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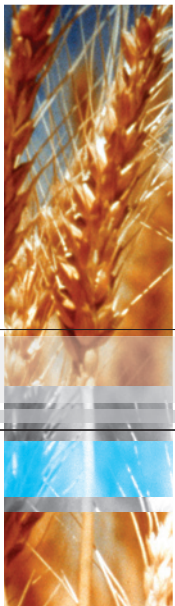

Carbon Dioxide Fertilisation and Climate Change Policy

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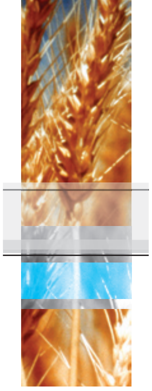
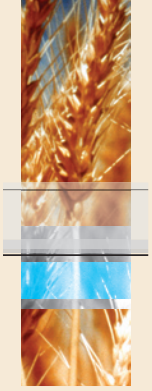


Contents



Executive Summary

Climate change is no longer a matter of interest just for the scientific community. It is now mainstream in policy formation across many sectors of modern society. In Australia, policy interests relating to effects of elevated carbon dioxide (CO_2) on plant productivity are based on the fact that these effects will flow directly - one way or another - into the economies of Australia's agricultural and forest industries, and thus will impact on the economic and social well being of all Australia's rural communities.

The purpose of this report is to assess our current understanding of the likely effects of increasing atmospheric CO_2 on plant growth in Australia under a changing climate. It aims to:

- clarify the current state of science, from a policy perspective, through an inclusive process that offers Australian experts an opportunity to present their views and evidence, and
- identify the important areas of science where there is not yet consensus, as an indication of the most important research challenges for the coming years.

The report is based on reviews of the scientific literature, interviews with Australian scientists, and a facilitated workshop involving experts from wide ranging disciplines.

There is strong consensus that at the leaf level elevated CO_2 increases the instantaneous rate of photosynthesis in woody plants and in some grasses, and it decreases the amount of water lost per unit carbon assimilated. Under most conditions and for most plants used in controlled environment experiments, these effects translate at the individual plant level to a positive growth response and an increase in water-use efficiency, that is, to an increase in carbon assimilated per unit of water transpired.

Scaling the effects of elevated CO_2 even from the leaf level to whole plant levels presents some difficulties in interpretation, however, due to the large number of ways that plants can allocate the additional photosynthate produced in the leaves. These difficulties arise primarily from the various phenological phases that plants go through during their life cycles, and the range of environmental and physiological constraints that they experience. In addition, essentially all of the experimental methodologies employed to date use a sudden step-wise increase in the concentration of CO_2 - often to a doubling of ambient. Thus, based on research to date there can be no conclusions drawn as to the capacity of plants or systems to adapt (or respond) to a gradual increase in CO_2 as occurring *in situ*.

Scaling from plants to ecosystems or production systems, and from short to long timescales is done by system-level experimentation and modelling. Given the importance of moisture constraints for Australian terrestrial systems, the degree to which elevated CO_2 may influence water use efficiency is of paramount importance. There is agreement that different water balance processes operate at different scales from the leaf to the plant to the ecosystem. Hence any attempt to extrapolate the effects of elevated CO_2 on plant water use efficiencies from micro-level studies to macro-level understanding must be undertaken with extreme care.

In scaling from individual plants to whole ecosystems, there is also strong consensus that differential growth responses among individual plants to elevated CO_2 will lead over time to change in species composition of the ecosystem - although the effects on ecosystem dynamics clearly remains unresolved. In addition, most elevated CO_2 experiments run for five years or less, and thus may not capture longer term effects, especially acclimation phenoma, longer term nutrient dynamics, and changes of turnover in carbon pools. It is also accepted that experiments run in small chambers or FACE (Free-Air Carbon Dioxide Enrichment) plots (1 m^2 to 30 m^2) behave as 'islands' of elevated CO_2 surrounded by ambient CO_2, which does not allow for full atmospheric feedbacks or interactions with herbivores or pollinators.

The intersection of the effects of elevated CO_2 with climate change is especially important given the overriding importance of weather and climate extremes for the strength of Australian plant-based industries. Although CO_2 effects become important only at longer timescales (decadal to century) compared with the effects of climate extremes, the interaction between CO_2 and climate effects may become important over shorter timescales if increased water use efficiencies are expressed at systems levels.

Models are critical tools to translate experimental findings and observations of plant and ecosystem responses into more generalised understandings. Most models developed to examine the effects of elevated CO_2 contain modules, usually based on empirical relationships. These modules simulate other aspects of ecosystem physiology that are important in determining the effects of elevated

CO_2 on biomass or yield. These include nitrogen cycle dynamics (inclusion of phosphorus dynamics is less common), allocation of carbohydrate to various plant organs, decomposition of soil carbon, plant phenological effects and, increasingly, management options.

Challenges and controversy may arise when models that have been developed primarily as research tools are later adapted for management or policy studies. There is a long-standing unresolved debate within the scientific community as to whether this is an appropriate approach or not. The fundamental issue lies around the treatment of uncertainty. Modellers are, of course, aware of the limitations, and carefully note that process modules within models must be tested rigorously, but nonetheless, the confidence levels attached to the parameterisation of various processes are normally treated in an implicit rather than an explicit manner. This debate is critical to understanding the use of models in supporting policy development.

Bearing in mind the constraints on the scientific knowledge base noted above and the lack of elevated CO_2 experimentation that has been done under Australian environmental conditions, the effects of changing climate and atmospheric CO_2 concentration on Australian plant-based industries can be summarized as follows.

Cropping (wheat) systems: Given the dearth of experimentally based information for Australian conditions, model-based analyses are the only way to estimate impacts of climate change on the Australian wheat industry. A sophisticated model-based assessment that included the effects of both elevated CO_2 and changes in climate means and extremes has proposed (i) small increases in mean production, but a significant probability of lowered production; (ii) marked regional differences in production; and (iii) enhanced production if growers respond with appropriate adaptation strategies. Nonetheless, given that the probabilities of positive or negative overall effects are roughly equal, we might well conclude on the basis of risk assessment that there is a serious cause for concern about the future of the current Australian wheat industry under global climate change.

Grazing systems: A detailed model-based study for Queensland of the impacts of doubling CO_2, increasing temperature, and varying rainfall suggests that 'safe' animal carrying capacity may increase, but major uncertainties remain on the effects of elevated CO_2 and climate change on nutritional quality of feed, plant-plant competition, both in terms of the composition of herbaceous species and of the woody:grass ratio.

Forestry systems: Compared with cropping and grazing systems, less is known about the effects of elevated CO_2 on Australian forests. The limited observational evidence available internationally is inconclusive but suggests that elevated CO_2 effects decrease as trees age, so the effects of elevated CO_2 on old growth or mature forests will be less than on short-rotation plantation forests, where it is likely that fast-growing saplings and young trees are more likely to respond to elevated CO_2 with enhanced net primary production.

The bottom-line messages of this report relate to fundamental questions about the effects of elevated CO_2 on Australian plant-based industries.

(i) How robust is the knowledge base on CO_2 effects?

The knowledge base on the effects of step-wise increases in atmospheric CO_2 on fundamental physiological effects at leaf level appears quite robust. There is increasing uncertainty, however, as the effects of elevated CO_2 on growth, yield, and water use are scaled up to monoculture cropping systems (e.g. wheat), perennial pasture/rangelands systems and short-rotation plantation forests. Uncertainty increases further when the effects are scaled up to mature forests over long timescales.

In addition, little is known about the effects at the system level when other effects of elevated CO_2 (e.g. carbon allocation, nutrient interactions, inter-species competition) are considered concurrently. There is a critical lack of relevant experimentation under Australian environmental conditions.

(ii) With what level of confidence can we apply to policy development our current understanding of elevated CO_2 effects?

Our confidence in the reliability of the knowledge base on the effects of elevated CO_2 on their own for policy development may be stronger for cropping and grazing systems than for the forestry industry (apart from short-rotation plantations). However, the effects of elevated CO_2 cannot be disentangled from the effects of climate change, which bring their own set of considerable uncertainties and gaps in understanding. Thus, when the cumulative and interactive impacts of elevated CO_2 and climate change are considered, our confidence in the reliability of the knowledge base for policy development in all agricultural and forestry systems in Australia is clearly in the 'low' category.

Given these uncertainties, a number of key research priorities were agreed.

- Increased synthesis of previous research on effects of elevated CO_2 from an Australian policy and management perspective;
- Additional experimental work on the effects of elevated CO_2 on Australian plant-based systems - with highest priority to (1) *in situ* wheat crops using standard management regimes of the semi-arid Australian wheat belt, and (b) whole tree studies in water-limited systems;
- Studies of multiple interacting factors on terrestrial production systems;
- Analysis of interactive effects of elevated CO_2 and extreme climate events;
- Adaptability of Australian terrestrial production systems;
- Pest and disease dynamics – in context of host-parasite relations – under conditions of global climate change.

1. Background: The Policy Context

Global change presents profound challenges to the relationship between policy and science. In an Australian context, global change, especially the accelerating changes in atmospheric composition and climate, have direct and significant implications for Australian primary industries, which depend on growth of vegetation as their fundamental basis. Scientific research on global change is no longer a matter of interest for the scientific community alone, but has become a critical element in policy formulation across many sectors of modern society.

The policy imperative has major implications for the interpretation and presentation of the results of scientific research. The issue of uncertainty is a key aspect of global change research that impacts the science-policy interface. What we know and what we don't know, and at what levels of confidence, often mean different things to scientists and to policymakers. The challenge is for the two communities – policy and research – to work together to understand both the value and the limitations of science as an essential ingredient in formulating policy to deal with global change. The impacts of increasing atmospheric CO_2 on vegetative growth is an example where scientific knowledge plays an important role in policy formulation in an Australian context.

The accelerating increase of CO_2 in the atmosphere is one of the most certain aspects of global change over the coming decades. Because atmospheric CO_2 is fundamental to the growth and productivity of terrestrial vegetation, on which much of Australian primary industry is based, as well as critical for the radiative properties of the atmosphere and hence climate, the changing atmospheric concentration of CO_2 will have far-reaching effects on both environment and economy. However, there is considerable uncertainty within the scientific community not only about climate but also about how much the increase in atmospheric CO_2 has been stimulating and will stimulate plant growth (the 'CO_2 fertilisation effect') in Australia under current climate change and future climate scenarios.

