaglia and Sands, 1997). Weck set a lower threshold of two months for the growing season as a necessity for forest and woodland ecosystems.
- In a study made for the ETSA Corporation in 1992, Boardman et al. found that two months growing season corresponded well with an average rainfall of 250 mm, to produce about 1.5 t/ha/y stemwood increment for hardwood species planted at 1000 stems per ha (a standard density adopted) on favourable sites.
- This limit corresponded well at low altitudes with “Goyder’s Line” (McGowan, 1990) delineated in the 1865 to signify the northern limit of sustainable cereal cropping in SA, based largely on vegetation indicators at the arid limit of woodland ecosystems.

**Application**

- The CVP estimation is simple to apply in its basic form, using monthly averages and applicable only to sites with optimal soil depth, adequate fertility and adequate soil aeration, averaged over species. It serves to provide a valuable indication of the maximum-likely steady-state increment of stemwood dry matter of ‘mature’ stands, and hence, long-term carbon sequestration rate, as well as more complex models.

**Forecasting**

- The CVP approach has the strong feature of all good forecasting models, like Dr. J Landsberg’s “3-PG” model described at the workshop, in that it is robust; it produces indications similar in scale to more complex models, and has the advantage of simplicity.

**Data available**

- It is able to utilize data that is readily available and often over a long time. When different species within a district are calibrated against productivity estimates, natural vigour differences can be found. This is the extent to which ‘tweaking’ has been applied. The CVP model outputs are also likely to indicate generically and realistically the impacts of changes in climate factor. The allow us to illustrate the impacts of climate change inside a region, or the impact of applying a major growth factor ameliorating climate, such as irrigation (Boardman, 1991).
A regional overview from Victoria.

Ian Mansergh
Flora and Fauna Program DNRE, PO Box 500, East Melbourne 3002

The RAC Forest and Timber Inquiry, (1992) summarised some basic problems that may face forests and woodlands under enhanced greenhouse climatic change. The relevant aspects of monitoring under the Montreal Criteria and aspects of the National and Victorian Biodiversity Strategies have all been utilised in the constructing a Victorian context. Broadly, the approaches involve the determination and amelioration of the potential adverse effects and, or lessening the net carbon release within the forest estate (enhancing native vegetation and increase carbon sequestration through forestry plantations on cleared land).

At a research level, modelling using selected fauna of se Australia, various climate change scenarios and BIOCLIM has been completed (Bennett et al. 1992, Brereton et al. 1995). Responses of forty-two fauna species from a range of habitats across the landscape were used as “indicators” of broader changes to the distribution and abundance of our biodiversity, including, in the longer term, forest types. Large scale changes are indicated. Precautionary strategies to ameliorate the potential adverse effects of the enhanced greenhouse effects and climate change have evolved in response to these studies. These strategies are primarily based on the biodiversity aspects as this area has the most applicable reseach results. These strategies have received official recognition in planning and other statutory documents (e.g. Dept Natural Resources and Environment, 1997)

There are several concepts upon which these strategies are based:

a) “greenhouse” refugia;

b) increasing the “robustness” of the natural systems (maximising the extent and health of native vegetation (enhanced ecosystem health will to make the changes to the biota more gradual; both within the broad expanses of our natural environments (National Parks and Forests) and in the more fragmented rural environment, where native vegetation persists as remnants;

c) systems of “biolinks” need to be enhanced or maintained.

d) open and flexible to incorporate on-going results of scientific research.

Some policy responses and implementation are provided below:

- Net gain in the extent and quality of native vegetation, with a no net loss scenario by 2001.
- Identification of greenhouse refugia.
- Biolinks have been identified at the broad statewide level: These are implemented in the context of the Forest Management Planning processes (Regional Forest Agreements.) co-ordinated with National Parks. In fragmented environments infrastructure such as the Catchment Management Authorities, local government and the planning provisions can be used to complement and assist programs such as “Bushcare” (NHT), TreeVic., Green Fleet and plantation establishment. These can increase the cover of native vegetation in biolink areas and mechanisms. When choosing sites for sequestration of carbon in trees the context of biodiversity conservation should be considered.
- accelerate the finalisation of the Comprehensive and Adequate Reserve System in Victoria.

Victoria is actively promoting forest plantations on cleared land which should increase the
capacity of some areas for carbon sequestration.

The information, analysis and evaluation of data presented in this forum will be used to refine the responses.

References


Australia's forest carbon sink: threats and opportunities from climate change

Richard Lucas¹ and Miko Kirschbaum²

¹ Bureau of Rural Sciences, P.O. Box E11, Kingston, ACT 2605.
² CSIRO Division of Forestry and Forest Products, P.O. Box E4008, Kingston, ACT, 2604.

Introduction

At the United Nations Convention on Climate Change in Kyoto, Japan, Australia was successful in its quest to achieve differentiated emission reduction targets and to include emissions from the land use change and forestry sector in national calculations. A major benefit of this agreement to Australia was that the planned regeneration and establishment of plantations would potentially increase the forest carbon sink substantially, thereby assisting Australia to meet its targets and fulfil international obligations.

The projections of carbon dioxide emissions, from 22.4 Mt CO₂ yr⁻¹ in 1995 to over 90.0 Mt CO₂ yr⁻¹ (Lucas 1997) did not, however, consider the impact of the future climate regimes on the forest carbon sink. Although the changes in climate are unlikely to impact noticeably on this sink over the next few decades, it is expected that by the turn of the next century the distribution and magnitude of carbon sinks may differ substantially.

This paper therefore aims to provide an insight into the future contribution of Australia’s forests and woodlands to the national carbon sink based on different scenarios of climate change. Recent estimates of the current and future area of forests and woodlands and their associated rates of carbon uptake are reviewed. Predictions of the forest and woodland carbon sink in 2100 using the CenW model (Kirschbaum, 1998a; Kirschbaum, 1998b) are then presented.

Background

In 1995, the National Forest Inventory reported 156.8 million hectares of forests and woodlands in Australia which included approximately 1 million hectares of hardwood and softwood (mainly Pinus radiata) plantations (Table 1). The magnitude of the carbon sink associated with these forests and woodlands is largely uncertain although the National Greenhouse Gas Inventory (NGGI) Committee (1997) estimated that, in 1995, the 26.4 million hectares of plantations and native forests managed mainly for timber production sequestered 74.8 Mt CO₂ yr⁻¹.

Using National Plantation Inventory (NPI) data (National Forest Inventory, 1997), Lucas et al. (1997) refined estimates of the hardwood and softwood plantation carbon sink from 1.9 Mt CO₂ yr⁻¹ and 24.6 Mt CO₂ yr⁻¹ respectively (NGGI Committee, 1997) to 2.7 Mt CO₂ yr⁻¹ and 12.4 Mt Gg CO₂ respectively.

Future expansion of the vegetation in Australia is likely to be facilitated through revegetation and expansion of the plantation estate. The National Vegetation Initiative (NVI), for example, aims to revegetate at least the area equivalent to that which is cleared of vegetation annually. The 2020 Vision aims to treble the 1995 plantation area to approximately 3 million hectares by 2020.
## Assumptions

The area of forests and woodlands in 2100 is difficult to predict, particularly as current schemes aim to complete revegetation or plantation establishment by 2020. For this reason, the analysis presented in this paper is based on the following assumptions:

- The current area of native forests mapped by the National Forest Inventory (NFI) would not change significantly.
- The areas revegetated and cleared of vegetation would be equivalent, thereby resulting in no net changes in forest and woodland area but a redistribution of the area.
- Sustainable harvesting would ensure that the carbon sink provided currently by native forests would be maintained.
- Plantations established by 2020 (predicted to be 3 million hectares) would be held in perpetuity and that the 9:1 ratio of softwood to hardwood plantation (in 1995) would be maintained.

