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Department of the Environment and Water Resources  
Australian Greenhouse Office

# The feasibility of forest free air CO<sub>2</sub> enrichment (FACE) Experimentation in Australia



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## **EXECUTIVE SUMMARY**

Future atmospheric and associated climatic changes are likely to have marked effects on Australian forest ecology impacting both wood production and the environmental services derived from forests. Increasing concentrations of CO<sub>2</sub> in the atmosphere have the potential to significantly affect forest growth rates, the amount of carbon stored in forest ecosystems, forest biodiversity and the quantity and quality of water derived from forested catchments. Increasing CO<sub>2</sub> concentration interacts in complicated ways with climate, land use and land management, and major disturbances such as bushfire to determine landscape and national impacts. Improved understanding of how elevated CO<sub>2</sub> affects wooded land systems and surface-atmosphere interactions, will also improve climate models and potentially the reliability of regional climate predictions.

This report examines a broad range of issues that would underpin a decision to establish forest FACE (Free Air CO<sub>2</sub> Enrichment) research facilities in Australia. In preparing this report, the authors invited and considered inputs from a wide range of scientific experts, representatives of the forest production and conservation sectors, and the leaders of forest FACE studies in North America and Europe.

Forest FACE studies, coupled with process-based models are the best approach to gaining evidence-based insights into the long-term effects of elevated CO<sub>2</sub> on forest ecosystem processes and properties. FACE enables study of stand-level processes over extended periods, especially feedbacks that affect soil nutrient and water availability and plant competition, and thus the long-term effects of elevated CO<sub>2</sub>. Long-term FACE studies also enable the interactions between climatic variability or change, elevated CO<sub>2</sub> and stand functioning to be explored.

There is a strong justification for establishing forest FACE studies in Australia, to build upon laboratory and whole-tree chamber studies on native species, and to complement on-going FACE experiments in temperate plantation forests growing on more fertile sites in the northern hemisphere. Australian forests have mostly evolved under water and nutrient limited conditions and regular disturbance, especially from fire. Thus Australian forest environments differ from those where existing FACE studies are being undertaken, and our sclerophyllous (hard leaved) vegetation may exhibit differing responses to elevated CO<sub>2</sub>.

For practical reasons, forest FACE experiments would be restricted to very few locations and experimental manipulations. It is clearly not possible to study the range of Australian forest ecosystems. Any selected site is not necessarily a good sample of even the broader range of that forest type, let alone the Australian forest estate. However, sites that have the broadly common characteristics (e.g. water and nutrient limitation) of a large portion of the forest estate can be studied. A viable approach is to use a comprehensive forest FACE study to test and improve existing process-based

models that integrate the key processes describing the effects of elevated CO<sub>2</sub> on forest carbon, water and nutrient cycles. The modelling framework is used to define the key gaps in current understanding, and research at the FACE site is then undertaken to address these gaps. The refined model becomes the tool for analyzing the potential effects of elevated CO<sub>2</sub> on the broader Australian forest estate.

Native eucalypt forests, plantations and rainforests are very different ecosystems, with contrasting importance assigned to various forest values (e.g. wood production, biodiversity, water yield). Thus the significance of any impacts of elevated CO<sub>2</sub> differs markedly in these forest types. Whilst there are valid reasons for conducting FACE studies in each of these forest systems, we recommend that an initial forest FACE study be established in either open dry sclerophyll forest or woodland that typically has a N-fixing woody understorey. Such forests dominate (>80%) Australian forested landscapes. Given the widespread and recurrent disturbance by fire of dry eucalypt forests, we recommend that fire be explored as a key variable in the FACE study.

However, we recognise that the providers of primary funding for a forest FACE study might have specific objectives (e.g. timber production, biodiversity conservation, water production) that could influence the preferred choice of site. Options for establishing a FACE study in a plantation or a rainforest should be further explored at a later time with appropriate stakeholders. We emphasise that FACE studies are easiest to conduct in young plantations, and logistically very difficult in tall, multi-species and heterogeneous rainforest.

There is now more than a decade of experience with forest FACE studies overseas that can be drawn upon to guide the establishment of a successful facility and associated research program in Australia. Of the techniques available, we recommend the use of a pure CO<sub>2</sub> injection method that requires less infrastructure and introduces less potential artefacts. Critical issues relating to the practical design and application of FACE technologies, such as the minimum size of FACE 'rings', control of CO<sub>2</sub> concentration within the stand, temporal increase in global CO<sub>2</sub> levels, and variable carbon dioxide quality, are discussed in detail in the report.

The costs of establishing and maintaining forest FACE depends largely on the size and number of 'rings' established and the "deal" that can be established for discounted CO<sub>2</sub> gas supply. The infrastructure costs may be ~ \$50-100 k per ring (30 m diameter) but depend on many factors. These are small in comparison to the annual cost of CO<sub>2</sub> (~ \$0.4M to \$1M per 30 m ring for a forest of 20 m height, based on discount commercial rates for CO<sub>2</sub>), and technical support (~\$350k pa). Indicative total annual running costs for a forest FACE employing 4 'rings' in 20 m high forest are approximately \$2M to \$4.5M. Commitment to running the FACE study for a decade or longer is required to enable long-term feedbacks to important forest processes to be expressed and understood. Given the high costs of CO<sub>2</sub>, partnering with industry to 'sponsor' some of this cost should be vigorously explored.

The high cost of establishing and maintaining a forest FACE facility, demands an efficient experimental design, and an integrated program of explanatory research that leads to interpretable findings and systematic refinement of models. The site must be readily accessible and attractive to a critical mass of multi-disciplinary scientists and students.

An Australian forest FACE facility would represent a long-term investment of national and international importance, and thus needs to be carefully designed and managed. A strong alignment between scientists, the full spectrum of relevant funding bodies and experimental infrastructure is needed. To facilitate this, we strongly recommend that a broadly-based Steering Committee that represents the key groups (governments, private sector interested in carbon, water and biodiversity, R&D corporations, research providers, and active researchers) investing in the facility and in the associated research be established. A Scientific Committee with adequate multi-disciplinary expertise (including elevated CO<sub>2</sub> research) is also needed to co-ordinate research at the site, ensure that key observations are undertaken and made readily available, and work closely with the Steering Committee. A strong collaborative model involving all participants is essential.

## **1. SYNTHESIS AND RECOMMENDATIONS**

**Recommendations** are referenced back to the Section of the Report where the issues are more fully discussed.

### **1. *The need for forest FACE.***

Future climate and atmospheric changes will have marked effects on both wood production and the environmental services derived from Australian forests. The concentration of CO<sub>2</sub> in the atmosphere is forecast to rise from the present day level of ~380 ppm to ~450 ppm by 2030, and to ~600 ppm by 2070. Forest FACE (Free Air CO<sub>2</sub> Enrichment) studies are the best approach to gaining insights into the long-term effects of elevated CO<sub>2</sub> on forest ecosystem processes and properties. Other approaches (e.g. open-top chambers, whole-tree chambers, controlled-environment studies) can provide useful supporting data but are most suitable for studying shorter-term physiological responses in small trees. FACE enables study of stand-level processes over extended periods (thus also capturing the effects of climatic variability and change), especially feedbacks that affect soil nutrient and water availability and plant competition, and thus the long-term effects of elevated CO<sub>2</sub>. Soil feedbacks are expected to develop progressively over a decade or longer, thus if a forest FACE facility is established, a long-term commitment to supporting it is essential.

### **2. *Core issues for forest FACE research.***

There are at least five key questions concerning the effects of elevated CO<sub>2</sub> on Australian forests that have strong policy and practical relevance:

- Are forest growth rates or total (biomass plus soil) carbon storage changing and do these differ with forest type?
- Are the quantity and quality of water produced from forests changing for given sets of climatic conditions?
- Are there impacts on forest biodiversity resulting from differential responses of plant species?
- How will any changes induced in forests affect continental and regional climate, and will incorporation of elevated CO<sub>2</sub> effects into climate models improve the reliability of regional climate projections?
- Are there effects on wood production and quality?

A common thread relevant to all these questions is whether carbon, nutrient and water cycles change in ways that alter forest (tree and understorey) growth rates. Thus, study of how elevated CO<sub>2</sub> affects these critical processes is central to a FACE study.

It is important to note that the effects of elevated CO<sub>2</sub> on Australian forests do not occur in isolation from change in other key drivers such as varying climate (rainfall, temperature, evaporative demand), land use (afforestation, deforestation, changing age structure resulting from harvest of native forests), and major disturbance such as bushfire. Elevated CO<sub>2</sub> interacts with these



factors to determine landscape-scale and national impacts, as well as feedbacks on Australia's climate system.

### **3. Forest FACE objectives and experimental design.**

There is a strong justification for establishing forest FACE studies in Australia, to build upon laboratory and whole-tree chamber studies on native species, and to complement on-going FACE experiments in temperate plantation forests growing on more fertile sites in the northern hemisphere. Australian forests have mostly evolved under recurrent water and nutrient limitations and regular disturbance, especially from fire. The resultant sclerophyllous (hard leaved) vegetation may exhibit differing responses to elevated CO<sub>2</sub>. There are very few studies of how water-nutrient interactions affect response to elevated CO<sub>2</sub> in general, thus Australian studies would help fill several key gaps in global understanding.

There are a number of feasible field experimental designs for study of CO<sub>2</sub> x water x nutrient interactions, and we ***Recommend (1) that experimental design options presented (Section 6.3), be further considered in the context of the priority placed on alternative research objectives.***

### **4. Designing a forest FACE study within a modelling framework.**

For practical reasons, forest FACE experiments will be restricted to very few locations and experimental manipulations. It is clearly not possible to study the range of forest ecosystems that might be considered 'representative' of Australian forests. Any selected site can not be considered as 'representative' of even the broader range of that forest type, let alone the Australian forest estate. However, a forest site can be selected that has characteristics (water and nutrient limitation, dominance of sclerophyllous vegetation with a N-fixing understorey) that are common to much of Australia's forest estate.

A way forward is to use a comprehensive forest FACE study to test and improve existing process-based models that incorporate the key processes determining the effects of elevated CO<sub>2</sub> on forest carbon, water and nutrient cycles. The modelling framework is used to define the key gaps in current understanding, and research at the FACE site is then undertaken to address these issues. In the current models, the major areas of uncertainty relate to stomatal and stand-level responses in trees that have evolved in highly varying water-limited environments, to the plasticity of carbon:nutrient ratios in vegetation and soil, to how allocation of C to above- and below-ground processes may change, and whether biological N - fixation may be stimulated under elevated CO<sub>2</sub>. The refined model becomes the tool for analyzing the potential effects of elevated CO<sub>2</sub> on the broader Australian forest estate. Thus, we ***Recommend (2) that the experimental location, design and research program of any forest FACE study be strongly guided by a modelling framework (Section 3.3).***

## 5. Choosing a site.

The location of any forest FACE experiment is determined by the following factors:

- The nature of the research question(s)(see point 2 above)
- Practical issues such as the cost of delivering CO<sub>2</sub> into the forest, and physical characteristics such as terrain and site uniformity
- Accessibility to an enthusiastic and critical mass of scientific expertise
- Risks that weather extremes or natural disasters will lead to damage or loss of the experiment

The pros and cons of locating a forest FACE study in dry open eucalypt forests, plantations, or rainforests in Australia are discussed in the report. We **Recommend (3)** *an initial forest FACE study be established in a eucalypt forest that is subject to both water and nutrient limitation, and that water availability be experimentally manipulated (Sections 3.1, 3.3, 6.1-6.3).*

The study could be in either open dry sclerophyll forest or woodland that typically has a N-fixing woody understorey. Such forests dominate (>80%) Australian forested landscapes. A key issue is whether the selected forest should be in a stage of recovery from a prior disturbance (such as fire), or should be 'mature' and in near quasi-steady state. There are valid arguments for either of these forest states, but much of Australia's forests are in recovery after recurrent disturbance, and the magnitude of response and ability to detect effects of elevated CO<sub>2</sub> on processes is greater for the disturbed state. We **Recommend (4)** *that fire be explored as a key variable in the design of a forest FACE study in dry sclerophyll eucalypt forest (Section 6.3).*

## 6. Which forest type should be chosen for study?

Plantations are not considered good analogues of the much more (100-fold) extensive native forests, because of selection of species (and genotypes) for rapid growth, application of management to minimise nutrient and water limitation to growth, and the absence of N-fixing understorey vegetation. However, elevated CO<sub>2</sub> and climate change may have significant effects on the economics and risks of wood production; thus there is merit in establishing FACE in plantations if wood production impacts is a high priority issue.

Whilst there is a strong global interest in how tropical rainforests may respond to elevated CO<sub>2</sub>, there is lesser interest in this in Australia because of the limited area of rainforest. Logistical issues are also much more challenging in rainforests because of the complex mixture of tree species and tall canopies. It is very difficult to study soil feedbacks on the nutrient cycle without treating a very large area of rainforest with elevated CO<sub>2</sub> and this is very expensive.

We **Recommend (5)** *that options for establishing FACE installations in plantations and rainforests be explored in greater detail at a later time (Sections 6.1 and 6.2).*

## **7. FACE-system choice.**

There is now more than a decade of experience with forest FACE studies overseas that can be drawn upon to guide the establishment of a successful facility and associated research program in Australia. There are three basic technologies available:

- Use of FACE 'rings' with vertical vent pipes used to disperse diluted CO<sub>2</sub> throughout the forest stand (Brookhaven National Laboratory approach used at the Duke Forest (North Carolina) and Oak Ridge (Tennessee) facilities in the U.S.).
- Pure CO<sub>2</sub> injecting 'ring' system (Miglietta method used at the POPFACE facility in Italy).
- WebFACE in which CO<sub>2</sub> is released via a network of fine tubes in the forest canopy (Korner method used at the Swiss WebFACE study on mature temperate forest).

The pros and cons of these are documented, along with information on their performance, and the costs of establishment and maintenance. We **Recommend (6)** *use of the pure CO<sub>2</sub> ring-injection method that requires less infrastructure, and does not introduce any risk of 'blower' effects (Sections 5.2 and 5.3).* This method also has the significant advantage of removing the need for expensive infrastructure at the ambient CO<sub>2</sub> 'control' plots.

Critical issues relating to the practical design and application of FACE technologies, such as the minimum size of 'rings', temporal variation in CO<sub>2</sub> concentration, and variable carbon dioxide quality, are discussed in detail in the report.

## **8. Indicative costs.**

The costs of establishing and maintaining forest FACE depends largely on the size and number of 'rings' established. The infrastructure costs may be ~ \$50-100 k per ring (30 m diameter) but depend on many factors. These are small in comparison to the annual cost of CO<sub>2</sub> (~ \$0.4M to \$1M per 30 m ring for a forest of 20 m height, based on discount commercial rates for CO<sub>2</sub>), and technical support (~\$350k pa). Indicative total annual running costs for a forest FACE employing 4 'rings' in 20 m high forest are approximately \$2M to \$4.5M. Refinement of these estimates is clearly necessary (Section 5.4).

## **9. Efficient experimental design.**

There are a range of options for increasing the efficiency of experimental design in forest FACE studies. Important considerations are monitoring key processes for several years prior to application of treatments; in lieu of limited replication, the application of regression approaches that incorporate detailed process measurements on each experimental plot; and use of highly replicated ambient CO<sub>2</sub> 'controls' to establish site level variance. The application of 'split plot' designs (i.e. within the rings) is not feasible with forest

FACE because of the need to have wide buffers to minimise the effects of extensive root exploration and litter dispersal. We **Recommend (7)** that key observations on forest behaviour are made for at least 1 year prior to commencing CO<sub>2</sub> enrichment (Section 6.3).

#### **10. Capitalising on the large investment in FACE infrastructure.**

It is critical that a FACE site be well utilized via conduct of high quality detailed research which can explain the observed integrated effect of treatments on forest growth and carbon, water and nutrient cycles. The experimental design and key observations must lead to interpretable findings. And the site must be accessible and attractive to a critical mass of multi-disciplinary scientists and students. Measurement of below-ground processes such as nutrient mineralization, soil respiration and root dynamics is critical, so that careful consideration must be given to soil properties during site selection.

#### **11. Forest FACE as a significant national research facility.**

A major forest FACE facility would be an important component of Australia's research infrastructure. As such it could form part of the Terrestrial Ecosystem Research Network (TERN) of the National Collaborative Research Infrastructure Strategy (NCRIS), and we **Recommend (8)** that engagement with TERN be explored as soon as possible (Sections 3.3 and 3.4). Multiple funding streams from both government and the private sector would need to be harnessed to support the establishment, maintenance and on-going research at the facility. Water authorities, mining companies, power generators, the forest industry, and research providers may 'invest' in such a facility. We **Recommend (9)** that Industry 'sponsorship' of the large cost of providing CO<sub>2</sub> should be vigorously pursued (Section 3.4). A strong collaborative model involving all participants will be essential.

#### **12. Management of a forest FACE research facility.**

A forest FACE facility represents a significant long-term investment and needs to be carefully managed within a stable institutional framework to provide independence, the maintenance of scientific rigour, and capacity for research integration. Possible models include those used by Co-operative Research Centres, or ARC Centres of Excellence. To facilitate the effective establishment and management of any FACE facility we **Recommend (10)** that a broadly-based Steering Committee that represents the key groups (governments, private sector interested in carbon, water and biodiversity, R&D corporations, research providers) investing in the facility and in the associated research is established, and that a Scientific Committee with adequate multi-disciplinary expertise including the direct effects of elevated CO<sub>2</sub> on plants, be formed to co-ordinate research at the site, ensure that key observations are undertaken and made readily available, and work closely with the Steering Committee.

## **2. PROJECT BRIEF**

The Australian Greenhouse Office (AGO) in the Department of the Environment and Water Resources contracted Ensis to undertake a scoping study of potential for options for Australian forest FACE experimentation to generate research outputs that would assist the Australian Government to:

- assess potential future fluxes of greenhouse gases associated with Australia's terrestrial ecosystems,
- develop policy relating to Australia's national greenhouse objectives, including development of views concerning the role of forest sinks in international policy discussions, and
- inform the management of forest and natural resource systems on how to mitigate any potential economic impacts, and increased greenhouse gas emissions under climate change.

The following methodology was agreed:

1. Consult with the full range of relevant stakeholders in the research community, industry and government under the overarching guidance of the National Committee on Elevated CO<sub>2</sub> Research.
2. Conduct a brief review of the possible direct effects of elevated CO<sub>2</sub> concentrations on Australian forests, the possible effects on the Australian continental carbon cycle, and identify the Australian forest systems that might be most responsive to elevated CO<sub>2</sub> concentrations. This review should include an analysis of how elevated CO<sub>2</sub> concentrations could affect forest water use and how any changes might affect the hydrology of forested areas.
3. Document the rationale for conducting forest FACE experiments – relative to other experimental methodologies available (e.g. whole tree chamber (WTC) experiments) – and any particular advantages or disadvantages that FACE methodologies may offer in the Australian context. Analyse the costs and benefits (both scientific and financial) of situating forest FACE experiments where they optimise linkages with other laboratory/field based elevated CO<sub>2</sub> experimentation. Also consider how the design or location of forest FACE experiments might maximise the opportunity to attract the co-investment that may be required to resource potentially costly forest FACE experiments.

4. Advise on issues associated with potential location of forest FACE experiments:
  - a) Would commercial eucalypt plantations provide a sufficient analogue of natural systems to provide data relevant to the modelling of the continental carbon cycle and other effects of elevated CO<sub>2</sub> concentrations on Australian forests?,
  - b) What are the pros and cons concerning situating forest FACE experiments where they most usefully inform climate change modelling (e.g. in tropical rainforests)?,
  - c) Where should FACE studies be located to most usefully inform understanding of the direct effects of elevated CO<sub>2</sub> concentrations on the overall Australian forest estate?,
  - d) Are (b) and (c) necessarily mutually exclusive?
5. Detail and evaluate the range of FACE technologies available for forest experiments, including daily CO<sub>2</sub> consumption and relative costs of establishment and maintenance. Consult with project leaders of USA based Oak Ridge (Dr Richard Norby) and Duke (Dr Ram Oren) forest FACE experiments.
6. Prepare a draft report covering tasks 2 - 5. This report should present the costs and benefits (scientific and financial) associated with the range of options (forest/technology) rather than recommending a preferred single option relating to specific forests/technologies.

Finalise scoping study report after comment from the AGO.

### 3. RATIONALE FOR CONDUCTING FOREST FACE EXPERIMENTS IN AUSTRALIA

#### 3.1 Nature of Australian forests and critical new information provided by forest FACE studies

Australia has about 160 Mha of forests, mostly eucalypt and acacia woodlands. There are about 2 Mha of plantations dominated by *Pinus radiata* grown for sawn wood and *Eucalyptus globulus* grown on short rotations for pulpwood. Table 1 summarises the area of important forest types. Because of their area, the native forests are dominant in terms of national carbon storage, impacts on hydrology and provision of forest biodiversity. Rainforest, whilst small in area, has very high biodiversity value and represent a forest type that is thought to be particularly important to the global carbon cycle response to atmospheric CO<sub>2</sub> concentration. Plantations are significant in terms of wood production and economic activity, and also can have significant regional impacts on the environment (e.g. benefits or disbenefits of greater water use depending on the situation in which trees are established) and communities. Australia's forests have some distinctive features which may make their response to elevated CO<sub>2</sub> different in some respects to that of forests growing in the northern hemisphere where the majority of studies to date have been conducted.

Table 1. Area of major vegetation groups of Australia in the late 20th century

Major vegetation group	Area (km <sup>2</sup> )	Major vegetation group	Area (km <sup>2</sup> )	Major vegetation group	Area (km <sup>2</sup> )
Cleared/modified native vegetation	982 051	Casuarina forests and woodlands	60 848	Acacia shrublands	654 279
Rainforests and vine thickets	30 231	Melaleuca forests and woodlands	90 513	Other shrublands	98 947
Eucalypt tall open forests	30 129	Other forests and woodlands	119 384	Heath	25 861
Eucalypt open forests	240 484	Eucalypt open woodlands	384 310	Tussock grasslands	528 998
Eucalypt low open forests	12 922	Tropical eucalypt woodlands/grasslands	254 228	Hummock grasslands	1 756 104
Eucalypt woodlands	693 449	Acacia open woodlands	114 755	Other grasslands, herblands, sedgeands and rushlands	98 523
Acacia forests and woodlands	560 649	Mallee woodlands and shrublands	250 420	Chenopod shrubs, samphire shrubs and forblands	552 394
Callitris forests and woodlands	27 724	Low closed forests and closed shrublands	8749	Mangroves, tidal mudflats, samphires and bare areas, claypan, sand, rock, salt lakes, lagoons, lakes	106 999

Source: Data from Australian Native Vegetation Assessment (2001)

In summary these differences include:

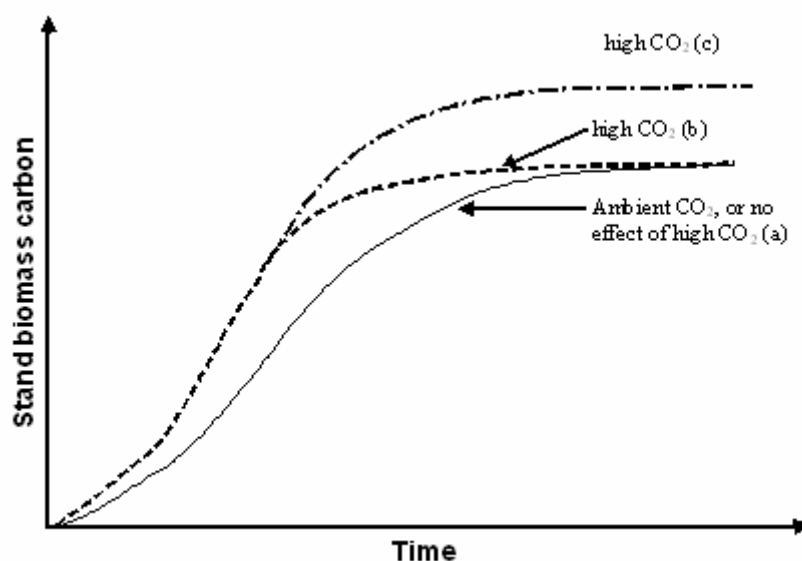
- Australian forests have evolved and grown in water and nutrient-limited environments, many of which are subjected to recurrent fire. This has resulted in complex species associations.
- Growth on old highly-weathered P-deficient soils. P availability also restricts N-fixation by native understorey legumes and thus soil N availability.
- Evolution of sclerophyllous (hard leaf) evergreen and open (low leaf area) tree crowns.
- Many adaptations to fire, including sprouting capacity of both trees and understorey. Only a small proportion of the eucalypt forests are killed by fire and thus few are even-aged (generally the wetter 'ash-type' forests). Most forests are multi-aged and subjected to 'gap' recruitment.
- Fire-stimulated regeneration of N-fixing understorey species which together with increased P mineralization can lead to a pulse of higher N input during the initial decade of stand recovery after fire disturbance.

Australia's forests contain a considerable stock of C in biomass and underlying soils. Barrett and Kirschbaum (2000) used the VAST model to estimate the C stock in each forest type by assuming they were near to 'steady state' (or 'mature') condition. Carbon stocks were approximately 8.3 and 9.8 Gt C in the biomass and soil respectively. The actual C stocks will be less than potential mature stocks because much of the forest estate is recovering from disturbances and thus has a lower C density. The total forest C stock of about 18 Gt is large (~40 times the total net annual greenhouse gas emissions for the entire Australian continent). Accordingly, it is important to know if this might be vulnerable to losses (from disturbance such as fire or insect attack, or increased soil respiration) under climate change or subject to increase (see Steffen and Canadell 2005, Hely et al. 2006).

There are two important questions in relation to the effects of the increasing atmospheric CO<sub>2</sub> concentration on the C balance of Australia's forests (summarised in Figure 1 below):

- Is the C storage in 'mature' forests increasing in some forest types and in the overall forest estate?
- Will the growth rates of newly established forest (eg. environmental plantings, plantations, eucalypt regrowth following harvesting) or forests recovering after disturbance such as bushfire, be increased under elevated CO<sub>2</sub>?