Despite many years of research and a large body of scientific literature on the effects of elevated atmospheric CO_2 on plants and plant systems, there is still a wide spectrum of views on the importance of the CO_2 fertilisation effect for Australian (and global) terrestrial production systems. While nearly all scientists agree that there is an instantaneous leaf physiological response to increased CO_2 in C_3 plants, the net effect on plants and on terrestrial production systems depends on the interaction of a wide range of factors such as temperature, moisture supply, nutrients, plant-plant competition, pests and diseases, acclimation, within-plant regulation and a variety of management treatments. Depending on these interactions, CO_2 fertilisation can lead to a net positive effect, little or no effect, and in some cases even a negative effect. While discussion, debate and further research are important for improving fundamental understanding of plant and ecosystem/production system responses to increasing atmospheric CO_2, the outcomes of this scientific process have a major bearing on a number of Australian Greenhouse Office (AGO) policy responsibilities. The AGO therefore has a strong interest in evaluating the current state of knowledge on this issue and in promoting progress towards a better understanding in order to have a sound scientific basis for policy development.

The policy interests are based on the fact that the effect of elevated CO_2 on plant productivity will flow directly into economic impacts on Australia's cropping, pastoral and forest industries. While CO_2 fertilisation is only one element of global change affecting these industries, it can be an important one depending on the circumstances. Thus, different views on the importance of CO_2 fertilisation relative to climate change can generate widely differing conclusions about the future of these industries, ranging from very positive to very negative. For example, under some circumstances wheat yields will increase with a "strong representation" of the CO_2 fertilisation effect in models but decline with a "weak representation" of it.

In such cases the consideration of uncertainties, confidence levels, risks and probabilities is crucial. The policy sector needs to have a reasonable level of confidence in the scientific community's assessments of how global change will affect crop, pasture and forest growth in order to understand impacts on these industries, and assist them to adapt to change. To build this confidence, it is essential to have a reliable understanding of how elevated CO_2 will affect plant growth and physiology under Australian conditions, interacting with changes in climate variables such as temperature, rainfall and evaporation.

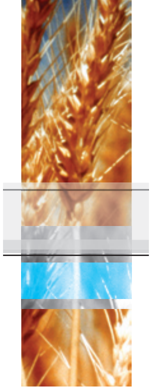
Given this background, it is timely to assess our current understanding – what is known with some degree of confidence and what is still subject to significant debate – about the likely effects of increasing atmospheric CO_2 on plant growth in Australia under a changing climate. Thus, the objectives of this project on the CO_2 fertilisation effect are to:

- clarify the current state of science, from a policy perspective, through an inclusive process that offers Australian experts on the topic an opportunity to present their views and evidence, and
- identify the important areas of science where there is not yet consensus, as an indication of the most important research challenges for the coming years.

It must be emphasised that the aim of this report is NOT an exhaustive or thorough scientific review of the effects of elevated CO_2 on plant and ecosystem physiology. Many such excellent reviews already exist, and a summary of their findings of relevance for Australia is given in Appendix 1. Rather, the intent is to draw on this knowledge base to explore those aspects of the topic that are especially relevant for (i) Australian conditions and ecosystems, and (ii) policy advice on the impacts of global change on Australia's plant-based industries.

In this report we use the terms 'climate change' and 'global change' as follows. 'Climate change' refers to changes in the means and statistical temporal and spatial patterns of air temperature, rainfall, humidity, windspeed and direction and atmospheric pressure. 'Global change' includes climate change but also includes changes in other aspects of the global environment, in this case changes in atmospheric composition such as the rising concentration of CO_2.

Finally, although it is beyond the scope of this report, the ultimate viability of Australia's primary industries depends on other important factors in addition to the biophysical environment, for example, changes in demographics, land use, the international market place or in international institutions such as the World Trade Organisation. Any comprehensive and complete analysis of the future of Australia's primary industries must thus take into account changes in both the biophysical and socioeconomic environments.



2. Organisation of the Report

We first present what is widely accepted about the basic physiology of the CO_2 fertilisation effect at the leaf and plant levels. We then discuss issues associated with scaling this understanding to the level of whole ecosystems and production systems. A discussion of approaches to modelling the effects of elevated CO_2 then follows. In these sections we first put forward those issues on which there is a strong consensus amongst the Australian expert community. Then we follow with a discussion of those issues of importance for Australian terrestrial ecosystems for which a consensus cannot yet be reached.

A discussion of the relative and interactive effects of climate and elevated CO_2 on Australian plant-based industries is then presented; the importance of weather and climate extremes is emphasised. Based on the scientific background presented in sections 3 through 6, the implications for policy and management of Australian plant-based industries is presented in a final section. Three of the most important for Australia - non-irrigated wheat cropping, grazing and forestry – are highlighted.

This report is based on a synthesis from three sources of information: (i) the international (including Australian) scientific literature on the topic, which is summarised in Appendix 1; (ii) individual interviews with Australian experts on various aspects of the effects of elevated CO_2 on terrestrial ecosystems, including Australian plant-based industries (cf. Acknowledgements section); and (iii) comments on and discussion of earlier drafts of this report, both in written form and at a workshop, as well as supplementary text evaluating the use of models for projecting the effects of elevated CO_2 into the future (Appendix 2). The main body of the report does not include specific, individual citations to all of the relevant literature but does include specific references to the figures and to the two studies on Australian wheat and grazing systems, respectively, included in the analysis of section 7. Appendix 3 presents an extensive list of the relevant literature, including the references cited in Appendix 1 (emphasis on reviews and key references) and in Appendix 2.

3. Basic Physiology of the CO_2 Fertilisation Effect

Although understanding the implications of the CO_2 fertilisation effect for Australian terrestrial production systems ultimately requires a systems approach, a consideration of the effects of elevated CO_2 on those basic aspects of leaf and plant physiology that are particularly important for Australian conditions is a necessary prerequisite.

Consensus. In terms of the basic physiology at the leaf level, there is a strong consensus that, under almost all conditions, elevated atmospheric CO_2:

- increases the instantaneous rate of photosynthesis in C_3 plants; and
- increases the transpiration efficiency of the leaf (C_3 and C_4 plants), that is, decreases the amount of water lost through transpiration per unit of photosynthate produced.

Scaling elevated CO_2 effects from leaf to plant presents problems due to the large number of ways plants can allocate the additional photosynthate produced in the leaves. These difficulties arise primarily from the various phenological phases that plants go through during their life cycles and the range of environmental constraints that they experience. Figure 1 (P. Kriedemann, pers. comm.) provides a schematic visualisation of this relationship. Young plants in the initiation phase are primed for strong growth and will thus respond strongly to an additional resource that promotes growth. As they enter the sustaining phase, plants will continue to respond to resources but at a lower rate. Plants in the latent, dormant or senescent phase are largely unresponsive to additional resources. Environmental constraints (e.g. moisture supply, nutrient suppy, light limitation, etc.), of course, modulate these relationships between provision of resources and growth.

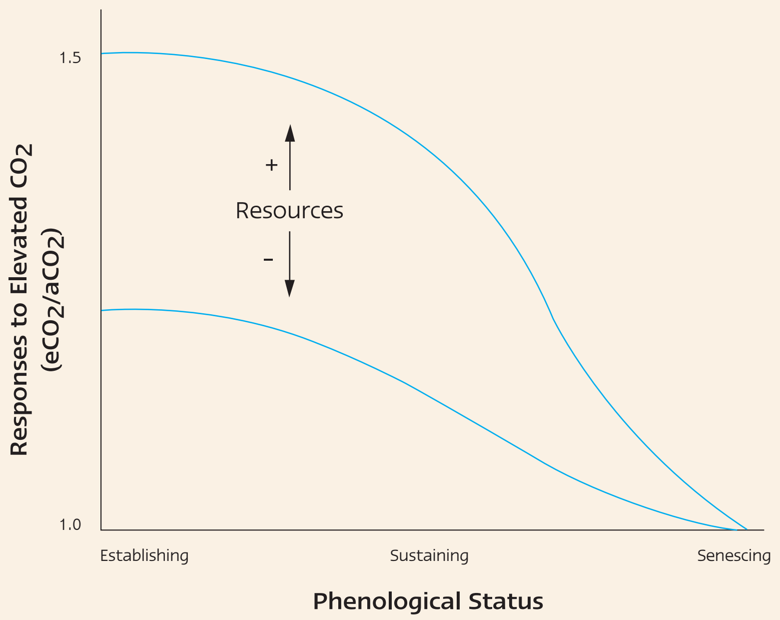


Figure 1 *Schematic diagram showing the plant-level relationship between response to elevated CO_2 (eCO_2) and phenological status as modulated by resource supply (cf. ambient CO_2 i.e. aCO_2). At the early, 'establishing' stage of plant development, the plant is primed for growth and is thus responsive to an increased supply of CO_2. Modulation by environmental constraints, for example, by nutrient inputs or increasing temperature, is also strong at this stage. The effects are still present, but at a reduced magnitude, during the 'sustaining' phase of a plant's life, and are much diminished in the 'senescing phase. (Figure courtesy of P. Kriedemann)*

Despite the difficulties of scaling from leaf to plant, research over the past couple of decades has achieved consensus on some important issues at the plant level. First, the vast majority of plants (and ecosystems) that have been studied in Australia and around the world under a wide variety of experimental conditions show a positive growth response to elevated CO_2, although the magnitude of the response varies widely with the level of environmental constraint and the phenological phase of the plant.

There is also strong consensus that, on balance, the transpiration efficiency at the leaf level stimulated by elevated CO_2 translates to increased efficiency of use of soil moisture at the plant level (WUE – Water Use Efficiency). The WUE effect is especially important for Australia, and indeed it could be argued that of all of Earth's inhabited continents, Australia is the one for which this CO_2-driven WUE effect is potentially most important given the overriding importance of moisture as a controlling factor of vegetation growth.