## Methods

Using the CenW model and based on the assumptions outlined above, predictions of annual Net Primary Production (NPP, $t \cdot ha^{-1} \cdot yr^{-1}$) and CO$_2$ uptake for Australia’s forests and woodlands in 2100 were calculated. NPP and CO$_2$ uptake in the current climate and under five climate change scenarios were estimated. The carbon sink associated with Australia’s *Pinus radiata* plantations in 2100 under the same climate change scenarios was also predicted.
Results

*Predicted annual NPP for Australia’s forests and woodlands.*

Under the current climate, the total annual NPP of forests and woodlands was estimated at 1,333 Mt (Table 3). The greatest increase in total annual NPP was predicted for a climate with 700 ppm and with no rise in temperature. Assuming, however, that atmospheric CO₂ will double by 2100 and temperature will rise by 3°, estimates of total annual NPP were predicted to range from 1,253 Mt to 1,615 Mt depending upon the rainfall regime (i.e., +/- 20%). The changes in annual NPP under different climate change scenarios are illustrated in the accompanying figure.

**Table 2:** Estimates of total annual Net Primary Production (Mt) for Australia’s forests based on the current climate and five climate change scenarios.

<table>
<thead>
<tr>
<th>Atmospheric CO₂</th>
<th>Temperature</th>
<th>Rainfall</th>
<th>NPP (Mt)</th>
<th>CO₂ equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 ppm</td>
<td></td>
<td></td>
<td>1,333.15</td>
<td>2199.70</td>
</tr>
<tr>
<td>700 ppm</td>
<td></td>
<td></td>
<td>1,649.23</td>
<td>2721.23</td>
</tr>
<tr>
<td>350 ppm + 3°</td>
<td></td>
<td></td>
<td>1,017.11</td>
<td>1678.23</td>
</tr>
<tr>
<td>700 ppm + 3°</td>
<td></td>
<td></td>
<td>1,476.05</td>
<td>2435.49</td>
</tr>
<tr>
<td>700 ppm + 3° -20%</td>
<td></td>
<td>-20%</td>
<td>1,253.30</td>
<td>2067.95</td>
</tr>
<tr>
<td>700 ppm + 3° +20%</td>
<td></td>
<td>20%</td>
<td>1,615.87</td>
<td>2666.19</td>
</tr>
</tbody>
</table>

The annual NPP (t ha yr⁻¹) was also predicted to vary between structural forest types (Table 3). With a doubling of atmospheric CO₂ to 700 ppm and no rise in temperature, an increase in the annual NPP of all structural forest types was estimated. For all other climate change scenarios, an increase in annual NPP was generally predicted although the structural forest types T2, M4 and L4 were anticipated to show reduced growth.

*Predicted total NPP for Pinus radiata plantations.*

Based on the current climate and a plantation area of 1 million hectares, total annual NPP was estimated to be 18.87 Mt (equivalent to 31.14 Mt CO₂). This is approximately double the estimate of Lucas *et al.* (1997) although similar to the NGGI Committee (1997) estimate. The doubling of CO₂ to 700 ppm with no rise in temperature was expected to increase the plantation carbon sink by approximately 7 Mt. However, under all other climate change scenarios, it was likely the plantation carbon sink will be either similar to current levels or reduced slightly. The anticipated changes in the carbon sink following trebling of the softwood (*Pinus radiata*) plantation area are presented in Table 5.

**Table 3:** Estimate of NPP for different forest and woodland structural classes and under different climate change scenarios.
<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>Net Primary Production (t ha yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Atmospheric CO₂, Temperature, Rainfall</td>
<td>350 ppm</td>
</tr>
<tr>
<td>Closed tall forest (T4)¹</td>
<td>17.74</td>
</tr>
<tr>
<td>Open tall forest (T3)</td>
<td>23.58</td>
</tr>
<tr>
<td>Tall woodland (T2)</td>
<td>12.14</td>
</tr>
<tr>
<td>Closed medium forest (M4)</td>
<td>19.24</td>
</tr>
<tr>
<td>Open medium forest (M3)</td>
<td>14.91</td>
</tr>
<tr>
<td>Medium woodland (M2)</td>
<td>8.19</td>
</tr>
<tr>
<td>Closed low forest (L4)</td>
<td>14.19</td>
</tr>
<tr>
<td>Open low forest (L3)</td>
<td>8.03</td>
</tr>
<tr>
<td>Low woodland (L2)</td>
<td>4.78</td>
</tr>
<tr>
<td>Eucalypt Mallee (Em3)</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 4: Estimates of annual Net Primary Production (Mt) for Australia’s *Pinus radiata* plantations (c 1 million hectares) under the current climate and five climate change scenarios.

<table>
<thead>
<tr>
<th>Atmospheric CO₂</th>
<th>Temperature</th>
<th>Rainfall</th>
<th>NPP (Mt)</th>
<th>CO₂ equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 ppm</td>
<td></td>
<td></td>
<td>18.87</td>
<td>31.14</td>
</tr>
<tr>
<td>700 ppm</td>
<td></td>
<td></td>
<td>25.86</td>
<td>42.67</td>
</tr>
<tr>
<td>350 ppm + 3°</td>
<td></td>
<td></td>
<td>15.87</td>
<td>26.18</td>
</tr>
<tr>
<td>700 ppm + 3°</td>
<td></td>
<td></td>
<td>17.97</td>
<td>29.66</td>
</tr>
<tr>
<td>700 ppm + 3° -20%</td>
<td></td>
<td></td>
<td>15.25</td>
<td>25.16</td>
</tr>
<tr>
<td>700 ppm + 3° 20%</td>
<td></td>
<td></td>
<td>19.31</td>
<td>31.85</td>
</tr>
</tbody>
</table>

Table 5: Estimates of annual Net Primary Production (Mt) for Australia’s *Pinus radiata* plantations (following trebling of the 1995 area to 3 million hectares) under the current climate and five climate change scenarios.
Annual Net Primary Production (kg ha⁻¹) in 2100
Under Different Climate Change Scenarios

CO₂ at 350 ppm
Temperature + 3 degrees
Rainfall - 20%

CO₂ at 700 ppm
Temperature + 3 degrees

CO₂ at 350 ppm

CO₂ at 700 ppm
Temperature + 3 degrees
Rainfall + 20%

Annual Net Primary Production (kg ha⁻¹)

- 1 - 1000
- 1001 - 5000
- 5001 - 10000
- 10001 - 15000
- 15001 - 20000
- 20001 - 25000
- 25001 - 30000
- 30001 - 35000
- 35001 - 40000
- No Data
Discussion and Conclusions

The analysis presented above is preliminary and further research is required. However, the study does suggest that:

- The predicted increase in the annual NPP of most forests and woodlands is likely to result in changes to the structure of Australia’s forests and woodlands.

- Many of these forests and woodlands (130.4 million ha) are currently not considered in Australia’s National Greenhouse Gas Inventory and yet these may represent a substantial additional sink for carbon (of 316 Mt C or 522 Gg CO2 yr\(^{-1}\) above current levels).

- The carbon sink provided by softwood plantations (and in particular \(P.\ radiata\)) will not change substantially (by a maximum of 35 Gg CO\(_2\) yr\(^{-1}\) under the best climate change scenario and if the 1995 area is successfully trebled).

- Revegetation and plantation expansion will, in most cases, maintain or enhance the forest carbon sink.

References


Climate change and Australia’s native forests: some economic implications

Clive Hamilton
The Australia Institute, PO Box 72, Lyneham, ACT 2602, Australia

1. Introduction

The impact of climate change on the distribution and growth rates of native forests in Australia will affect economic activities associated with native forests. While the first consideration appears to be the impact of climate change on the availability of logs taken from native forests to be milled or chipped, the picture is more complex. I will argue that the impact on the native forest segment of the logging industry will probably be quite small. But before developing that argument, the following point should be noted. When assessing the likely economic implications of climate change it is just as important to consider the implications of measures to reduce emissions as it is to consider the impact of climate change itself on forests. Responses to the Kyoto Protocol may have major impacts on forest industries in Australia quite apart from the effectiveness of the Protocol at slowing climate change.