**Figure 1.** Notional possible effects of elevated CO<sub>2</sub> on forest above-ground growth rate and biomass C stock at equilibrium when grown from initial zero above ground stocks. High CO<sub>2</sub> may have no effect (a), or increase growth rates without increasing biomass carbon at equilibrium (b,) or increase growth rate and biomass carbon storage at equilibrium (c). These effects can apply to a newly created forest, or to a forest recovering from a disturbance such as bushfire. Temporal change in ecosystem (biomass + dead organic matter + soil) carbon storage may show a different pattern to that for above-ground biomass carbon.

The effects of elevated CO<sub>2</sub> on growth rates of commercial forests, on water yield from forested catchments, and on biodiversity values are also important. The effects of elevated CO<sub>2</sub> on eco-hydrology are a critical issue given the projections for lower rainfall and higher temperatures over much of Australia. This is reviewed in Section 4.2.

The effects of increasing CO<sub>2</sub> on forest properties and processes need to be build into global climate models that are now incorporating an 'interactive biosphere' (e.g. the CSIRO/BOM/Universities ACCESS initiative). Doing so may improve the reliability of such models for making regional climate projections at the scale and accuracy required for impacts analysis and adaptive response.

Whilst there are process-based models based on best available science that can be used to predict the potential effects of increasing CO<sub>2</sub> concentration on forest growth and water balance (see Section 3.3), there are considerable uncertainties about how well the assumptions that underpin the models represent processes in Australian sclerophyllous (hard leaf) forests that have evolved and grow in water and nutrient-limited environments (see Section 4). There is a clear need to test and improve available models, so as to increase confidence in predictions of how Australian forests may respond to elevated CO<sub>2</sub>.

### **3.2 Role and limitations of other methods for studying the effects of elevated CO<sub>2</sub> on forests**

FACE methods have been developed for the study of the effects of elevated CO<sub>2</sub> on forests because all other methods have greater limitations than does the FACE approach. Long et al. (2004) show that even for the best designed open-topped chambers (OTCs), temperature within the chamber is elevated and consequently VPD is higher, despite light levels being significantly lower for a large part of the day. Plant-atmosphere coupling, including rainfall interception and wind effects, are also significantly altered by the presence of the OTC. Whilst such changes are also observed in OTCs where the CO<sub>2</sub> concentrations are not increased (pseudo-controls), it is known that elevated CO<sub>2</sub> concentrations change the response function of photosynthesis, stomatal conductance (Gs) and growth to these factors (see Section 4) and therefore we cannot simply ignore the impact of the chamber *per se*. The influence of the edge effect (wall effect) on plant growth is also very significant in all but the largest OTC experiments, a problem not encountered by FACE experiments.

In a meta-analysis of available data, Ainsworth and Long (2005) found trees responded more to elevated CO<sub>2</sub> in FACE than in chamber studies, but these results were heavily swayed by the strong response of young fast growing poplar saplings in the EuroFACE facility (Gifford 2004). Whilst FACE studies also have limitations (see Ainsworth and Long, 2005), they are considered to be the most realistic mimic of future elevated CO<sub>2</sub>. FACE methods overcome artefacts produced by enclosing trees, make it feasible to work with tall stands of trees, and allow sufficiently large plots to be treated to enable study of stand-level processes including interaction between tree crowns, and the feedbacks in the quantity and quality of litter produced above and below-ground. Further, by allowing larger areas to be treated, FACE creates the possibility of calibrating remote-sensing methods and thus offers the potential for up-scaling of responses to the landscape.

The following approaches can be complementary to forest FACE studies:

- Whole tree chambers (eg. Medhurst et al. 2006), such as those being used at the Hawkesbury site, are suitable for physiological studies over a few years on trees up to about 10 m in height. The net exchange of C and water by the tree/soil system can be inferred indirectly from measurements of the atmospheric flux of CO<sub>2</sub> and water. The microclimate is modified inside the chambers, and this is commonly adjusted for by running untreated (control) trees within the enclosures. Study of soil feedbacks is problematical unless the root system of individual trees is confined (effectively creating large 'pots'), and even then the length of study is generally too short. Interactions between trees can not be studied.
- Open-top chambers have been widely used in elevated CO<sub>2</sub> studies, but are only suitable for small trees and woody shrubs such as the scrub oak community at Cape Canaveral, in Florida. Micro-climate can be significantly modified (greater temperature and water vapour,

reduced air flow and changed light quality) as discussed above. The same issues apply to confinement of the root system, as for whole tree chambers.

- Responses to elevated CO<sub>2</sub> can differ somewhat in open top chambers compared with FACE studies for crop plants and trees (see Ainsworth and Long, 2005), although qualitatively the results have been similar for crops.
- Open-top chamber methods are probably best suited to studying the effects of elevated CO<sub>2</sub> on short to medium-term (up to a few years) plant physiological process, rather than for defining quantitatively the change in plant or soil C stocks and within-ecosystem feedbacks.
- Laboratory and glasshouse studies can be used to examine effects of elevated CO<sub>2</sub> on plant physiological processes under closely controlled environmental conditions with separation of variables. This can be useful for understanding key processes and for formulating models. Studies should be short-term to avoid severe artefacts resulting from factors such as trees becoming pot bound (Arp, 1991).

### **3.3 Framework for integrating FACE research with other research on elevated CO<sub>2</sub> (modelling framework and key observations)**

As discussed above, FACE studies aim to quantify the effects of elevated CO<sub>2</sub> on key processes and to measure integrated stand-level responses under 'natural' conditions. Insights gained from other approaches (Section 3.2) can be complementary. Process-based models are an effective tool for synthesising knowledge on how forests respond to elevated CO<sub>2</sub>, and for identifying key uncertainties that need to be further studied. In current models, major uncertainties relate to stomatal responses in trees that have evolved and grown in water-limited environments, to the hydrological response of forested sites, to the plasticity of carbon:nutrient ratios in vegetation, naturally senesced litter (above and below ground) and soil organic matter, to how allocation of C to above- and below-ground processes may change, and to whether N fixation by symbiotic and non-symbiotic N-fixing organisms will be stimulated under elevated CO<sub>2</sub>.

All available information should be used to formulate, parameterise, test and refine models of forest growth, net ecosystem C storage and water balance. These models become the integrating framework, and once validated, become the tool for estimating responses to elevated CO<sub>2</sub> in differing forests under contrasting environmental conditions. The models must be comprehensive (cover the coupled C, water and nutrient cycles) and involve linkages between vegetation, atmosphere and soil (eg. CenW, CABALA, others). The following are critical processes, drivers and properties to be modelled:

1. light interception and photosynthesis
2. stomatal conductance and evapo-transpiration

3. plant respiration
4. N-fixation, nutrient cycling and plant nutrient status
5. allocation of C to biomass components
6. litter (including root) production and quality
7. decomposition of litter and associated nutrient release
8. soil respiration and soil nutrient availability
9. changes in biomass C and soil C stocks
10. key climatic drivers
11. soil water balance
12. inter-species plant competition (forest growth dynamics)
13. tissue chemistry
14. herbivory

Ideally, as many of the above as possible should be monitored to provide a 'core' data set on differently treated plots at the FACE installation. This will allow model performance to be tested, and will provide a basis for refining models. Some of the above are critical drivers or integrative measures of key ecosystem processes – climate (10), soil water (11), change in C stocks (9), litter dynamics (6, 7) and soil respiration (8). Measuring these will give confidence that rates of key processes have been well simulated. Controlled environment studies are useful in understanding the response of photosynthesis, respiration, Gs and to some extent allocation under controlled conditions.

Clearly, a very comprehensive field-based research program is required to help explain forest responses to elevated CO<sub>2</sub>, and it is critical that this is closely linked to modelling activities. Controlled environment studies can be carefully targeted to gain insights into important processes that are difficult to study in the field.

### **3.4 Opportunities for investment in forest FACE research**

Establishment and maintenance of a forest FACE facility, and its utilization for productive research, would require many partners to co-invest in the initiative. Provision of the infrastructure and its continued operation (provision of CO<sub>2</sub>, system running and maintenance, and undertaking of key site measurements) is at such a scale (several \$ million annually depending on experimental design) that significant on-going government and private sector funding will be required. Infrastructure support under NCRIS should be investigated. It may be possible to gain supply of the large amount of CO<sub>2</sub> required at a 'subsidized' rate if a clean industrial source can be found within a reasonable proximity to the site, and if the producer is prepared to 'sponsor' the study (but see sections 5.3.2 and 5.4.2). Given that annual cost of CO<sub>2</sub> is very significant and will constrain the size and number of plots that can be treated, this issue should be vigorously explored.

Water authorities, mining companies, power generators, and the forest industries may invest in a FACE facility. The major objectives of these 'investors' will vary e.g. the forest industry is likely to give priority to improving

understanding of effects on productivity of plantations. Should a forest FACE facility proceed, a broadly-based stakeholder Steering Committee will be needed to guide the overall objectives and conduct of the study. The managers of the facility must encourage all researchers (from universities, CSIRO, government, industry) to contribute to the research program. A Scientific Committee with multi-disciplinary expertise would also be needed to co-ordinate studies, ensure that key observations are taken and made readily available, and to work closely with the Steering Committee. Establishment of effective linkages with other networks (e.g. ARCNESS, Terrestrial Carbon-cycle Sub-Committee of the AAS National Committee for Earth Systems Science) and funding bodies (e.g. ARC, FWPRDC, AGO etc) would be essential in order to resource and engage an adequate program of research, and thus capitalise on the large investment in the forest FACE infrastructure.

## **4. REVIEW OF THE POSSIBLE DIRECT EFFECTS OF ELEVATED CO<sub>2</sub> ON AUSTRALIAN FORESTS**

### **4.1 The forest carbon cycle**

The forest carbon cycle involves the formation of plant dry matter by photosynthetic carbon fixation followed by its deposition on and in the ground as plant “litter”. Turnover times range from very short for soluble compounds exuded by roots that are utilised by soil microflora, up to centuries for dead tree trunks, and even longer for some pools of soil organic matter. The stocks of C held in the various plant and soil organic pools and the rates at which carbon passes through those pools are heavily constrained by interaction with mineral nutrient cycles and the hydrologic cycle. Elevated CO<sub>2</sub> concentration can affect this cycle directly by stimulating net photosynthesis and reducing transpiration from leaves. It may also influence the cycle (both the pool sizes and the rates of C transit through the pools) indirectly through its indirect effects on litter decomposability, mineral concentrations in organic matter, plant temperature, and soil moisture levels.

#### **4.1.1 Photosynthetic responses of tree leaves to CO<sub>2</sub> enrichment**

An increase in the atmospheric concentration of CO<sub>2</sub> from current ambient to a value in the range of 500-1000 ppm increases the rate of photosynthesis. This increase is a result of increased supply of substrate (CO<sub>2</sub>) to chloroplasts and a decrease in photorespiration (Eamus and Jarvis 1989).

Woodlands and forests are significant components of the global carbon cycle, accounting for more than half of the total net annual carbon uptake by terrestrial ecosystems. Although the short-term (minutes-to-hours), leaf-scale responses of photosynthesis to increased CO<sub>2</sub> concentrations are well known and mechanistically understood, this is not true for the long-term (years-to-centuries), large-scale (tree-to-stand-to-landscape) responses because of the confounding and mostly poorly understood feedbacks involving carbohydrate accumulation, acclimation of photosynthesis via effects of N supply and gene expression, change in leaf area index and light interception, allocation patterns, and landscape water balance and nutrient turnover.

Several recent reviews summarise the data concerning the response of leaf- and tree-scale photosynthesis to CO<sub>2</sub> enrichment. On average, trees show a larger response in light-saturated photosynthesis ( $A_{\max}$ ) to CO<sub>2</sub> enrichment than crops or grasses (Ainsworth and Long 2005). Ainsworth and Long (2005) found an average 47% increase in  $A_{\max}$ , larger than the 31% average observed by Curtis and Wang (1998) but similar to that 51% observed by Medlyn et al. (1999). However, when integrated over the day, C gain was largest for shrubs (+ 45%) and grasses (+ 38%) compared to trees (+25%).

This general picture, of increased rates of assimilation in response to CO<sub>2</sub> enrichment, is not always observed. Bernacchi et al. (2003) examined the

photosynthetic response of three species of poplar in a FACE experiment in Italy before and after coppicing. Prior to coppicing, they found an approximate 38% increase in the rate of light saturated assimilation, an increased apparent quantum yield and an increased daily integrated rate of C gain. There was no effect of CO<sub>2</sub> enrichment on Gs in the first year of study. Despite an unimpeded root volume, down regulation of photosynthesis was observed in the form of a decline in maximum rate of light-saturated carboxylation ( $V_{c,max}$ ) and maximum rate of ribulose-1,5-bisphosphate regeneration ( $J_{max}$ ), in the first (pre-coppicing) year of study. However, following coppicing the stimulation of assimilation was not observed in two of three species of poplar examined. A role for sink strength (the ability to consume fixed carbon) and the enhanced accumulation of carbon in the roots prior to coppicing, was suggested as causing the lack of stimulation of photosynthesis following coppicing. This observation is particularly relevant to Australian forested landscapes where lignotubers play a prominent role in supporting regrowth following fire, drought, or storm damage.

The stimulation of photosynthesis is predicted, from theory, to be larger at high rather than low temperature (Long et al. 2004). This prediction has been supported by meta-analyses of published data. On average,  $A_{max}$  was increased by 30% when temperatures are greater than 25°C, compared to a stimulation of 19% when temperatures are less than 25°C. Furthermore, the percentage stimulation of photosynthesis in response to CO<sub>2</sub> enrichment is generally larger under water limited conditions than more mesic conditions. *For Australian conditions, where temperatures are high, water limitations to growth are common, and N and P limitations to growth are likely to be extensive, there is an imperative to examine the response of stands of trees to CO<sub>2</sub> enrichment from early growth through to canopy closure and well beyond.*

#### **4.1.2 Australian data– photosynthesis and stomatal conductance**

Hovenden and co-workers (Hovenden et al. 2006) have established a FACE experiment in lowland *Themeda Austrodanthonia* grassland in Tasmania. Rings (1.5 m diameter) expose grassland to ambient or CO<sub>2</sub>-enriched conditions and ambient or elevated (+ 2°C) temperature. To date, no growth or physiological data have been published.

Two groups of researchers have published on the responses in young trees of several Australian species to CO<sub>2</sub> enrichment. The first is the tropical tree ecophysiology group led by Eamus (Eamus et al. 1993, 1995a,b, Goodfellow et al. 1997), who examined the photosynthetic, growth and stomatal responses of two savanna tree species, a monsoon vine forest species and a tropical tree crop to CO<sub>2</sub> enrichment. The second group is from the Research School of Biological Science (RSBS) at the Australian National University (ANU), led by John Evans.

The tropical ecophysiology group observed the following:

For *Maranthes corymbosa* (monsoon vine forest evergreen tree):

- apparent quantum yield and light saturated rate of assimilation was increased by CO<sub>2</sub>-enrichment, by 25 – 40% and 10 – 20% respectively. Gs declined by 10 – 30%.
- The magnitude of the response to CO<sub>2</sub> enrichment differed between morning and afternoon, a result ascribed to differences in soil moisture and atmospheric vapour pressure deficit between morning and afternoon. The influence of these factors on responses of Gs and photosynthesis to CO<sub>2</sub> enrichment was discussed earlier.
- The soluble protein content of leaves of *Maranthes* was not affected by CO<sub>2</sub> enrichment but the total foliar N content decreased.
- A decline in photosynthetic potential (acclimation of photosynthesis) was observed through time.

For *Eucalyptus tetrodonta* (evergreen savanna tree species):

- Assimilation rate was increased by CO<sub>2</sub> enrichment and there was no evidence of photosynthetic acclimation over the 30 month experimental period. Indeed, the difference between ambient grown plants and plants grown under CO<sub>2</sub> enrichment increased over time.
- For low values of leaf-to-air vapour pressure difference (LAVPD), there was no impact of CO<sub>2</sub> enrichment on assimilation rate (expressed per unit leaf area, unit dry weight or unit soluble protein). However, for large LAVPD, CO<sub>2</sub> enrichment caused large (15 – 30%) increases in assimilation rate.
- The sensitivity of photosynthesis to temperature and the temperature optimum for photosynthesis was increased by CO<sub>2</sub> enrichment.

For *Mangifera indica* (evergreen rainforest tree species):

- Apparent quantum yield increased in response to CO<sub>2</sub> enrichment and this effect was larger in the dry season than in the wet season.
- Light saturated assimilation rate was larger in response to CO<sub>2</sub> enrichment and was larger in the morning than the afternoon for both ambient and CO<sub>2</sub> enriched trees.
- The afternoon decline in A<sub>max</sub> was larger under CO<sub>2</sub>-enriched conditions in the dry season than the wet season, a result ascribed to the impact of sink limitations in the dry season (Goodfellow et al. 1997). A<sub>max</sub> was stimulated to a greater extent by CO<sub>2</sub> enrichment in the dry season than in the wet season.
- The percentage decline in Gs between wet and dry seasons was smaller under CO<sub>2</sub> enrichment than ambient conditions.
- There was no evidence of photosynthetic down regulation over the 28 month period of study.

Root growth was not constrained in pots in any of these studies and CO<sub>2</sub> enrichment occurred 24 h d<sup>-1</sup>.

*From these studies it is clear that the impact of seasonality of temperature, soil and atmospheric water content upon the photosynthetic response of*



*Australian tree species to CO<sub>2</sub> enrichment is significant and that significant differences in response to CO<sub>2</sub> enrichment occurs among species.* However, in all cases, an increase in  $A_{\max}$  and a decrease in  $G_s$  were observed.

From the RSBS group, Evans et al. (2000) examined the growth and photosynthetic characteristics of ten *Acacia* species growing in small pots filled with sand when exposed to ambient or CO<sub>2</sub>-enriched conditions (Evans et al. 2000; Atkin et al. 1999, Schortemeyer et al. 1999, 2002). They found that either 9 of the 10 species or 5 out of 10 species, depending on time of measurement, showed an increased rate of photosynthesis, whilst up to five species may have showed a decline in photosynthetic rate, when measured under CO<sub>2</sub>-enriched conditions compared to ambient conditions. The slow growing *A. aneura* was consistently shown to have reduced growth (Atkin et al. 1999) and reduced photosynthetic rate (Evans et al. 2000). Unusually, only 6 of the 10 species showed a decline in  $G_s$ . Most importantly (given that many Australian forests have a significant *Acacia* component to them), the impact of CO<sub>2</sub> enrichment on the ratio of electron transport and Rubisco activity per unit foliar N was not uniform and depended on the species being examined. The four slowest growing species did not exhibit a change in foliar N content, but the six fast growing species showed a decline of 10% (Atkin et al. 1999).

Nitrogen supply rate to fast growing species could limit the growth response to CO<sub>2</sub> enrichment (Eamus and Jarvis 1989). *Acacias*, being N fixers, could potentially overcome this limitation once nodulated (Schortemeyer et al. 2002). In possible support of this hypothesis was the observation that the relative growth rate of 6 of 7 *Acacia* species examined under CO<sub>2</sub>-enriched conditions maintained an enhanced growth rate throughout the 150 day experimental period, rather than exhibiting a decline over time. Furthermore, the amount of N fixed per plant increased in 5 of the 6 species that had a larger relative growth rate and it was shown that this was not merely a result of larger roots on larger plants under CO<sub>2</sub>-enriched conditions, but in fact was a result of an enhanced specific nitrogenase activity of the nodules in some, but not all, species examined (Schortemeyer et al. 2002). *These data strongly support the view that an Australian FACE should include N fixers in the species mix examined.*

#### **4.1.3 Acclimation of photosynthesis and stomatal conductance**

In many studies the stimulation of growth and photosynthesis observed in the initial stages of exposure to high CO<sub>2</sub> concentrations is larger than that observed after many months or years exposure (Eamus and Jarvis 1989, Drake et al. 1997). Acclimation of photosynthesis is frequently observed in response to CO<sub>2</sub> enrichment. Acclimation is generally observed as a reduction in the level of enhancement of the rate of photosynthesis (also called down regulation) and can be attributed to a decreased maximum apparent carboxylation velocity ( $V_{c,\max}$ ) and a decrease in the investment in Rubisco, the enzyme responsible for the primary fixation of CO<sub>2</sub> in C<sub>3</sub> plants (Rogers et al. 2001; Long et al. 2004). Photosynthetic down regulation is generally accompanied by a reduction in the amount of N present in the leaf

and an increase in the amount of non-structural carbohydrates in the leaf (Eamus et al. 1995b, Ainsworth and Long 2005).  $V_{c,max}$ , the maximum rate of electron transport, and the amount of Rubisco and nitrogen in the leaf decline by 5 – 20% in most FACE studies although Rogers and Ellsworth (2002) observed no decline in total foliar N content or protein content in *Pinus taeda* needles. Most importantly, they did find a significant decline in Rubisco activity measured *in vivo* (-25%) or *in vitro* (-35%) for one-year-old needles but not in current-year-needles. This reduction in activity was associated with reduced levels of Rubisco and increased foliar carbohydrate levels, supporting the hypothesis that loss of activity was due to differential gene expression mediated via increased foliar carbohydrates. Long-term downward acclimation of photosynthesis and decreased levels of Rubisco protein has also been observed in open-top-chambers (Adam et al. 2004).

Trees tend to show the smallest down regulation, and shrubs and grasses the largest reductions in  $V_{c,max}$ ; whilst there was no impact of CO<sub>2</sub> enrichment on  $J_{max}$  in trees and an 8% reduction in  $J_{max}$  for grasses (Ainsworth and Long 2005). However, there is much variability in the response of both to CO<sub>2</sub> enrichment. In the meta-analysis of Medlyn et al. (1999),  $J_{max}$  of European trees declined by 12% but Ainsworth and Long (2005) found no significant effect. DeLucia and Thomas (2000) did not observe any change in  $V_{c,max}$  but they did find an increased rate of ribulose biphosphate (RuBP) regeneration. A significant increase in  $J_{max}$  was observed in the Duke FACE site, but significant decreases were observed in the NV Desert and Eschikon sites, and no effect occurred at 3 other FACE sites (Ainsworth and Long 2005). A role of sink capacity within the canopy of a single tree has been inferred, since down regulation can be seen in leaves from low in the canopy but not in leaves from the upper canopy of the same tree (Takeuchi et al. 2001).

Decreased leaf nitrogen resulting from reduced allocation to Rubisco is small (~5%) in forest FACE experiments (Long et al. 2004). There is a need for long-term FACE experiments for trees in Australia to examine long-term trends in C uptake, N allocation and productivity.

Reduced amounts or reduced activity of Rubisco are generally assumed to explain this loss of photosynthetic potential. Two hypotheses have been proposed to explain the reduced amount or activity of Rubisco. First, this may result from an increasing N limitation with increased growth under conditions of high CO<sub>2</sub> concentrations. As N limitations increase there is a decline in allocation of N to photosynthesis (and hence reduced levels of Rubisco) or there is a non-specific protein dilution effect, resulting from the fact that the available N has to be allocated across a larger mass of leaf material per plant. However, N dilution in the field (as opposed to in pots) is likely to be minimal because of the potential for an increase in the volume of soil explored by roots under elevated CO<sub>2</sub> conditions (Long et al. 2004).

An alternative explanation for the reduction in activity or amount of Rubisco lies in the observation that increased sucrose levels in mesophyll cells can repress Rubisco gene expression (Long et al. 2004). Accumulation of sucrose in leaves is the result of the supply of fixed carbon exceeding

demand. Demand for C within a plant can be reduced by water stress, low temperatures, a determinate growth habit and nutrient limitations (including low N or P availability).

$A_{\text{sat}}$  (light saturated rate of assimilation) was increased by 34% in C3 plants in FACE meta-analyses of Long et al. (2004). Therefore, despite the observed decline in  $V_{\text{c,max}}$  and amount of Rubisco, assimilation rate was still stimulated by CO<sub>2</sub> enrichment. Indeed, the 34% increase lies in the theoretical range of 14% to 44% based on the Farquhar model and it suggests that despite the decline in  $V_{\text{c,max}}$  and the amount of Rubisco, photosynthetic stimulation by CO<sub>2</sub> enrichment was not diminished over time (ie there was no down regulation of the rate of photosynthesis *per se*). However, total C uptake by a plant is equally determined by the rate of non-light saturated photosynthesis and much of a canopy may spend much of its time at light levels lower than saturating. Theoretically, increasing the CO<sub>2</sub> concentration of air from 370 to 550 ppm will increase apparent quantum yield by 14% at 25°C. Long et al. (2004) calculate a stimulation of 13% across the FACE studies reviewed, indicating an absence of down regulation of photosynthesis.

Long et al. (2004) conclude that changes in Rubisco and nitrogen represent acclimation (that is, a set of changes that increase fitness to the environment). The loss of Rubisco appears to be a selective loss of this protein rather than a non-selective loss of all proteins to conserve nitrogen. Saxe et al. (1998) conclude that down-regulation of photosynthetic capacity tends to occur in plants exposed to environmental stress (especially trees). Similarly, Long et al. (2004) show that the reduction in  $V_{\text{c,max}}$  in response to CO<sub>2</sub> enrichment was larger for stressed plants than unstressed plants (9% compared to 22%). However, leaf position within the canopy appears to be a major determinant of whether this loss is observed or not. Sun leaves tend not to show any change but shade leaves do, although it is possible that this represents a function of leaf age rather than leaf position (Körner 2003; Rogers and Ellsworth 2002).

Reductions in  $G_s$  due to CO<sub>2</sub> enrichment are typically 20 – 30% and appear to not change over time, that is, there is no acclimation. The change in  $G_s$  observed is consistent with the observed maintenance of a constant  $C_i/C_a$  (the ratio of the concentration of CO<sub>2</sub> inside the leaf to that outside the leaf) (Long et al. 2004). Use of reciprocal transfer experiments, whereby plants grown under ambient CO<sub>2</sub> conditions are transferred to CO<sub>2</sub> enriched conditions, and *vice versa* confirm that stomatal acclimation does not occur (Goodfellow et al. 1997).