Figure 2 (J. Evans, pers. comm., after Passioura 2002) depicts how the yield of wheat could possibly be enhanced under elevated CO_2 at the dry end of a water-limited system, a situation relevant for most of Australia's wheat-growing areas. Two aspects of the figure are especially important. First, although the absolute value of the enhancement increases as moisture availability increases, the relative effect is greater at the drier end. This can be disproportionately important to the economic viability of the production enterprise. Second, there is a lower limit to soil available moisture below which the plants/production system is no longer viable (due to death or dormancy of most of the plants). Elevated CO_2 can likely move this threshold to somewhat lower values of soil available moisture but cannot eliminate it. This feature is important in analysing the intersection of the CO_2 fertilisation effect with climate change (see Section 6).

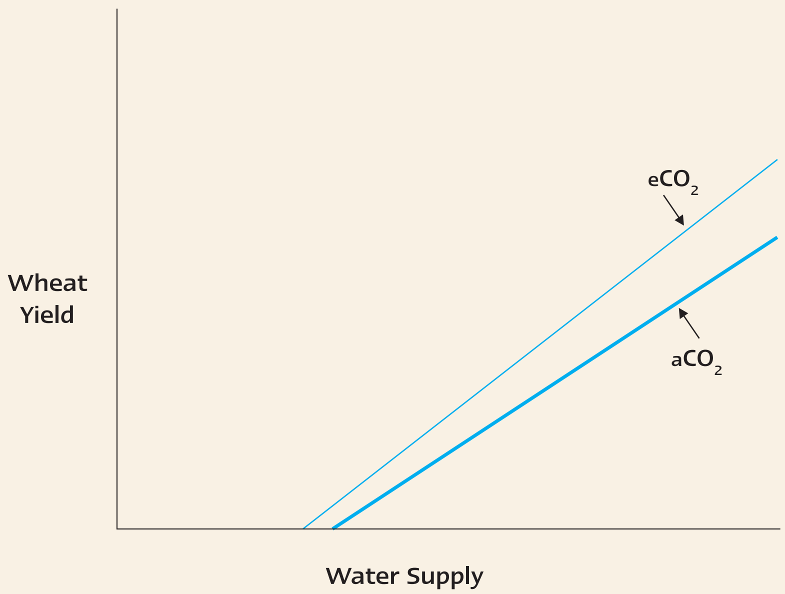


Figure 2 *Schematic figure showing the hypothesised effect of elevated atmospheric CO_2 (eCO_2) compared with ambient CO_2 (aCO_2) on yield at the dry end of soil available moisture for a non-irrigated wheat system. (Figure courtesy of J. Evans, based on original figure from Passioura 2002).*

Although Figure 2 is designed for a non-irrigated wheat production system (an annual plant), it could possibly also be applied to a less intensively managed perennial pastures/rangelands. The threshold of soil available moisture is important in this case too, and the CO_2 fertilisation effect will be significant under moderate drying but will disappear under severe droughts as water stress increases beyond a critical threshold. An example of this phenomenon can be seen in the Queensland savanna FACE experiment (Figure 3; Stokes et al. 2003), which showed a strong response of perennial vegetation to elevated CO_2 in a year with moderate drought (where rainfall was 832 mm compared to an average annual rainfall of 1083 mm) but no response in a year with severe drought (443 mm rainfall). Thus, the extremity of droughts and sequences of droughts is clearly important in determining the size of the CO_2 fertilisation effect for perennial vegetation.

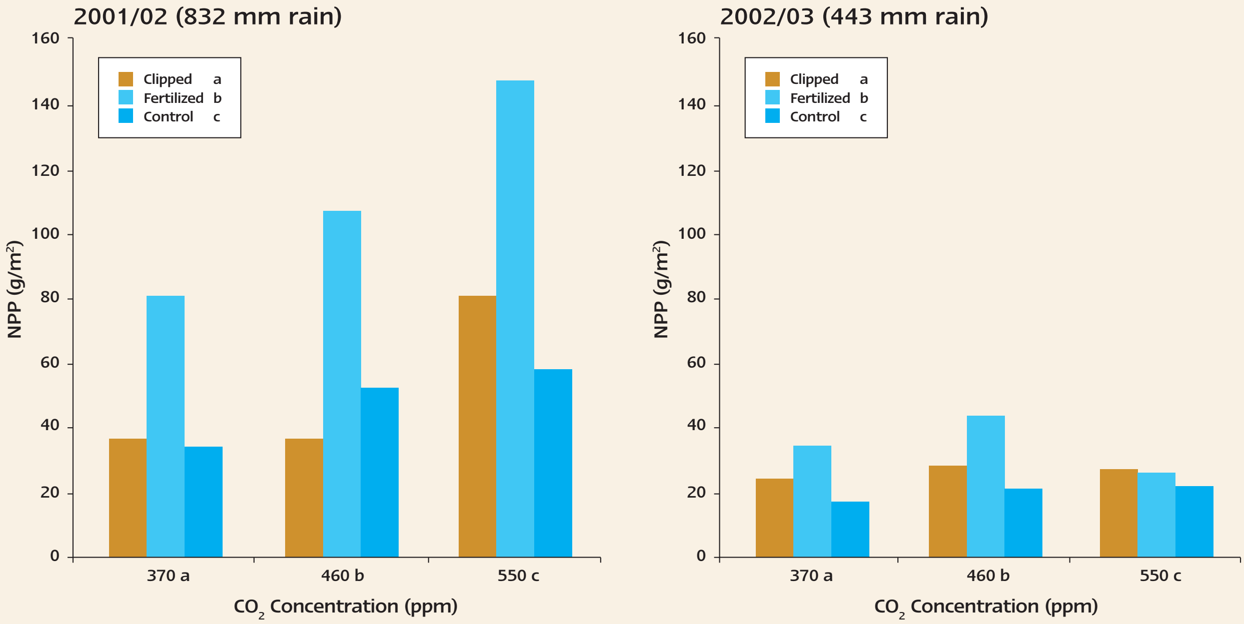


Figure 3 *Aboveground net primary production (NPP) of perennial grasses in North Queensland for two years as affected by FACE (Free-Air Carbon dioxide Enrichment) treatments. Treatments sharing the same letter were not significantly different: LSD p>0.05. (Stokes et al. 2003)*

No Consensus Yet. There are several important aspects of the plant-level physiological response to CO_2 for which there is no consensus yet. These aspects are best understood by viewing plants themselves as complex systems which respond to forcings in complex and often highly nonlinear ways rather than as simple organisms whose growth is limited by individual factors in isolation or in sequence. From this perspective it is more appropriate to view elevated CO_2 as providing an additional resource that the plant may then reallocate in various ways to optimise its performance. In Australian conditions this can often take the form of allocating photosynthate to roots or root exudates to enhance access to nutrients such as N and P or to access additional moisture.

Two issues are particularly important for Australian (and other) terrestrial systems but are not yet adequately understood:

Fate of Additional Photosynthate. While there is strong consensus that elevated CO_2 stimulates photosynthesis at the leaf level, there is much less agreement as to allocation of the carbon and thus to the ultimate fate of the additional photosynthate: aboveground biomass, belowground biomass, yield (e.g. reproductive organs), root exudates, etc. The issue is important for crops, in terms of yield of grain v. additional plant biomass, and for forestry and grazing systems, where the ratio of additional biomass in stemwood or aboveground biomass to that in roots (the 'shoot:root ratio') is important for timber or forage production. More fundamentally, there is still no consensus as to what drives the actual level of CO_2 fixed by the plant and the allocation of the additional carbon fixed: the demands of sinks in the plant or the provision of more resources or a mix of both.

Nutrient Limitation. As Australian soils are generally nutrient poor, the response of Australian terrestrial systems to elevated CO_2 may be correspondingly limited. The evidence, however, is not as clear-cut as might be expected. There is some evidence that the nitrogen cycle may be accelerated somewhat under elevated CO_2 so as to partially remove this nutrient limitation. However, the time scale at which nutrient dynamics interact with elevated CO_2 is also important as longer-term feedbacks can modulate initial responses. Elements other than N are also important for plant metabolism and can thus interact with elevated CO_2 effects. In an Australian context potential limitation by phosphorus is important but there have been fewer elevated CO_2 experiments on interaction with P than with N. Limitation by micro-nutrients has also been observed to be important in a number of experiments but has received even less attention than N or P.

In summary, at a fundamental level, the importance of possible nutrient limitation of growth, even for the most common nutrient - nitrogen, under elevated CO_2 is largely unknown and is still being debated. Basically, it is not known whether the C cycle drives the N cycle, or whether the C cycle is limited by the N cycle, and on what timescales. In reality, the interaction of plant growth with biogeochemical cycling in general operates as a system, with drivers and feedbacks at a number of scales.

4. Scaling Issues

Applying scientific understanding to management and policy issues requires a strong and coherent systems perspective. Therefore, scaling the understanding gained from plant-scale experiments over limited time periods to the level of production systems over longer timeframes is crucial (Figure 4; Medlyn and McMurtrie 2004).