Therefore it will be convenient to begin our analysis by noting some germane features of the Protocol. The paper will then consider the likely impact of the Kyoto Protocol on the plantation sector before considering the implications of climate change for economic activity associated with native forests in Australia, including logging. For the purposes of analysis, we choose the year 2050 to provide a time-frame for our rough projections since it is around that time that the impacts of climate change on forests will be unmistakable.

This paper is not a detailed analysis of economic impacts but an overview of the influences. It will assist in focusing on the key economic issues that require further detailed study. It is worth noting that while this paper focuses on the impacts of climate change on forests, the bigger policy questions relate to emissions from combustion of fossil fuels.

2. The Kyoto Protocol

Several provisions of the Kyoto Protocol will have a major influence on the management of the world’s forests over the next decades. These provisions arise in the context of the Protocol’s emission targets (known as QELROs) for OECD countries and economies in transition (the signatories to Annex 1). In addition, it is widely recognised that the Kyoto Protocol is only the first step in reducing the world’s emissions. While the Protocol requires the major Annex 1 nations to reduce their emissions by 6-8% below 1990 levels by the year 2012, climate scientists believe that global emissions will need to be reduced by 70% to stabilise climate change. Thus more stringent targets for Annex 1 countries will be necessary over the next decades and developing countries will be required to begin cutting their emissions.

From the viewpoint of forest management, three aspects of the Protocol are particularly important. They relate to forests as sources and sinks, the provision for an international system of emissions trading, and the establishment of the Clean Development Mechanism. Sources and sinks
Article 3, Paragraph 3 of the Protocol states:

‘The net changes in greenhouse gas emissions from sources and removal by sinks resulting from direct human-induced land use change and forestry activities, limited to afforestation, reforestation, and deforestation since 1990 ... shall be used to meet the commitments ...’

In other words, the targets set for Annex 1 countries take a net approach, that is, they include carbon emitted from and sequestered by forests. A country that in the commitment period 2008-2012 has forests that act as a net sink for carbon dioxide will be required to cut its emissions from burning fossil fuels (and other sources) by less. How will the Protocol’s rules affect management of native forests in Australia? In the long term existing native forests are neither net sinks or net sources, but exist in a state of near carbon equilibrium – a fact confirmed by analysis by the Resource Assessment Commission (RAC 1992, K15). Changing management prescriptions for existing native forests do not fall within the definition of sinks in the Protocol; attention should focus only on new plantations established after 1990 on land cleared prior to 1990.

On the other hand, land that is ‘deforested’ becomes a net source, a fact that is a problem for developing countries since in some cases deforestation is a large component of current emissions.

The situation is reversed in Australia since we are no longer clearing large tracts of native forests. Indeed, because of clearing in the past we have expanses of cleared land that is suitable for reforestation. Although some details of how net emissions are measured remain to be agreed, the Protocol will probably give a major fillip to plantation forestry, a topic explored below.

Another aspect of net emissions is especially significant for Australia. Two weeks before the Kyoto Conference of the Parties, the Australian Government realised that the provisions of the Protocol for counting emissions from land use change would have great policy significance. The last-minute inclusion of emissions from land use change was claimed as a victory for the Australian delegation, but there is considerable disquiet among other Parties about the easy ride Australia will have.2 The details of what to count and how to measure emissions from land use change are due to be worked out at the next conference of the parties in Buenos Aires in November. The relevant paragraph of the Protocol reads as follows:

‘The Conference of the Parties ... shall, at its first session or as soon as practicable thereafter, decide upon modalities, rules and guidelines as to how and which additional human-induced activities related to changes in greenhouse gas emissions and removals in the agricultural soil and land use change and forestry categories, shall be added to, or subtracted from, the assigned amount [of carbon stocks in 1990] ...’ (Article 3 Paragraph 4)

In 1990 land clearing accounted for 23% of Australia’s total net emissions. However, the rate of land clearing appears to have been declining since the 1970s, and since some of the carbon is released over a twenty-year period after clearing, this affects the long-term profile of

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2 European Union Commissioner Peter Jorgenson is quoted as saying after the Kyoto document was finally agreed: “The Australian increase is wrong and immoral. It’s a disgrace and will have to change” (quoted by Anna Reynolds in Arena Magazine February-March 1998).
Australia’s emissions. According to the official inventory, emissions from land clearing since 1990 have been declining so rapidly that they have offset increases in emissions from fossil fuel combustion and other sources, so that Australia’s total emissions were 3.1% lower in 1995 than they were in 1990.

While this is a topic of utmost importance for Australia’s commitments under the Protocol this paper will focus on the forestry sector, that is, the temperate forests of the coastal regions and the plantation forests that compete with them.

Emission trading

The Protocol agreed to the development of a system of trading in emission credits. Paraphrasing to clarify its meaning, Article 6, Paragraph 1, states:

For the purpose of meeting its commitments any Annex 1 Party may trade emission reduction units with another Party. These units must result from projects aimed at reducing emissions from sources or enhancing removals by sinks. Any projects resulting in reductions from sources or enhancement of sinks must be additional to any that would otherwise occur.

Trading will occur only between Annex 1 Parties to the convention, that is, those that sign up to emission reduction targets. Private or public entities will be able to undertake activities that generate ‘certified emission credits’. Any Annex 1 country that expects to reduce its emissions below its specified target will be able to sell its surplus emission credits to other Annex 1 countries as long as they are generated by projects that would not otherwise occur. Alternatively, private firms and public instrumentalities may establish emission-saving projects and sell the certified emission credits to the highest bidder at home or abroad. The economic rationale for emissions trading is that trading will allow emission reduction activities to be concentrated in countries and activities where they are cheaper.

In anticipation of trading, there has been considerable commercial activity around the world. A Canadian firm offers certifiable and auditable emission credits from wind farms. US electricity utilities are developing a shadow market to test the system and the Chicago Board of Trade has taken a keen interest. Various studies have suggested that emission credits may sell in the vicinity of US$25 for each tonne of carbon dioxide. However, the Costa Rican government has been anticipating the possibility of emissions trading for some time and is now selling rights to a tonne of carbon dioxide sequestered in its forests for as little as US$5/tonne of CO₂. However, it is very unlikely that these credits will qualify under the Kyoto Protocol because the carbon in question is not from new sinks but from tropical forests that would otherwise become sources. The credits in question would arise under the Clean Development Mechanism discussed below.

The Clean Development Mechanism

The Kyoto Protocol includes provision for the Clean Development Mechanism (CDM), a variation on the Joint Implementation scheme already being trialed. The Protocol states that the purpose of the CDM is to assist developing countries to achieve sustainable development

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3 The Canadian firm referred to above offers emission credits for C$35 per tonne of CO₂.
and to assist countries with emission reduction targets to achieve compliance. The CDM will allow Annex 1 countries to achieve some of their national emission reductions through activities in other countries. Essentially, industrial countries will be able to undertake projects in developing countries that result in reductions in greenhouse gas emissions and claim ‘certified emission reductions’ as contributions to their emission obligations under the Protocol.

For example, Japanese firms may invest in methane capture projects at landfill sites in the Philippines and claim the emission savings from burning the methane as part of Japan’s national targets. Alternatively, Germany may provide funds for the establishment of additional forest plantations in Indonesia and count the additional carbon dioxide sequestered in the trees towards its national emission reduction target. Costa Rica is already well advanced in arrangements for selling ‘emission credits’ from forestry activities, including preservation of forests that (it is claimed) would otherwise be cleared.

There are, however, several major stumbling blocks that will limit the opportunities to reduce global emissions through the CDM. Firstly, there is a great deal of scope for cheating whereby developed countries could avoid their obligations to reduce national emissions. The Protocol foreshadows some strict guidelines to determine the acceptability of proposed projects. The emissions reductions from each proposed CDM project will need to be certified by a body established by the Convention and the climate change benefits will need to be ‘real, measurable and long-term’.