*An Australian forest FACE experiment would enable study of the influence of leaf position (within the canopy), canopy closure and N and water limitations on the photosynthetic and stomatal responses to elevated CO<sub>2</sub> concentration under conditions of high average temperatures, large evaporative demands, poor soil quality and highly variable rainfall.*

#### **4.1.4 Dark respiration**

Elevated CO<sub>2</sub> concentration at night might reduce plant dark respiration rates but the evidence is suspect. While a change in respiration rates per unit mass for plants that have grown and developed in elevated CO<sub>2</sub> might be expected, and indeed observed in woody species (Curtis and Wang 1998) as a result of changes in chemical composition, there have also been numerous reports of *direct* inhibition of plant dark respiration of around 10-15% under doubled CO<sub>2</sub> concentration that occurs immediately and is completely reversible by decreasing the CO<sub>2</sub> concentration again (Drake et al. 1999). There have been reports that night time-only elevated CO<sub>2</sub> can increase plant growth (e.g. Griffin et al. 1999), but that does not seem to be a common observation and has not been reported for tree species. Reviews of the evidence of respiratory suppression by high CO<sub>2</sub> concentrations have led to the conclusion that observations showing direct effects at the whole plant level are probably artefactual (Gifford 2003, Gonzalez-Meler et al. 2004). There are several measurement artefacts that confused the experimental interpretation. Gonzalez-Meler et al. (2004) concluded that, while direct CO<sub>2</sub> suppression of certain enzyme activities and mitochondrial oxygen uptake can be observed, these effects do not translate into a suppression of respiration at the plant tissue or whole plant level.

#### **4.1.5 Growth**

Most individual-tree responses have been observed on young trees grown in some kind of shoot and root enclosure. Key to the FACE approach is to recognize that young plant responses may not reflect older plant responses, individual plant responses may not reflect responses of groups of interacting plants, enclosure of roots in containers may restrict the total plant growth response to CO<sub>2</sub>, and short term responses may not persist in the long term (“acclimation” or “down-regulation”).

Results in the literature represent a spectrum of different types of experimental system and plant species rendering a brief, but all-data encompassing review, problematic. Accordingly for brevity we here emphasise a review of reviews.

The first review of the growth responses of plants, including woody species, to elevated CO<sub>2</sub> was benchmark analysis of 770 published observations by Kimball (1983). For the data reviewed at that time, the background ambient concentration (mostly in the 1960s and 1970s) averaged about 330ppm. The average “doubled-CO<sub>2</sub> effect” from that base for the nine woody species (apple, birch, cottonwood, fir, gum, maple, pine, spruce, sycamore) was 36% enhancement of growth in relatively short term experiments. This compares with an average growth enhancement for *all* immature C<sub>3</sub> species in that 1983 review of 51% enhancement. At that time most studies would have been carried out with plants grown from seed in some sort of controlled environments in which water and nutrients would have been supplied in abundance but light levels may have been lowered by the enclosure or inadequate lamps.

There are several reasons as to why one would expect forest trees in the longer term to exhibit lower growth responses in more recent studies than the +36% from the early experiments on seedlings summarised by Kimball (1983). These include:

- The growth-rate response of immature plants grown as spaced plants exceeds that expected for communities because of the opportunity for leaf area amplification of the response.
- With global atmospheric CO<sub>2</sub> concentration having increased (to 380 ppm by 2006) the CO<sub>2</sub> doubling response of plant growth from that ambient level will now be less than in earlier times because plants are now operating higher up the saturating CO<sub>2</sub> response curve of photosynthesis.
- In the field, other environmental inputs (especially mineral nutrients) may constrain growth and, over time, as nutrients are taken up into the enhanced growth, their restricted availability in the soil for further response would become more intense.
- Photosynthetic acclimation to elevated CO<sub>2</sub> concentration may occur, perhaps as an expression of mineral nutrient supply constraints.
- Many controlled environments may be at lower than field light intensities; the % plant growth responses to elevated CO<sub>2</sub> concentration have sometimes been found to be higher at low irradiance than at high irradiance (Gifford 1979a). Furthermore, the lack of variation in light and temperature that characterises the natural environment may also alter the response of plants to elevated CO<sub>2</sub>.
- Other negative feedbacks at the ecosystem level could set in over time such as changed natural rates of herbivory (Knepp et al. 2005).

There are also potential reasons for natural-system percentage-responses of growth to be *larger* than for many controlled environment responses, notably the lack of pot-size restriction (the bonsai effect) in the field (Arp 1991), the increased %-response when water supply is limiting in the short term (Gifford 1979a, b), and the potential for a positive feedback via C-driven ecosystem-acquisition of more nitrogen from the air in the long term (Gifford 1992, 1994).

A decade later Ceulemans and Mousseau (1994) focussed a review on woody plants but did not include a quantitative stratified analysis of the compiled data set. They listed results from a large number of short term (mostly less than 1 year) chamber or glasshouse experiments reported between 1989 and 1993. Highly diverse conditions had been adopted and plants were always very young or grown from seed. The large positive CO<sub>2</sub> effects on leaf area usually reported indicate that the plants were well spaced in the chambers rather than arranged to form closed canopies. Thus the average biomass increase, as a result of the approximately doubled CO<sub>2</sub> concentration of +38% for conifers and 63% for broadleaf species is likely to be much higher than would be experienced in a closed forest in which leaf area amplification, were it to occur, would not increase the amount of solar radiation intercepted by leaves.

Another 4 years later, Curtis and Wang (1998) performed a statistical meta-analysis on experimental data from the literature published between 1986 and 1996 for CO<sub>2</sub> effects on tree biomass accumulation taking the effects of other stresses into account. Across 102 chamber studies the overall average CO<sub>2</sub> response of shoot + root biomass was +29% for studies in which ambient CO<sub>2</sub> concentration was less than 400ppm and the enriched concentration was between 600 and 800ppm. These results embraced experiments involving fertility stress, low radiation, ozone stress, UVB stress, high or low temperature stress or no stress. With no identified stresses, the %-response to CO<sub>2</sub> was +31%. With nutrient stress present the response was reduced to +16%. Under low light levels as the only stress, the average response of whole plant biomass was +51%.

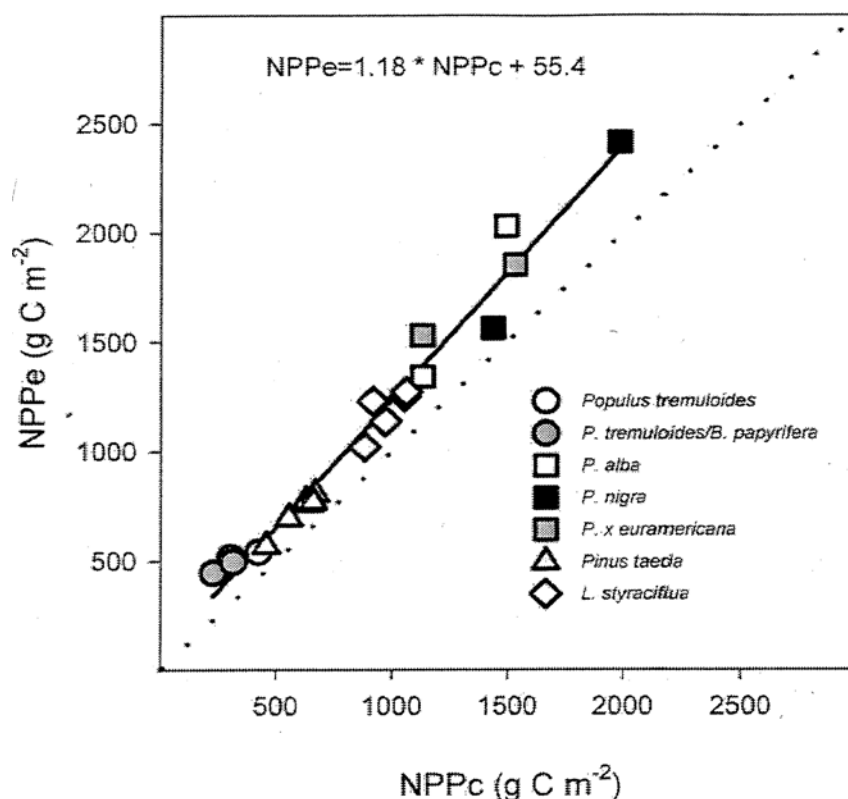
Thus, again, for short term experiments in enclosures a positive response, in the range of approximately 15 – 50% depending on other environmental variables, was still emerging from the experiments. However, these studies did not address longer term feedbacks that might cause down-regulation of the response. Foremost in investigators' minds in the 1980s was the potential restriction imposed by the rate of soil N-mineralisation into soluble forms suitable for plant uptake. Concepts leading eventually to the enunciation of the "progressive nitrogen limitation" (PNL) hypothesis (Luo et al. 2004) became popularised. Under the progressive N-limitation notion more and more of the potentially available soil N is tied up in vegetation as the growth responds to elevated CO<sub>2</sub> gradually restricting the response of tree growth. An earlier more comprehensive hypothesis was that the N supply-rate limitation feedback onto growth-responsiveness to CO<sub>2</sub> is one that operates over the relatively short time scale of a few seasons, but that in the longer term of decades to centuries (that is appropriate to questions of global climate change) it is likely to be the carbon supply to an ecosystem that determines the amount of N in circulation in it (Gifford 1992, 1993, 1994, Gifford et al. 1996) – the "nitrogen cycle tracks the carbon cycle" hypothesis. By 2006 proponents of the PNL concept had started to conclude that the nitrogen cycle and the carbon cycle are closely coupled to each other (Luo et al. 2006a, Luo et al. 2006b, Finzi et al. 2006).

Important to the evidence supporting the PNL concept were the results from the initial 7 years of the loblolly pine FACE study at Duke University - the first forest-FACE experiment (Oren et al. 2001). In that study the annual carbon increment in woody tissue (above- plus below-ground) declined from year to year. Over the first 3 years woody growth of the forest under the 200ppm elevation of CO<sub>2</sub> concentration averaged a 34% increase over the ambient CO<sub>2</sub> control. But the response had declined to less than 10% by 2000 after 7 years of elevated CO<sub>2</sub> concentration. This was ascribed to most of the available N being used up after 3 years. Thus the PNL hypothesis seemed to apply. The experiment has continued and since that time, the picture has changed: as the absolute rate of forest growth in the ambient plots declined from year to year the fractional growth response to elevated CO<sub>2</sub> concentration increased sharply after 2000 (R. Oren and H.M. McCarthy, personal communication). The high rates of response measured from 2003 to 2005 may have been to do with a large differential between the ambient and

elevated CO<sub>2</sub> plots in top loss and defoliation during an ice storm in December 2002: the elevated CO<sub>2</sub> trees were less affected by the ice than were the ambient (McCarthy et al. 2006). The high fractional response in 2005 might have also been a reflection of that year being a drought year (R Oren pers. communication). It is yet to be determined whether the recovery of the response after year 7 is in part an expression of the increased carbon input causing the forest to acquire more N from the atmosphere as hypothesised by Gifford (1992). These results emphasise the need for Forest FACE experiments to continue long enough for the slow pace of forest ecosystem behaviour, and occurrence of extreme weather events, to be expressed and for comprehensive measurements of ecosystem processes to accompany growth measurements.

Over the 12 years of the loblolly FACE study so far, the average response of annual woody increment to 200ppm CO<sub>2</sub> enrichment above an average ambient control of about 370ppm has been +30%. It compares with the average 36% response of seedling growth rate found for a 330ppm increase above a 330ppm ambient base in Kimball's (1983) review. Interpolating linearly for the 36% increase in rate between 330ppm and 660ppm, an 18% response is predicted between 370ppm and 570ppm. (Alternatively, and better, using a quadratic interpolation, assuming a 50ppm CO<sub>2</sub> compensation point, the "expected" loblolly response to the 200ppm enrichment from 370-570ppm would be 23% rather than 18%). Thus the first forest-FACE study is yielding, on average over 12 years, a stronger growth response of woody tissue growth (30%) than the original chamber results summarised by Kimball (1983) would predict by simplistic application of relative growth enhancement observations.

It is better to use NPP, rather than woody growth, as a basis of comparison of growth to allow for fine root and leaf turnover. Norby et al. (2005) has carried out just such a comparison for the four plantation-FACE experiments in existence (DukeFACE on *Pinus taeda*, AspenFACE on *Populus tremuloides*, ORNL-FACE on *Liquidamber styraciflua*, and EuroFACE on several *Populus* species). The average ambient CO<sub>2</sub> concentration for these studies was 376ppm and they all used 200ppm enrichment. Figure 2 shows a regression of NPP under 200ppm CO<sub>2</sub> elevation against NPP under the ambient atmosphere that averaged 376ppm. There is a remarkable uniform CO<sub>2</sub> enrichment effect across the wide range of NPP observed over the several years. At the median of the range observed, the regression predicts that the CO<sub>2</sub> enrichment increased by 23%. This is similar to the prediction, scaled to a 376-570ppm contrast, that the original Kimball (1983) review indicated (ie ~18% using linear interpolation or ~23% using quadratic interpolation). Thus over four studies with very different plantation trees, the chamber results and FACE results are concordant. The authors note that there was no evidence of a negative feedback onto NPP as a result of lack of N-availability in the four studies. However, all four studies were conducted on relatively fast growing young plantation species in soils that one would expect to be more fertile than typical for Australian native forests.



**Figure 2.** Response of ecosystem net primary production to a 200 ppm CO<sub>2</sub> enrichment (e) over several years for all the plantation field FACE sites. From Norby et al (2005).

Although the four plantation systems had remarkably similar %-increases in NPP under 200ppm CO<sub>2</sub> enrichment, the deployment of that increase in C acquisition was very different between some of them. DeLucia et al. (2005) reported that in the loblolly pine the increment in NPP over the first 5 years appeared mostly in long lived woody tissues (stem and root), in the liquidambar forest the increment in productivity was allocated mostly to fine roots that tend to have short lives. Thus the nutrient dynamic feedbacks are likely to be very different between the coniferous system and the broad leaf deciduous system. In the coniferous loblolly system the incremental growth will gradually tie-up mineral nutrients in long lived woody tissue such that there is potential for progressive mineral limitation to develop over time unless added carbon enables the ecosystem to access otherwise unavailable minerals (Gifford 1992, 1994). In the liquidambar system, the accelerated fine-root turnover will rapidly cycle minerals back into soil organic matter. With that process one might expect soil organic C stocks to increase under the elevated CO<sub>2</sub> more under the liquidambar than under the loblolly system. Indeed, consistent with that logic, in the loblolly system no increase of bulk mineral soil C and N, or of particulate organic fraction C & N content, was observed after 6 years of elevated CO<sub>2</sub> (Lichter et al. 2005). By contrast, in the liquidambar plantation soil, C stocks had been increased 2.20 t C ha<sup>-1</sup> by the first 5 years of elevated CO<sub>2</sub> (Norby et al. 2006).



For Australia, with its many fire-prone evergreen broadleaf forests, it is important from the point of view of the national carbon budget under globally increasing CO<sub>2</sub> concentration to know whether any consequential accumulation of C in such ecosystems is occurring largely above ground (as in evergreen needle-leaf loblolly), where it is vulnerable to rapid release by fire, or below ground (as in broadleaf deciduous liquidamber) where it is relatively protected from rapid release by fire. Clarification of such potential changes against large spatial variation requires well-designed experiments, having excellent pre-treatment site characterisation, conducted over long time periods of at least a decade.

In conclusion, the FACE studies on overseas young plantation forests so far have all shown systematic increases in forest net primary production (growth rate) and in net carbon accrual into the ecosystems over several years under elevated CO<sub>2</sub> concentration that are quantitatively consistent with the responses of the much shorter term experiments conducted before the 1983 benchmark review (Kimball 1983) on much younger trees in enclosure studies. No persistent “acclimation” of the growth response has been observed in the field.

Some outstanding issues yet to be discovered for the growth response to elevated CO<sub>2</sub> are:

- Does the proposed short term (0-5 years) “progressive nitrogen limitation” to productivity response to elevated CO<sub>2</sub> become overtaken by the proposed longer term “nitrogen cycle follows the carbon cycle” phenomenon in Australian forest systems that are also both water and phosphorus co-limited?
- As a forest approaches maturity (ie when tissue and plant death rate approaches new growth rate) does the forest live biomass, and whole-ecosystem C stocks, stabilize at a higher level under elevated CO<sub>2</sub> concentration?
- How do Australian trees tend to allocate CO<sub>2</sub> induced increases in NPP between long-lived woody components and fast turnover litter components?
- Under typical Australian conditions of low rainfall dry sclerophyll type of evergreen forest, does elevated CO<sub>2</sub> have a larger % enhancement effect or a smaller % effect on annual NPP and accumulation of live biomass than for the four northern hemisphere temperate plantations?
- Under common Australian conditions of low phosphorus nutrition, concurrent with low rainfall, is the elevated CO<sub>2</sub> effect on growth and biomass accumulation lower than for the four northern hemisphere temperate plantations?

#### **4.1.6 Potential effects on forest ecosystem carbon cycle**

A variety of potential effects on the pools and fluxes of C in forest ecosystem are possible. These range from:

- no effect

- a strong initial positive increase of plant biomass that within a few years relaxes back to no effect owing to mineral nutrient limitations,
- a strong long term effect on standing stocks both above and below ground as the elevated CO<sub>2</sub> conditions provide the trees with the metabolic energy to acquire more of the mineral nutrients in the soil and air that require energy to mobilise.

Further possible effects involve unexpected changes to insect herbivory: either increased due to the need for the insects to eat more leaf to gain enough nitrogen for survival; or decreased owing to the lower N-contents of leaves reducing insect fecundity and herbivore numbers; or altered due to the activity of herbivore parasites and predators. Many options are possible, but only observations will determine reality.

## ***4.2 Atmospheric CO<sub>2</sub> concentrations and ecohydrology – a primer***

### **4.2.1 Australia is dry, getting drier in parts and demand for water in increasing**

That Australia is a dry continent is undoubted. Mean annual rainfall is approximately 400 mm, which is much lower than that of Africa (750 mm), North America (800 mm), South America (1800 mm) or Europe (820 mm). Total annual rainfall is highly variable, but Foran and Poldy (2002) estimate an average input of about 3,350,000 GL of rain to the continent. However, because of the large evaporative demand of the atmosphere over much of Australia for most of the year, about 90% of this is evapotranspired each year. The remaining 10% is lost to sea as river flow. Consequently there is little spare capacity in the continent's water budget for supplying new demands for water (for example, increased demand as the population increases or the area of irrigated crops and pastures increases, or for increased allocations to the environment).

Rainfall along the eastern seaboard and in SW Australia has been declining for the past 50 years. Up to 80 mm per decade has been lost from annual rainfall. Simultaneously, demand for water in the 20<sup>th</sup> century increased substantially because of increasing population and demand by agricultural and other industries. This demand was met by increased extraction from rivers, increased construction of dams and increased extraction from groundwater stores. Between 1983 and 1996, for example, groundwater extraction doubled and exceeded the rate of recharge in a large number of aquifers.

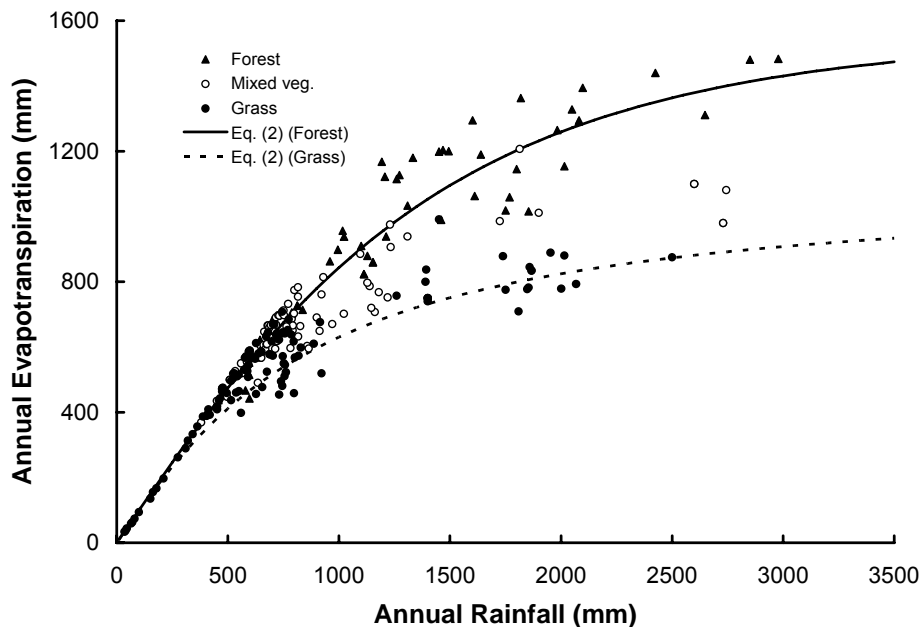
*Given the above, it is clear that understanding how climate and atmospheric change will influence the ecohydrology of Australian landscapes is vital. A forest FACE experiment incorporating a focus on water will allow a better understanding of this issue for forested landscapes.*

#### 4.2.2 Recharge, vegetation water use and climate relationships

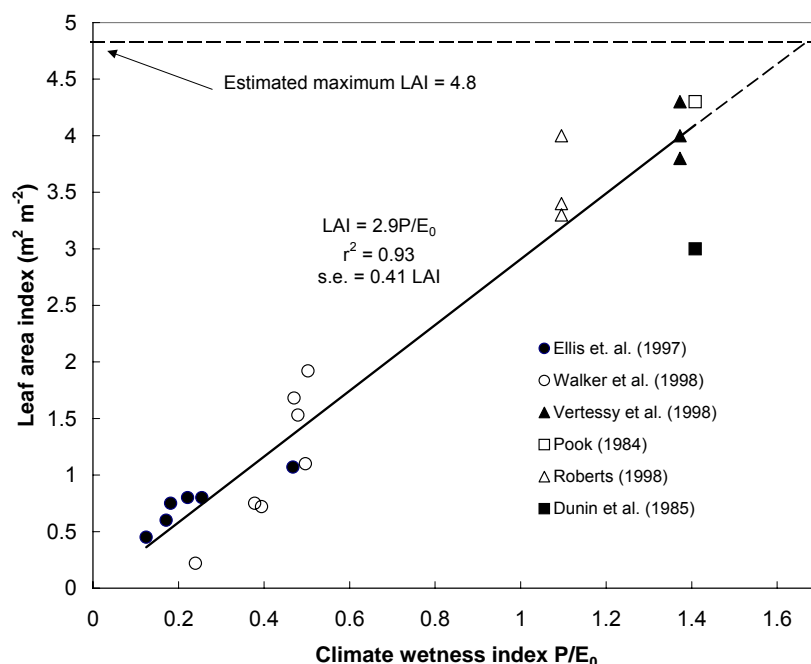
The amount of recharge of aquifers beneath landscapes with a natural cover of wooded and forested catchments in Australia is typically between 0.1 and 10 mm per year for temperate Australia. Significantly altering the vegetation cover of landscapes alters the hydrological balance. For instance, denuding landscapes of trees causes recharge to increase by an order of magnitude or more, thereby raising the water-table and causing dryland salinity across much of temperate Australia. River flow and river salinity are also responsive to significant changes in vegetation cover across landscapes.

Vegetation growth and water use increase as rainfall increases from very low levels (~200 mm rainfall per year) to moderately high levels of rainfall (~ 1200 - 1400 mm annual rainfall). At very high levels of rainfall (2000 mm or more), water use and productivity tend towards an asymptotic value. Figures 3 and 4 demonstrate these relationships. However, the relationship between rainfall and annual evapotranspiration, climate wetness and LAI, and LAI and evapotranspiration may differ markedly in the future compared with today.

*As discussed in the following section, and summarised in Figure 5, climate and atmospheric change may alter leaf area index, tree water use, annual catchment water balance and thus the ecohydrology of Australian landscapes. These issues are discussed later in this report.*



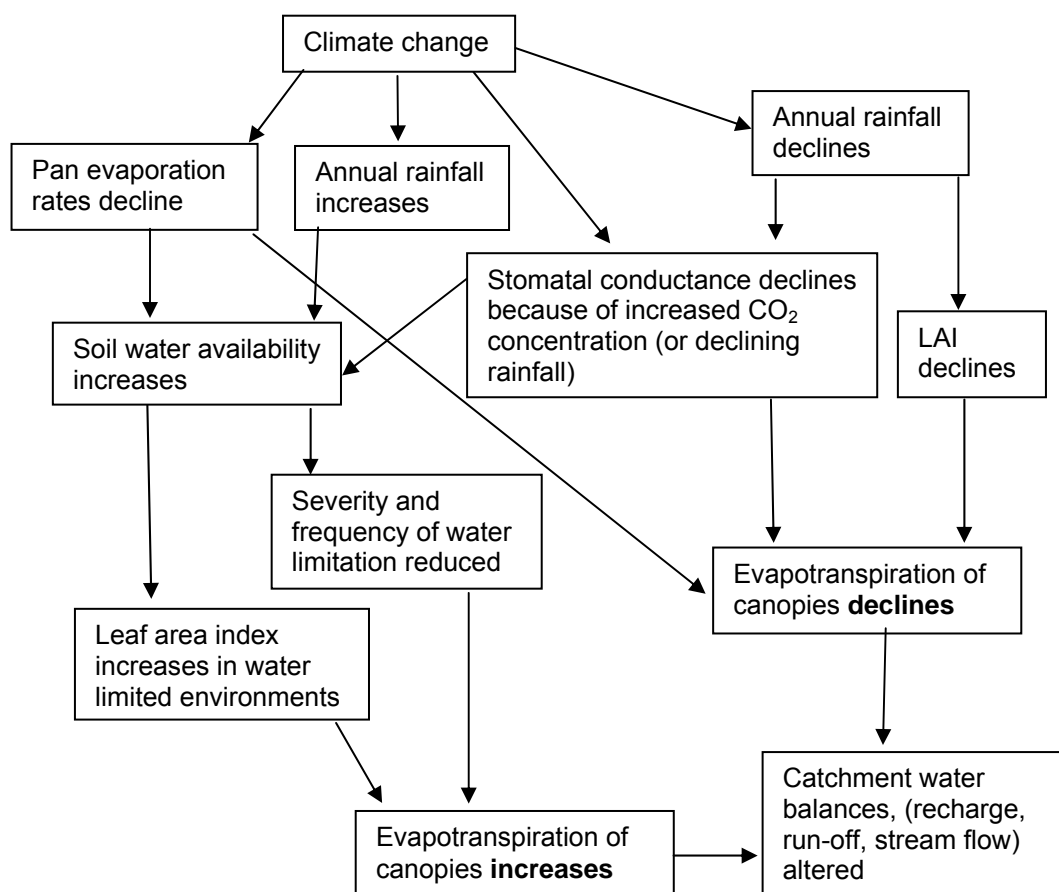
**Figure 3.** Relationship between annual evapotranspiration and rainfall for different vegetation types. After Zhang et al. (1999).