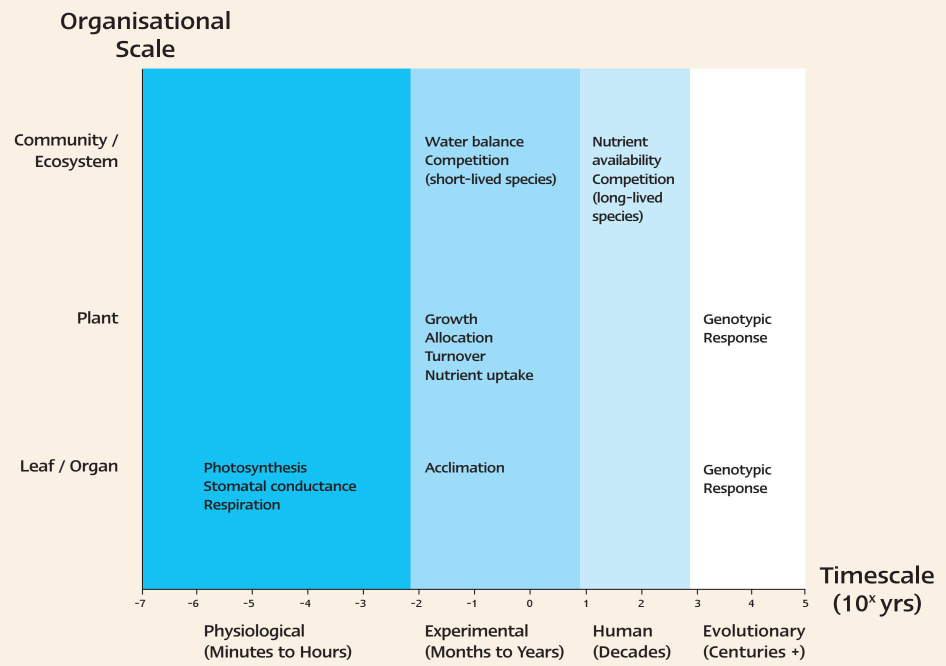


Figure 4 *A summary of timescales on which different processes become important in determining plant response to changes in atmospheric CO_2 concentration, and the organisational scales at which these processes occur (Medlyn and McMurtrie 2004). Note that experiments on the effects of elevated CO_2 on terrestrial ecosystems usually occurs at smaller scales in both time and organisation that those important for policy development. This emphasises the importance of scaling processes. In this figure the term Genotypic Response refers to a gene-based capacity to make adjustments in plant form or function that confers a selection advantage in nature or enhanced productivity under cultivation.*

Consensus. Given the importance of moisture constraints for Australian terrestrial production systems, the degree to which the WUE effect is expressed at larger scales is important. There is agreement that different water balance processes operate at different scales from leaf to tree/plant to stand/ecosystem and so scaling up the WUE effect must be undertaken with care. For a leaf transpiration efficiency is roughly proportional to the CO_2 concentration, but at the whole-plant, stand and landscape levels (for grasslands, at least), WUE must be downscaled somewhat to account for canopy-level water balance feedbacks. The effect does not disappear however, and remains quantitatively significant in most cases.

In scaling from individual plants to whole ecosystems, there is also strong consensus that the observed differential growth responses amongst individual plants in response to elevated CO_2 will lead over time to a change in species composition of the ecosystem. Virtually no species responds to elevated CO_2 in precisely the same way, and there are important differences in response for annual v. perennial, C3 v C4, indeterminant v. determinant. There can even be significant differences amongst genotypes of the same species. This competition effect may be especially important for Australian grazing systems and mixed forests from a long-term perspective.

No Consensus Yet. There are several issues where conflicting data or lack of data prevent consensus:

(i) A particular issue of concern is competition between Australian native grasses and invasive species in grasslands and rangelands. Data is sparse but there is some indication (cf. the Queensland savanna FACE experiment) that invasive, annual grasses outcompete native Australian perennials under elevated CO_2 and very dry conditions. This is an important issue for forage quality and merits further research.

(ii) There are likely to be second-order ecosystem-level effects that are difficult to predict *a priori* but could override the direct, physiological responses of plants to elevated CO_2. An example is the enhanced growth under elevated CO_2 of woody seedlings in savannas, which would allow them to grow more quickly beyond the size at which they are especially vulnerable to fires. This would tend to enhance the woodiness of savannas. This effect remains at the hypothesis stage at present, as do nearly all such proposed second-order ecosystem-level effects.

(iii) There are some lines of evidence (e.g. some tree ring studies) that suggest that the historic increase in atmospheric CO_2 concentration from 280 to 380 ppm has had an impact globally on terrestrial vegetation but none of the evidence is conclusive, given that many other environmental and management factors have also varied over this period. This is an important issue. Lack of conclusive evidence of an historic CO_2 fertilisation effect makes it more difficult to assess in a policy context the potential future significance of increasing atmospheric CO_2 for Australian terrestrial production systems.

Caveats on Scaling CO_2 Experimental Results. Much of our current understanding of the effects of elevated CO_2 on terrestrial ecosystems comes from manipulative experiments. Data from such experiments are also often used to calibrate and test models (see next section). However, it is very important to recognise that there are substantial differences between the experimental conditions under which plants and ecosystems are subjected to elevated CO_2 in experiments and the conditions under which real ecosystems in the field experience increasing atmospheric CO_2. These constitute serious constraints in the scaling of experimental understanding to the real world. Three of the most important of these constraints are:

(i) Virtually all elevated CO_2 experiments apply a step-change in CO_2 concentration to the plants or ecosystem; it is unlikely that plants or ecosystems will respond in the same way to a gradual increase in CO_2 concentration as they do to a step-change. In addition, studying only two CO_2 concentrations (ambient and one level of elevated CO_2) cannot elucidate the shape of the CO_2 response curve between (and beyond) those points.

(ii) Most elevated CO_2 experiments are run for five years or less and thus may not capture longer term effects, especially acclimation phenomena, longer term nutrient dynamics and changes in slow turnover carbon pools.

(iii) Most experiments run in small chambers or FACE (Free-Air Carbon Dioxide Enrichment) plots (1 m^2 to 30 m^2) behave as 'islands' of elevated CO_2 surrounded by ambient CO_2, which does not allow for full atmospheric feedbacks or interactions with herbivores or pollinators.

5. Modelling the CO_2 Fertilisation Effect

Validated models that have demonstrated ability for predicting accurately at the scale needed are the critical tools required to translate understanding of plant and ecosystem response to CO_2 gained from experiments and observations into products useful to the policy and management sectors. Thus, the issue of model reliability is central to application of scientific understanding to policy. Here we focus on the formulation and testing of models in Australian impacts studies and highlight the next steps needed to improve the models.

5.1 Consensus on Modelling Approaches

The approaches to simulating the two first-order physiological effects of elevated CO_2 are generally the same in all models. (i) Photosynthesis is normally simulated mechanistically using modules based on fundamental physiology (usually the so-called 'Farquhar-von Caemmerer-Berry equation'); and (ii) WUE is simulated by many models using a relationship empirically determined from fitting experimental data, although some models now use more process-oriented formulations. Most treatments of WUE normally account for various compensating effects of increasing leaf temperature and increasing leaf area index of the plant/ecosystem.

Most models contain modules, usually based on empirical relationships, that simulate other aspects of ecosystem physiology that are important in determining the effects of elevated CO_2 on biomass or yield. These include nitrogen cycle dynamics (inclusion of phosphorus dynamics is less common), allocation of carbohydrate to various plant organs, decomposition of soil carbon, plant phenological effects and, increasingly, management options.

Overall, a model's structure represents a coherent hypothesis or theory about how a system operates, so testing models is essential for building confidence in their skill to simulate system behaviour. All models used in Australian global change impact studies have, to the best of our knowledge, been carefully tested against the experimental and observational data that is available from around the world. In general, the models have performed well when tested against experimental data; there is usually a good match between modelled and experimentally determined values for particular parameters. In short, 'good practice' has been followed in developing, testing and using models.

Nevertheless, models are still subject to critical constraints. The caveats listed above for elevated CO_2 experiments should be borne in mind here also as data from these experiments are used to develop and test models. In addition, the data available for model testing are often not appropriate for the environmental conditions in Australia for which the model will be used. Models are thus limited to a large extent by the type and reliability of the databases generated through experimentation and observation and by the theory on which they are based or which they express. Model development and testing can also be severely limited by lack of sufficient, long-term observational data, for example, data from CO_2 flux-measuring stations. Partly because of these limitations, models are appropriate and very useful research tools to generate and test hypotheses, a function which is very important for the scientific research community but which presents challenges for their use in policy formulation. The commentary in Appendix 2 gives more detail about the serious challenges to using even well-established crop (wheat) models to draw policy-relevant conclusions about the response of wheat to elevated CO_2.

The challenges and controversy arise when models that have been primarily developed as research tools are later adapted for management and policy studies. There is a long-standing, unresolved debate within the scientific community about whether this is an appropriate approach or not. The fundamental issue lies around the treatment of uncertainties and of poorly known processes in the models. In a research mode, parameterisation of such processes is necessary and important, and the ways in which modellers treat these parameterisations can push the science forward by generating testable hypotheses that challenge experimentalists (just as novel experimental results challenge the modellers). The iterations between modellers and experimentalists is an essential part of the scientific process.

However, the same research models generate knowledge that is often used for developing policy. Here the treatment of uncertainties and poorly known processes must be viewed in a different light. The range of potential uncertainties is often buried within the model architecture and is not fully represented in model outcomes; in addition, the confidence levels attached to the parameterisation of various processes are normally treated in an implicit rather than explicit manner. Modellers are, of course, aware of these limitations, and carefully note that process modules within the models must be tested as rigorously as possible in their own right, in addition to testing the outputs of the model as a whole.

Given these limitations, some scientists argue that research models are not the best tools to use in policy studies, rather that simpler models aimed at directly simulating parameters of interest to the policy and management sectors are more appropriate. These simpler models would treat the uncertainties and confidence limits in a more explicit manner, allowing those developing policy to make judgements on the reliability of the scientific knowledge base in relation to other factors (e.g. economic). On the other hand, others argue that the full complexity of research-oriented models should be brought to bear on policy and management issues as they achieve the most realism. The debate is critical to understanding the use of models in supporting policy development.

5.2 Challenges for Improving Models

Despite the skill currently evident in impact study models, the modelling community recognises the need for continued improvement. An almost universal suggestion from the modelling community is that there needs to be much closer and better interaction between the modellers and the experimental community. More specifically, future elevated CO_2 experiments should be designed in a collaborative way by experimentalists and modellers; the experiments should be designed to a large degree using model results as inputs specifically to test models.

More specifically, the next generation of models simulating the CO_2 fertilisation effect can benefit from improved understanding in the following areas:

- Interaction between CO_2 response and soil nutrient dynamics
- Interactions between low soil moisture content, low nutrient levels and elevated temperature under elevated CO_2 on yield of key crops (e.g. wheat)
- Effects of elevated CO_2 on components of canopy development (initation, unfolding, expansion, final size, etc.)
- Photosynthetic down-regulation under continuous elevated CO_2 (and other feedback processes within the plant itself)
- Change in tissue composition under elevated CO_2
- Carbon allocation
- Fine root dynamics; 'speeding up' of C cycling v. C storage in biomass
- 'Hydraulic architecture', in terms of the response of very tall trees to elevated CO_2

The addition of more complete whole plant/ecosystem physiology in models allows the CO_2 fertilisation effect to be simulated in the context of other changes in the plant/ecosystem environment, a more realistic approach to global change impact studies. Many models can now do this. For example, Figure 5 (Kirschbaum 2004) shows the results of 20-year simulations of the CO_2 fertilisation effect using a tree growth model for four very different sites. The simulations included added water and/or added nitrogen to generate response surfaces for systems of different fertility and water availability. Runs were made for ambient and doubled CO_2 concentration. Each point on the response surface represents the response of the system to doubled CO_2 concentration under contrasing initial conditions (but not to changing water or nutrient conditions). The value of such response surfaces is that they indicate if strong nonlinearities in the system exist, and where potential thresholds of CO_2 responsiveness might occur, given various sets of initial conditions. This knowledge will be important for the newer type of impact study based on enhancing resilience and exploring limits to adaptability (cf. Section 7). The constraints about the use of models as policy tools discussed above and in Appendix 2 apply also to these simulations of more complex system behaviour.