Secondly, there is considerable suspicion about the role of ‘greenhouse sinks’ in tackling the problem of climate change since new forest sinks buy time but do not solve the problem. As a result, a large ‘discount factor’ is likely to be applied to each tonne of carbon fixed in trees. This may diminish the commercial attractiveness of forest plantations when the returns need to be split between the foreign investor and the host country.

A further difficult issue relates to how to measure the emission savings from projects approved under the CDM. The Protocol states clearly that reductions in emissions will be certified only if they are ‘additional to any that would occur in the absence of the certified project activity’. Thus investments in more efficient power plants or new plantations must be premised on some agreement as to what would happen if the CDM project did not go ahead. The project proponents will need to demonstrate that a less efficient coal-burning technology would be used in the absence of the project, or that a forest would be cleared or a plantation would not be established if the project did not proceed. It is apparent that the claimed emissions reduction benefits become the subject of argument.

These problems suggest that the most attractive opportunities to generate certified emission credits under the CDM will lie in methane capture from landfills or biodigestion plants with the methane converted into electricity or transport fuel. Investment in plantations, and certainly the purchase of rights over existing forests that ‘would otherwise be cleared’, will be and should be subject to stringent conditions. Plantations are much more likely to qualify for emission credits if they occur in Annex 1 countries.

3. Impacts on the plantation sector

The most important issue for the forest industries in Australia is how the Kyoto Protocol and associated domestic policies will affect the incentives for establishing new plantations. This
in turn will be influenced by climate change itself, since climate change will alter the conditions in each catchment that determine the growth rates of various species.

In Australia, there are already several companies planning to establish forestry plantations with a view to selling emission credits on the international market. The Emission Traders Association of Australia has recently been launched. Building on the recent Plantations, 20-20 Vision strategy, it is likely that domestic greenhouse policies will give greater encouragement to plantations as a means of reducing Australia’s net emissions. Various schemes are being canvassed in the private sector to link heavily emitting activities with new sinks, including allowing major emitters such as power stations to invest in forestry sinks as ‘offsets’ against their own emissions. Some are proposing that Australian coal exporters should ‘bundle’ coal sales with emission credits so that buyers in Japan in particular can burn coal while offsetting the emissions for which they have responsibility. Last year a scheme known as Green Fleet was launched under which vehicle owners could pay an annual fee to a fund that would establish enough trees to offset the annual emissions from their vehicles. (The scheme has not been a great success to date.)

The basic commercial fact is that the opportunity to generate tradable emission credits will alter the economics of plantation establishment and management. A number of major firms are already doing the calculations in order to assess the viability of investment in a major new program of plantation establishment. To date, most of the information is commercial in confidence, but a rough idea can be obtained.

As always, the picture becomes more complex when we look at it more closely; there are several crucial issues that need to be resolved before we can decide how much added value the opportunity of generating emission credits will give to a new plantation. Using plantations as a certifiable means of fixing carbon for the purpose of meeting national targets faces several significant constraints. If generating emission credits becomes a principal commercial incentive for establishing plantations, plantations will need to be managed in different ways, ways that increase and protect the value of carbon stored. This will affect species selection, silvicultural management, fire control and the end uses of the logs. For example, will a Pinus radiata plantation fix more carbon if it is cleared every 30 years or thinned after 20 years and cleared at age 40? Plantation establishment is energy intensive, a fact that will require the value of a tonne of carbon sequestered to be discounted.

In addition, audit trails will be necessary to certify that timber is put to the end uses that have been assumed for the purposes of allocating emission credits. Irrespective of the end uses and the silvicultural methods chosen, there is likely to be a large discount factor applied to each tonne of carbon actually stored in the trees and soil due to the limited periods over which carbon is fixed for various end-use products.

Although a detailed assessment is not possible here, an idea of the orders of magnitude can be obtained from some simple calculations. A full life cycle analysis is needed in order to determine the net impact of a plantation forest on carbon sequestration. According to a New Zealand study, 1 ha of Pinus radiata established on grassland will sequester approximately 112 t of carbon in perpetuity (Maclaren 1996). This needs to be discounting to account for emissions associated with plantation establishment, harvesting and processing and the limited time before the carbon is released back into the atmosphere (Maclaren estimates that only
12% of the carbon present in a harvested stand has a life expectancy of more than 5 years). A discount factor of 50% may be appropriate. The price of emission credits is uncertain, but industry experts indicate that the currently quoted price is US$5.00-5.70 per tonne of CO2 for a certified emission reduction certificate. This converts to around A$30 per tonne of carbon giving an emission credit value of around $1600 for each hectare of plantation. Analysis by ABARE (1993) indicates that the costs of Australian plantations need to be cut by around $2000 per hectare to make the products competitive internationally. Thus the opportunity to acquire emission credits seems likely to give plantation timber products a significant competitive advantage.

Existing commercial interest and policy responses to climate change are likely to lead to a boom in plantation establishment in Australia. By the third or fourth decade of the next century there could well be a glut of plantation softwood and an emerging surplus of plantation hardwood, although Australia may be in a stronger position than other Annex 1 countries because of superior growing conditions. In its analysis, the RAC concluded that this is likely to give rise to a potential oversupply of timber due to significant plantation expansion into previously cleared areas (RAC 1992, K13). This will make plantation timber very cheap.

In these circumstances the key issue is the size of the market for plantation timber. There are four potential sources of market growth.

1. Substitution of plantation timber for timber from native forests. This is feasible for commodity grade timbers leaving native forest timbers for appearance grades.

2. Substitution for alternative building products, especially steel and cement. In addition to a price advantage this will require market development as tastes are slow to change. Steel and cement are energy intensive and will suffer cost increases as a result of policy measures to reduce emissions from fossil fuel combustion.

3. Substitution of sustainably managed biomass for fossil fuels using technologies such as wood gasification.

4. Exports and import substitution. In the first instance there is considerable scope for replacing imports of softwood in Australia. However, there is great uncertainty about the state of the international markets for timber, as other countries may invest heavily in new plantations and growth rates of boreal forests could be markedly affected by climate change.

Lack of markets may be the major constraint on the development of the plantation sector. Rather than promoting new plantation establishment, a better policy response may be to assist in the development of markets for plantation timber.

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4 The National Greenhouse Gas Inventory Committee makes the following assumptions in its Workbook 4.2, Carbon Dioxide from the Biosphere (Revision 2 1997, p. 37). Harvested timber is divided into four pools according to rates of decay – less than one year (paper, etc.), over 10 years (fibreboard etc.), over 25 years (packing crates, furniture) and over 50 years (building timber, fence posts etc.).

5 This is likely to rise, perhaps to a substantially higher level, as it may well prove difficult to generate sufficient certified emission credits, and because other emission abatement measures are likely to be significantly more expensive (although not as expensive as the fossil fuel industries have claimed).
4. Impacts on native forests

The principal economic activities dependent on native forests are shown in Table 1. We discuss the principal ones, asking what the impact of climate change and measures to mitigate climate change might be, taking 2050 as our target year.

4.1 Logging

Over the last 20 years the native forest logging industry has been facing increasing competition from plantation softwoods, despite the fact that native forest logging is subsidised in a number of ways. Figure 1 shows that while the volume of hardwood sawlogs removed has been declining slowly for 20 years, the volume of softwood sawlogs has been rising.

This trend is almost certain to continue, perhaps at a faster pace, and is the single most important influence on the future course of the industry. The plantation-based industry will dominate most segments of the market for timber products. This conclusion is based on the expected static demand for sawn timber and the increasing supply of plantation timber. Demand for sawn timber is not expected to grow over the next decade.6 ABARE, for example, expects total consumption to decline slightly from 4.47 million cubic metres in 1993-94 to 4.45 million in 1999-2000 (ABARE 1994). However, the RAC noted that since timber production is less energy intensive than other building materials (such as steel, bricks and concrete) there may be more substitution to timber as a construction material (RAC 1992, K13). To the extent that there is a such a shift the increased demand is likely to benefit plantation rather than native forest timber.