**Figure 4.** LAI of natural eucalypt forest in southern Australia versus a climate wetness index (average annual rainfall  $P$  divided by average annual pan evaporation  $E_0$ ). From Ellis et al. (1999).

#### 4.2.3 A conceptual framework for examining the influence of climate change and CO<sub>2</sub> concentration on ecohydrology

Figure 5 provides a series of possible changes at tree, canopy and landscape-scales for the impact of climate change and CO<sub>2</sub> enrichment on landscape ecohydrology. The major conclusion to be drawn from Figure 5 is that catchment water balances are likely to be affected by CO<sub>2</sub> enrichment and that given the importance of managing Australia's water resources, a FACE experiment that addresses this issue will be of national importance.



**Figure 5.** Possible links between climate change and altered catchment water balance. The major unknown is the outcome of the balance between declining stomatal conductance and pan evaporation, and hence reduced water use by tree canopies (the right hand side of the figure) and the alternative pathway presented on the left whereby LAI increases and hence canopy water use increases. Not presented in this figure are effects on major disturbances such as bushfire, or on shifts in allocation of carbon between root and shoot biomass (see below for discussion). Also not shown is the impact of changed rainfall intensity that affects run-off fraction.

#### 4.2.4 Possible linkages between woody thickening, water availability and climate change

Increases in above-ground woody biomass, reflected as an increase in shrub density in aerial photographs, have been recorded for the semi-arid regions of Australia (Fensham and Fairfax 2003). Between 1948 and 1997, for example, overstorey cover increased from a regional average of 11.5% to 13.5% and understorey cover increased from 1.3% to 2.0% in Queensland. Similar increases in woody density have been observed in other parts of the world such as South Africa (Hoffman and O'Connor 1999, Gifford and Howden 2001). *Increases in woody biomass will influence the albedo of Australia's landscapes and the water balance of those landscapes through changes in leaf area index and hence rates of canopy water use.*

Most of the woodlands of Australia are water-limited. Climate and atmospheric change will alter the amount, the timing and spatial distribution of rainfall and increase the supply of CO<sub>2</sub> for photosynthesis. Pan evaporation rates have declined at many sites between 1970 and 2002 (Roderick and Farquhar 2002). It would be expected, therefore, that these changes may affect vegetation growth in Australian landscapes and this could be reflected in the standing biomass (carbon density) and water use. Woody thickening (increased standing biomass) will reduce grass production, and alter the local, and potentially regional, carbon and water budgets. These issues are now discussed more extensively.

In contrast to the common expectation that global warming would result in increased evaporative demand, there is no general trend of increasing Australian continental evaporation from open water surfaces – a measure of evaporative demand. This is in line with similar findings elsewhere in the world (Gifford et al. 2007). Indeed the overall continental trend for pan evaporation ( $E_{\text{pan}}$ ) over almost four decades has been confirmed to be slightly downwards by between 1 and 3 mm yr<sup>-2</sup> (Roderick and Farquhar 2004, Sharples and Hutchinson 2005, Rayner 2007), though with a “homogenised” data set (ie adjusted for assumed errors), (Jovanovic et al., submitted) there is a question as to whether the continental average decline of -2.5mm yr<sup>-2</sup> was significantly different from zero. The overwhelming cause of the trend at stations showing such decline is declining windspeeds (Roderick and Farquhar 2006; Rayner 2007). Thus it seems that global warming has not increased evaporative demand in Australia and that independence of the temperature and pan evaporation trends over the last 3 – 4 decades cautions against assuming that potential evaporation increases with global warming (Jovanovic et al., submitted).

Increased levels of deep soil moisture favour woody C3 shrubs rather than grasses (the Walter Hypothesis of grass-shrub interaction; Walter 1971). Vapour pressure deficit (VPD) has decreased for water-limited ecosystems of Africa, Australia and the Indian sub-continent (Nemani et al. 2003). This, together with decreasing evaporative demand measured by pan evaporation for the arid and semi-arid regions of southern Africa and Australia, raises the question “where is the water going?” Either soil moisture content is increasing or excess moisture is being lost through actual evapotranspiration or increased run-off. The latter appears to be the case, and is reflected in both simulations and run-off studies (Labat et al. 2004), but does not account for all the excess moisture. There is evidence of global soil moisture increasing (Robock et al. 2005), with a positive soil moisture trend for the period 1958-2002 in the Ukraine, for example. While models of global warming predict summer soil desiccation, there is no evidence for this in observations yet, even though the Ukraine has been warming for the entire period (Robock et al. 2005). For arid and semi-arid regions of the southern hemisphere, evidence of increases in soil moisture in response to climate change is limited. However, elevated moisture levels across land-use gradients has been documented in sparsely grassed, deep sand-dunes of the southern Kalahari (Van Rooyen 1999). This higher soil moisture status may explain the

increased success of C3 shrubs and trees, including *Acacia mellifera* and *Rhigozum trichotomum*, as evidenced by woody thickening.

Another factor that may be contributing to the increasing soil moisture levels is decreasing Gs resulting from increasing atmospheric CO<sub>2</sub> levels (observed for most woody taxa; Medlyn et al. 2001; Eamus and Jarvis 1989). It is presumed that the increase from pre-industrial concentrations of CO<sub>2</sub> to present-day levels has had and will have a continuous effect.

A simple prediction is apparent from this scenario of observed woody thickening. If transpiration rates (per unit leaf area) have declined (because of increased atmospheric CO<sub>2</sub> concentration) and the rate of photosynthesis (per unit leaf area) has increased, over the past century, then long-term increases in WUE should be observed in the field. In support of this is the observation that a significant long-term increase in WUE over the past 100 years has been reported (Sauer et al. 2004).

A second major prediction from this discussion of woody thickening is that continental river run-off rates might be expected to increase, if soil moisture increases are maintained for several years prior to the attainment of a new, higher, equilibrium LAI. In recent years, modelling and field observations suggest that there is indeed a direct CO<sub>2</sub> effect on rates of run-off and that run-off has been increasing throughout much of the 20<sup>th</sup> century (Labat et al. 2004; Gedney et al. 2006). Indeed, Gedney et al. (2006) conclude from their analyses, that reduced transpiration from vegetation was the most important factor explaining increased run-off and that alternative explanations for the run-off trends were not supported by the data.

For water limited woodlands, aspects of these interactions have been investigated by Bond et al. (2000, 2003). Tree abundance in many such systems (for example, savannas, which cover 25% of Australia) is constrained by disturbance (fire, herbivory) and increases in CO<sub>2</sub> concentration could reduce this limitation and may be a contributing factor explaining woody thickening in savannas. Bond et al. (2003) used a Dynamic Global Vegetation Model (DGVM) to examine growth responses of trees and grasses at a low and high atmospheric CO<sub>2</sub> concentration (relative to contemporary levels). At high CO<sub>2</sub>, woody growth was promoted and Bond et al. (2003) suggested that this growth advantage would be particularly significant for post-fire recovery of tree saplings, providing a competitive edge over competing grasses. At low CO<sub>2</sub> (~180 ppmv) sapling recovery rates were low and trees were replaced by grasses. These simulations suggest that atmospheric change may have profound effects on savanna structure and function, especially when other impacts of climate change (modified rainfall patterns, enhanced fire risk, enhanced nitrification) are factored in. Savanna and associated ecosystems support approximately 1/5th of the world population and clearly increased knowledge of such interactions will provide improved understanding of savanna processes and guide better management. Savannas cover about 24% of the Australian continent, and if temperate open woodland is included, this equates to about 80%.

#### 4.2.5 Tree water use

Cech et al. (2003) observed an 11% decline in mean daily sap flux density in response to CO<sub>2</sub> enrichment for 14 broadleaved trees in a 30 m high mixed species forest in Switzerland. However, the response was highly species specific with some species (eg *Acer* and *Prunus*) showing a large response, and some species showing almost no response (*Quercus* and *Fagus*). This variation among species is commonly observed. Thus Wong and Dunin (1987) showed a reduced rate of transpiration for a eucalypt under CO<sub>2</sub>-enriched conditions. This is similar to the results of Kellomaki and Wang (1998) and Wullschleger and Norby (2001); all found decreased transpiration rates in response to CO<sub>2</sub> enrichment. In contrast, Pataki et al. (1998), Ellsworth (1999) and Schäfer et al. (2003) observed no effect of CO<sub>2</sub> enrichment on transpiration of *Pinus taeda*. The cause of a reduced rate of water use is not always attributed to a decline in Gs. Tognetti et al. (1998, 1999) showed that the decline in water use of two oak species was the result of a decrease in total leaf area per tree rather than a decline in Gs.

Much of this variability in the response of tree water use to CO<sub>2</sub> enrichment is most likely a function of the differential response of stomata to CO<sub>2</sub> enrichment under conditions of high and low evaporative demand. The percentage reduction in sapflux density observed by Cech et al. (2003) was largest when vapour pressure deficit (VPD) was small (ie moist air) and smallest when VPD was large. During a relatively dry period, the effect of CO<sub>2</sub> enrichment was reversed – that is, sapflux density (Js) increased compared to control trees, possibly because of enhanced leaf water status in the preceding period when Js was reduced and so soil moisture was “conserved”. This is in contrast to the results of Wullschleger and Norby (2001) who found that sap velocity declined by 13% only when VPD was large and net radiation (Rn) was large. Kellomaki and Wang (1998) similarly show that the response of transpiration rate to CO<sub>2</sub> enrichment was determined by the VPD and Rn of the day.

Hanson et al. (2005) used a refined version of the LINKAGES model to simulate change in forest water use due to changes in atmospheric CO<sub>2</sub> concentration and temperature. They observed a decline in stand-scale water use of 20% over the year, mostly attributed to the input of a 9% reduction in Gs and a 7.5% increase in leaf area. When increased air temperature was included in the modelling along with a CO<sub>2</sub> increase, canopy water use decreased by 24%.

In addition to significant variation in the response of tree water use to CO<sub>2</sub> enrichment, there are significant differences between years in the response of a single species at a single site. Wang et al. (2005) examined the response of transpiration and water use of *Pinus sylvestris* trees to CO<sub>2</sub> enrichment. They found that during the 3rd year after the start of fumigation with CO<sub>2</sub> (the first year of measurement), tree water use (expressed per tree) was enhanced by 14% but in the 4<sup>th</sup> and 5<sup>th</sup> years, tree water use was decreased by 13 and 16%, relative to control trees. The cause of the difference in response of tree water use was ascribed to the imbalance between changes in canopy conductance (Gc) and leaf area in the three study years (see below). This



further emphasises the importance of considering canopy responses to CO<sub>2</sub> enrichment, rather than stomatal responses, when considering the possible responses of forest water use to CO<sub>2</sub> enrichment.

Tree water use is very much a function of the radiation and VPD climate experienced by the canopy. Li et al. (2003) observed a significant decline in transpiration rate of *Quercus myrtifolia* growing in open-top-chambers in Florida when exposed to CO<sub>2</sub> enrichment. Whilst much of the reduction was because of the reduced Gs observed in response to CO<sub>2</sub> enrichment, and the decoupling factor was low for this ecosystem (0.25), a significant additional factor was an increase in self-shading resulting from the increase in leaf area index of 20 – 40% (Li et al. 2003). This contrasts with the results of Gielen et al. (2003) who found that after canopy closure the effects of CO<sub>2</sub> enrichment on canopy architecture, light absorption and LAI were minimal.

It is important that the key drivers of tree water use (soil water availability, LAI, VPD, solar radiation, G<sub>s</sub>) are measured in studies examining the effects of elevated CO<sub>2</sub> if we are to advance our understanding.

*An Australian forest FACE experiment will be able to specifically examine canopy water use and rates of soil recharge, under CO<sub>2</sub> enriched conditions. Determining effects of elevated CO<sub>2</sub> on the catchment water balance in woody systems is clearly in the national interest.*

#### **4.2.6 Soil moisture and plant water status under CO<sub>2</sub> enriched conditions**

Reduced transpiration (E) at the tree-scale could result in an enhanced soil moisture content which may have two impacts, over the medium and longer terms (Morgan et al. 2004). Over short time frames (weeks, months) enhanced soil moisture could result in a larger Gs for CO<sub>2</sub> enriched trees than control trees, for example, during dry periods. Higher soil moisture would also lead to greater turnover of soil organic matter and mineralization of nutrients. Over long time-frames (decades and longer) increased woody growth may result and stand density and LAI may be increased (see below for discussion of LAI responses). Reduced E or increased soil water content has been observed in grasslands, crops, salt marsh and alpine grasslands, but responses in woody species are less clear. Cech et al. (2003) showed that CO<sub>2</sub> enrichment increased soil moisture content in mid-summer, and Hungate et al. (2002) showed reduced E and increased soil moisture content under CO<sub>2</sub>-enriched conditions in a scrub-oak shrubland FACE, despite LAI increasing. In a unique aspect of that study, they showed that groundwater uptake by the oak was probably reduced by elevated CO<sub>2</sub>. The importance of groundwater to ecosystem structure and function is only recently being recognised in Australia (Eamus et al. 2006).

Canopy water use is generally reduced by CO<sub>2</sub> enrichment in grasslands (Field et al. 1997, Niklaus et al. 1998) and in FACE tree experiments (Wullschelger and Norby 2001, Cech et al. 2003). For the grassland studies, savings of up to 87 mm annually were observed and this was translated into

larger soil moisture contents for parts of the year. Wullschelger and Norby (2001) calculated a 20 mm saving in water use which could be converted to an extra 38 g biomass produced per m<sup>2</sup> of ground area in a sweetgum forest. Similarly, Owensby et al. (1997, cited in Wullschlegler et al. 2002a) showed increased soil water content and increased assimilation during periods of low water availability. Implications for Australia of these results are significant, given the woody thickening hypothesis above and given the frequency and extent of drought and water limitations to growth that are observed across almost all of temperate Australia.

Can reduced Gs and reduced rates of tree water use maintain a favourable plant water status for longer, in response to CO<sub>2</sub> enrichment? Agricultural plants generally have a less negative (more favourable) water potential under CO<sub>2</sub> enriched conditions. Eamus et al. (1995a) observed that CO<sub>2</sub> enrichment increased leaf water potentials in two tropical Australian tree species. Wullschlegler et al. (2002a) reviewed many of the studies published between 1990 and 2000 and showed that the majority of studies show a positive impact of CO<sub>2</sub> enrichment on water status. For example, Eamus et al. (1995a) and Tognetti et al. (2000a, b) found an increased cell turgor, better osmotic adjustment and more favourable water balance, and decreased whole plant hydraulic conductance for a number of woody species. These differences were larger during drought than more mesic conditions, indicating the importance of this effect during periods of low water availability. In contrast, Tognetti et al. (1998) found decreased sap flux and decreased hydraulic conductance too, but no effect on leaf water potential, a result in agreement with that of Ferris and Taylor (1994), who observed no effect of CO<sub>2</sub> enrichment on leaf water potential. Occasional studies show leaf water potential declines with CO<sub>2</sub> enrichment (Centritto et al. 1999) but such responses appear to be rare. The increase in leaf water status that is generally observed in broad leaved species in response to CO<sub>2</sub> enrichment can result in Gs being higher during drought (Heath and Kerstiens 1997).

Coniferous species generally have stomata that are less responsive to CO<sub>2</sub> enrichment than broad-leaved species and this can mean that they have a less responsive plant water status than broad-leaved species. Ellsworth (1999) examined water potential (soil, and pre-dawn and midday needle water potentials) of *Pinus taeda* fascicles growing in a FACE experiment. He observed no impact of CO<sub>2</sub> enrichment on soil water potentials nor pre-dawn or mid-day needle water potential during a drying cycle. Similarly there was no effect of treatment on turgor loss point and osmotic potential at full hydration, further supporting the conclusion of no impact of CO<sub>2</sub> enrichment on the water relations of needle-leaves species. This is in contrast to the increased leaf water potentials observed for a broad-leaved Australian tropical trees grown under CO<sub>2</sub>-enriched conditions (Eamus et al. 1995a). They observed that for both a savanna eucalypt and a closed monsoon forest species, maximum turgor and bulk volumetric elastic modulus increased and osmotic potential at zero turgor decreased for trees grown under CO<sub>2</sub>-enriched conditions (Eamus et al. 1995a). Because of the decline in Gs and transpiration rates observed, whole tree hydraulic conductance (Lp) was reduced in both species under CO<sub>2</sub>-enriched conditions. Meinzer et al. (1988)

has shown how the  $L_p$  of a tree is linearly correlated with the maximum daily  $G_s$  and the observed decline in  $L_p$  in the study of Eamus et al. (1995a) confirms this response. Furthermore, Eamus et al. (1995a) show how transpiration rate and  $L_p$  are correlated. This may have significant implications for the hydraulic architecture of trees grown under CO<sub>2</sub>-enriched conditions since hydraulic constraints limit tree growth and photosynthetic rate (Ryan and Yoder 1997).

Not only did Ellsworth (1999) not find an effect of CO<sub>2</sub> enrichment on  $G_s$  and needle water potential, but he found no evidence of water savings in CO<sub>2</sub>-enriched plots. This is similar to the result of Nowak et al. (2004) who found no increase in soil moisture content throughout a four year FACE experiment in the Mojave desert. These authors concluded that increased productivity (involving increased LAI) offset the potential savings in water use resulting from decreased  $G_s$ . Although the possibility of the “blower effect” in FACE experiments cannot be discounted, the fact that water content at 0.5m and 1.85m depth was unaffected in the Mojave study suggests that the lack of a response was real.

Solute accumulation is a principal mechanism by which CO<sub>2</sub> enrichment may influence plant water relations (Eamus et al. 2006). There are extensive reports of solute accumulation increasing in response to CO<sub>2</sub> enrichment including Morse et al. (1993), Ferris and Taylor (1994), Eamus et al. (1995b) and Vivin et al. (1996). However, this result is by no means universal and Tschaplinski et al. (1995) found no effect in 3 tree species, a result they ascribed to the rapid growth of leaves which may deplete C reserves and thereby reduce the capacity for osmoregulation. Similarly, Picon-Cochard and Guehl (1999) and Polley et al. (1999) observed no effect of CO<sub>2</sub> enrichment on osmoregulation. In their review, Wullschleger et al. (2002a) concluded that the effect of CO<sub>2</sub> enrichment on solute accumulation is secondary and minimal.

*As stated in 4.2.5 above, an Australian FACE experiment will be very valuable in improving knowledge of the effects of elevated CO<sub>2</sub> on water use by Australia's woody vegetation.*

#### **4.2.7 Stomatal conductance responses**

Conifers generally show the smallest response of  $G_s$  to CO<sub>2</sub> enrichment (compare Lodge et al. 2001 and Wullschleger et al. 2002b with Ellsworth et al. 1995 and Pataki et al. 1998). In her meta-analyses, Medlyn et al. (2001) found that conductance was reduced by an average of 21% in broad leaved deciduous, woody species, and by 8% for evergreen broadleaved woody species. This meta-analysis also showed that stomata of young trees (< 10 y old) exhibited a larger response (- 25%) than old (> 10 y) trees (-9%) and water-stressed trees showed a larger response than those having no water stress or a nutrient stress.

Although Medlyn et al. (2001) did not find any impact of CO<sub>2</sub> enrichment on the response of  $G_s$  to vapour pressure deficit or soil water potential, many

other researchers do find an interaction. Thus Morison and Gifford (1983), Berryman et al. (1994), Wang et al. (2005) and Lodge et al. (2001) found that stomatal responses to vapour pressure deficit and a number of other regulators of stomatal aperture were significantly altered by CO<sub>2</sub> enrichment. Similarly, Wullschleger et al. (2002b), Heath (1998) and Kellomaki and Wang (1998) found that the reduction in G<sub>s</sub> in response to CO<sub>2</sub> enrichment was dependent on vapour pressure deficit and soil water content.

Some of the reduction in G<sub>s</sub> can be attributed to a change in stomatal index or stomatal density. Eamus et al. (1993) and Berryman et al. (1994) found 12% and 20% reductions in stomatal density, respectively, in two tropical tree species in response to CO<sub>2</sub> enrichment. Such reductions are generally (Woodward 1987; Roth-Nebelsick 2005) but not universally (Thomas and Harvey 1983) observed. Such variability may be a result of differences in growth conditions during the experiments. Thus, Tricker et al. (2005) found, in their 5y FACE experiment, that stomatal index decreased in the first year and stomatal density in the first 2 years, when the canopy was open. However, once the canopy was closed, CO<sub>2</sub> enrichment had no effect on either density or index. Goodfellow et al. (1997) showed that the impact of changes in stomatal density was minimal in terms of determining the absolute leaf conductance value.

Although changes in G<sub>s</sub> have often been used to infer that changes in transpiration rate and hence tree water use also occur, there are many reasons why such an inference can be wrong or of the wrong magnitude. First, changes in G<sub>s</sub> alter leaf energy balances and hence the gradient of vapour pressure difference between inside and outside the leaf. Second, G<sub>c</sub> is a function of leaf area index, canopy volume and canopy properties such as surface roughness. Consequently changes in leaf-scale conductance cannot be used to accurately predict canopy-or stand-scale changes in water use. We know of only one example of the difference between stomatal and canopy conductance under CO<sub>2</sub> enriched conditions by Wullschleger et al. (2002b), although comparisons of stomatal and canopy conductance behaviours under ambient conditions are more common (see Zeppel 2006). Wullschleger et al. (2002b) observed that although G<sub>s</sub> was reduced by 44% under CO<sub>2</sub> enriched conditions, G<sub>c</sub> was reduced by only 14%. As observed for G<sub>s</sub>, the impact of CO<sub>2</sub> enrichment on G<sub>c</sub> was dependent upon soil moisture and vapour pressure deficit, with a smaller impact (less than 0.2 mol m<sup>-2</sup> s<sup>-1</sup>) observed when vapour pressure deficit was large or soil moisture content was low early and late in the growing season, but large (0.6 mol m<sup>-2</sup> s<sup>-1</sup>) in the mid-season.

Wang et al. (2005) examined the impact of CO<sub>2</sub> enrichment on G<sub>c</sub> of Scots pine (*Pinus sylvestris*) growing in open-top-chambers. A small but significant decline in G<sub>c</sub> was observed and the decline increased in the 3<sup>rd</sup>, 4<sup>th</sup> and 5<sup>th</sup> year of fumigation. The impact of CO<sub>2</sub> enrichment on G<sub>c</sub> has not previously been examined despite its importance in determining canopy transpiration rate and hence catchment water balance. Despite this consistent decline in G<sub>c</sub> for all three years, the response of tree water use was not consistent. Thus, in the first year after fumigation started, tree water use was increased by 14%, but it had decreased by 13 and 16% in the 4<sup>th</sup> and 5<sup>th</sup> years of

fumigation with CO<sub>2</sub>. The increase in water use in the first year was attributed to the fact that the increase in leaf area per tree in the first year was much larger than the decline in G<sub>c</sub> in the first year and because there was an increased sensitivity of G<sub>c</sub> to high VPD in the CO<sub>2</sub>-enriched trees (Wang et al. 2005). The decline in tree water use in the 4<sup>th</sup> and 5<sup>th</sup> year of fumigation with CO<sub>2</sub> was attributed to the fact that the decline in G<sub>c</sub> was larger than the increase in leaf area per tree. This study highlights the importance of examining large-scale responses (ie, larger than leaf and tree) of woody vegetation as it is generally difficult and often erroneous to make simple extrapolations from leaf to canopy-scale processes.

#### **4.2.8 Effects of CO<sub>2</sub>-enrichment on plant water relations in water limited environments**

Plant water relations are of central importance to the growth and competitive outcomes of plants in the landscape. Indicators of stressful water relations in the short to medium term include reduced leaf water potential, reduced G<sub>s</sub> and reduced water use per unit leaf area. In the medium to longer-term stressful water relations are revealed by reduced growth (biomass increment) reduced leaf area expansion and declining LAI.

It is well documented that CO<sub>2</sub> enrichment influences G<sub>s</sub> and the allocation of carbon between leaf, stem and root. Generally, leaf area per plant and root biomass increase, as does water use efficiency (WUE).

Potentially, CO<sub>2</sub> enrichment could ameliorate impacts of drought through reduced G<sub>s</sub>, increased osmotic regulation and increased root growth. Root and leaf morphology and reduced stomatal density may also ameliorate drought effects.

There tends not to be any influence of CO<sub>2</sub> enrichment on root to shoot ratio (Wullschlegel and Norby, 2001). In any case, the most important factor for water and nutrient uptake is not root mass, it is either rooting volume or the surface area of fine roots. Although King et al. (1997) observed increased root surface area in *Pinus taeda* and *P. ponderosa*, this result was because of increased plant growth overall, not a change in allocation (ie it was an allometric response).

Fine root mass (or area) to leaf area ratio is a good measure (supply to demand ratio) of the potential impact of CO<sub>2</sub> enrichment on plant water relations. Berryman et al. (1993) in a north Australian rainforest species (*Maranthos corymbosa*), found that CO<sub>2</sub> enrichment increased the root weight to leaf area ratio in the short-term, but this effect was rapidly lost. In six CO<sub>2</sub> enrichment field experiments with deciduous trees, fine root mass to leaf area ratio increased with CO<sub>2</sub> enrichment, but there was no change in conifers (Tingey et al. 2000). It is very difficult experimentally to show changes in rooting volume or changes in the capacity of roots to absorb water (as opposed to a change in the rate of transpiration). Increased root growth in early stages may increase establishment of seedlings, especially in dry conditions. Polley et al. (1996) showed increased establishment of *Prosopis*

*glandulosa* in dry conditions and an increase in the ratio of lateral to total root mass and lateral root mass to leaf area. Tischler et al. (cited in Polley et al. 1996) showed root mass at depth increased under CO<sub>2</sub> enrichment, and this uncoupled the tree from competition with grasses. Norby et al. (2006) found that annual production of fine roots was more than doubled by CO<sub>2</sub> enrichment, whilst Norby et al. (2004) showed that the increase in fine root production in a 6 year FACE experiment with sweetgum was the principal cause of the increased productivity of sweetgum in response to CO<sub>2</sub> enrichment.