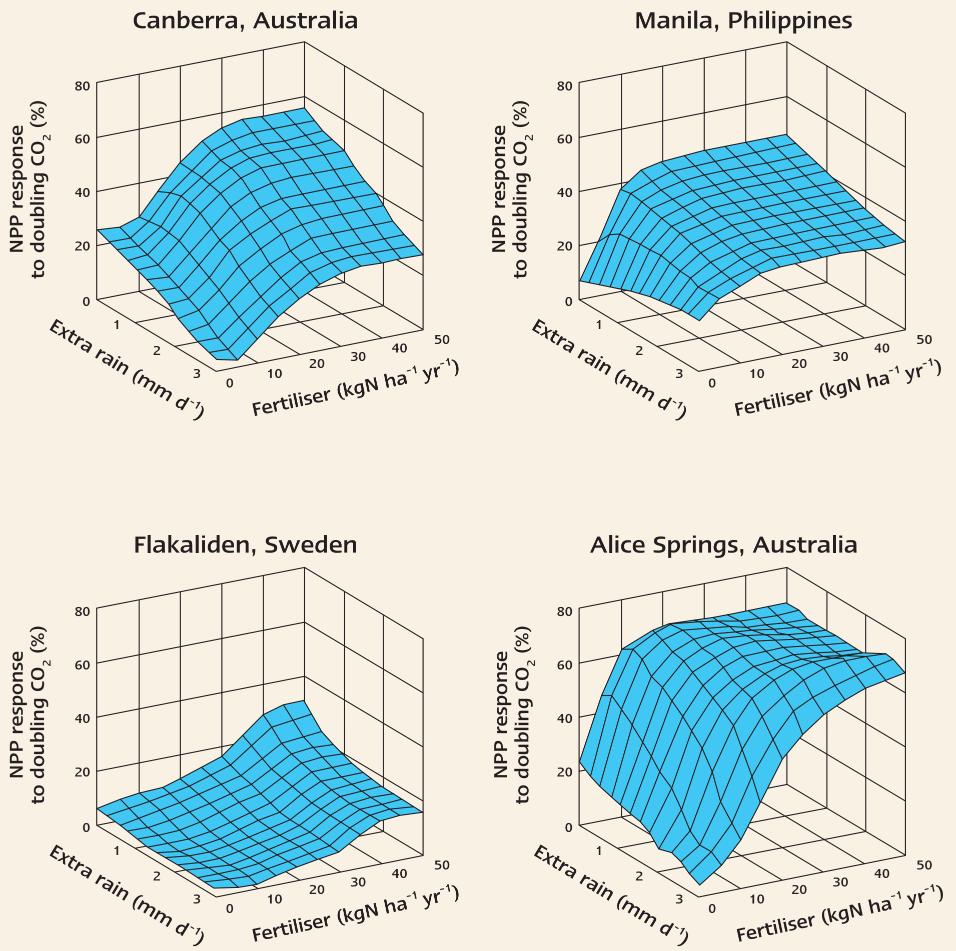


Figure 5 *Response of NPP (Net Primary Productivity) to doubling CO_2 concentration under different base conditions, simulated by a tree growth model. Four climatically very different sites were used to provide the base climatic conditions, and at each site, simulations were run over a range of water and fertiliser additions (Kirschbaum 2004).*

6. Placing the CO_2 Fertilisation Effect in a Climate Change Context

The intersection of the CO_2 fertilisation effect with climate change is especially important for Australia, with its highly variable climate and generally semi-arid or arid conditions. Australian terrestrial production systems have evolved in a climate where extreme weather and climate events, especially related to the hydrological cycle, are relatively common (in comparison with most northern hemisphere production systems) and thus where the ***pattern*** (magnitude and frequency) of extremes (of 'good years' and 'bad years') is important for the long-term viability of the production enterprises. Thus, any significant change in the pattern of weather and climate extremes, particularly any change in moisture regime, as a result of climate change is of overriding importance for the future of Australian plant-based industries.

The issue of potential changes to the current pattern of climatic extremes in Australia is crucial. Climatic extremes can change because of changes in the mean climate, changes in climate variability or both. Globally, there is a growing body of evidence showing with some confidence that climatic extremes are already changing. These include higher maximum and higher minimum temperatures over nearly all land areas, increased heat index over land areas, more intense precipitation events and increased summer continental drying and risk of drought in a few areas. These trends are projected with a high degree of confidence to continue through this century.

In terms of Australia's weather and climate, the frequency of hot days has increased and the frequency of cold/frost days has decreased; heavy rainfall events have increased, especially since the 1960s; droughts have become more frequent, persistent and intense during the last 20–30 years; and there has been an increase in the frequency of intense cyclones and an increase in the development of severe east coast low pressure systems in the last 20 years. In the southwest corner of Western Australia, there has been a 20% decrease in winter rainfall since the mid-1970s and a decrease in winter rainfall more generally across southern Australia. Clearly the probability of continuing change in weather and climate extremes over Australia must be considered when analysing global change impacts on Australian production systems.

In comparing changes in the pattern of weather and climate extremes to the CO_2 fertilisation effect, it is important to note the different timescales on which they operate. Obviously the year-to-year pattern of weather and climate extremes is important for annual crops and for the pastoral industry at short timescales and ***changes*** to the pattern of extremes can be important at longer timescales. The CO_2 fertilisation effect, on the other hand, builds slowly over time and only becomes significant in comparison to weather and climate effects at multi-decadal or century timescales.

Despite the apparent insignificance of the CO_2 fertilisation effect at short timescales compared to weather and climate effects, the ***interaction*** between CO_2 and climate effects is potentially important for Australian production systems on shorter timescales. Figure 2 provides a good conceptual framework for analysing in more detail the interaction of CO_2 with moisture regime for annual crops like wheat. The following points are important:

- If the wheat system experiences a moister climate, both the CO_2 and climatic effects operate in the same direction to increase the productivity of the system. This would be represented by a shift of the system to the right in Figure 2.

- In the driest years for which any yield occurs, the WUE effect has its greatest relative effect and so CO_2 fertilisation can be quantitatively important for the system, perhaps even to the point of counteracting most or all of the loss of productivity due to reduced moisture, depending on the degree of drying.
- In a year of drought that is too severe for any grain yield (the extreme left of Figure 2, where the low moisture threshold is exceeded), the wheat system has no response to elevated CO_2 because the system is no longer viable and yields nothing. However, there is a 'window' of dry conditions in which elevated CO_2 allows some yield when none would have occurred without elevated CO_2.

The above analysis may also apply to grazing systems based on perennial grasses, as suggested by the results of the Queensland FACE experiment for a year of moderate drying compared to a year of severe drought (cf. Section 3 and Figure 3). However, the increased complexity of a grazing system compared to an annual crop (e.g. the importance of plant-plant interactions and of herbivory) will complicate the analysis for grazing systems.

In summary, this analysis emphasises the importance of the dry end of Figure 2 in terms of global change impacts on Australia's cropping and grazing systems. The figure highlights the balance between (i) the ameliorating effects of elevated CO_2 (reduction in the negative effects on yield of moderately dry years, and possible shift towards drier conditions in the location of the threshold between viability and non-viability) and (ii) the damaging effects of extremely dry years (where yield drops to or near zero). Thus, in an Australian context, the coupling of the CO_2 fertilisation effect with the frequency and severity of droughts, and sequences of droughts (e.g. multi-year droughts), will likely be the determining biophysical factors for the viability of Australia's cropping systems, and probably grazing systems, in future.

7. Implications of the CO_2 Fertilisation Effect for Industry

The following are the key features of the science of CO_2 fertilisation that are important for policy in an Australian context for any of the major plant-based industries:

- Of all the inhabited continents, the relative CO_2 fertilisation effect is likely to be most important for Australia, given the overriding control of the moisture regime over primary productivity and the fact that the WUE effect is perhaps the most robust feature of CO_2 fertilisation.
- There is a range of moisture conditions, bounded at both ends, where the CO_2 effect on WUE is most important. Beyond this range, the effect diminishes in relative importance (at the wet end) or does not play a signficant role (at the very dry end when the threshold of system viability is crossed).
- Assuming thresholds in moisture regime are not crossed (cf. Figure 2), CO_2 may provide an important buffering capacity by dampening the reduction in yield in dry years, which is important economically, and therefore reduces the risk of large losses. However, elevated CO_2 effects will not completely counteract the negative effects of severe droughts (i.e. bring the yield back up to levels found under adequate rainfall).
- Given the interaction between the CO_2-driven WUE effect and moisture regime, any projections of the fertilisation effect for Australian systems should not be undertaken in isolation from an analysis of climate change, particularly changes in extreme events and sequences of extreme events (e.g. droughts). Conversely, projections of climate change impacts should not be conducted in isolation from the effects of elevated CO_2, in particular on WUE.
- It is more difficult to project impacts of global change, including the CO_2 fertilisation effect, on more complex production systems based on perennial plants (grazing, forestry) compared to simpler agricultural monocultures based on annual plants (e.g. wheat).
- A general caution: there are still large uncertainties in our understanding and simulation of many aspects of CO_2 physiology, especially allocation of additional carbon within ecosystems, interactions with nutrient cycles and long-term effects. There is even more uncertainty in projections of future climate change. Thus, any analyses of future effects of global change on production systems should ***NOT*** be viewed as 'predictions' but rather as case studies of one or a few of many possible futures. Although some features of climate can be projected with more certainty than others, the range of possible futures and the probabilities of their actually occurring, especially at particular locations or in particular regions, cannot be known with a reasonable degree of certainty.
- The above point implies that policy/management approaches to impacts/adaptation should place more emphasis on: (i) risk assessment of a wide range of outcomes, including low-probability/high impact events, and (ii) enhancing the resilience of production systems to a wide range of possible future biophysical (and socio-economic) changes instead of relying on one or a few scenario-based studies to generate an adaptation strategy.