On the other hand, a large volume of plantation softwood will come onto the market over the next decade and beyond due to plantations established in the late 1960s, 1970s and 1980s under a series of Softwood Forestry Agreements sponsored by the Commonwealth. A detailed study by Judy Clark (1995) of existing plantation-based industry made projections of the availability of plantation timber in the years 2000 and 2005. The projections have been endorsed by the major softwood companies in Australia. Total wood supplies from plantations are expected to almost double from 9.6 million cubic metres per annum in 1994 to 18.5 million cubic metres in 2005. Of this, softwood sawlogs are expected to reach 10.6 million, softwood chip logs 4.9 million and plantation eucalypt 3.0 million (see also Hamilton 1995).

Clark concludes that plantation products are likely to replace nearly all native forest sawn timber by the turn of the century. In the pulp and paper industry, the supply of fibre from softwood and hardwood plantations, along with recycled paper, will by 2005 be enough largely to eliminate the use of native forest hardwoods and to provide for substantial exports.

Clark’s analysis was funded by the Department of Environment, Sport and Territories. It has been challenged by a study commissioned by the native forest logging companies.

Much of the competition in the market will be played out at the regional level. A recent study by Margules Poyry Pty Ltd of timber supplies in southern NSW anticipates that hardwood sawlog availability will fall from 175,100 m³ at present to between 145,200 m³ and 175,500 m³ by 2020 while the availability of softwood sawlogs will increase by 150% from 843,000

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6 I have argued above that there are untapped markets for timber to replace other building products. These markets are likely to be filled by plantation timbers.
m³ currently harvested to 2,087,000 m³ available for harvest in 2020 (Margules Poyry 1997). In other words, by 2020 the supply of softwood sawlogs will be twelve times the supply of native forest sawlogs.

In addition to the increased supply and falling prices of plantation timber, another factor is likely to increase pressure to reduce the size of the native forest segment of the industry. The preservation value of Australia’s diminishing supply of undisturbed native forests will continue to rise. In other words, there will be increased pressure to devote native forests to other uses, notably species preservation, other ecological values, recreation values and the tourism industry. A number of analyses of strengthening community preferences for preservation support this view. The current Regional Forest Agreement process will see the size of reserves increased.

4.2 Tourism

Tourism, both foreign and domestic, is an industry that relies heavily on Australia’s forest environments. Climate change may have significant adverse effects on tourist activities and the value of the industry. On the other hand, to the extent that the expansion of the plantation sector reduces the profitability of native forest logging, ecosystem diversity and species survival may be protected.

A recent study estimated the contribution of one species, the koala, to the Australian inbound tourism industry (Hamilton and Hundloe 1997). Koalas have an iconic status in attracting foreign tourists. A representative survey of departing foreign tourists revealed that:

- Sixty seven per cent of respondents said that nature-based activities were very important or quite important to their experience in Australia.
- Seventy five per cent of inbound tourists said that, when making the decision to come to Australia they hoped to see a koala, and 70 per cent of departing tourists reported that they had actually seen one.
- When asked whether they would have changed their decision to come to Australia if there were no unique wildlife, 11 per cent said ‘yes’.

This last figure has been used to estimate the tourist revenue that would be lost in the absence of unique Australian wildlife, of which the koala is an extremely important part. Combined with information on amounts spent on viewing koalas and buying ‘koalabilia’ in Australia (visiting zoos and wildlife parks, accommodation, photographs with koalas and souvenirs) it was estimated that koalas contribute around $1.1 billion annually to the Australian tourism industry, a figure expected to increase rapidly over the next decade.

If climate change threatens the survival of some of Australia’s unique wildlife then this will undoubtedly affect the desirability of Australia as a tourist destination. In addition, the existence value and recreation values that Australians attach to forest ecosystems and wildlife will decline causing a loss of welfare. A range of studies indicate that the ‘willingness to pay’ to ensure the survival of species and the preservation of forest ecosystems is high (see Hamilton 1996). However, most people regard forest protection as important for ethical reasons rather than economic ones.

4.3 Water supply
It is well known that silvicultural management affects water flows in forested catchments. It is less well appreciated that there are users of this water that may be adversely affected by logging (see Dargavel, Hamilton and O’Shaughnessy 1995). Apart from the logging industry, the most important users of water from forests on the Eastern seaboard are residents of cities that depend for their water supplies on logged catchments. Studies indicate that accounting for water values can have a critical influence on the economics of silvicultural management.

A study by Read Sturgess considered various options for silvicultural management in the Thomson Catchment, an area that supplies a large share of Melbourne’s water.

The base case prices for sawlogs ranged from $35 to $60 per cubic metre and the base case price for urban water was estimated at $530 per megalitre. Using a discount rate of 4%, the study calculated net present values for the silvicultural options and reported the difference between NPVs for the status quo and each other option. The cost-benefit analysis showed that among the options considered, the existing management of the Thomson catchment is the most inefficient. According to this analysis the best options are either a very long rotation (200 years) or a complete end to logging. The clear conclusion is that, using the estimated prices for timber and water, the loss of timber as the rotation is lengthened is more than compensated for by the increased water yields. If other values were taken into account, in particular ecological values, it is likely that the results would favour long rotations or no logging options even more strongly.

After objections from the timber industry, the 1992 Read Sturgess study was revised by Read Sturgess and Tasman Economic Research (1994). The second study differed from the first by valuing water in a different way; and considering a wider range of silvicultural options. The study found that the total value of the water yielded by the Thomson catchment each year is more than 10 times the total value of the timber harvested from the catchment each year. The base case results indicate that longer rotations are economically preferable especially when combined with strip thinning also at long intervals. This was also the conclusion of the 1992 study. Once again the conclusion drawn is that, when account is taken of the value of water in one of its alternative uses (urban consumption), then the current management regime of the catchment is one of the least efficient options.

The impact of climate change on urban water supplies from forests is complex. The two principal influences will be the impacts of climate change itself on precipitation and the future of logging in native forests. Increased precipitation may cause the marginal value of water to fall thereby changing the economics of the Thomson catchment.

5. Conclusions

Summarising, the key conclusions of this paper are as follows:

1. The Kyoto Protocol will have very important implications for the world’s forests, just as climate change itself will.
2. Inclusion of forestry sinks and emission trading is very likely to stimulate a boom in new plantation establishment.

3. The opportunity to sell certified emission reduction certificates will give plantation timber a significant competitive advantage.

4. There may be a glut of plantation timber in 30-40 years time so that the main problem will be developing markets for plantation timber. Australia may be able to replace imports of softwood and develop export markets.

5. There are unlikely to be major economic implications for the native forest logging industry since it is likely to be much smaller than it is now due to commercial pressures that will be heightened by an increase in plantation establishment.

6. The impact of climate change and the Kyoto Protocol on world supplies of and demands for timber remain very uncertain.

7. Impacts of climate change on the ecological health of Australia’s native forests may have a large impact on the Australian tourism industry and on recreation and other values Australians attach to native forests.

Clearly, a great deal of detailed analysis of long-term impacts is required since analysis of the industry rarely extends beyond the next 10 years. One key issue if the extent to which the forest and forest-dependent industries, as well as governments, prepare themselves for the uncertainty associated with climate change and forests.

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Greenhouse Challenge Sinks Workbook

Mark Jackson
Greenhouse Challenge Office

The Greenhouse Challenge Office negotiates voluntary agreements with companies and industry associations willing to take action to reduce greenhouse gas emissions. Cooperative Agreements are plans of action agreed by companies at CEO level, and have measurable outcomes which are monitored over time by the participating companies, with an independent audit function coordinated by the Office. The credibility of the agreements depends on systematic, scientific monitoring of net emission reduction performance against agreed targets over time.