In conclusion, it is possible that increased tree root growth under CO<sub>2</sub> enrichment can increase drought tolerance and increase establishment, but the experimental data is scarce. This is clearly of importance to Australian ecosystems where disturbance (and hence establishment) and drought are recurrent features of the landscape.

WUE, or more properly, instantaneous transpiration efficiency (ITE), can increase under CO<sub>2</sub>-enriched conditions (Eamus 1991). An approximate doubling of ITE is observed across a large number of studies. WUE, defined in terms of biomass produced per unit water transpired, is possibly a better measure of the impact of CO<sub>2</sub> enrichment on plant water relations than ITE because it integrates over a longer time than ITE. Water use efficiency typically shows a 20-50% increase in response to an approximate doubling of CO<sub>2</sub> concentration. The influence of CO<sub>2</sub> enrichment on WUE appears to increase under water limiting conditions (Wullschleger et al. 2002a). Increased WUE does not necessarily mean decreased whole tree water use. Centritto et al. (1999) found that total water use was unaffected by CO<sub>2</sub> enrichment in droughted cherry, but WUE was increased substantially in CO<sub>2</sub>-enriched trees. Canopy development is a key factor that allows WUE and tree water use to show different responses, as is the length of time that stomata may remain open enabling transpiration to occur.

For canopies that are open and well-coupled to the atmosphere (that is, canopy water use responds to changes in atmospheric water content and solar radiation), changes in G<sub>s</sub> induced by CO<sub>2</sub> enrichment can reduce E. However, when canopies are more closed, such as in rainforests, and are thus aerodynamically uncoupled from the atmosphere, changes in G<sub>s</sub> are relatively unimportant. For the open woodlands and shrublands of Australia, changes in G<sub>s</sub> are likely to be important in determining canopy water use, unless the change in LAI is very large. In the absence of recurrent disturbance, it is possible that the long-term changes in LAI will result in an equilibrium between LAI and water use. However, with recurrent disturbance this may not occur.

Although much has been written about ITE and WUE (Eamus 1991) it is likely that these are poor metrics for determining the impact of CO<sub>2</sub> enrichment on hydrology. The more critical issue is the extent to which CO<sub>2</sub> enrichment influences the hydrology (or water balance) of a site or catchment because this is the scale at which management and economic and environmental impacts are felt. This issue is discussed later. However, a potentially major

response of plants to CO<sub>2</sub> enrichment is a change in leaf area index (Fig. 6). Any such response is likely to be important at the scales of interest because of the role of LAI in light interception and hence C fixation and also its role in water use and catchment water balance. Changes in LAI in response to CO<sub>2</sub> enrichment are now discussed.

#### **4.2.9 LAI and larger-scale eco-hydrological impacts**

Mechanisms for increased LAI in response to CO<sub>2</sub> concentration include leaf initiation and expansion due to increased sugar availability, improved water status of the shoot, and decreased rates of leaf senescence, or simply an expression of larger plant size.

In Australia, leaf area per tree increased under CO<sub>2</sub> enrichment for two of four tropical tree species (Berryman et al. 1993; Duff et al. 1994; Goodfellow et al. 1997). This increase was most likely an allometric (size related) response and probably does not reflect the long-term response LAI of tropical trees growing under CO<sub>2</sub> enriched conditions. Indeed for one species, after two years exposure to CO<sub>2</sub>-enriched conditions and after canopy closure had occurred, there was no effect of CO<sub>2</sub> enrichment on total leaf area per tree (Goodfellow et al. 1997). However, significant increases in LAI for immature, open canopy woody systems does appear to be commonly observed (Kellomaki and Wang 1997; Goodfellow et al. 1997; Tissue et al. 1997) and such long-term increased LAI may also be of significance for plantations where faster growth and higher LAI in the early years may rapidly deplete soil moisture reserves leading to increased sensitivity to drought. *Similarly, in systems exposed to recurrent disturbance, such as bushfire, any accelerated recovery of LAI in regenerating systems will influence the ecohydrology of the system compared to that under present conditions.*

Hymus et al. (2002) examined LAI development of a Florida scrub-oak ecosystem exposed to CO<sub>2</sub>-enriched conditions in an OTC system for 3 – 5 years after a fire, and found that LAI was consistently higher under elevated CO<sub>2</sub>, with the effect larger in summer (+ 55%) than in winter (+20%). Importantly, Hymus et al. (2002) showed that the increased LAI was an allometric one, ie the trees were larger under CO<sub>2</sub> enriched conditions and LAI increased proportionally. It remains to be seen whether this increase in LAI remains after canopy closure.

In contrast to highly disturbed or young, actively growing stands of trees, it is most likely that a zero or minimal increase in LAI will occur in 'mature' forests in response to CO<sub>2</sub> enrichment. Norby et al. (2003) examined average and peak LAI in a *Liquidambar styraciflua* FACE experiment during 4 years of exposure to CO<sub>2</sub> enrichment. They found no impact of CO<sub>2</sub> enrichment at any time. Similarly, Wullschlegel and Norby (2001) found no change in LAI in a mature sweetgum FACE experiment. Although Hymus et al. (2002) and Norby et al. (2003) concluded that there are insufficient data from which to draw firm conclusions about the response of LAI of woody ecosystems to CO<sub>2</sub> enrichment, it appears likely that at canopy closure, LAI will not be increased. Ainsworth and Long (2005) and Long et al. (2004) concluded in reviews of the

literature that there is a general lack of LAI response in trees growing in FACE experiments. For example, Gielen et al. (2001) observed that an increase in LAI in response to CO<sub>2</sub> enrichment observed in the first year of a *Populus* spp FACE experiment was lost in the second year at canopy closure. Similarly, Hattenschwiler et al. (1997) found no effect on LAI of stands of *Quercus ilex* exposed to CO<sub>2</sub> enrichment for decades.

Most modelling analyses of the effects of increasing CO<sub>2</sub> on forest growth assume an increase in LAI (Neilson and Drapek 1998). Kergoat et al. (2002) used a global vegetation model to explore changes in LAI and evapotranspiration in various biomes assuming a doubling of atmospheric CO<sub>2</sub> concentration in the future. However, given the general absence of LAI change in closed woodland systems observed in FACE experiments, the underlying model structure which produced changes in LAI in response to CO<sub>2</sub> must be questioned.

In a detailed examination of the influence of CO<sub>2</sub> enrichment on LAI and light interception, Gielen et al. (2003) undertook a 3 year examination of light profiles, leaf angles, light absorption and LAI in a poplar FACE experiment in Italy. They found that at canopy closure and in subsequent years, the effects of CO<sub>2</sub> enrichment on canopy architecture, light absorption and LAI were minimal, results that agree well with those of DeLucia et al. (2002) for a pine forest. It was also concluded that despite increased quantum yield under CO<sub>2</sub> enriched conditions, there was no enhanced survival of leaves deeper within the canopy.

For ecosystems with a high LAI of the overstorey, the decoupling coefficient ( $\Omega$ ) is generally large, indicative of a canopy where aerodynamic factors regulate transpiration more than stomatal behaviour. Therefore, changes in Gs in response to CO<sub>2</sub> enrichment have a smaller effect on transpiration than is observed for the same reduction in Gs in canopies having a low LAI. Most woody ecosystems in Australia are likely to have a low or moderate  $\Omega$ , indicating a strong stomatal control of transpiration. The importance of differentiating between stomatal-scale responses and canopy-scale responses is highlighted by Wullschlegel et al. (2002b), who found in a 12 year old closed canopy stand of *Liquidambar styraciflua* that despite a large decrease in leaf-scale Gs (a 44 % reduction) in response to CO<sub>2</sub> enrichment, Gc was reduced by only 14 % and annual water use of the trees declined by only 7.5 % in response to CO<sub>2</sub> enrichment. There was no impact of CO<sub>2</sub> enrichment on LAI and therefore this difference in the magnitude of the response of Gs and Gc was not because of differences in LAI, but rather, they reflect intrinsic differences in behaviour of Gs and Gc.

The approach taken by Berry and Roderick (2006) is an extension of the original model developed by Berry and Roderick (2004). In the earlier paper, the authors conclude that the transpirational water use of deciduous and sclerophyllous evergreen trees increased in a CO<sub>2</sub> enriched environment. They show that when comparing a hypothetical natural vegetation cover that could have existed in the present day in the absence of European vegetation-clearing with the possible vegetation cover that may have existed just prior to



European settlement of Australia, that the CO<sub>2</sub> enrichment that has occurred in the past 250 y has increased transpiration by 34 mm y<sup>-1</sup>, from 190 mm to 224 mm, an increase of 18% (Berry and Roderick 2004). Such an increase may be a function of increased tree density and reduced pan evaporation rates.

### **4.3 Responsiveness of different Australian forest systems**

Figure 2 shows that in terms of the effect of 200 ppm CO<sub>2</sub> enrichment on Net Primary Production there has been a consistent ~20% increase for the four forests studied overseas with FACE to date. What might be expected in diverse Australian forests? There have been no studies in Australia yet on any whole forest ecosystems under elevated CO<sub>2</sub> conditions, so we can only speculate, based on scientific principles, as to the likely responsiveness of Australian forests. Australian forests are mostly evergreen broadleaf types ranging from very low stature, low basal-area, low productivity woodlands in arid environments to tall, highly productive wet sclerophyll and tropical rainforests. Australia's forests have some unique features (Section 3.1), so the generality of responses found elsewhere need to be tested and models adjusted as required (Section 3.3).

To gain an insight into whether growth of Australian tree species will respond to elevated CO<sub>2</sub> under FACE conditions, we rely on the fact that controlled environment and other enclosure studies gave good qualitative, and to some extent quantitative, guidance to what was found under FACE conditions in the northern hemisphere (see Section 4.1.2). Table 2 lists growth studies in controlled environments or open topped chambers that have been conducted on Australian tree species that have provided data on key growth parameters. All have been conducted on young spaced plants. The table shows that all species studied have the physiological capacity to exhibit increased leaf net photosynthesis rate (based on gas exchange measurements of plants grown in elevated CO<sub>2</sub> concentration), and increased net assimilation rate (based on growth analysis of plants grown in elevated CO<sub>2</sub> concentration), of a similar magnitude to that found on non-Australian tree species and other species (ie in the range of about +10-50% increase under elevated CO<sub>2</sub> conditions). This is true for both semiarid zone species and rainforest species. Table 2 also shows that for the young spaced plants this leads to increased dry weight when temperatures are sufficient for growth, and that leaf area expands causing in some cases large amplification of the growth response in the early exponential phase of development. It is expected that once canopy closure occurs, this opportunity for leaf area amplification to further stimulate growth will no longer apply. A comparison of inherently fast- and slow-growing species of *Acacia* (Atkin et al. 1999) showed that the fractional increase in absolute growth to elevated CO<sub>2</sub> concentration was little affected by their rate of growth, with differences due primarily to preferential partitioning of incremental growth to leaf area, rather than to difference in the net C assimilation rate per unit leaf area.

Table 2 also shows that when nitrogen availability is a co-limiting resource, the CO<sub>2</sub> response of tree-growth is diminished but not necessarily eliminated. For N-fixing *Acacia* species grown with adequate phosphorus, elevated CO<sub>2</sub> concentration increased biological N-fixation by plants dependent on symbiotic N-fixation for their N-supply, as shown in many other rhizobial symbiotic species (Schortemeyer et al. 1999). Australian studies on non-native legume species has shown that low phosphorus availability diminishes the fractional response of leguminous N-fixation to elevated CO<sub>2</sub> to the point at which, when phosphorus supply is low enough, neither growth nor N-fixation responds to elevated CO<sub>2</sub> concentration (Edwards et al. 2005, 2006). However, in these short term experiments with N-fixing species at low phosphorus levels, where the P-status is too low for an overall positive growth response to elevated CO<sub>2</sub>, the elevated CO<sub>2</sub> conditions do cause an increase in C- and N-partitioning below ground at the expense of above ground growth (Edwards et al. 2006). In the longer-term this may increase mineral nutrient acquisition that will facilitate ecosystem adjustment towards expressing some response to CO<sub>2</sub> aboveground too. Studies with an Australian native grass grown with low available labile-phosphorus under elevated CO<sub>2</sub> concentration, showed that the main way that elevated CO<sub>2</sub> allowed the grass to access unavailable P was by increased root growth rather than increasing the release of organic acids, which solubilise non-labile phosphorus, per unit of root (Barrett and Gifford 1999). For Australia, it is necessary to conduct long-term experiments on native forest with a N-fixing understorey that typically grows on low P-status soils to evaluate these relationships and test the hypotheses under realistic conditions and time scale (see Sections 3.1, 3.3 and 6.4).

The above analysis, and the modeling studies of Kirschbaum (1999, 2005) suggest that there is no single generic response to elevated CO<sub>2</sub>. Responses to elevated CO<sub>2</sub> will depend on forest age, and the relative co-limitation of water and nutrient supply, with greatest relative responses expected in younger water-limited systems that do not have strong nutrient limitation. Responses may be less in wetter, strongly nutrient-limited environments. It is likely that the strong water x nutrient interactions which control growth in most Australian forests (Raison and Myers, 1992), will also be a major determinant of the magnitude and persistence of responses to elevated CO<sub>2</sub>.

# The feasibility of forest free air CO<sub>2</sub> enrichment (FACE) experimentation in Australia

**Table 2.** Results of CO<sub>2</sub> enrichment experiments on Australian tree species. LA (leaf area), R:S (root:shoot), P<sub>n</sub> (net photosynthesis), NAR (net assimilation rate), Gs (stomatal conductance).

Species	Ref	System	Period of enrich.	ppm	Soil	Spacing	Light	Average temp	Water	N regime	P regime	% change due to elevated CO <sub>2</sub>						
												Total DW growth	LA	R:S	P <sub>n</sub>	NAR	Gs	leaf [N]
<i>E. pauciflora</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	high N	adequate	139	87			18.7		-21
<i>E. pauciflora</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	low N	adequate	212	117			37.9		-22
<i>E. pulverulenta</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	high N	adequate	218	166			25.2		-18.7
<i>E. pulverulenta</i>	Wong et al. 1992	Glasshouse	98d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	low N	adequate	158	71			26.8		-18
<i>E. camaldulensis</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	high N	adequate	166	67			20.3		-26
<i>E. camaldulensis</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	low N	adequate	75	21			10.8		-31
<i>E. cypellocarpa</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	high N	adequate	210	108			29.9		-25
<i>E. cypellocarpa</i>	Wong et al. 1992	Glasshouse	100d	660	5Lpots, loam	spaced saplings	winter & spring	28/18°	adequate	low N	adequate	85	27			12.3		-29.8
<i>E. pauciflora</i>	Roden et al. 1999	Field OTC	150d winter	~ 700	in field	spaced saplings	natural	~0°C	adequate	adequate	adequate	0	0	0	–		–	
<i>E. pauciflora</i>	Roden et al. 1999	Field OTC	75d spring after winter	~ 700	in field	spaced saplings	natural	spring & rising	adequate	adequate	adequate	53.5	34.3	17.6	30		-29	
<i>Doryphora sassafras</i>	Roden et al. 1997	Growth chamber	67d	700	Soil+ peat+ sand	Spaced cuttings	v.low metal halide with "sunflecks"	30/15°	adequate	adequate	adequate	42	32	4		37		
<i>Acmena smithii</i>	Roden et al. 1997	Growth chamber	67d	700	Soil+ peat+ sand	Spaced cuttings	v.low metal halide with "sunflecks"	30/15°	adequate	adequate	adequate	75	42	5		88		
+ <i>Mangifera indica</i>	Goodfellow et al. 1997	Field chambers	80 weeks	700	soil in the field	Grafted Saplings 2.4 m <sup>2</sup>	Field in the tropics	Field-tracking	adequate	adequate	adequate	61	34	17	50		-62	
<i>Acacia coriacea</i>	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	59	32	-3		30		

*The feasibility of forest free air CO<sub>2</sub> enrichment (FACE) experimentation in Australia*

Species	Ref	System	Period of enrich.	ppm	Soil	Spacing	Light	Average temp	Water	N regime	P regime	% change due to elevated CO <sub>2</sub>						
												Total DW growth	LA	R:S	P <sub>n</sub>	NAR	Gs	leaf [N]
Acacia aneura	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	-21	-31	-8		24		
Acacia tetragonophylla	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	62	27	-9		32		
Acacia coleii	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	104	59	-20		33		
Acacia dealbata	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	124	129	-21		24		
Acacia implexa	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	90	53	-9		26		
Acacia melanoxylon	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	192	135	0		28		
Acacia irrorata	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	74	42	-17		20		
Acacia saligna	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	64	27	-4		39		
Acacia mearnsii	Atkin et al. 1999	Glasshouse	12 weeks	700	Sand	From seed, spaced pots	Natural	22/17°	adequate	adequate	adequate	56	25	-8		40		
Eucalyptus tetradonta	Duff et al. 1994	Shade house	32 weeks	700	10 L pots. Perlite, sand, peat vermiculite	From seed	Natural	30° 24 hour average	adequate	adequate	adequate	68 to 227	50 to 81	-27 to +23				-15 to -50
Eucalyptus miniata	Berryman et al. 1993	Shade house	32 weeks	700	10 L pots. Perlite, sand, peat	From seed	Natural	30° 24 hour average	adequate	adequate	adequate	-18 to +18	-24 to 0	-34 to 0				-36 to 0

*The feasibility of forest free air CO<sub>2</sub> enrichment (FACE) experimentation in Australia*

Species	Ref	System	Period of enrich.	ppm	Soil	Spacing	Light	Average temp	Water	N regime	P regime	% change due to elevated CO <sub>2</sub>						
												Total DW growth	LA	R:S	P <sub>n</sub>	NAR	Gs	leaf [N]
					vermiculite													
Maranthes corymbosa	Berryman et al. 1993	Shade house	32 weeks	700	10 L pots. Perlite, sand, peat vermiculite	From seed	Natural	30° 24 hour average	adequate	adequate	adequate	61	38	0				
Maranthes corymbosa	Eamus et al. 1993	Shade house	30 weeks	700	10 L pots. Perlite, sand, peat vermiculite	From seed	Natural	30° 24 hour average	adequate	adequate	adequate					25 to 34	- 10.5 to - 36	
Eucalyptus tetradonta	Eamus et al. 1995	Shade house	52 weeks	700	NT soil, planted in the ground	From seed	Natural	30° 24 hour average	adequate	adequate	adequate					26		Soluble protein content:- 15

## 5. EVALUATION OF AVAILABLE TECHNOLOGIES FOR FOREST FACE

### 5.1 Tree-FACE facilities

Open air CO<sub>2</sub> systems involving trees have been established in 7 locations around the world (Table 3).

**Table 3.** *Tree FACE systems that have been established up until 2006.*

Country	Location	Trees	Ring diam	[CO <sub>2</sub> ]
Australia	Yabulu, Queensland	Eucalyptus and Acacia seedlings planted in savanna	15 m	550 ppm
Italy	Viterbo, Tuscany	Poplar plantation	20 m	550 ppm
Switzerland	Hofstetten	Mature temp. forest	webFACE	600 ppm
Switzerland	Stillberg-Davos	Larch/pine ecotone	1.3 m	550 ppm
USA	Durham, NC	Loblolly pine plant'n	30 m	+200 ppm
USA	Rhineland, WI	Aspen plantation	30 m	+200 ppm
USA	Oakridge, TN	Sweetgum plant'n	25 m	550 ppm
UK	Henfaes, Wales	Birch, Beech, Alder	8 m	+200 ppm

Of these only the Hoffsteten experiment was performed on a “mature” forest. It used the “Webface” approach (see below). All the rest used “ring-FACE” designs. For the others, the trees have been planted either near the time of FACE establishment or well before. A single replicate ring-FACE was established in a tropical rainforest in Panama and tested in a dry and a wet season cycle. It was discontinued after the trial owing to a funding shortfall for developing a replicated experiment (C. Potvin, pers commun. 2006).

System design problems particular to establishing FACE rings in forests include disturbance of the site during building of the facility, the difficulty (expense) of adequate replication, and the need to have control of CO<sub>2</sub> concentration over a considerable spread of heights having different windspeed and turbulence regimes. Further, given that for forests the need for multi-year studies is even more imperative than for shorter stature vegetation, the zone of CO<sub>2</sub> control needs to be able to be increased in height year by year.

## **5.2 The methodology**

### **5.2.1 Brief historical overview of open-air CO<sub>2</sub> enrichment**

Lundegårdh (1927) found that CO<sub>2</sub> released at ground level through perforated iron pipes in 10 m x 10 m field plots increased the yield of sugar beet and oats by 16-30%. At that time the ambient CO<sub>2</sub> concentration was about 300 ppm. It was not until the 1960s (by which time ambient CO<sub>2</sub> concentration was about 320 ppm) that open-field CO<sub>2</sub> enrichment of crops was again explored in square and rectangular arrays of ground-level release (Kretchman 1969, Harper et al. 1973). The methodology for open air CO<sub>2</sub> enrichment was advanced by Allen's (1974, 1975) aerodynamic studies of the horizontal and vertical dispersion of line-released CO<sub>2</sub> in vegetation to develop a 2-dimensional CO<sub>2</sub> dispersion model. The idea of experimental field facilities for studying the effects of future global atmospheric CO<sub>2</sub> concentrations was launched soon afterwards. It was urged by Zvi Enoch at a conference in Athens, Georgia, USA (Lemon 1983). At the meeting Enoch proposed a multi-national effort to use underground sources of CO<sub>2</sub> to enrich managed and unmanaged vegetation with CO<sub>2</sub> in a controlled way to study growth rates, water loss and physiological processes under continuous elevated CO<sub>2</sub> concentration. He circulated a questionnaire seeking interested parties. L.H. Allen proposed the name "free air-stream CO<sub>2</sub> enrichment", a name which he later reduced to Free Air CO<sub>2</sub> Enrichment – FACE.

Early discussions and calculations on open air release of pure CO<sub>2</sub> led to a report concluding that unacceptably large rapid fluctuations in concentration (Shinn and Allen 1985) and high costs (Drake et al. 1985) may be serious drawbacks of the idea. However, during the 1980s these early approaches and ideas became advanced by interaction with researchers into field release of air pollutants (Miller et al. 1980, Greenwood et al. 1982, McLeod and Fackrell 1983) to produce workable controlled-release designs for FACE involving vertical gas release pipes arranged in a circle rather than a rectangular array on the ground. These activities on free air release of air pollutants over vegetation in Britain, the Netherlands and Germany helped inform the FACE objective. By 1984-85 discussions about ways forward proceeded, involving scientists from the Brookhaven National Laboratory in New York and several others including L.S. Evans, L.H. Allen, D.N. Baker, R.C. Dahlman, G.R. Hendrey, K.F. Lewin, H.H. Rogers, N.J. Rosenberg and J.S Shinn (Allen 1992). The rapidly emerging availability of cheap high speed computers/controllers able to run PID (proportional/integral/differential) algorithms helped reduce the major problem of concentration fluctuations. Further, bringing together the release of CO<sub>2</sub> from a circular array of vertical pipes rather than a rectangular array at ground level, with the use of upwind release in the changing wind field, and pre-dilution of the CO<sub>2</sub> in a flow of air to reduce concentration fluctuations produced the first practical designs by the Brookhaven National Laboratory, New York (Hendrey et al. 1988a,b,c). This involved bleeding pure CO<sub>2</sub> into a large flow of air from blowers, the diluted air being fed through a circular large-diameter plenum pipe surrounding the experimental vegetation zone into vertical pipes with large diameter holes in

them through which the CO<sub>2</sub>-enriched air flowed over an arable crop (at 33 m<sup>3</sup> min<sup>-1</sup> at the Arizona site) (Hendrey et al. 1993). The control system released the CO<sub>2</sub>-enriched air through the vertical risers, the release zone being computer-controlled to be always upwind of the experimental “sweet-zone”. Thus a flow of air was directed into the open air creating an artificial air-flow across the test vegetation. Considerable engineering and software design, modelling and testing work at the Brookhaven National Laboratories went into this “two-fluid FACE” system (Lipfert et al. 1992). The net air flow of diluted CO<sub>2</sub>, it was later found, could introduce a “blower-effect” artefact in some systems (see Section 5.3.7).

Later Miglietta, in Italy, introduced a new injection approach to FACE based on the fact that a fine sonic-velocity jet of gas released into another gas disperses within about 10-20cm of release (Miglietta et al. 1997, 2001). This removed the need for the bulky and expensive paraphernalia of blowers, large diameter plenums and risers and large capacity valves. It also meant that zero enrichment control plots, having exactly the same bulky paraphernalia without the CO<sub>2</sub> addition, was no longer needed. Thus costs came down. The approach also facilitated the possibility of mini-FACE with diameters of only a meter or two for low stature vegetation.

The taller the vegetation, the larger (both in terms of diameter and height) a FACE ring needs to be (see Section 5.3.6) and the higher the CO<sub>2</sub> supply requirement. Equally, the sparser the trees are in an ecosystem, the larger a FACE ring needs to be to have sufficient replicate-ring similarity and enough trees to study. For very tall forest systems Körner adopted another approach for releasing CO<sub>2</sub> through an extensive network of fine tubes wound around the branches of the crowns of forest trees – Web-FACE (Pepin and Körner et al. 2002).

### **5.2.2 The BNL CO<sub>2</sub> pre-dilution system used in the Duke Forest (Durham, North Carolina, USA) (FACTS1)**

This forest FACE system was applied to a loblolly pine (*Pinus taeda*) plantation (Photo 1) approximately 10 m tall at the time (1993), but growing by ~1 m yr<sup>-1</sup>, is a version of the Brookhaven National Laboratory (BNL) design involving pre-dilution of pure CO<sub>2</sub> with a large radial fan. This system had its first experimental application and performance testing in the Maricopa study-site in Arizona used for field crops before application to the Duke Forest. This system of enrichment requires a fetch of about 2-3 m for adequate mixing of CO<sub>2</sub>. Thus the FACE ring needs to have a diameter that is 4-6 m wider than the experimental “sweet-zone” within which measurements are primarily made.