7.1. Cropping Systems: Wheat

The global change impacts on wheat are more well-studied and understood than most terrestrial production systems as wheat is one of the most important cereal crops globally. However, there are significant constraints to translating the international experimental results on elevated CO_2 effects on wheat to Australian conditions. For example, the wheat FACE experiment at Maricopa AZ, USA (an average 16% increase in yield with an increase from ambient CO_2 to 550 ppm in CO_2), was carried out under both irrigated and fertilised conditions (e.g. 350kgN. ha^{-1}) whereas about 90% of Australian wheat is grown under non-irrigated conditions and nearly all of it at much lower levels of fertiliser than used in the FACE experiment. In effect, most research on global change impacts on wheat has been carried out at the right end of Figure 2 whereas the dry end of the range where wheat is grown, and the threshold between viability and non-viability, are the important features of Figure 2 in terms of global change impacts on the Australian wheat industry. Given this dearth of experimentally based information for Australian conditions, model-based analyses are the only way to project global change impacts on the Australian wheat industry.

Such an analysis of the potential impacts of global change at 2030 and 2070 on the industry was carried out recently (Howden and Jones 2001). To the best of our knowledge, this is one of the most thorough such analyses carried out anywhere in the world on a cropping system, and includes an important set of detailed analyses not often done – probabilities of extreme outcomes as well as mean values, regional differences as well as national averages, estimation of the effects of adaptation strategies, and extension of productivity change estimates to economic effects, including export value.

The key findings of the report are summarised in Tables 1 and 2. Briefly, they are: (i) in the absence of any adaptive management by the grower, only very small increases in mean production by 2030 and 2070 (3% and 1.8%, respectively), but with a significant probability of lowered production; (ii) marked regional differences in production are likely to occur; (iii) likely fall in value of wheat exports due to mainly to increased domestic consumption; and (iv) enhanced production if growers respond with appropriate adaptation strategies (up to 8% increase in mean production).

Table 1. *Category of impact, sites in each category and summary of impacts for Australian wheat yield in the year 2070 (Howden and Jones 2001).*

Category	Sites	Impacts
Largely negative impacts	Wongan Hills Geraldton Katanning	Mean regional productivity reduced by 3 to 15%, with a 52 to 90% chance of productivity being below current levels. Mean value of production reduced by $13 M to $104 M per year with a 52 to 97% chance of being below current levels.
Some risk of negative impacts but larger probability of positive impacts	Minnipa Horsham	Mean regional productivity increased by about 6% but with an 18-25% chance of being below current levels. Mean value of production increased by $10 M to $15 M per year with a 25 to 27% chance of being below current levels.
Generally beneficial impacts but small risk of negative impacts	Moree Dubbo Dalby	Mean regional productivity increased by about 12% but with a 5-14% chance of being below current levels. Mean value of production increased by $15 M to $24 M per year with a 13 to 14% chance of being below current levels.
Likelihood of largely beneficial impacts	Emerald Wagga	Mean regional productivity increased by about 9% to 13% but with a 0-8% chance of being below current levels. Mean value of production increased by $13 M to $24 M per year with a 1 to 4% chance of being below current levels.

Table 2 *Effect of climate change and CO_2 increase for the years 2030 and 2070 on percent change in average production (currently 21.7 Mt), value of production (currently $4.2 billion) and value of exports (currently $3.3 billion) assuming either current management practices or adapted management practices. The values in parentheses are the maximum and minimum values. These can be quite different from the average as they are the extreme 'tail' of the likely outcomes (Howden and Jones 2001).*

		Year 2030	Year 2070
Yield	- current	3.1 (-9.1 to 10.1)	1.8 (-33.7 to 19.8)
	- adapted	8.0 (-2.0 to 16.8)	8.5 (-32.8 to 29.0)
Value of production	- current	0.4 (-7.4 to 4.0)	-0.8 (-29.8 to 9.1)
	- adapted	1.6 (-4.5 to 6.7)	1.6 (-27.5 to 13.7)
Value of exports	- current	-2.5 (-13.7 to 2.9)	-4.8 (-44.0 to 9.8)
	- adapted	0.0 (-8.8 to 7.3)	-0.6 (-41.0 to 16.5)

The interpretation of this and other more complex impact studies of this type must be undertaken with care as they include a range of outcomes at various levels of probability. On the surface, it could be concluded from the study that global change is unlikely to present a fundamental challenge (nor an opportunity) to the Australian wheat industry, especially because technological, management and socio-economic changes to the industry by 2030 and 2070 will almost surely be much greater than the very modest changes (3% and 1.8%) in production projected as a result of global change. On the other hand, it could also be concluded that there will be a limited overall potential benefit from global change (ca. 10%) but that the potential negative effects are much greater (ca. 30%). Thus, given that the probabilities of positive and negative overall effects are roughly equal, might well conclude on the basis of a risk assessment that there is serious cause for concern about the future of the Australian wheat industry under global change.

As noted in Section 6, the intersection between the CO_2 fertilisation effect and climate change is important for Australian plant-based industries and this is reflected in the wheat study of Howden and Jones (2001). Although the study considers the entire range of extremes projected by the nine GCM (General Circulation Models) used to simulate future climate in the study, the relatively small changes in ***mean*** yields projected in the study are probably due to the fact that the statistical modes of reductions in rainfall and increases in temperature for the set of GCMs are quite modest. Modest reductions in rainfall may, for many locations, imply that the wheat system is still within the dry end of its operating range (cf. Figure 2), where the relative effects of elevated CO_2 are the greatest.

The uncertainties associated with global change impact studies must also be acknowledged. The limitations of and uncertainties associated with our understanding of the CO_2 fertilisation effect, both in terms of experiments and models, have been outlined earlier in this report (cf. Section 5 and Appendix 2). At least two other types of uncertainty are also important. The first of these deals with other system-level effects that can impact on the future viability of Australian plant based industries. Two examples follow.

- Nutrient (N and P) limitation can be compensated for in intensively managed systems but this may require additional costs to the grower to allow full expression of the CO_2 fertilisation effect.
- The incidence of pests and diseases will almost surely change under global change, although the direction and magnitude of change are hard to project. Nevertheless, there is a high probability that specific management strategies and possibly new technologies will be required to combat pest/disease problems under global change. These would also likely incur additional cost to the grower.

Second, the uncertainties associated with projections of future climate are at least as large, and probably larger, than those associated with the CO_2 fertilisation effect. Uncertainties associated with climate projections include the following:

- Fundamental changes to the projection of climate change globally occur as our understanding of the factors affecting climate improves and their inclusion in GCMs is implemented. Examples include the interactive carbon cycle, the consideration of aersols (beyond sulphate) and more general aspects of atmospheric chemistry, and the inclusion of interactive and dynamic terrestrial vegetation.

- Extreme events and sequences of events that are already occurring are beyond the range of climate extremes projected for this decade and for much of this century. The four-year drought in eastern Australia is an example of such an event, and attribution studies link the event to persistent high sea surface temperatures in the Indian and western Pacific oceans, which are in turn linked in part to enhanced greenhouse gas forcing. Similarly, the extreme drought experienced in North Queensland in 2002/03 (cf. Year 2 of the Queensland savanna FACE experiment) lies outside the range of projections of rainfall change out to 2070 at least so would not be captured in impact studies.
- Abrupt changes are very difficult to simulate. None of the current generation of GCMs can simulate the abrupt changes seen in the ice core records and other proxy records from the past. Should the most well-known of these - the shutdown of the North Atlantic thermohaline circulation - actually occur during the second half of this century, it would almost surely lead to much hotter and perhaps drier conditions in Australia, well beyond those now projected for 2070.

In summary, the type of multi-faceted impact study carried out by Howden and Jones (2001) for the Australian wheat industry points the way towards a new generation of impact studies. The challenge is to develop comprehensive studies that complement climate scenario-driven approaches with (i) risk analyses based on low probability but potentially devastating future climate events/projections, including extremes beyond those encompassed by GCM-generated scenarios but seen in current extreme events or in records of the past; and (ii) studies focusing on the resilience and adaptability of the production system itself to a broad range of potential changes in its biophysical and socio-economic environment.

7.2. Rangelands Grazing

A detailed study of global change impacts on Queenland's grazing lands was carried out by Hall et al. (1998) and is indicative of the type of issues that arise more broadly in Australian rangelands. The study adopted a systems approach based on the flow of plant dry matter and its utilisation by animals, through to estimates of 'safe' carrying capacity. Global change scenarios consisted of doubling CO_2, increasing temperature, and varying rainfall by + or -10% over present values. The aggregated results for Queensland as a whole resulted in an increase in 'safe' carrying capacity of +3 to +45% depending on location and particular rainfall scenario. An interesting result was the importance of increasing CO_2 in mitigating or amplifying the effects of changing temperature and rainfall.

Three aspects of elevated CO_2 effects are especially important for Australian rangelands:

- The nutritional quality of Australian forage tends to be low so the impact of elevated CO_2 on it is a critical issue. Interestingly, the two major effects of elevated CO_2 on nutritional quality act in opposite directions so the overall effect is difficult to determine. It is likely that the N:C ratio in leaves, already relatively low, will decrease further under elevated CO_2. However, the concentration of soluble carbohydrates in the leaves goes up with increasing CO_2, and this is particularly important for the digestability of the forage and hence the usage of forage nitrogen.
- In the longer term the effect of elevated CO_2 on competition between plants and thus on the composition of the rangeland will be important. For example, the possible increased potential for annual, 'weedy' grasses to invade perennials under increasing CO_2 would lead to a significant shift in ecosystem composition/structure.

- The effect of elevated CO_2 in stimulating the early growth of woody species in savannas (cf. Section 4) may contribute, along with grazing pressure and fire suppression, to the so-called woody weed/vegetation thickening phenomenon.