The Office recently commissioned a consortium comprising AACM International, Forestry Technical Services, and Clean Commodities Inc, to develop a Workbook on quantification of vegetation related sinks for CO₂. The Workbook will be published in early 1998.

This will be of great assistance to those companies which are, or will be, developing cooperative agreements which feature sink creation. There is considerable interest from companies in this means of reducing their net emissions, with development of timber plantations and participation in Landcare activities being the two most notable forms of action being taken to date.

The Workbook will document some project level methodologies and default values for quantification of vegetation related sinks for CO₂, to:

- assist companies developing cooperative agreements through the Greenhouse Challenge Office to incorporate sinks in their inventories, action plans and reports, and
- assist GCO staff to assess such information provided by companies.

The workbook aims to cover -

- Indicative information on a range of commonly managed species and vegetation types, regarding their likely growth rates on a representative range of appropriate sites, and the sequestration rates which would apply in each case.
- Methodologies for monitoring/measuring carbon sequestration associated with biomass increase and soils, suitable for providing scientifically credible data for the purpose of reporting on projects to the Greenhouse Challenge Office.
- Methodologies for estimating and measuring carbon emissions associated with the activity for which the sink is claimed.
- Recommendations for appropriate default values and “accounting conventions”.
- Issues relating to ownership and/or management control of activities upon which the claim sequestration is based.
- Guidance on sources of further information/expertise on quantification of sinks.

The first version of the Workbook will focus on enabling companies to quantify the greenhouse benefits of agroforestry, plantation forestry, and environmental and landcare plantings.
Montreal process criteria and indicators

Criteria about sustainability but indicators and data collected will allow us to track other things such as impacts global change.

Indicators followed by an "a" are those for which most data are available. Indicators followed by a "b" are those which may require the gathering of new or additional data and/or a new program of systematic sampling or basic research.

Criterion 1: Conservation of biological diversity

Biological diversity includes the elements of the diversity of ecosystems, the diversity between species, and genetic diversity in species.

Indicators:

Ecosystem Diversity
a. Extent of area by forest type relative to total forest area; (a)
b. Extent of area by forest type and by age class or successional stage; (b)
c. Extent of area by forest type in protected area categories as defined by IUCN* or other classification systems; (a)
d. Extent of areas by forest type in protected areas defined by age class or successional stage; (b)
e. Fragmentation of forest types; (b)

Species Diversity
a. The number of forest dependent species; (b)
b. The status (rare, threatened, endangered, or extinct) of forest dependent species at risk of not maintaining viable breeding populations, as determined by legislation or scientific assessment; (a)

Genetic Diversity
a. Number of forest dependent species that occupy a small portion of their former range(b)
b. Population levels of representative species from diverse habitats monitored across their range. (b)

Criterion 2: Maintenance of productive capacity of forest ecosystem

Indicators:
a. Area of forest land and net area of forest land available for timber production; (a)
b. Total growing stock of both merchantable and nonmerchantable tree species on forest land available for timber production; (a)
c. The area and growing stock of plantations of native and exotic species; (a)
d. Annual removal of wood products compared to the volume determined to be sustainable;(a)
e. Annual removal of non-timber forest products (e.g. fur bearers, berries, mushrooms,
game), compared to the level determined to be sustainable. (b)

**Criterion 3: Maintenance of forest ecosystem health and vitality**

**Indicators:**

a. Area and percent of forest affected by processes or agents beyond the range of historic variation, e.g. by insects, disease, competition from exotic species, fire, storm, land clearance, permanent flooding, salinisation, and domestic animals; (b)

b. Area and percent of forest land subjected to levels of specific air pollutants (e.g. sulfates, nitrate, ozone) or ultra violet B that may cause negative impacts on the forest ecosystem; (b)

c. Area and percent of forest land with diminished biological components indicative of changes in fundamental ecological processes (e.g. soil, nutrient cycling, seed dispersion, pollination) and/or ecological continuity (monitoring of functionally important species such as nematodes, arboreal epiphytes, beetles, fungi, wasps, etc.). (b)

**Criterion 4: Conservation and maintenance of soil and water resources**

This criterion encompasses the conservation of soil and water resources and the protective and productive functions of forests.

**Indicators:**

a. Area and percent of forest land with significant soil erosion; (b)

b. Area and percent of forest land managed primarily for protective functions, e.g. watersheds, flood protection, avalanche protection, riparian zones; (a)

c. Percent of stream kilometers in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation; (b)

d. Area and percent of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties; (b)

e. Area and percent of forest land with significant compaction or change in soil physical properties resulting from human activities; (b)

f. Percent of water bodies in forest areas (e.g. stream kilometers, lake hectares) with significant variance of biological diversity from the historic range of variability; (b)

g. Percent of water bodies in forest areas (e.g. stream kilometers, lake hectares) with significant variation from the historic range of variability in pH, dissolved oxygen, levels of chemicals (electrical conductivity), sedimentation or temperature change; (b)

h. Area and percent of forest land experiencing an accumulation of persistent toxic substances. (b)

**Criterion 5: Maintenance of forest contribution to global carbon cycles**

**Indicators:**

a. Total forest ecosystem biomass and carbon pool, and if appropriate, by forest type, age class, and successional stages; (b)

b. Contribution of forest ecosystems to the total global carbon budget, including absorption and release of carbon (standing biomass, coarse woody debris, peat and soil carbon); (a or
b) Contribution of forest products to the global carbon budget. (b)

**Criterion 6: Maintenance and enhancement of long-term multiple socio-economic benefits to meet the needs of societies**

**Indicators:**

*Production and consumption*

- a. Value and volume of wood and wood products production, including value added through downstream processing; (a)
- b. Value and quantities of production of non-wood forest products; (b)
- c. Supply and consumption of wood and wood products, including consumption per capita; (a)
- d. Value of wood and non-wood products production as percentage of GDP; (a or b)
- e. Degree of recycling of forest products; (a or b)
- f. Supply and consumption/use of non-wood products; (a or b)

*Recreation and tourism*

- a. Area and percent of forest land managed for general recreation and tourism, in relation to the total area of forestland; (a or b)
- b. Number and type of facilities available for general recreation and tourism, in relation to population and forest area; (a or b)
- c. Number of visitor days attributed to recreation and tourism, in relation to population and forest area; (b)

*Investment in the forest sector*

- a. Value of investment, including investment in forest growing, forest health and management, planted forests, wood processing, recreation and tourism; (a)
- b. Level of expenditure on research and development, and education; (b)
- c. Extension and use of new and improved technology; (b)
- d. Rates of return on investment; (b)

*Cultural, social and spiritual needs and values*

- a. Area and percent of forest land managed in relation to the total area of forest land to protect the range of cultural, social and spiritual needs and values; (a or b)
- b. Non-consumptive-use forest values; (b)

*Employment and community needs*

- a. Direct and indirect employment in the forest sector and the forest sector employment as a proportion of total employment; (a or b)
- b. Average wage rates and injury rates in major employment categories within the forest sector.
- c. Viability and adaptability to changing economic conditions, of forest dependent communities, including indigenous communities; (b)
- d. Area and percent of forest land used for subsistence purposes. (b)

**Criterion 7: Legal, institutional and economic framework for forest conservation and sustainable management**
**Indicators:**

*Extent to which the legal framework (laws, regulations, guidelines) supports the conservation and sustainable management of forests, including the extent to which it:*

a. Clarifies property rights, provides for appropriate land tenure arrangements, recognizes customary and traditional rights of indigenous people, and provides means of resolving property disputes by due process;
b. Provides for periodic forest-related planning, assessment, and policy review that recognizes the range of forest values, including coordination with relevant sectors;
c. Provides opportunities for public participation in public policy and decision making related to forests and public access to information;
d. Encourages best practice codes for forest management;
e. Provides for the management of forests to conserve special environmental, cultural, social and/or scientific values.