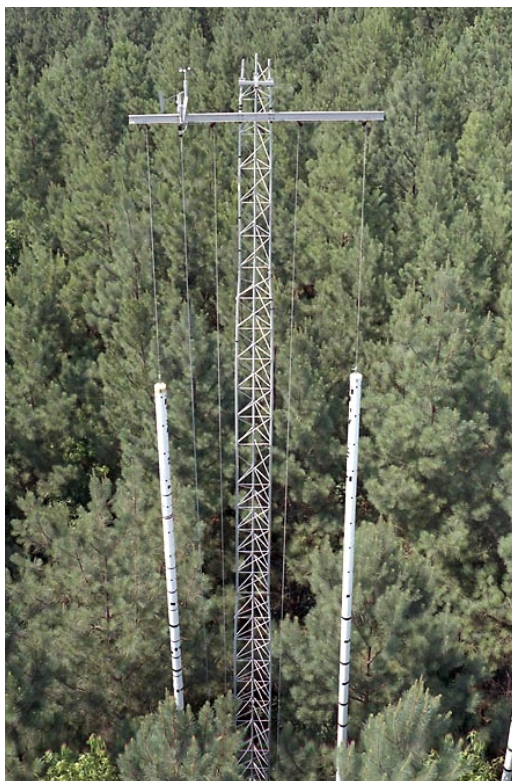




**Photo 1.** Duke aerial. Photo from Duke University FACE research site  
website: <http://face.env.duke.edu/images.cfm>

### ***The physical setup***

Descriptions of the Duke FACE system is in Lewin et al. (1994) and Hendrey et al. (1999). The CO<sub>2</sub> is diluted to 30,000ppm in an air flow of 102 m<sup>3</sup> min<sup>-1</sup> through a 38 cm diameter circular plenum pipe to distribute the CO<sub>2</sub>-enriched air to 32 vertical ventilation pipes (15 cm diameter) spaced around the 30 m diameter FACE ring. Although ideally the plenum would be buried below ground, as it is in the Swiss grassland FACE, that would be too disruptive to an established forest site. The vertical pipes are suspended from 16 aluminium lattice masts (12 m extendable to 20 m without guy-ropes), with protruding spars to support the pipes (Photo 2). Each mast is set in a 4 m<sup>3</sup> concrete base arranged in a circle within the plenum circumference. The engineering construction is quite massive for this system. As the foundations for the concrete bases had to be dug by hand to avoid destroying the forest, it was an expensive operation (R. Norby. pers.comm.). Large butterfly valves at the base of each vertical pipe allow air to flow or not. The 2.5 cm air exit holes are in clusters of three every 50 cm from 2 m off the ground. The central holes of each cluster were directed towards the ring centre and the other two were directed inwards but at an angle of 60° from the central one.



**Photo 2.** Duke Vertical vent pipes. Photo from Duke University FACE research site website: <http://face.env.duke.edu/images.cfm>

### ***Operation and performance***

Owing to the inherent eddy structure of atmospheric turbulence, it is impossible to have a control system that keeps the concentration at the central CO<sub>2</sub> monitoring spot constant (ie within the resolution of the CO<sub>2</sub> sensor) even with a steady wind from one direction. There must be variability when air having above-ambient and above-target CO<sub>2</sub> concentration is released into an ambient air flow. Variability of wind-speed and wind-direction further exacerbates the control problem at the centre of the circle. And the fact that the plume of released CO<sub>2</sub> disperses into the ambient air as it moves away from the release points means that the concentrations elsewhere in the ring must be different and vary - changing from above-target (on average), close to the release point to below-target on the leeward side of the ring. For a tall forest, in which CO<sub>2</sub> is released at several levels into a wind regime that changes with height and vegetation density, there are added difficulties of achieving uniform enrichment vertically. To establish the spatial and temporal pattern of CO<sub>2</sub> concentration throughout the 3-dimensional space of a forest-FACE is itself an essential but expensive task. The published description of variability is not as good as would be liked to address questions of the impact of variability on vegetation responses to elevated CO<sub>2</sub> concentration (see below).

The control system uses information on the “instantaneous” (actually 3-4 s average) CO<sub>2</sub> concentrations of ambient air and air at the centre of the ring at a height within the canopy (He et al. 1996), and the wind-speed and wind direction monitored above the canopy. Owing to sample tube lengths, the CO<sub>2</sub> signal is received about 7 seconds after air is sampled. The algorithm adopted

in the BNL FACE uses a proportional/integral/differential (PID) approach augmented with an anticipatory feed-forward term (Hendrey et al.1999). The CO<sub>2</sub> flow rate delivered into the air-stream at any instant,  $F_t$  is the sum of four components:

$$F_t = F_{int} + F_{prop} + F_{dif} + F_{wind}$$

$F_{int}$ , is the integral control component. It is the overall CO<sub>2</sub> flow rate needed to enrich the average air flow to give the target centre-point CO<sub>2</sub> enrichment in the long term. It is determined by the cumulative difference between the target enrichment and the actual enrichment.

$F_{prop}$  is the immediate proportional control component that adds or subtracts flow according to how far away, and in which direction, the actual concentration is away from the intended target value at the centre of the ring at each instant.

$F_{dif}$  is the differential control component. It adds or subtracts flow according to how rapidly the error signal is decreasing or increasing. A low pass filter of about 45 seconds is applied to  $F_{prop}$  and  $F_{dif}$  to prevent small, fast fluctuations causing rapid “hunting” of the injection rate. This term has been turned off in some systems as it did not seem to improve control.

$F_{wind}$  is a term to take account of the variable time (depending on wind speed) it takes for the change in concentration to arrive at the centre of the ring. This is achieved by anticipating the implication of an instantaneous change of wind-speed compared with the recent average. It also allows for the fact that some flow would be needed even in still air to assist diffusional dispersal from the ring.

Important performance criteria are the mean enriched CO<sub>2</sub> concentration at the central control point (where air intake for CO<sub>2</sub> sensor control is located), the variability about that mean at the central control point, the spatial variability within the experimental “sweet-zone” away from that control point relative to the target concentration, and the temporal variability throughout the sweet-zone including the very short-term variability. Short-term variability is important from two perspectives. One is from the perspective of patterns in temporal concentration fluctuations interacting resonantly with the characteristic time constants of stomatal function and photosynthetic metabolism, thereby causing spuriously dampened or exaggerated responses. The other relates to the way that an appropriate mean is calculated that takes into account the strong non-linearity of response of photosynthesis and  $G_s$  to CO<sub>2</sub> concentration. These two aspects are considered in Section 5.3.4.

It has become conventional to describe the performance of FACE systems in terms of the fraction of time that the 1 minute average concentration is within certain percentages (often 90% or 80%) of the set target. Data can be presented as summaries over different timescales. Table 4 shows the annual

performance of the Duke Forest FACE at the location of CO<sub>2</sub> control over 10 years.

**Table 4.** *The annual performance of the Duke Forest FACE system at the central control point 8 m off the ground using 1-minute average concentrations as the primary records. The target enrichment is 200 ppm above ambient. The delivered target is the actual CO<sub>2</sub> treatment attained during the scheduled treatment periods (ie daylight periods) during the periods when the CO<sub>2</sub> was turned on for a given calendar year. Variation around that target is presented as the percentage of time the actual one minute average [CO<sub>2</sub>] was within 10% and 20% of the target concentration.*

(Source: [http://www.bnl.gov/face/Duke\\_Forest\\_FACE\\_Performance.asp](http://www.bnl.gov/face/Duke_Forest_FACE_Performance.asp)).

Year	Target [CO <sub>2</sub> ] (ppm)	Delivered [CO <sub>2</sub> ] (ppm)	Time within 10% of target (%)	Time within 20% of target (%)
2005	582	585	62	89
2004	579	581	66	91
2003	573	573	70	92
2002	569	568	74	94
2001	572	571	65	90
2000	569	568	64	89
1999	570	568	70	93
1998	575	572	70	93
1997	572	568	65	91
1996	574	570	69	93
Mean	573.5	572.4	67.5	91.5

Superb overall annual and decadal mean control performance has been achieved at Duke. Over 10 years the concentration at the control point was within 1ppm of the 200ppm enrichment goal on average. This was achieved by 92% of 1-minute average concentrations being within 20% of 200ppm enrichment goal i.e. between 160ppm and 240ppm above the ambient CO<sub>2</sub> concentration.

The performance at the control point in less than 1-minute averaging times is not so well documented. The shortest time frame of monitoring is the “grab sample” which in practice represents a 3-4 sec average owing to the smearing of signal along the length of the air sampling lines (Hendrey et al. 1999). Figure 6 (Fig. 7 from Hendrey et al. 1999) shows the probability distributions of concentrations averaged over 5 min, 1 min and 3-4 sec at the Duke site during summer 1995.

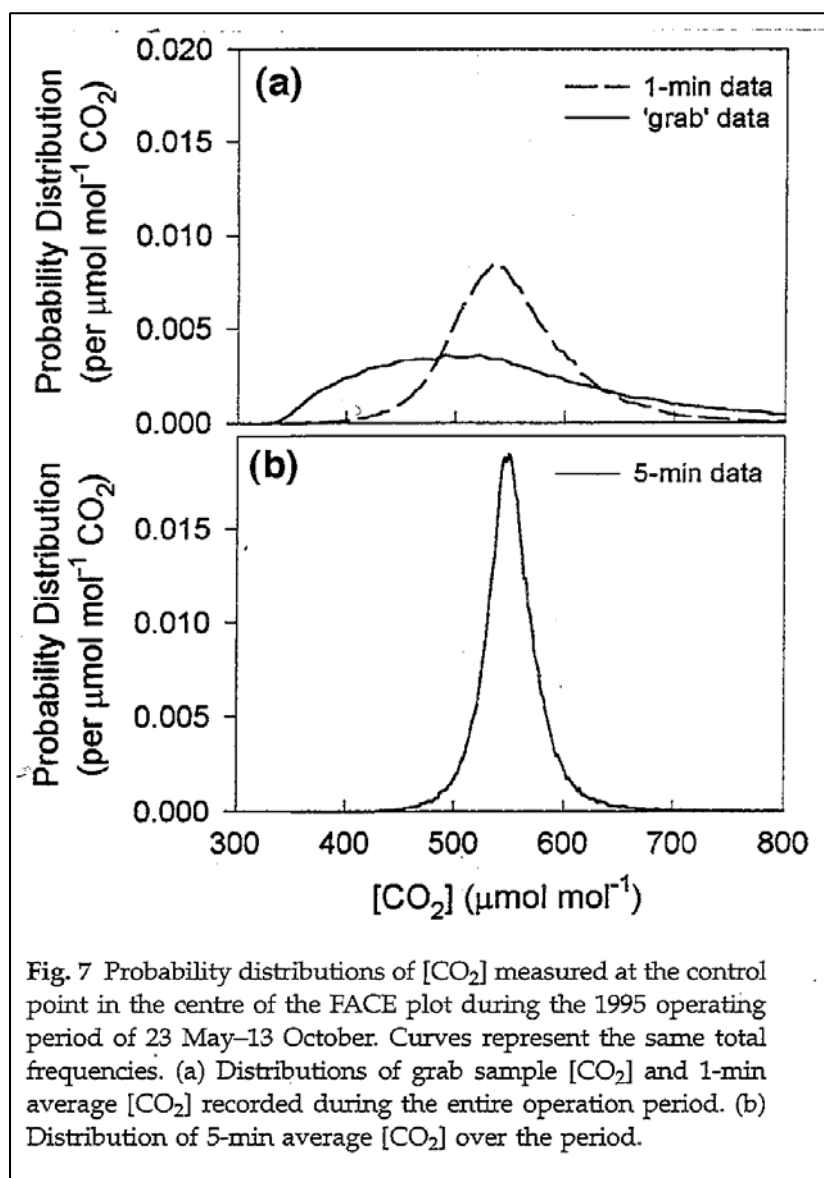


Fig. 7 Probability distributions of [CO<sub>2</sub>] measured at the control point in the centre of the FACE plot during the 1995 operating period of 23 May–13 October. Curves represent the same total frequencies. (a) Distributions of grab sample [CO<sub>2</sub>] and 1-min average [CO<sub>2</sub>] recorded during the entire operation period. (b) Distribution of 5-min average [CO<sub>2</sub>] over the period.

**Figure 6.** From Hendrey et al. (1999)

The curves illustrate how the ranges of concentrations contributing to the mean spread out as the sampling-periods over which concentrations are averaged are shortened. For the “grab samples” the average enriched values, over the 3–4 sec over which they were averaged, spread from ambient to over 800ppm. Doubtless if the sampling/measurement system were re-configured to enable 1-sec averages to be monitored then there would be a few examples of extremely high concentration. This is relevant to appreciating the physiological interpretation of the arithmetic mean enrichment that is reported (see Section 5.3.4).

The above performance data are for the controlled concentration at the single controlled-spot in the centre of the rings. Elsewhere in the rings the concentrations cannot be so stable. The amount of CO<sub>2</sub> coming out of the vertically distributed holes was manually preset with tape partially covering the holes to attempt to maintain vertically the target concentration on average. The level of success in terms of annual averages is shown in Figure 7 (Fig. 9 from Hendrey et al. 1999) where significant systematic spatial variation is



seen. There is no published information on grab sample distribution of concentrations in the higher parts of the canopy.

### **5.2.3 The BNL system at Oak Ridge, Tennessee, USA**

The Oak Ridge study on a sweetgum (*Liquidambar styraciflua*) plantation established in 1997, uses a modified version of the BNL design (Norby et al. 2001). The plot diameters are smaller at 25 m and the sweet-zone is considered to be 20 m diameter. There are 24 vertical vent pipes (Photo 3) and the blower delivers 2 m<sup>3</sup> s<sup>-1</sup> with the CO<sub>2</sub> injected at the blower outlet (Photo 4). Ten vent pipes that are most upwind of the centre of the ring are opened at any one time. But when the windspeed is less than 0.4 m s<sup>-1</sup>, every other vent around the entire circle is opened. When the windspeed exceeds 6 m s<sup>-1</sup> for more than 5 minutes, CO<sub>2</sub> injection is stopped to reduce CO<sub>2</sub> costs. There are two CO<sub>2</sub> enriched rings and three identical ambient CO<sub>2</sub> rings including the blowers but with no added CO<sub>2</sub>. The forest was planted in 1988 and baseline growth measurements were made in 1993 before the FACE systems were installed when the trees were 12 m high. They now exceed 18 m. The vertical vent pipes have been increased in height accordingly.

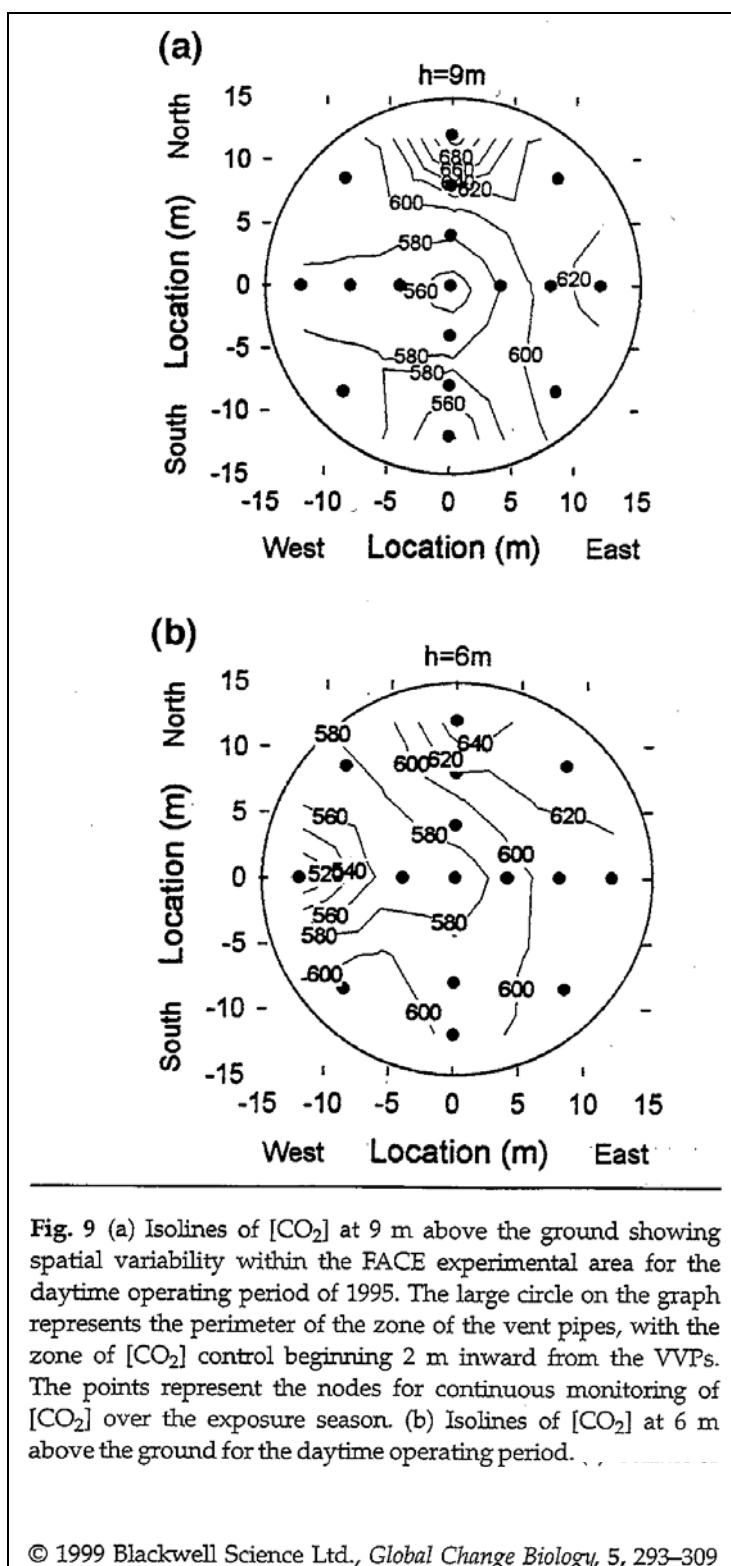


**Photo 3.** ORNL vertical vent pipes. Photo from Oak Ridge National Laboratory website: <http://www.esd.ornl.gov/facilities/ORNL-FACE/index.html>



**Photo 4.** ORNL blower. Photo from Oak Ridge National Laboratory website:  
<http://www.esd.ornl.gov/facilities/ORNL-FACE/index.html>

The control system and algorithms are similar to those adopted at the Duke Forest site, but enrichment continues at night as well as by day. Owing to the naturally higher night-time CO<sub>2</sub> concentration, because stiller air at night traps respiratory CO<sub>2</sub>, the control level is also higher by night – 645ppm in 1999 (Norby et al. 2001). The day time target was 564ppm, but because the CO<sub>2</sub> was turned off for about 10% of the time owing to high winds, equipment failure, non-delivery of CO<sub>2</sub>, and operation-suspension for experimental purposes, the actual annual daytime average has been lower at 533ppm. As at Duke Forest (Table 4), the Oakridge site reports (Norby et al. 2001) that when the system is on, 90% of 1-min averages are within 20% of the set-point.



**Figure 7.** Annual average daytime CO<sub>2</sub> concentrations throughout the Duke FACE rings at 6 m and 9 m heights. From Hendrey et al. (1999).

#### 5.2.4 The pure CO<sub>2</sub> injection ring-system

During the late 1990s an Italian group at the National Research Council (CNR), Florence (Miglietta et al. 2001) and a Japanese group (Okada et al.



2001) developed FACE systems based on injection of pure CO<sub>2</sub> from a horizontal ring of release points. The Italian (CNR) system was deployed on a poplar plantation (EuroFACE), the Japanese system on rice (RiceFACE). The CNR system has also been deployed in the SoyFACE facility at the University of Illinois (Leakey et al. 2004), as a mini-ring system at the TasFACE facility at the University of Tasmania (Hovenden et al. 2006) and as mini-ring systems in Denmark and California.



**Photo 5.** EuroFACE ring aerial. Photo from EuroFACE website:  
<http://www.unitus.it/euroface/>

These systems employ a hexagonal ring of horizontal tubes (Photo 5) held up at two or more levels above the ground by vertical poles (Photo 6). This system has the advantage of being light-weight and quickly deployable. It does not use pre-dilution of the CO<sub>2</sub> and hence has no “blower effect.” The pure CO<sub>2</sub> is injected at high pressure from numerous minute holes (0.2-0.5 mm diameter, at approximately 5 cm intervals) in the light-weight horizontal plastic pipes (eg domestic irrigation black polyethylene pipe). The mass-rate of injection is determined by the pressure applied under the control of an electronic pressure regulator receiving a DC-voltage signal controlled from a computer. The gas is emitted at sonic velocity leading to rapid mixing within decimetres owing to the fluid dynamic properties of the shock-wave that forms at the exit of the hole (Miglietta et al. 2001). For example, in the Japanese FACE the CO<sub>2</sub> concentration declined to 2000ppm within 20 cm at a windspeed of 0.2 m s<sup>-1</sup>. The Italian system gave 100-fold dilution within 3 cm of the jet and essentially complete dispersal within 10 cm of the release point.



**Photo 6.** EuroFACE CO<sub>2</sub> release tubes. Photo from EuroFACE website:  
<http://www.unitus.it/euroface/>

The EuroFACE facility established in a young poplar plantation in Italy is described by Miglietta et al. (2001). It had an octagonal release diameter of about 22.5 m servicing an experimental sweet-zone of 16 m diameter (Photo 7). The horizontal octagon of 20 mm diameter PVC tubes was held at canopy height using telescopic poles (initially) starting at only 50cm when the saplings were first planted (Photo 6). As the trees grew fast the supports were changed to meteorological masts. The horizontal tubes were in fact adjacent pairs of tubes (the two black tubes in Figure 6). One of the pair had 350 twist-drilled or laser-drilled 0.3 mm diameter holes per side while the other had 280 holes per side. Solenoid valves were used to open gas to the tube having 350 holes at the most upwind position at any instant and to the flanking-neighbour tubes around the hexagon with 280 holes. This was to render the open-hole density perpendicular to the wind direction equal across the full width of the ring having in mind that the flanking tubes are at 45° to the wind direction. The tubes were oriented with the holes pointing towards the middle of the ring. The equipment was located at the centre of the FACE ring. This reduces the lag time between air sampling and the CO<sub>2</sub> concentration being determined. The computer control algorithms are adapted from the PID-based approach of Lewin et al. (1992) for the BNL system.





**Photo 7.** EuroFACE site aerial. Photo from EuroFACE website:  
<http://www.unitus.it/euroface/>

Control-performance of pure CO<sub>2</sub> FACE is similar to that of BNL FACE. In the Japanese Rice-FACE the average seasonal performance of 4 rings, for 30 second sample average CO<sub>2</sub> concentration at the centre of the ring, was within 20% of target 87% of the season, and within 10% of the target for 59% of the season for (Okada et al. 2001). For the Italian EuroFACE the 1-minute average CO<sub>2</sub> concentration was within 20% of target for 91% of the season and within 10% of the target for 75% of the season. As an overall summary the CNR-system maintain a 1-min average CO<sub>2</sub> elevation at the control point in the centre of the rings to within 20% of the target for 87-95% of the time (Hendrey and Miglietta 2006). These performances are comparable with the 1 minute averages for the Duke Forest FACE (Table 4).

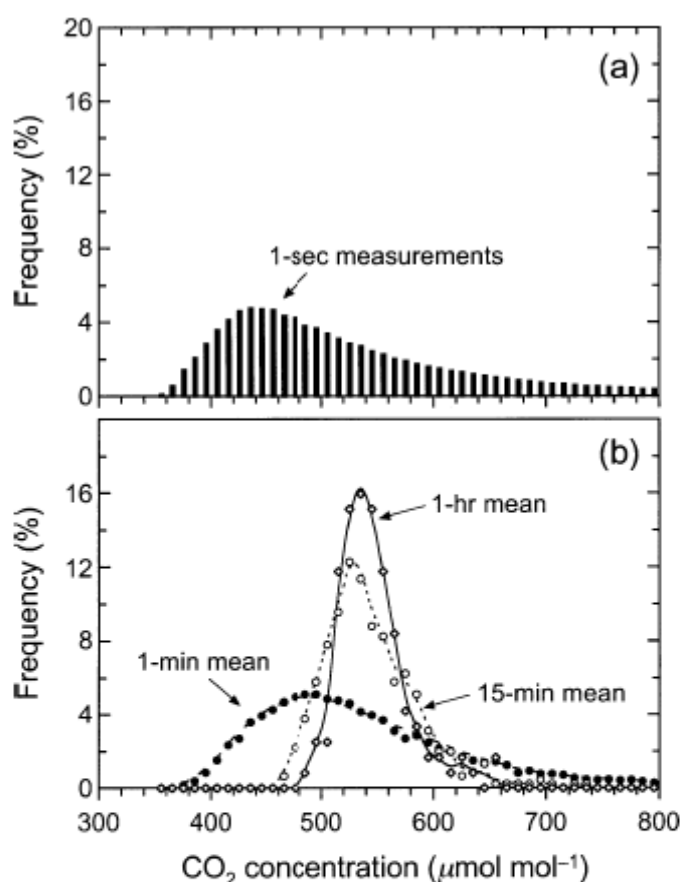
### **5.2.5 The pure CO<sub>2</sub> injection WebFACE system**

Körner conceived the WebFACE concept to address the CO<sub>2</sub> response of mature closed canopy forests that are too tall (eg >30 m) to accommodate an adequately sized FACE ring on a restricted-size research budget and to avoid damage during installation (Pepin and Körner 2002). However, as the method involves lacing fine tubes throughout the canopy it does require a crane to be installed by helicopter into the forest. It is therefore a relatively cost effective option in a situation where a canopy crane has already been installed for other purposes. However, if only one fixed position canopy crane is available, there is a statistical problem that only one area can be CO<sub>2</sub>-enriched. There could be an additional problem of some level of CO<sub>2</sub> contamination to the control (ambient-CO<sub>2</sub>) plot that lies within the same radius reach of the crane-boom. In the Swiss WebFACE, the CO<sub>2</sub> enriched area contained 14 large trees (6 tree species) in an approximately 20 m x30 m oval area in one quadrant of the crane's 30 m radius of reach (Pepin and Körner 2002).