7.3. Forestry and Horticultural Trees

Compared to cropping and grazing systems, less is known about the effects of elevated CO_2 on Australian forests, either native or plantation, or on other commerically-important woody plants such as fruit trees or grape vines. In addition, there is the generic problem of interpreting short-term experiments for a plant with a much longer lifetime. The observational evidence (cf. Appendix 1) is not yet conclusive but suggests that elevated CO_2 effects decrease as trees age so that the long-term effects of elevated CO_2 on forests can be overestimated if they are based on extrapolation of experimental results on seedlings or young trees (see also Figure 1). However, for short rotation plantation forests, the experimental evidence is more relevant and it is likely that fast-growing saplings and young trees will respond to elevated CO_2 with enhanced net primary production.

There is, however, a particular problem for Australia: there is a dearth of information on the effects of elevated CO_2 on Australian trees, or on any trees in semi-arid or water-limited conditions. Thus, modelling approaches using models which have, by necessity, been tested primarily against experimental data from other continents are the only way at present to estimate CO_2 effects on Australian forests.

Several other issues are potentially important for Australian forests:

- There is mixed evidence on the effects of elevated CO_2 on horticultural trees, some showing an acceleration of development (shorter time to maturity) rather than a sustained increase in biomass or yield but others showing sustained increases in biomass and yield over long time periods (ca. 15 years).
- Ontogenetic factors are especially important for long-lived woody species but are not well understood.
- There may be completely unexpected effects, such as the experimental evidence that elevated CO_2 pre-disposes young snow gum trees to frost damage.

The results presented above for all three systems (wheat, grazing, trees) need to be treated with due caution given the unavoidable constraints in using research models for policy applications (cf. Section 5 and Appendix 2).

8. Future Research Challenges

The areas where there is not yet consensus in our understanding of the CO_2 fertilisation effect provides a good basis for examining future research challenges. We outline six such challenges below:

- Synthesis of research on elevated CO_2 from an Australian ***policy and management perspective***. This study showed that there is considerable work on Australian systems that, although usually incorporated in scientific reviews, is not widely known in the policy or resource management communities. A more thorough 'desk study' of what has already been done and what is known with some confidence will provide a better underpinning for future policy development.
- Additional experimental work on the effects of elevated CO_2 on Australian systems. In terms of supporting policy development, two such systems are important: (i) an *in situ* wheat crop grown under normal and adapted management conditions, with emphasis on the dry end of the moisture regime, no water additions, and low fertiliser inputs; and (ii) whole tree studies in semi-arid or water-limited systems. Note that such experiments should be designed more closely with the modelling community to ensure that models are tested directly by the experiments and to improve experimental focus. Furthermore, long term, *in situ* studies on perennial systems are exceptionally valuable, as one of our biggest gaps is the scarcity of long-term data on CO_2 effects.
- Study of multiple, interacting factors on production systems. At present this is best done through modelling approaches, but not single- or double-factor scenario-driven approaches. The use of response surfaces for the impacted system (cf. Figure 5) may be useful to identify the existence and location of thresholds or 'tipping points in the system.
- Analysis of extreme events. For use in impact/adaptation studies, more emphasis should be placed in examining climate scenarios for outliers and extreme events rather than changes in means, and in improving projections of such extreme events. In addition, emphasis should be placed on analysis of extreme events that are occurring now. Impact studies should include an analysis of how extreme events or sequences of extreme events will impact production systems, and how they will interact with elevated CO_2 effects (e.g. the extent to which elevated CO_2 can ameliorate drought conditions).
- Adaptability of Australian production systems. The Australian agricultural sector has already shown considerable adaptability to current modes of climate variability and to extremes. Some key questions are: What are the limits to adaptability? Can production systems be adapted to maximise the benefits of elevated CO_2?
- Pests/disease dynamics under global change. Although much good work has been done already, this is still an area where surprises, possibly severe surprises, are not only possible but probably should be expected. The effect of elevated CO_2 on leaf nutrition quality and hence on pest dynamics was often cited in the interviews in this project as an important issue, but there is no consensus on the magnitude, or even the direction, of the effects.

9. Interpreting Science for Policy: Some Concluding Remarks

With regard to policy, the fundamental questions that this report raises about the effects of elevated CO_2 on Australian plant-based industries are: (i) How robust is the knowledge base on the effects of elevated CO_2? (ii) With what level of confidence can we apply to policy development our current understanding of elevated CO_2 effects?

(i) The knowledge base on the effects of elevated CO_2 is very robust with regard to fundamental physiological effects at leaf level (stimulation of instantaneous photosynthetic rate in C_3 plants and increase in transpiration efficiency for both C_3 and C_4 plants); moderately robust when scaled up to monoculture cropping systems (e.g. wheat), perennial pasture/rangelands systems and and short-rotation plantation forests under many environmental conditions; but not very robust when scaled up to forests over long timescales. However, an important limitation to this assessment is the relative lack of experimentation under Australian environmental conditions, which reduces somewhat the robustness of the international knowledge base when applied to Australian plant-based industries.

(ii) Based on a scale of 'low', 'medium' or 'high', our confidence in the reliability of the knowledge base on elevated CO_2 effects ***on their own*** for policy development would probably be 'medium' for cropping and grazing systems and 'low' for the forestry industry (apart from short-rotation plantations). However, as noted many times in this report, the effects of elevated CO_2 cannot be disentangled from the effects of climate change (and indeed from other environmental factors), and these bring their own sets of considerable uncertainties and gaps in understanding. Thus, when the impacts of ***global change*** (in contrast to elevated CO_2 on its own) on Australian plant-based industries are considered, our confidence in the reliability of the knowledge base must be in the 'low' category.

In addition to this overall message, we emphasise three additional messages that have come out of this project and that we believe are important for the development of policy:

- Current scientific understanding of the importance of the CO_2 fertilisation effect under Australian conditions suggests a shift in perception of the situation from:

"The effect is either important or not important, and hence will tip global change impacts from an overall negative to an overall positive response"

to:

"Under what conditions is the CO_2 fertilisation effect likely to be important and how can management be adapted to take best advantage of it?"

- Shifts in patterns of climate and weather extremes present more significant challenges to adaptation for Australian plant-based industries than do slow changes in climatic means. Studies of impacts on and adaptation of Australian plant-based industries to global change should therefore (i) place more emphasis on risk analysis based on the probability of extreme events rather than adaptation/management strategies built on scenarios based on changes in mean values; and (ii) analyse the impacts on production systems of the extreme events (e.g. severe and/or extended droughts) being experienced now; (iii) assess the interaction of elevated CO_2 effects with climate impacts to determine those situations where CO_2 can have a significant ameliorating effect on deleterious climate change, especially with management adaptations.
- The most robust adaptation strategy is clearly to build as much resilience and adaptability into a production system towards a wide range of possible changes, including extremes of climate and weather, rather than to plan for a specific scenario. Some critical questions nevertheless remain: What are the limits of adaptability for key Australian plant-based industries, even taking into account possible benefits from the CO_2 fertilisation effect and improved technology and management? What is the probability that these limits might be exceeded by future global change? Are Australian primary industries willing to take these risks?

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Appendices

Appendix 1: The Global Knowledge Base

This mini-review draws from the extensive literature on manipulative experiments that study the effects of increased atmospheric CO_2 concentration on wheat, grasslands and forests. Elevated or increased atmospheric CO_2 refers to 500 ppm unless otherwise indicated.

The main findings of this review are as follows. Experimental evidence shows that rising CO_2 concentration will increase wheat yields, provided ample quantities of nutrients and water are available. In semi-arid regions, increased water use efficiency due to elevated CO_2 could partially alleviate effects of water stress on yield. Climate variability and extreme events are likely to have a more profound effect on grain yields than changes in mean climate. For grasslands, elevated CO_2 may increase NPP (Net Primary Productivity) on average at around 15%. Systems in cold environments or with intrinsic low soil fertility may experience no gains. Forest NPP is also likely to benefit from the CO_2 fertilization effect but contrasting evidence points towards either a higher or a much more modest increased NPP compared to that of crops and grasslands.

More detailed descriptions of those aspects of current international knowledge base of particular relevance for Australian systems are given below.

Wheat

Agricultural yield. Wheat shows consistent increases in grain yield at elevated CO_2 with ample availability of water and nutrients and Australian research has contributed significantly to this conclusion. Average increase for FACE is 16% (1996 and 1997 Arizona FACE; Pinter *et al.* 1996, 2002), and around 20% for 113 chamber experiments (31% increased at 700 ppm of CO_2, Amthor 2001).

There are a number of site specific conditions that modulate the elevated CO_2 response and that remain not fully understood. This was clearly shown by results on yield increases from 5% to 121% in response to 700 ppm CO_2 concentration in 19 experiments conducted in a European network. All sites used similar open top chambers, water and fertilisation treatments, and Minaret as wheat variety (Jager *et al.* 1999).

Interactions with water availability. Based on fundamental physiological understanding, a well established hypothesis indicates that under elevated CO_2 but with water limiting conditions the ***absolute*** yield would decrease but the ***relative*** (per cent) effect of elevated CO_2 on yield would be greater due to increased water use efficiency. This hypothesis has been widely supported by experiments with ample nutrient supply (for wheat: Kimball 1983; Cure 1985, 1986). FACE experiments show increased wheat yield by 16% at ample water and N, and by 23% at low water (Pinter *et al.* 1997, 2002).

Interactions with nutrient availability. Effects of elevated CO_2 on wheat yield with low supply of nutrients result in smaller increased yields than when ample nutrients are available. Some experiments report no yield gains or decreased yields in such low nutrient conditions (references in Amthor 2001). FACE experiments show increased wheat yield by 16% at ample water and N, but only by 8% at low N (Kimball 2002). It has been suggested that readily available nutrients may be used up by the vegetative growth and become more limited to supply the needs of reproductive development (Mitchell *et al.* 1993) in a similar way as for water-limited conditions.

Interactions with warming. Generally, the increase in atmospheric CO_2 concentration and the accompanying temperature rise act in opposite directions. While CO_2 fertilisation increases growth rate and water use efficiency, higher temperature increases the development rate and shortens growth duration in temperate and dry climatic regions. Thus, the net result will be heavily dependent on the water availability and optimal temperatures versus the magnitude of temperature change.