*Extent to which the institutional framework supports the conservation and sustainable management of forests, including the capacity to:*

a. Provide for public involvement activities and public education, awareness and extension programs, and make available forest related information;
b. Undertake and implement periodic forest-related planning, assessment, and policy review including cross-sectoral planning and coordination;
c. Develop and maintain human resource skills across relevant disciplines;
d. Develop and maintain efficient physical infrastructure to facilitate the supply of forest products and services and support forest management;
e. Enforce laws, regulations and guidelines;

*Extent to which the economic framework (economic policies and measures) supports the conservation and sustainable management of forests through:*

a. Investment and taxation policies and a regulatory environment which recognize the long-term nature of investments and permit the flow of capital in and out of the forest sector in response to market signals, non-market economic valuations, and public policy decisions in order to meet long-term demands for forest products and services;
b. Non-discriminatory trade policies for forest products;

**Capacity to measure and monitor changes in the conservation and sustainable management of forests, including:***

a. Availability and extent of up-to-date data, statistics and other information important to measuring or describing indicators associated with criteria 1-7;
b. Scope, frequency and statistical reliability of forest inventories, assessments, monitoring and other relevant information;
c. Compatibility with other countries in measuring, monitoring and reporting on indicators.

**Capacity to conduct and apply research and development aimed at improving forest management and delivery of forest goods and services, including:***

a. Development of scientific understanding of forest ecosystem characteristics and functions;
b. Development of methodologies to measure and integrate environmental and social costs and benefits into markets and public policies, and to reflect forest related resource depletion or replenishment in national accounting systems;
c. New technologies and the capacity to assess the socioeconomic consequences associated with the introduction of new technologies;
d. Enhancement of ability to predict impacts of human intervention on forests;
e. Ability to predict impacts on forests of possible climate change.
# Workshop Attendees

<table>
<thead>
<tr>
<th>First name</th>
<th>Surname</th>
<th>Organisation</th>
<th>Address</th>
<th>Telephone</th>
<th>Fax</th>
<th>E-Mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kay</td>
<td>Abel</td>
<td>Australian Greenhouse Office</td>
<td>GPO Box 621</td>
<td>02 6274 1433</td>
<td>02 6271 1439</td>
<td><a href="mailto:kabel@greenhouse.gov.au">kabel@greenhouse.gov.au</a></td>
</tr>
<tr>
<td>Mike</td>
<td>Austin</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284</td>
<td>02 6242 1758</td>
<td>02 6241 3343</td>
<td><a href="mailto:m.austin@dwe.csiro.au">m.austin@dwe.csiro.au</a></td>
</tr>
<tr>
<td>Snow</td>
<td>Barlow</td>
<td>Bureau of Rural Sciences</td>
<td>PO Box E11</td>
<td>02 6272 4951</td>
<td>02 6272 4734</td>
<td><a href="mailto:sbarlow@brs.gov.au">sbarlow@brs.gov.au</a></td>
</tr>
<tr>
<td>Damian</td>
<td>Barrett</td>
<td>CSIRO Plant Industry</td>
<td>GPO Box 1600</td>
<td>02 6246 5157</td>
<td>02 6246 5270</td>
<td><a href="mailto:D.Barrett@pican.pi.csiro.au">D.Barrett@pican.pi.csiro.au</a></td>
</tr>
<tr>
<td>Bryson</td>
<td>Bates</td>
<td>CSIRO Water Resources</td>
<td>Private Bag</td>
<td>08 9387 0330</td>
<td>08 9387 8211</td>
<td><a href="mailto:bryson.bates@per.dwr.csiro.au">bryson.bates@per.dwr.csiro.au</a></td>
</tr>
<tr>
<td>Carl</td>
<td>Binning</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284</td>
<td>02 6242 1671</td>
<td>02 6241 3343</td>
<td><a href="mailto:c.binning@dwe.csiro.au">c.binning@dwe.csiro.au</a></td>
</tr>
<tr>
<td>Bob</td>
<td>Boardman</td>
<td>Forestry SA</td>
<td>GPO Box 2284</td>
<td>08 8303 9900</td>
<td>08 8303 9999</td>
<td><a href="mailto:boardman.board@pi.sa.gov.au">boardman.board@pi.sa.gov.au</a></td>
</tr>
<tr>
<td>Trevor</td>
<td>Booth</td>
<td>CSIRO Forests and Forest Products</td>
<td>PO E4008</td>
<td>026 281 8259</td>
<td>026 281 8312</td>
<td><a href="mailto:Trevor.Booth@ffp.csiro.au">Trevor.Booth@ffp.csiro.au</a></td>
</tr>
<tr>
<td>Peter</td>
<td>Cornish</td>
<td>State Forest NSW</td>
<td>Locked Bag 23</td>
<td>02 9980 4269</td>
<td>02 9484 3976</td>
<td><a href="mailto:peterc@ironbark.forest.nsw.gov.au">peterc@ironbark.forest.nsw.gov.au</a></td>
</tr>
<tr>
<td>Peter</td>
<td>Catling</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284</td>
<td>02 6242 1712</td>
<td>02 6241 3343</td>
<td><a href="mailto:p.catling@dwe.csiro.au">p.catling@dwe.csiro.au</a></td>
</tr>
<tr>
<td>Steve</td>
<td>Cork</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284</td>
<td>02 6242 1731</td>
<td>02 6241 3343</td>
<td><a href="mailto:S.Cork@dwe.csiro.au">S.Cork@dwe.csiro.au</a></td>
</tr>
<tr>
<td>Alan</td>
<td>Cummine</td>
<td>Australian Forest Growers</td>
<td>24 Napier Close, Deakin ACT 2600</td>
<td>02 6236 8309</td>
<td>015 988 927</td>
<td><a href="mailto:cummine@safetyweb.com.au">cummine@safetyweb.com.au</a></td>
</tr>
<tr>
<td>Ian</td>
<td>Curruthers</td>
<td>Australian Greenhouse Office</td>
<td>GPO Box 621</td>
<td>02 6274 1405</td>
<td>02 6274 1439</td>
<td><a href="mailto:icarruthers@greenhouse.gov.au">icarruthers@greenhouse.gov.au</a></td>
</tr>
<tr>
<td>Name</td>
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<tr>
<td>Gary Dolman</td>
<td>DPIE</td>
<td>GPO Box 858, Canberra ACT 2601</td>
<td>02 6272 4500</td>
<td>02 6272 4875</td>
<td><a href="mailto:gary.dolman@dpie.gov.au">gary.dolman@dpie.gov.au</a></td>
<td></td>
</tr>
<tr>
<td>Hans Drielsma</td>
<td>Forestry Tasmania</td>
<td>GPO Box 207b, Hobart TAS 7001</td>
<td>03 6233 8181</td>
<td>03 6233 8191</td>
<td><a href="mailto:hans.drielsma@forestry.tas.gov.au">hans.drielsma@forestry.tas.gov.au</a></td>
<td></td>
</tr>
<tr>
<td>Mike Doherty</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284, Canberra ACT 2601</td>
<td>02 6242 1766</td>
<td>02 6241 3343</td>
<td><a href="mailto:m.doherty@dwe.csiro.au">m.doherty@dwe.csiro.au</a></td>
<td></td>
</tr>
<tr>
<td>Mark Dudzinski</td>
<td>CSIRO Forests and Forest Products</td>
<td>PO E4008, Kingston ACT 2604</td>
<td>02 6281 8332</td>
<td>02 62818312</td>
<td><a href="mailto:Mark.Dudzinski@ffp.csiro.au">Mark.Dudzinski@ffp.csiro.au</a></td>
<td></td>
</tr>
<tr>
<td>Derek Eamus</td>
<td>NT University</td>
<td>NTU, Darwin NT 0909</td>
<td>08 8946 6716</td>
<td>08 8946 6847</td>
<td><a href="mailto:d-eamus@bligh.ntu.edu.au">d-eamus@bligh.ntu.edu.au</a></td>
<td></td>
</tr>
<tr>
<td>Graham Farquhar</td>
<td>Research School of Biological Sciences</td>
<td>ANU ACT 0200</td>
<td>02 6249 3743</td>
<td>02 6249 9995</td>
<td><a href="mailto:Farquhar@rsbs-central.anu.edu">Farquhar@rsbs-central.anu.edu</a></td>
<td></td>
</tr>
<tr>
<td>Klara Finkele</td>
<td>CSIRO</td>
<td>Environmental Mechanics</td>
<td>02 6246 5834</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roger Gifford</td>
<td>CSIRO Plant industry</td>
<td>GPO Box 1666, Canberra ACT 2601</td>
<td>02 6246 5441</td>
<td>026 246 5000</td>
<td><a href="mailto:r.gifford@pi.csiro.au">r.gifford@pi.csiro.au</a></td>
<td></td>
</tr>
<tr>
<td>Angela Gilmore</td>
<td>Australian Greenhouse Office</td>
<td>GPO Box 621, Canberra ACT 2601</td>
<td>02 6274 1405</td>
<td>02 6274 1439</td>
<td><a href="mailto:agilmore@greenhouse.gov.au">agilmore@greenhouse.gov.au</a></td>
<td></td>
</tr>
<tr>
<td>Julian Gorman</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284, Canberra ACT 2601</td>
<td>02 242 1794</td>
<td>02 6242 1512</td>
<td><a href="mailto:j.gorman@dwe.csiro.au">j.gorman@dwe.csiro.au</a></td>
<td></td>
</tr>
<tr>
<td>Clive Hamilton</td>
<td>The Australia Institute</td>
<td>37 Geils Court, Deakin ACT 2600</td>
<td>02 249 6221</td>
<td>026 249 6448</td>
<td><a href="mailto:ausinst@netinfo.com.au">ausinst@netinfo.com.au</a></td>
<td></td>
</tr>
<tr>
<td>Neil Hamilton</td>
<td>Institute for Sustainable Futures</td>
<td>PO Box 123 Broadway NSW 2007</td>
<td>02 9209 4355</td>
<td>02 9209 4351</td>
<td><a href="mailto:Neil.Hamilton@uts.edu.au">Neil.Hamilton@uts.edu.au</a></td>
<td></td>
</tr>
<tr>
<td>Roger Hnatiuk</td>
<td>Bureau of Rural Sciences</td>
<td>PO Box E11, Kingston ACT 2601</td>
<td>02 6272 3428</td>
<td>02 6272 3882</td>
<td><a href="mailto:Roger.hnatiuk@brs.gov.au">Roger.hnatiuk@brs.gov.au</a></td>
<td></td>
</tr>
<tr>
<td>Mark Howden</td>
<td>CSIRO Wildlife &amp; Ecology</td>
<td>GPO Box 284, Canberra ACT 2601</td>
<td>02 6242 1679</td>
<td>02 6242 1512</td>
<td><a href="mailto:mark.howden@dwe.csiro.au">mark.howden@dwe.csiro.au</a></td>
<td></td>
</tr>
<tr>
<td>Leslie Hughes</td>
<td>Macquarie University</td>
<td>North Ryde, NSW 2109</td>
<td>02 9850 8195</td>
<td>02 9850 8245</td>
<td><a href="mailto:lhughes@rna.bio.mq.edu.au">lhughes@rna.bio.mq.edu.au</a></td>
<td></td>
</tr>
<tr>
<td>Mark Jackson</td>
<td>Greenhouse Challenge office, DPIE</td>
<td>GPO Box 858 Canberra 2601</td>
<td>02 6271 6640</td>
<td>02 6271 6450</td>
<td><a href="mailto:m.jackson@dpie.gov.au">m.jackson@dpie.gov.au</a></td>
<td></td>
</tr>
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<tr>
<th>First name</th>
<th>Surname</th>
<th>Organisation</th>
<th>Address</th>
<th>Telephone</th>
<th>Fax</th>
<th>E-Mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ian</td>
<td>Noble</td>
<td>Research School of ANU</td>
<td>ANU</td>
<td>02 6249 5092</td>
<td>02 6249 5095</td>
<td><a href="mailto:noble@RSBS-central.anu.edu.au">noble@RSBS-central.anu.edu.au</a></td>
</tr>
</tbody>
</table>