The WebFACE approach also utilises the rapid mixing of a gas emitted at near sonic speeds from minute ports. Small (0.5 mm) laser-drilled holes in 4.3 mm internal diameter drip irrigation tubes were used in the Swiss WebFACE. For the cluster of fourteen CO<sub>2</sub>-enriched trees, the WebFACE array consisted of about 25,000 holes in about 8.5 km of tubing. The tubing was wrapped around the primary branches and interlaced among the smaller branches of the upper and middle canopy as uniformly as possible. The hole density was about 10-20 m<sup>-3</sup> of the upper canopy but less in the lower canopy.

The windspeed and direction data were monitored at 45 m - well above the top of the forest. CO<sub>2</sub> monitoring was via 24 intakes (18 in the upper canopy and 6 in the lower) scattered throughout the canopy with intakes about 40 cm from the nearest CO<sub>2</sub> release-hole. These sample points were each read individually in an 8 minute cycle, and the last 1-second reading from each channel after the line-purging period used for control. The 8-minute averages of the 24 sets of one-second readings were used for the feedback control. Pure CO<sub>2</sub> was continuously pulsing, under solenoid valve control, into the injection network with the fraction of each 2-second pulse-cycle during which CO<sub>2</sub> flowed determined in proportion to the deviation of the last 8 minute average from the target concentration. Thus this approach did not use PID control but did use an average concentration sampled from over the entire treatment volume as the target for control rather than a single central measurement point.

The performance of this system is illustrated in Fig 8. Overall 1-minute means of the 24 distributed measurement points were within 10% of target for 47% of the time, and within 20% of target 76% of the time. Although this performance seems not quite as good as for the ring-FACE systems the performance data are for the average of the distributed network of sampling points across the entire enriched area rather than just for the central control point cited for the ring-FACE systems. For the ring FACE system the distributed performance is certain not to be as good as that at the point of central control. Thus the WebFACE system seems to have a similar performance to that of the ring-FACE systems, but the amount of performance data available makes comparison very difficult. One would expect the short-range spatial variation of a WebFACE approach to be higher than for a ring-FACE approach.



**Fig. 3** **a** Frequency distribution of 1-sec measurements of CO<sub>2</sub> concentration performed at 28 m above ground in the center of the CO<sub>2</sub>-enriched area during 2 weeks in August 2001. These data represent ~5-s averages of instantaneous CO<sub>2</sub> concentrations that are continuously analyzed (at 5 Hz) and recorded each second. The cumulative frequency corresponds to 93% of the total frequency. **b** Frequency distribution of 1-min, 15-min and 1-h average CO<sub>2</sub> concentrations calculated from the 1-s measurements. Each *bar* or data point represents the midpoint of a 10 μmol mol<sup>-1</sup> CO<sub>2</sub> concentration class. Mean daytime wind speed during these CO<sub>2</sub> measurements ranged between 1.4 and 3.6 m s<sup>-1</sup>

**Figure 8.** From Pepin and Körner (2002)

### 5.2.6 Australian FACE systems

The OzFACE savanna system at Yabula near Townsville was a modified two-fluid system (Stokes et al. 2005). Pure CO<sub>2</sub> was pre-diluted with an in-line fan (as with the BNL design) but released through a 15 m octagon of horizontal 9 m pipes 9 cm in diameter as in the pure CO<sub>2</sub> systems. The horizontal pipes started at 40 cm from the ground but had adjustable height. Gas release was through 150, 8 mm holes in each 6 m length. The holes pointed horizontally

inwards or downwards at 22° or 45° to the horizontal. A modified BNL control algorithm was used to control which ports were open and the gas flow rates. Enrichment was for 24 hr per day.

The TasFACE grassland FACE system (Hovenden et al. 2006) is a 1.5 m diameter pure CO<sub>2</sub> FACE of the EuroFACE design. Pure CO<sub>2</sub> is injected into the open air stream from a horizontal circular vent pipe through numerous laser-drilled holes (0.3 mm). With the small diameter of the ring the CO<sub>2</sub> was injected from around the entire ring 24h per day and controlled at 550ppm using a PID algorithm. All CO<sub>2</sub> gas was scrubbed to remove any traces of ethylene.

## **5.3 Important technical issues**

### **5.3.1 Carbon dioxide use rate**

The daily rate of carbon dioxide use depends on the area being enriched, the height being enriched, the concentration of enrichment, whether enrichment is by night as well as by day, and the windspeed. Pepin and Körner (2002) and other sources refer to the following estimates of the rates of CO<sub>2</sub> use in various FACE facilities on a seasonal average basis (Table 5) but these values seem rather approximate.

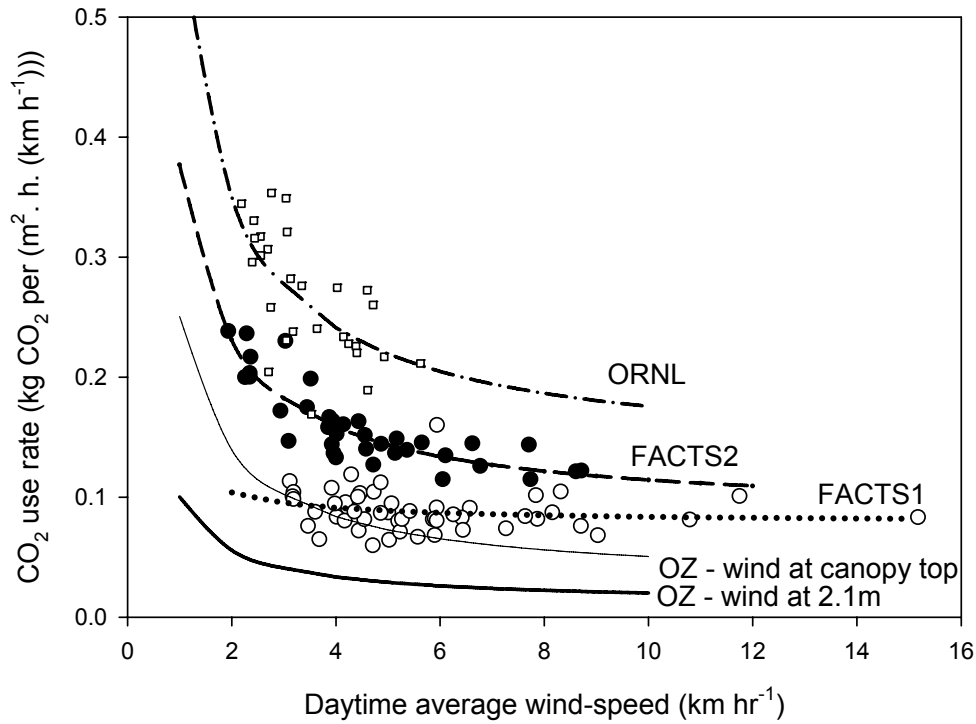
Recent data allow for new estimates. The Duke Forest ("FACTS 1"), and Rhinelander ("FACTS 2"), Aspen site place their real-time daily CO<sub>2</sub> use statistics on the worldwide web as a diagnostic tool. Both these sites use the BNL FACE system, have 30 m rings and target CO<sub>2</sub> enrichment of 200ppm above ambient. During the course of preparing this report, daily data have been taken off the web several times each week and presented in the form shown in Figure 9. This Figure shows that for nearly the same system (30 m BNL FACE) the rate of CO<sub>2</sub> use per unit area of effective experimental sweet zone (532 m<sup>2</sup>) varies significantly. For both sites the rate of use per unit area per hour per km/hr of windspeed, declines a little the stronger the wind.

**Table 5.** *Estimated season average rates of CO<sub>2</sub> use per ring in various FACE facilities. From 1. Pepin and Körner 2002; 2. Stokes C.J. (personal communication) and 3. Norby (personal communication).*

Site	m <sup>2</sup> [CO <sub>2</sub> ]		kg h <sup>-1</sup>	kg h <sup>-1</sup> m <sup>-2</sup>	source
	per ring	target			
Swiss WebFACE	550	500	200	0.37	1
Duke BNL FACE	532	550	260	0.49	1
Nevada BNL FACE	491	550	150	0.31	1
Arizona BNL FACE	491	550	89	0.18	2
Tennessee BNL FACE	491	550	194	0.62	3

In addition C.J. Stokes (pers. comm.) has analysed data from the Townsville OzFACE system. The data have been calculated with respect to the wind-speed at the top of the grass canopy and also at the height of 2.1 metres that was used by the control system. The curves differ because the wind-speed close to the grass averaged 40% of that at 2.1 m. This difference in apparent CO<sub>2</sub> use efficiency indicates how difficult it is to compare systems based on the data available, and to forecast what the CO<sub>2</sub> use rate could be for a proposed facility.

In addition facilities seem to vary in their normalised CO<sub>2</sub> use. The apparent low CO<sub>2</sub> use of the OzFACE system probably mostly reflects the fact that CO<sub>2</sub> was released only at one level close to the ground, whereas the forest FACE systems have multiple heights of CO<sub>2</sub> release owing to the tallness of the trees (15-25 m). However, the three BNL forest FACE systems have a 2 to 3-fold range in CO<sub>2</sub> use for 200ppm enrichment. The source of this variation is not clear, but issues such as the height (within or above the canopy) at which windspeed is measured, and the depth of the crown over which CO<sub>2</sub> is controlled, are worthy of further examination.



**Figure 9.** Carbon dioxide use for enrichment to 550ppm in several FACE systems as a function of daily daytime average wind speed per unit area of experimentally available sweet zone. Open circles and fitted dotted line are for the Loblolly Pine FACE at Durham, North Carolina (“FACTS1”). Solid circles and dashed line are for the Aspen-FACE at Rhinelander, Wisconsin (“FACTS2”). The N. Carolina and Wisconsin data are spot daily-daytime data downloaded during the period of preparation of this report from the diagnostic websites that display (but do not archive) relevant information to calculate the data shown on a day-by-day basis. The solid lines are for the OzFACE facility in Townsville (Stokes, pers. comm.) using either the windspeed at 2.1 m height (thick line) or at grass-top (thin line) in the calculations and plot. The Oak Ridge National Laboratory, Tennessee (“ORNL”) data are represented by the open squares and broken line and are for August 2006, provided by R. Norby (pers. communication).



### **5.3.2 Carbon dioxide quality**

Early experience in elevated CO<sub>2</sub> research in Australia indicated that Australian CO<sub>2</sub> sources have in the past varied hugely in their contamination with hydrocarbons, most pertinently ethylene (Morison and Gifford 1984). Ethylene is a powerful plant growth regulator in the part per billion range and can reduce growth, even over-riding the positive CO<sub>2</sub> effect in some species. The effect varies with species and hence is especially important when investigating mixed species response to elevated CO<sub>2</sub>. There has been no systematic investigation of the ethylene levels in various sources in Australia. There are several commercial suppliers of CO<sub>2</sub> in the nation. The British Oxygen Company, for example, has spent a great deal of money striving to routinely remove hydrocarbons including ethylene from its product for agricultural applications. Yet personal experience (Roger Gifford) has indicated that food-grade commercial CO<sub>2</sub> can still change the colour of the indicating granules (Purafil<sup>TM</sup>) used routinely to scrub ethylene out of the gas. Whether that observed colour change is truly due to ethylene absorption is not positively known, but seems likely. Nevertheless, the issue of potential ethylene contamination and its removal for a FACE facility is one that needs to be taken seriously. The cost of scrubbing several tonnes of CO<sub>2</sub> per day with large columns of Purafil<sup>TM</sup> would not be a minor one. Without certainty that there is no ethylene contamination, the work is not worth doing – the effects can be so significant for some species. Accordingly, for such a massive and expensive operation as a forest FACE, once a cheap enough source of CO<sub>2</sub> has been identified, it would be prudent to run controlled environment experiments using the species to be studied in the FACE, to establish whether passing the gas through ethylene scrubbers made any difference to plants' growth and development.

### **5.3.3 Night-time enrichment**

For the pre-dilution system of the BNL FACE, one solution to the blower effect increasing air temperature by night (see Section 5.3.7) is to not run FACE at night. This has the added advantage of reducing CO<sub>2</sub> costs. Although the explanation for the occasional report of increased growth of plants exposed to only night-time CO<sub>2</sub> enrichment remains elusive, the lack of credible evidence that dark respiration is inhibited by high CO<sub>2</sub> concentrations (see Section 4.1.4) suggests that there is no compelling need to enrich CO<sub>2</sub> at night in FACE experiments.

At night stomata are closed and night time water loss is minor compared with that during the day. Any effects of CO<sub>2</sub> concentration on night time Gs are therefore likely to be inconsequential.

### **5.3.4 Actual as compared to effective mean CO<sub>2</sub> concentration**

Hendrey highlighted awareness of the implications of the inevitable large variability in CO<sub>2</sub> concentrations within the sweet-zone of a FACE ring (Gifford 2004). Owing to the eddy structure of mixing, there is a limit to which variability of concentration cannot be reduced without increasing the artificial

windspeed. In addition, there is generally only one spot where the control algorithm is controlling the concentration. Elsewhere in the ring, where most of the photosynthesis occurs, the instantaneous concentrations could vary much more widely than at the control point. The performance routinely reported for FACE systems is for the 1 minute average concentrations at the central control point. The “grab samples” sometimes reported, while for one second duration are calculated to actually represent 3-4 sec averages owing to the smoothing effect of sample transit along narrow tubes with gas adhering to the walls. A fraction of such 3-4 sec average samples are at ambient concentration, or above 800ppm (eg. Figure 7). Inevitably a larger fraction would be above 800ppm if instantaneous CO<sub>2</sub> concentrations were determined.

One of the implications of such variability is that the ‘physiologically-relevant’ concentration to which the plants are exposed is less than the arithmetic mean of the instrumental concentration. This is because the photosynthetic response to CO<sub>2</sub> is non-linear and saturates at ~800 ppm. Thus every time the actual concentration exceeds 800ppm it should be set at a value of 800ppm to give the correct “physiological concentration”. Given that the distribution of instantaneous CO<sub>2</sub> concentrations (as opposed to 3-4 sec averages) is not generally known, it is difficult to estimate by how much the effective physiological average CO<sub>2</sub> concentration in FACE rings is lower than the arithmetic mean – but it is sure to be lower. Accordingly, measured growth responses in FACE rings to date are sure to be somewhat lower, for the stated arithmetic mean concentration, than they should be.

On the question of fluctuations in the CO<sub>2</sub> concentration interfering resonantly with plant function, the significance is less clear. Gifford (2004) discussed the publications in which systematic sub-minute fluctuations in concentration caused substantially reduced growth or photosynthetic responses in wheat (Hendrey et al. 1997), rice and trees (Holtum and Winter 2003) to elevated CO<sub>2</sub>. Given the likelihood of systematic elements to the fluid-dynamically inevitable fluctuations of CO<sub>2</sub> concentration in FACE rings, combined with the huge costs of FACE experimentation, this phenomenon warrants closer examination by controlled experiment.

### **5.3.5 Background ambient CO<sub>2</sub> concentration**

One problem with elevated CO<sub>2</sub> experimental research is that the ambient CO<sub>2</sub> concentration is increasing by 1-2ppm per year with little chance of that rate slowing down over the next decades. It is not practicable to decrease the CO<sub>2</sub> concentration of air for the ambient (control) plots in a FACE study. When the first elevated CO<sub>2</sub> studies on plants in the context of the impact of global atmospheric change were conducted in controlled environment cabinets in the early 1970s, the ambient CO<sub>2</sub> concentration was 325 to 330ppm. It is now 380ppm. Preindustrially it was about 280ppm and just before the end of the last ice-age it was about 180ppm. Thus significant effects of the globally increasing CO<sub>2</sub> concentration on vegetation have already taken place. The inherent saturating response of plant photosynthesis and growth to CO<sub>2</sub> concentration means that further responses to elevated CO<sub>2</sub> will be less for a given increase in CO<sub>2</sub> concentration. Failure to take that into account in comparing results obtained over the years can lead to the spurious conclusion that recent FACE studies show a lower sensitivity of growth and yield to CO<sub>2</sub> enhancement effects than earlier enclosure studies (Tubiello et al. 2006). It is therefore important to take this changing background into account. For a forest FACE study needing to be carried out for at least a decade to address key research issues, the changing ambient control concentration needs to be considered in the interpretation of results.

### **5.3.6 What sized ring diameter for forests?**

Three aspects determining the minimal size for a forest FACE ring are 1) the technicalities of whole-stand CO<sub>2</sub> enrichment, 2) representation of the ecosystem diversity by replication, and 3) root distribution issues.

Obviously the taller the vegetation the larger the ring diameter must be to obtain uniform enrichment. A 1 m ring might suffice for a “bowling-green-FACE” with a ring-diameter to plant-height ratio of about 50, but would clearly not work in a 30 m tall forest. There has been no definitive discussion of the minimal size of a FACE rings, having vertical vent pipes releasing CO<sub>2</sub>, in relation to tree height (Allen et al. 1992). But we suggest that for sufficiently uniform CO<sub>2</sub> concentration it would, as a rule of thumb, be necessary for the ring diameter to be about 3x the plant height as was adopted for the BNL forest FACE (He et al. 1996) at the outset. By that rule, a 30 m rainforest would need ~90 m rings. Given the huge expense to run 3 or 4 such large rings, a replicated WebFACE system may be relatively attractive in such forests despite its inadequacies.

Another way to look at this is to consider that the tree crowns, where most of the photosynthesis occurs, is only a fraction of the tree height and might be considered typically to be about 5-10 m depth. It is this zone which has been emphasised for controlled CO<sub>2</sub> release in the forest FACE systems to date. Then a 30 m ring is 3-6x the width of the primary enrichment depth and would be satisfactory. However, when investigating whole ecosystem response to elevated CO<sub>2</sub> concentration in the long term, the behaviour of the understorey

vegetation and recruitment of new saplings is important. For that objective, the intention should be to enrich the entire height of the ecosystem. Achieving adequate control is problematic probably requiring a larger ring than when just the top 5-10 m of the crown is subjected to controlled elevated CO<sub>2</sub>.

The unit of replication in forest ecosystems needs to be the community of plants rather than individual trees. What area of forest is the minimal area for a replicate plot? This depends on the degree of biological variability of the ecosystem and on the vegetation height. Issues relating to the statistical design of a forest FACE study are discussed in Section 6.

Another concern is the width of the buffer zone to ensure that the root systems of the CO<sub>2</sub> enriched plants are encompassed by the area of enrichment. If root-systems of non-enriched trees encroach into the ring (and vice versa) the competitive relationships under elevated CO<sub>2</sub> concentration will not be operating correctly. Since tree roots can extend laterally beyond the crown and, at least for some species including *Pinus* (Wood and Batchelard 1970) and *Populus* (DesRochers and Lieffers 2001), roots from adjacent trees graft onto one another, this is a substantial issue. Since water, minerals and photo-assimilate can pass between trees through the grafted root network, a much wider buffer may be needed in a forest-FACE than in a crop-FACE. The 2-3 m buffer zone in which the CO<sub>2</sub> may mix adequately seems inadequate from the point of view of the enriched tree root systems being entirely within the CO<sub>2</sub> enriched sweet zone.

### **5.3.7 The blower effect**

The two-fluid BNL design, involving pre-dilution of the air to 30,000ppm, sends a net flow of air across the FACE ring that is additional to the natural wind field. This was found to alter the microclimate sufficiently in the Arizona FACE study with wheat to affect the results (Pinter et al. 2000). Under higher natural wind speeds the blower influence was not detectable. But under low windspeed, notably under the stable air conditions at night, the added air movement was both measurable and problematic.

The result for the BNL FACE system in Arizona was despite the initial study of the impact of the BNL FACE system on microclimate for the Duke forest FACE system in 1994 finding little effect there (He et al. 1996). At that facility, micrometeorological tests found that the blower increased horizontal wind-speed only 0.03 m s<sup>-1</sup> (an increase of 10%) and increased temperature within the canopy by only 0.1°C at night under stable atmospheric conditions.

### **5.3.8 Experimental design of a FACE study**

The cost of running FACE is high. Accordingly it is especially important to have efficient experimental design. Efficient design naturally involves use of randomly located ambient- atmosphere control plots. Formally, more statistical power can be achieved for a given number of plots by introducing more treatment levels with less replication of each, and introducing sub-

treatments in each ring (such as different water or nutrient levels) in a split plot design (Filion, Dutilleul and Potvin 2000).

In the OzFACE facility, the rings were run at ambient, 460ppm and 550ppm, with 2 replicates of each. This provided a more powerful design than 3 replicates of two CO<sub>2</sub> levels. It also gives the possibility to examine the results for linearity or curvature of response, although natural variability may make it challenging to detect departure from linearity.

Forests, especially non-plantation forests, are much more variable than sown crops and pastures. Accordingly more ring replication is needed to detect treatment effects. Four replicates seem prudent as a minimum. Given the considerable doubt about there being any effect of CO<sub>2</sub> during darkness (see Section 5.3.3), deploying funds for CO<sub>2</sub> gas to enrich an added replicate should be a much higher priority than enriching by night.

Although from a statistical point of view, adopting split-plots by dividing each ring up to incorporate treatments such as added fertiliser, or water, adds statistical power to detect effects, as well as physiological interpretative power, this approach is not recommended for forest FACE. First, the good performance of FACE control applies only at the central point of control. Inevitably there is a gradient of average CO<sub>2</sub> concentration from high at the windward edge to low at the lee edge of the ring as the released gas disperses. Thus the prevailing windward zone will on average have a higher CO<sub>2</sub> concentration than the prevailing leeward zone as is evident in Figure 8a. In the crown of the Duke Face (when at 9 m) the annual average concentration was 700ppm at the most northern edge, 550ppm at the centre and again 550ppm at the most southern edge. If split plots are adopted it would be necessary to have at least a year of careful distributed performance monitoring (both vertically and horizontally) to divide the necessary subdivision of the plot to ensure equal average concentrations between the subplots.

A second drawback of split plots is that, for trees, the fraction of the plot occupied by each tree, and the extent of the root systems and zone of above-ground litter fall, is much larger than for each grass or crop plant. Thus any treatment to the soil will influence non-target trees as well as those within the intended subplot. In other words, the needs for buffer zones around subplots would occupy too much of the ring.

Thus if any additional treatments are involved (eg. more CO<sub>2</sub> levels or manipulation of water or nutrients) these must be applied either with more whole rings or as a function of time within plots for which a further treatment is applied after a certain number of years. An extension of that point is that when replication is low, it is imperative to have a solid body of data about the forest performance in the FACE ring before the CO<sub>2</sub> is turned on. Then the forest behaviour can be documented before and after CO<sub>2</sub> enrichment. See Section 6.3 for further discussion of FACE design issues.

### **5.3.9 For how long should a study commit?**

CO<sub>2</sub> enrichment of an existing forest creates a significant problem of interpretation that is not encountered when growing plants from seed in elevated CO<sub>2</sub>. The response to step change of concentration does not represent the response of trees that will grow in that elevated concentration when the change occurs gradually. A step increase in any environmental factor like CO<sub>2</sub> creates transient process responses that would not occur if that change occurred gradually over time (Luo and Reynolds 1999), if only because of the large pools of carbon and nutrients that exist in trees relative to the annual fluxes.

A forest will experience, through time, a series of adaptive feedbacks, some of which cannot be replicated without growing the forest with gradually (real-time) increasing CO<sub>2</sub> concentration. The feedbacks can work in both directions, in which the transient result leads to either unrealistic expectations for high responses to change because negative feedbacks would set in over timescales longer than the transient experiment (Luo and Reynolds 1999), or to low responses because the ecosystem does not have time in the period of a transient experiment to re-organise to optimise the opportunities that enhanced CO<sub>2</sub> provides (e.g. enhanced N-fixation by the ecosystem).

However, an experiment conducted with real-time gradual change of CO<sub>2</sub> concentration, would provide no basis for prediction because the findings would come in after the real-world change has already happened. So, for an existing forest, a compromise has to be struck between a short-term step-change experiment that offers little or no predictive value because most of the internal-ecosystem feedbacks, compensations and amplifications have not had time to play out, and a long term real-time ramp experiment that also offers no predictive value because the effects have occurred in the real world before the data are analysed and used in a predictive model. Long-term (>10 years) studies that go beyond some of the fast transient responses are needed, and ancillary process investigations that provide the information needed to interpret the time course of the observed responses are necessary.

## **5.4 Costs**

### **5.4.1 Infrastructure**

For the BNL design, the infrastructure costs are high, but depend critically on the specific situation such as value of the land rental, cost of installing all-weather road access for heavy trucks and equipment, and installing power and water to the selected site. It is not a trivial exercise to estimate costs for any specific facility. Kimball (1993) in consultation with G.R. Hendrey estimated the initial setup costs to be \$50k (1990 US\$) per ring for the 22 m crop FACE ring equipment plus the cost of installing roads and utilities and other costs (incl labour) for installation of the equipment. Schultze and Tenhunen (1993) estimated the costs for establishing 3 rings in a mixed forest stand in Germany would be 684,000 Deutsch Marks for hardware. And

Schulze and Mooney (1993) listed the capital costs of four large FACE rings to be 375,000 European Currency Units (ECU).

More recently Canadell *et al.* (2006) suggested that the installation costs for x8, 22 m BNL-type rings for low stature crops in Australia (incl liquid-CO<sub>2</sub> tank and evaporator, electricity, and weather station) would be A\$352k. It is unclear whether this includes the cost of providing roads and construction labour. Before proceeding with any plan a very careful system design and realistic costing would have to be carried out.

Infrastructure such as a fixed lift (preferably on tracks) in each ring to provide access to tree crowns for research measurements will also be required (Photo 8).

The initial capital costs for a pure CO<sub>2</sub> injection system are expected to be much lower than that of the BNL system because of much less substantial hardware requirements. However, we have not yet identified an Australian company capable of laser drilling holes in plastic tubes, so the cost of getting the laser drilled tubing from overseas needs investigation.