The experimental evidence for elevated CO_2 and warming interactions is limited, but a review of 17 experiments with wheat reveals some general trends (Amthor 2001). Fifteen of those experiments show increased yield due to elevated CO_2 (without warming). Sixteen of the experiments show reduced yield due to warming (without elevated CO_2). The combination of both elevated CO_2 and warming show a much more variable response (as expected) with smaller yields in 11 experiments and greater yields in six experiments. Overall, the combined effect of elevated CO_2 and warming had a negative, nill or small positive effect effect on yield depending on how much warming and how much CO_2 increase was involved.

Yield quality. Although total biomass or crop yield may increase under elevated CO_2, crop quality or grain composition may change. Non-legume crops often have lower N content unless they receive additional fertiliser, and some grains produced under elevated CO_2 had lower % protein content than those grown at ambient CO_2 (Thompson and Woodward 1994, Rogers *et al.* 1998, Pleijel *et al.* 1999, 2000, Fangmeier *et al.* 1996b and references from Amthor 2001).

Grasslands and Forests

Net Primary Productivity. Net primary productivity (NPP) of 16 sites representing bogs, grasslands, temperate forests, and desert increased by 12% for an equivalent 550 ppm CO_2 concentration (Nowak *et al.* 2004a). The data mostly represent elevated CO_2 effects without additions of extra water or nutrient. Forest had the highest NPP increase (about 20%) followed by bogs, and grasslands (9%). Aboveground primary productivity (APP) of grasslands increased by 19% at elevated CO_2. Earlier syntheses of grassland studies using open top chambers showed a lower 17% (Campbell and Stafford-Smith 2000) and 15% (Mooney *et al.* 1999) increase of APP at 700 ppm CO_2; some grasslands showed no aboveground biomass responses to elevated CO_2 (Mooney *et al.* 1999).

Interactions with water availability. As indicated above, an early hypothesis postulated that elevated CO_2 effects on NPP would increase as water availability decreases. However, from the review of Nowak *et al.*, only APP in grasslands shows this behaviour, which may be particularly important for grazing systems in semi-arid regions. This is consistent with results from open top chamber experiments, except for those cases where extreme dry years were reported or low N levels were present in soils and plant tissue (Le Cain *et al.* 2003; Morgan *et al.* 2004; Owensby *et al.* 1999). In the Mojave Desert (USA), the wetter the year, the higher the absolute and relative increase in APP under elevated CO_2. However, below a threshold of precipitation of around 150-250 mm yr^{-1}, APP is unaffected by elevated CO_2 (Nowak *et al.* 2004b).

Interactions with nutrient availability. Additions of moderate to high quantities of nutrients (mostly nitrogen) result quite consistently in increased elevated CO_2 effects on the NPP of deserts, grasslands, and trees/forests (Curtis and Wang, 1998; Wand *et al.* 1999; Nowak *et al.* 2004a). More interestingly, a few grasslands with intrinsic low soil fertility show little or no response to elevated CO_2, and they responded favourably when nitrogen was added (references in Mooney *et al.* 1999, and Nowak *et al.* 2004a). Hungate *et al.* (2003) demonstrated that all possible N sources could not generate all N required by four of the six terrestrial models used in the IPCC-TAR CO_2-climate simulations, indicating a likely global N limitation to the maximum benefit of CO_2 fertilisation.

Interactions with warming. The combined effect of warming and elevated CO_2 is more likely to yield an overall global positive effect of NPP for moderate increases in temperature (< 2°C). This case is modestly supported by an experiment with *Acer sps.* growing in open top chambers (Norby *et al.* 2004).

Scaling in space and time. ***Space.*** It is largely accepted that a dominant mechanism by which productivity may increase under elevated CO_2 is due to reduced stomatal conductance and hence increased water use efficiency. The effect has been clearly shown for grasslands and crops, and less clearly shown for forests. Efforts to scale up water relations under elevated CO_2 to landscape and regional scales show that increased soil water may not be realised if reduced plant transpiration leads to a drier and warmer atmosphere, which in turn would enhance evaporative losses (Körner, in preparation; Morgan *et al.* 2004).

These atmospheric feedbacks cannot be dealt with in chamber and FACE experiments because the small dimensions of the plots do not allow the coupling between vegetation and the atmospheric boundary layer. Elevated CO_2 effects on air temperature and moisture may be small in semi-arid regions like Australia.

Time. Experiments with fast growing seedlings, saplings and young trees (most commonly used in manipulative experiments to gain insights on forest behaviour at elevated CO_2) show a consistent enhancement of NPP from a few percent to 25% when grown at 550 ppm CO_2. However, data from these experiments cannot be directly scaled up to reproduce the behaviour of mature forests and long-term CO_2 fertilisation effects.

Some studies, however, give insights into the type of CO_2 responses that mature and close-canopy forests will experience. The lines of evidence are (i) the Duke Prototype FACE in which increased growth of *Pinus taeda* due to elevated CO_2 disappeared after three years because of nutrient limitation (Oren *et al.* 2000); (ii) mature temperate forests in Switzerland where CO_2 fumigation of canopies showed increased growth during the first year of exposure to elevated CO_2 but the effect became smaller in subsequent years (Körner, personal communication), and (iii) FACE in the Swiss tree line with 27 year old trees of *Pinus uncinate* and *Larix decidua* show that CO_2 -growth enhancing effects disappeared by the third year of CO_2 exposure (Handa *et al.* 2004, in preparation).

Although these results need to be interpreted as carefully as those from studies with young trees, they support a view that the overall effects of elevated CO_2 in forests is overestimated (when based solely on the current bulk of experimentation with young trees). The mechanism behind this small or no sensitivity to elevated CO_2 is not always clear but nutrient limitation could be a possibility. Other evidence also points out that the CO_2 fertilisation effect primarily increases growth rate so that trees grow faster and mature earlier. A faster turnover time does not mean an increase mean carbon storage in biomass (Körner 2003, Körner, in preparation).

Appendix 2: Evaluation of the Use of Three Well Established Wheat Productivity Simulation Models to Draw Conclusions about Wheat Response to Elevated CO_2 Concentration.

Roger Gifford[1] and Mark Howden[2]

[1]CSIRO Plant Industry and [2]CSIRO Sustainable Ecosystems

The following commentary was prompted by discussion at the project workshop about the use of models to inform policy, focusing on the example of wheat productivity under elevated CO_2. The following specific assertions were the subject of discussion, and their clarification is aided by the commentary that follows:

1) *Non-validated, inaccurate models can be a serious impediment to sound policy development.*

2) *Most simulation models of crop/ecosystem systems have not been validated and may never be able to be validated.*

3) *Those that have, such as high profile wheat production and NPP models, have been shown to be highly ineffective at prediction.*

The authors agree that there is danger in inexpert application of agro-ecological and productivity models and to the following evaluation of the above points.

1) Non-validated, inaccurate models can be a serious impediment to sound policy development.

The use of complex or complicated computer models, the workings of which cannot be evaluated by a user for lack of time and expertise, poses special risks to inexperienced users as it may provide a sense of unjustified verisimilitude and unchallengeable authority. Clearly, it is important that models be used only for those systems for which they have been designed and for those variables and domains of validation for which they have been tested with independent data and found to be effective. There is a need to inform potential users in policy domains that complicated models can not be completely validated – they are in effect hypotheses about how a system works and should be viewed as such. In each new situation in which they are applied we can evaluate whether or not the data are consistent with the hypothesis. Over time they can build up confidence in model performance in a defined domain. Model setup remains critical however – garbage in means garbage out. Consequently, there will be a need for continuing professional input from scientists experienced with both more empirical data as well as modelling capabilities. There is risk of invalid conclusion when a user, inexpert with the model, either extrapolates its domain of application too widely, or where a small subroutine or relationship is inserted to test a particular idea without the implications of this model change being fully considered or tested.

2) Most simulation models of crop/ecosystem systems have not been validated and may never be able to be validated.

Validation of entire agro-ecosystem or ecosystem models is generally not possible just as validation of econometric and future climate models is impossible (for many of the reasons why such models are constructed in the first place). However, it is possible to validate components of the models *within defined domains*. If the view adopted and fully understood by policy makers, and extended to their clients, is that models are hypotheses, then many of the contentious issues relating to the use of the models will be reduced.

There are other points about valid application of models. Provided that the model has adequate descriptions of the key processes operating, then re-application to new situations should require re-parameterisation – not calibration/tuning. There can also be uncertainty in the measured (or observed) factors – not all the uncertainty stems from the models. There is also skill required in using models effectively – another possible source of uncertainty in some validation studies.

There is a need for users of modelled information to be better informed about the limitations and benefits of the use of modelled data. This ranges from 1) ensuring that the people who run models 'off-the-shelf' are adequately parameterising the model and constructing modelling experiments appropriately, 2) advisers who understand the specific way in which results were generated and who can synthesise these results but maintain the necessary caveats and 3) better informed users who are able to understand and appreciate the implications of both the results and caveats

3) Those (models) that have, such as high profile wheat production and NPP models, have been shown to be highly ineffective at prediction.

This point refers to use of the high profile wheat production models that engendered Gifford's statement at the project workshop and to net primary production models which have recently been reviewed for their output for long term average NPP for the Australian continent.

The high profile wheat models had been validated in certain domains in peer reviewed journals, but when applied to British historic wheat yields failed completely (Landau *et al.* 1999). The originators of those models in their published rejoinder/commentary (Jamieson *et al.* 1999) concluded with the explanation "*that direct crop physiological responses to weather are not the major cause of yield variation in British wheat crops.*" Thus the application of the models to British wheat yields was seen as applying them to the wrong domain. This example underlines the hazard of applying production models without intimate understanding of the system to which they are applied and sounds a warning to inexpert application of off-the-shelf models.

Net primary production models are very different from crop production or agroecosystem models. The NPP models (Roxburgh *et al.*, in review) were not in fact validated models but gave a range for long term average NPP for Australia spanning almost an order of magnitude (0.38 to 3.3 Gt C yr^{-1}). Ground-truth validation of them is essentially impossible on expected research budgets. Hence policy development that would draw on information about continental NPP should be very cautious indeed especially if it were to rely on just one or a few of such models

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