CSIRO Resource Futures
<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Address</th>
<th>Phone 1</th>
<th>Phone 2</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ken Old</td>
<td>CSIRO Forests and Forest Products</td>
<td>PO Box E4008 Kingston ACT 2604</td>
<td>02 6281 8329</td>
<td>02 6281 8277</td>
<td><a href="mailto:ken.old@ffp.csiro.au">ken.old@ffp.csiro.au</a></td>
</tr>
<tr>
<td>Tony Press</td>
<td>Environment Australia</td>
<td>GPO Box 787 Canberra ACT 2601</td>
<td>02 6274 1973</td>
<td>02 6274 1322</td>
<td><a href="mailto:tony.press@dest.gov.au">tony.press@dest.gov.au</a></td>
</tr>
<tr>
<td>John Raison</td>
<td>CSIRO Forests and Forest Products</td>
<td>PO Box E4008 Kingston ACT 2604</td>
<td>02 6281 8280</td>
<td>02 6281 8312</td>
<td><a href="mailto:John.Raison@ffp.csiro.au">John.Raison@ffp.csiro.au</a></td>
</tr>
<tr>
<td>Penny Reyenga</td>
<td>Bureau of Rural Sciences</td>
<td>PO Box E11 Kingston ACT 2604</td>
<td>02 6272 3757</td>
<td>02 6272 5992</td>
<td><a href="mailto:penny.reyenga@brs.gov.au">penny.reyenga@brs.gov.au</a></td>
</tr>
<tr>
<td>Paul Ryan</td>
<td>Queensland Forestry Research</td>
<td>MS483 Fraser Road, Gympie, Queensland 4570</td>
<td>075 482 0868</td>
<td>075 482 8775</td>
<td><a href="mailto:ryanp@gfri1.se2.dpi.qld.gov.au">ryanp@gfri1.se2.dpi.qld.gov.au</a></td>
</tr>
<tr>
<td>Will Steffen</td>
<td>CSIRO</td>
<td>GPO Box 284 Canberra ACT 2601</td>
<td>02 6242 1755</td>
<td>02 6241 3343</td>
<td><a href="mailto:W.Steffen@dwe.csiro.au">W.Steffen@dwe.csiro.au</a></td>
</tr>
<tr>
<td>Robert Sutherst</td>
<td>CSIRO Entomology</td>
<td>CRC Tropical Pest Management, Gehrmann Labs, University of Queensland, Australia 4072</td>
<td>07 3365 1851</td>
<td>07 3365 1855</td>
<td><a href="mailto:roberts@ctpm.uq.edu.au">roberts@ctpm.uq.edu.au</a></td>
</tr>
<tr>
<td>Peter Thomas</td>
<td>DPIE, Forest Division</td>
<td>GPO Box 858, Canberra ACT 2601</td>
<td>02 6272 4620</td>
<td>02 6272 4875</td>
<td><a href="mailto:Peter.Thomas@dpi.e.gov.au">Peter.Thomas@dpi.e.gov.au</a></td>
</tr>
<tr>
<td>Mark Westoby</td>
<td>School of Biological Sciences</td>
<td>Macquarie University NSW 2109</td>
<td>02 8508196</td>
<td>02 9850 9354</td>
<td><a href="mailto:mwestoby@rna.bio.mq.edu.au">mwestoby@rna.bio.mq.edu.au</a></td>
</tr>
<tr>
<td>Jann Williams</td>
<td>Charles Sturt University</td>
<td>PO Box 789 Albury NSW 2640</td>
<td>02 6051 9622</td>
<td>02 6051 9897</td>
<td><a href="mailto:jawilliams@csu.edu.au">jawilliams@csu.edu.au</a></td>
</tr>
</tbody>
</table>