**Photo 8.** ORNL canopy lift. Photo from Oak Ridge National Laboratory website: <http://www.esd.ornl.gov/facilities/ORNL-FACE/index.html>

#### **5.4.2 CO<sub>2</sub>**

The cost per ring of CO<sub>2</sub> gas depends on the size of the ring, the height of the zone of enrichment, the average wind speed of the site, whether night time enrichment is engaged in, the enrichment level of the FACE, and the efficiency of the enrichment system.

The efficiency of the enrichment system seems to vary considerably between systems - as yet not wholly explicably (Fig 5 above). The CO<sub>2</sub> requirement per m<sup>-2</sup> of ground area encompassed by the ring per hour per km h<sup>-1</sup> of wind speed varies 2 to 3 fold from 0.1 to 0.25 at a daytime average windspeed of 4

km hr<sup>-1</sup>. For a single 30 m diameter ring (area of 708 m<sup>2</sup>) located at a site having a daily average daytime wind-speed of 4 km hr<sup>-1</sup>, the CO<sub>2</sub> requirement for 14 hours of day-time enrichment by 200ppm would be in the range 4 to 10 t CO<sub>2</sub> per day. If there were 4 rings run for 365 d yr<sup>-1</sup> then the annual CO<sub>2</sub> use would be in the range 5,840 to 14,600 tonne CO<sub>2</sub> pa.

The cost of CO<sub>2</sub> is a significant part of the cost of FACE systems but depends heavily on where it comes from. If a “free” source can be identified from some industry that has spare waste gas that option should be carefully explored. There are however some major potential issues with “free” sources. One drawback is that the supply might not remain free or cheap or available for the duration of the study (>10 years) or the promise of free supply might not come to fruition, so contingency plans need to be made for that eventuality. Another is that it may not be as “free” as expected once the facilities for cleaning the gas, storage and transporting it to the research site are considered. Whether sources are from an underground supply or an industrial combustion supply, the gas may need to be purified to remove hydrocarbons especially ethylene (though not necessarily); purification may be the most expensive aspect of commercial production in any event. If it is not guaranteed ethylene-free, and no ethylene-scrubbing system is installed on site, then the experiment may be at risk of being irrelevant if batches of ethylene-contaminated gas are received from time to time owing to un-announced source-switching by the supply company. Such events may not be known to the facility staff, so a system of ‘quality control’ needs to be introduced.

The commercial sources like British Oxygen Company, Air Liquide, or Linde can all supply in bulk by tanker, but until negotiations are entered into for a specific plan it is not possible to forecast what the final price might be. Perhaps they will be willing to subsidise the cost as we understand may occur for some sites in the USA. A quote that one author (RMG) had in 2006 from one of the suppliers was a 70% discount from the normal bulk supply rate when required at the rate of 3 tonne per day. However at that discounted rate the cost was still A\$256/tonne plus delivery and storage tank rental (Photo 9). Storage tank rental could be about \$50,000 pa, or more if the system requires a vaporizer to prevent freezing up as the liquid CO<sub>2</sub> expands (Photo 10). Another supplier at that time quoted a discounted rate of A\$350-450/tonne plus a delivery charge and storage tank rental.





Photo 9 Tanker delivery. Photo from Oak Ridge National Laboratory website:  
<http://www.esd.ornl.gov/facilities/ORNL-FACE/photos.html>



Photo 10 Tank with vaporizer at the Aspen FACE experiment in Rhinelander, Wisconsin. Photo from Brookhaven National Laboratories website:  
<http://www.bnl.gov/face/FACE-EngineeringOperations.asp>

Thus, at the lower unit-cost quotation, the 5,840 to 14,600 tonne CO<sub>2</sub> pa calculated above for four rings (at a mean daytime wind-speed of 4 km/h) would cost somewhere between \$1.5M and A\$3.7M per annum (and close to 50% more than those figures if the mean daytime windspeed of the site were 6km/h), plus at least \$50,000pa for onsite storage plus any electricity costs for running the on-site storage tank system, plus delivery gas charges, which may depend on how far the research site is away from the CO<sub>2</sub> supply depot. We stress that these figures are likely to change markedly based on negotiation with specific suppliers for large amounts of CO<sub>2</sub>. See Section 3.4 for further discussion on possible ways of reducing CO<sub>2</sub> costs.

The fact that the reason for the 2.5-fold range in CO<sub>2</sub> use rate between similar rings systems is not yet fully understood and has a major impact on the costliness of the project, indicates the need for a careful study of the causes of apparent efficiency variation.

### **5.4.3 Operational**

The complexity of a FACE system requires a full time experienced engineer managing it 365 day per year. Thus there needs to be an engineer plus a senior technician to be on duty when the engineer is not, and one technical support person as a minimum system-management team. Assuming direct salaries of A\$80k, A\$60k and A\$40k pa for the technical people with a multiplier to cover on-costs and organisational overheads. This cost may total approx. \$350k pa. it may be cost-effective to provide some on-site accommodation.

In addition to CO<sub>2</sub> and staff the facility will have costs of electrical power and water. For the BNL system the power costs are not insignificant. For the pure CO<sub>2</sub> injection system power costs are much less.

Liability insurance costs need consideration, given the risks associated with use of extensive hardware distributed within the forest, and of working at heights of up to 30 m on masts, cranes, lifts and hoists (Photo 11).



**Photo 11.** Working at heights. Photo from Oak Ridge National Laboratory website: <http://www.esd.ornl.gov/facilities/ORNL-FACE/index.html>

The FACE approach to elevated CO<sub>2</sub> research gains an important advantage over smaller enclosure systems in involving a large area of vegetation in which a lot of different, but interrelated, research projects can be run. But this does require a commitment to associated costs (See also Section 3.3).

## **6. CONSIDERATIONS FOR THE LOCATION AND DESIGN OF AUSTRALIAN FOREST FACE STUDIES**

As discussed in Section 3, there are several diverse and important questions relating to the effects of elevated CO<sub>2</sub> on Australian forests where application of forest FACE studies would be valuable. These potentially encompass a range of forest types with studies having varying emphasis on carbon, water or biodiversity. In section 3.2 we advocate a modelling framework for identifying knowledge gaps, guiding site selection and experimental measurements, and as a means of estimating the possible effects of elevated CO<sub>2</sub> in contrasting forest environments.

Here we discuss key factors relevant to conducting FACE studies in particular forest types, then propose some options for experimental design to increase efficiency of forest FACE studies, and conclude by briefly discussing generic requirements for successful FACE implementation.

### ***6.1 Can plantations be a useful analogue for native forests?***

The concept that plantations provide a useful analogue for native forests is based on the assumption that the knowledge gained, and hypotheses tested, from the simpler plantation systems are useful in predicting the response to elevated atmospheric CO<sub>2</sub> in more complex forests.

For this concept to be pertinent, knowledge must be relevant and transportable between systems.

Given the variation in response to elevated CO<sub>2</sub> between species reported in the literature there must be some doubt that there will be sufficient similarity in response to make it viable to use plantations as analogues for native forests.

#### **Ecophysiology**

The majority of Australia's eucalypt forests are located in water-limited regions. In contrast the most commonly used plantation eucalypts (*E. globulus* and *E. nitens*) both originate from relatively moist and cool environments. *E. globulus* in particular has limited capacity to moderate water use under dry conditions and as a result has experienced drought deaths in a number of areas in south-western Australia. Thus while it is the most widely planted eucalypt in Australia, *E. globulus* is unlikely to provide a useful analogue for eucalypts from Australia's drier regions.

The dissimilar physiological characteristics and the small area of the Australian environment that is similar to the mesic environment from which this species is endemic means that it is unlikely to be a useful analogue for native systems.

#### **Forest Age (stage of growth cycle)**

Another major impediment to the use of plantations as analogues for native systems is that plantations are generally at a very different stage of growth to native eucalypt forests. Most eucalypt plantations in Australia are grown on short rotations for pulp wood production, so that most plantations are in a dynamic expansion phase rather than a steady state phase when the stand (ecosystem) is more in equilibrium with the available resources. There is some evidence that the large responses observed in young plantation systems are not always observed in older (post canopy closure?) stands (see Section 4).

This raises the issue of the conditions under which forests (both native and plantation) are most responsive to elevated CO<sub>2</sub>. The presence of initial rapid response, which declines over time, suggests increasing limitation of other resources required for growth. Once the trees have fully utilised the resources (water and nutrients) that are available at a site, then continued growth response relies on greater efficiency of use of these resources. This raises issues of at what stage of a forest or plantation cycle the impact of CO<sub>2</sub> should be examined, if the aim is to understand for how long the response will be sustained.

Most plantations of eucalypts have been established on land that has been farmed for many decades. This means that generally there are plentiful supplies of water and nutrients on such sites, and this has enhanced plantation growth rates in the first rotation. Except in rare circumstances where trees have access to water stored in very deep profiles, or have access to ground water, this enhancement of growth lasts for less than a rotation. As the conditions in the future for plantations on these sites will not include access to extensive amounts of stored water it is suggested that second rotation sites be considered for study because they are likely to be more representative of a broad range of sites in the future. Further, if results from plantation systems are to have any relevance to native forests then attempting to match site resource conditions would be an advantage. Table 6 compares the key characteristics of native forest and plantation systems.

**Table 6.** Comparison of plantation and native forest systems

NATIVE FORESTS	PLANTATIONS
<b>Ecology</b>	
<ul style="list-style-type: none"> <li>• Diverse species</li> <li>• Complex structure                             <ul style="list-style-type: none"> <li>- structural components (over-storey / understorey)</li> <li>- often multi age</li> </ul> </li> <li>• Approach equilibrium with site</li> <li>• Fire often a regular component</li> <li>• Slow growth rates (species, no management)</li> <li>• Considerable competition within stand/system</li> <li>• Contain N-fixing understorey</li> <li>• Regeneration/recruitment is on-going</li> <li>• LAI usually less than in plantations</li> </ul>	<ul style="list-style-type: none"> <li>• Monocultures</li> <li>• Simple structure                             <ul style="list-style-type: none"> <li>- Only an overstorey of uniform age, and often grown on short rotations</li> </ul> </li> <li>• Fire excluded</li> <li>• Fast growth rates (species, management)</li> <li>• Competition managed (early growth stage, thinning)</li> </ul> <p>Shorter rotation times, so that longer –term changes (near equilibrium) are less important</p>
<b>Site characteristics</b>	
<ul style="list-style-type: none"> <li>• High to low rainfall</li> <li>• Low nutrient supply</li> <li>• Hydrological equilibrium</li> </ul>	<ul style="list-style-type: none"> <li>• High to moderate rainfall.</li> <li>• Relatively high nutrient status.</li> <li>• Hydrologic imbalance (initially).</li> <li>• Fertilized</li> </ul>
<b>Physiological characteristics</b>	
<ul style="list-style-type: none"> <li>• Often slow growing</li> <li>• Low nutrient requirement</li> <li>• Endemic to water-limited sites                             <ul style="list-style-type: none"> <li>- capacity to limit water loss</li> <li>-- high drought tolerance, or avoidance</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Selected for fast growth</li> <li>• High nutrient requirement</li> <li>• Generally from mesic sites                             <ul style="list-style-type: none"> <li>- High water demand</li> </ul> </li> <li>• Limited drought tolerance or avoidance strategies</li> </ul>

Although plantations can not be considered as a good analogue for native forests, elevated CO<sub>2</sub> and climatic change can have important impacts on the risks and economics of wood production. Thus there is merit in establishing FACE in plantations, but with a more specific research focus than in native forests.

## **6.2 FACE studies in tropical rainforests and other tall forests**

There have been no FACE studies in rainforests anywhere in the world except for a several-week, single-ring trial in Panama (see Section 5.1). Globally, rainforests contain about 40% of the terrestrial C stock, and are considered to be significant in terms of their impact on the climate system. It is also argued that the NPP and water yield from such forests may be very responsive to elevated CO<sub>2</sub>. Some (eg. Laurance et al. 2004) have argued that increasing atmospheric CO<sub>2</sub> may be an important driver of recently observed changes in tree communities in undisturbed rainforests including increased growth rates of most genera in Amazonian plots since the 1980s (Laurance et al. 2005). Others such as Nelson (2005) have debated this, and Laurance et al. (2005) have urged the conduct of FACE research in rainforests to help resolve the role of elevated CO<sub>2</sub>.

There may be an opportunity for Australia to make an important global research contribution by conducting a FACE study in Queensland rainforests. This would complement work proposed as part of the new Marine and Tropical Sciences Research Facility (MTSRF). However, there are many logistical issues to address.

Table 1 shows that the area of tropical rainforests and vine thickets (30,321 km<sup>2</sup>) and tall open eucalypt forests (30,129 km<sup>2</sup>) in Australia is small compared to eucalypt woodlands (693,449 km<sup>2</sup>), acacia forests and woodlands (550,649 km<sup>2</sup>) and eucalypt open woodlands (384, 310 km<sup>2</sup>). Using data in Chen et al. (2003) and Roxburgh et al. (2004), it may be estimated that the NPP of the most productive regions of Australia are approximately 2 – 5 times higher than the least productive wooded areas. Despite this, the contribution of Australian rainforest and tall open forests to Australia's C budget is small.

There are several factors that make conducting FACE studies in tropical rainforests particularly problematic:

1. The height and complexity (multi-layered structure and complex species composition) make the technical challenges of siting a FACE system in a rainforest significantly more problematic (and expensive). The area required to sample a representative patch of rainforest in a FACE experiment is large. A WebFACE design is likely to be more practical than a ring FACE but even then the typical presence of tall individuals emerging above a lower highly uneven canopy-top renders CO<sub>2</sub> concentration control in WebFACE especially difficult. The density of the entangling vines in the exposed tops of rainforest trees would make it problematic to entwine the fine tubing effectively among the leaves to provide uniform enrichment. In addition the extension of foliage down the entire 25-35 m typical height of a rainforest means that uniform enrichment would be needed throughout this entire

photosynthetic zone. This would require considerable technical development before it was achievable.

2. It is very difficult to study soil feedbacks on the nutrient cycle without treating a very large area of rainforest with elevated CO<sub>2</sub> and this is very expensive. Attempting to CO<sub>2</sub> enrich individual trees within a rainforest would not achieve the objectives of full ecosystem response understanding involving within-ecosystem feedbacks.
3. The huge species diversity in tropical rainforest (many tens of tree species per hectare) makes it virtually impossible to find nearby plots that are similar enough to represent comparable plots for treatment.
4. The prevalence of cyclones and tropical thunderstorms in tropical Australia make the probability of storm damage (to the equipment and/or the ecosystem) much higher than in temperate Australia. The probability of differential damage to ambient and enriched zones would be high.
5. Tropical Australia presents a more difficult climate within which to keep complex field systems functioning owing to the highly corrosive high humidity and, often salinity, of the atmosphere.
6. The costs of maintaining a consistent scientific and technical support presence in the tropics is larger than that in temperate Australia.
7. Finding locations that are technically preferred and also close enough to research centres of excellence to attract collaborative researchers is even more problematic in the humid tropics than in temperate areas.
8. Tropical Australia is not water-limited, and experiences only minimal seasonality in temperature, in stark contrast to the rest of Australia where productivity is limited by water availability and where temperature variability is much larger.
9. If a canopy crane were used to install the tubing network of a WebFACE, it would be problematic to install several enriched plots within the circumference of the crane that did not produce some enrichment of the adjacent 'untreated' forest. The areas would be too close together. Thus several cranes might be required to enable replication and this would add further expense.

## **6.3 Some design options**

### **6.3.1 Settings and constraints**

For both plantations and native forests, limited water supply, high evaporative demand, and nutrient-depleted soils are the major features that set Australian forests apart from other systems in which FACE has been used. In plantations nutrient supplies are either high (from prior agricultural fertilisation) or supplemented during the rotation. In native forests nutrient and water limitations apply, and nutrient limitation may increase under elevated CO<sub>2</sub>. Native forests are not fertilized, and it is unclear (but a critical factor for determining the longer-term response to elevated CO<sub>2</sub>) whether N fixation will increase under elevated CO<sub>2</sub> because of strong P limitations in many systems. N fixation rates often increase after fire (Raison et al. 1993), because fire rejuvenates populations of native legumes and also temporarily increases soil P availability (Romanya et al. 1994). Thus elevated CO<sub>2</sub> may increase growth rates during the recovery period following major forest disturbances.

Given the above, FACE installations in Australia should test hypotheses related to how dry and infertile conditions influence the response to elevated CO<sub>2</sub>.

A key constraint in the design of FACE installations is the practical size of the treatment rings. The amount of CO<sub>2</sub> required is dictated by the volume of air that needs to be enriched. This depends on ring diameter and tree height. With the high CO<sub>2</sub> costs expected (see Section 5.4.2) it seems ill-advised to suggest that a ring diameter larger than the maximum size tested in the world to date of 30 m should be exceeded. This sized plot is necessary to allow those ecosystem processes that are specific to forest ecosystems to be influenced by and studied under conditions of elevated CO<sub>2</sub>. If the plot diameters are set at 2-3 times the height of the vegetation then the maximum tree height is in the order of 10 – 15 m. An upper limit of 20 m may be feasible. This constrains the type and/or stage of development of forest systems that can be considered as candidates for FACE and precludes all tall forests. For many plantations that show rapid early growth, it confines studies to the early-mid part of plantation crop cycle. Thus one of the strong candidates for a native forest study is the medium rainfall woodlands (see also Section 3.2). These systems generally fit this height/size constraint, however the low tree density of some woodland systems may also further constrain the systems that can be effectively studied (too few trees within the FACE ring).

Most FACE studies have been conducted in plantation systems where the structural and functional complexity is less than in native forests. Plantations are generally composed of single species of uniform age, have little understorey and are either established on sites with improved fertility (following decades of agriculture) or are fertilized to remove nutrient limitations. Plantations are still subject to the variation in climatic conditions experienced in Australia where water supply limits the growth of almost all



plantations. It is suggested that water limitations be the focus of any work conducted in plantations.

### **6.3.2 Possible experimental designs**

The very high cost of CO<sub>2</sub> may limit any studies to use of 4 CO<sub>2</sub> - fumigated 'rings'. We see two basic designs possible for FACE systems. One is to replicate the treatments and use factorial analysis. The other is to increase the number of treatments without replication and analyse the data using regression analysis. If the only treatment considered is the elevation of CO<sub>2</sub> then 4 replicates of one elevated CO<sub>2</sub> level, or 2 replicates of two elevated CO<sub>2</sub> levels can be used. If there is no replication, then 5 rates of CO<sub>2</sub> (ambient plus 4 elevated concentrations) can be studied. The loss, through misadventure, of an experimental "plot" from either of these experimental designs is likely to have considerable impact on the effectiveness of the study.

If the approach taken is to examine directly the impact of manipulation of either CO<sub>2</sub> alone or in combination with a modification of water supply then the design of native and plantation FACE systems would be similar. However, fire which modifies the supply of nutrients and the demand for water in native systems, could also be used as a treatment. Given the wide lateral extent of tree rooting, the possibility of root grafting between adjacent trees, and the undesirability of cutting through roots to install impervious septa (effectively creating large *in-situ* pots), it is not practicable to have varying water (or nutrient) availability as sub-plots within the FACE rings.

#### **1. Elevated CO<sub>2</sub> without altering the supply of water**

**Option A - Replicated design:** 2 levels of CO<sub>2</sub> x 4 reps  
(Ambient and Elevated CO<sub>2</sub>) x 4 Replicates resulting in 4 elevated CO<sub>2</sub> treatment plots.

The suggested enhancement of CO<sub>2</sub> is 200 ppm

**Option B - Replicated design:** 3 levels of CO<sub>2</sub> x 2 reps

(Ambient, Low elevated CO<sub>2</sub>, High elevated CO<sub>2</sub>) x 2 Replicates resulting in 4 elevated CO<sub>2</sub> treatment plots.

The suggested enhancements of CO<sub>2</sub> are 150 ppm (low) and 250 ppm (high)

**Option C - Regression design: 5 levels of CO<sub>2</sub> x 1 rep**

A regression analysis using 5 rates of CO<sub>2</sub> without replication

Ambient, + 100, + 200, + 300, + 400 ppm resulting in 4 elevated CO<sub>2</sub> treatment plots

**2. Elevated CO<sub>2</sub> and Water treatments**

**Option C: 2CO<sub>2</sub> x 2 water x 2 reps**

Examine the interaction between water supply and CO<sub>2</sub> supply using a replicated design (2 reps).

Note: water supply could be supplemented by irrigation or reduced by interception. Supplementation (irrigation) is easier than reducing water input.

2 CO<sub>2</sub> x 2 water x 2 reps = 8 plots (4 CO<sub>2</sub> -enhanced rings, 4 ambient CO<sub>2</sub> rings).

**Option D: 3CO<sub>2</sub> x 2 water x 1 rep.**

Examine the interaction between elevated CO<sub>2</sub> and water supply, using a regression approach without replication.

(Ambient CO<sub>2</sub>, Ambient plus 150 ppm, Ambient plus 250 ppm) x  $\pm$  water = 6 plots (4 CO<sub>2</sub> -enhanced rings, 2 Ambient CO<sub>2</sub> rings)

Note: With all these designs the replication of the non-elevated CO<sub>2</sub> treatments can be increased as this will not substantially increase the costs of the infrastructure. However it will increase the costs of data collection.

**3. Native forest FACE incorporating fire as a treatment**

Examination of the interaction between elevated CO<sub>2</sub> and the water and nutrient limitations commonly experienced in Australian native forests, could be investigated in a number of ways. The impact of nutrient and water supply on ecosystem function could be investigated by the direct manipulation of these variables (see above). Alternatively, the impact of these variables could be studied by burning the forest and assessing the impact of the 'disturbance' on the supply of nutrients and water, and how this interacts with elevated CO<sub>2</sub>.

## There are alternative designs to such a study:

### (a) Time Series Approach

Ambient CO <sub>2</sub> 'mature' unburnt forest	CO <sub>2</sub> treatment commenced, no fire	CO <sub>2</sub> treatment continued with $\pm$ burn at year 10
0-----5 years	5-----10 years	10-----20 years

There would be 2 CO<sub>2</sub> treatments (ambient, high CO<sub>2</sub>) x 2 reps

### (b) Parallel Treatments

Ring 1	+ CO <sub>2</sub> – fire
Ring 2	+ CO <sub>2</sub> + fire
Ring 3	- CO <sub>2</sub> – fire
Ring 4	- CO <sub>2</sub> + fire

With 2 reps = 4 high CO<sub>2</sub> rings

If the objective of the FACE studies is to construct better models of the impact of the elevation of CO<sub>2</sub> in conjunction with variable water and nutrient conditions, then direct manipulation of those variables may be the preferred approach. A fire study on the other hand, may provide insights into the effects of elevated CO<sub>2</sub> during the recovery phase after disturbance, which incorporates change in important ecosystem processes such as increased N fixation rates.

With all forest FACE studies in dry environments there is a risk that unplanned wildfire could affect all or some plots, changing the course of the experiment.

## **6.4 Other important considerations**

Provision and maintenance of the FACE infrastructure, is only the initial step in a successful forest FACE initiative. The infrastructure provides the opportunity for a comprehensive and well integrated program of research that will result in a much improved capacity for predicting the effects of increasing CO<sub>2</sub> on Australian forests over time, and in different locations across the country. The nature of the modelling and related research program required is outlined in Section 3.4. A large, well coordinated multi-disciplinary research effort will be required. Thus it is essential that the FACE facility is accessible and attractive to a critical mass of scientists and students. Consideration also needs to be given to how public funding that could support research at the site can be best co-ordinated. Unless there is an effective program of research, the benefits of the very large investment in the infrastructure and maintenance of the FACE installation will not be realised.

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## **8. APPENDIX**

### **Stakeholder consultation - process and list of those consulted**

The review team was asked to consult widely with scientific experts (national and international), and other relevant industry stakeholders.

Selected science leaders in high CO<sub>2</sub> and related climate research were invited to provide written comment addressing points 3-5 of the above methodology. Discussions were held with several science leaders to explore issue in greater detail. The scientists consulted are listed below.

The forestry and forest conservation sectors were also canvassed for input. The broad views of those with interests in wood production were obtained via discussions with the National Association of Forest Industries (NAFI), the Forest and Wood Products Research and Development Corporation (FWPRDC) and the Australian Plantation Products and Paper Industry Council (A3P). Issues related to forest biodiversity and conservation were discussed with senior managers from the WA Department of Environment and Conservation.

Scientists invited to contribute to the scoping study:

- Dr Andrew Ash and Dr Chris Stokes, CSIRO Sustainable Ecosystems.
- Dr Will Steffen, CRES Australian National University.
- Dr Graham Farquhar, RSBS Australian National University.
- Prof. Andy Pitman, Macquarie University.
- Prof. Ross McMurtrie and Dr Belinda Medlyn, University of New South Wales.
- Dr Mark Hovenden, University of Tasmania.
- Dr Pep Canadell, CSIRO Marine and Atmospheric Research.
- Dr Miko Kirschbaum, RSBS Australian National University.
- Prof. Nigel Stork and Dr Mike Liddell, James Cook University.
- Dr David Ugalde, Australian Greenhouse Office.
- Dr Christian Körner, University of Basel.
- Dr Ram Oren, Duke University.
- Dr Richard Norby, Oak Ridge National Laboratory.
- Dr David Ellsworth (University of Michigan) and Dr David Tissue (Texas Tech University).
- Prof. Mark Adams, University of New South Wales
- Dr Craig Barton, NSW Department of Primary Industries
- Prof. Jann Conroy, University of Western Sydney.
- Prof. Douglas Godbold, University of North Wales, Bangor
- Prof Catherine Potvin, McGill University, Canada

Forest Industry Representatives and Managers consulted:

- Allan Hansard, National Association of Forest Industries (NAFI).

- Dr Glen Kile, Forest and Wood Products Research and Development Corporation (FWPRDC).
- Australian Plantation Products and Paper Industry Council (A3P).
- Dr Neil Burrows and Dr Ian Abbott, WA Department of Environment and Conservation.
- Dr Michael Battaglia, CRC for Forestry, Ensis.
- Mr Steve Pickering, Hansol PI.