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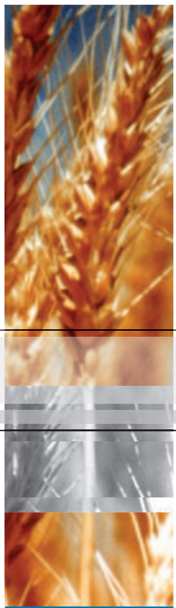

A Guide to Establish FACE Experimentation: Annual Cropping in Australia

Technical Report
Released by the National Committee on Elevated CO_2 Experimentation, Chair Professor Timothy Reeves.

Prepared by Pep Canadell with contributions from other members of the Technical Advisory Group; Peter Grace, Sara Hely, Mark Howden, Tim Reeves, Bill Slattery, Will Steffen and David Ugalde.

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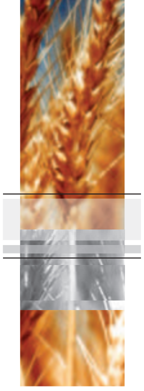
Communications Director,
Australian Greenhouse Office
Department of the Environment and Heritage
GPO Box 787
CANBERRA ACT 2601



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1. Introduction

Average global surface temperature and climate variability have increased over the past two centuries as a result of anthropogenic greenhouse gas emissions (IPCC 2001). Atmospheric concentrations of carbon dioxide (CO_2), the single most important of these gases, have increased from about 280 parts per million (ppm) before the Industrial Revolution to the current level of 380 ppm. carbon dioxide concentrations are currently the highest recorded in the last 400,000 years (Figure 1).

Through measurements of atmospheric CO_2, radiocarbon 14C-CO_2, various ratios of atmospheric elements, and carbon emission inventories, it has been established with absolute certainty that the increased concentrations are due to carbon emissions from fossil fuel combustion and deforestation.

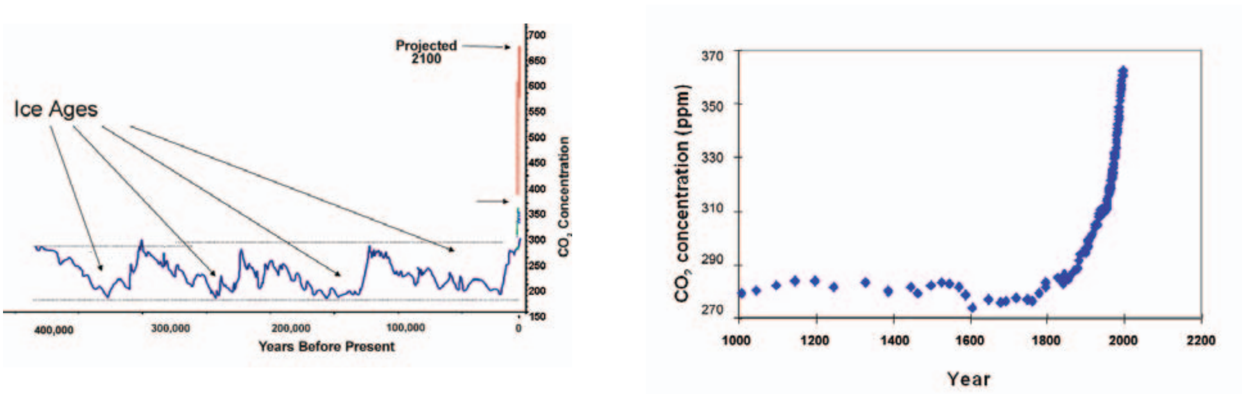


Figure 1. Trends in atmospheric CO_2 concentrations over different time scales (Source: GCP 2001 (left); NOAA-CSIRO (right))

The impacts of increased atmospheric CO_2 are twofold. Firstly, it contributes to the enhanced greenhouse effect and climate change. Secondly it impacts on productivity of terrestrial vegetation by supplying carbon for growth.

Annual average temperatures in Australia have increased by 0.8ºC since the beginning of last century. Since 1950 there have been increased incidence of very hot days, fewer frosts, and a redistribution of precipitation. Climate projections for the coming decades show continuing changes in the distribution and amount of precipitation around Australia, and an overall warming trend. Climate variability and extremes are expected to increase on what is already a highly variable climate.

The purpose of this document is to serve as a blueprint for a national program to address the risks of climate change to Australia's grains industry, including identifying the information requirements to develop adaptive strategies. As a first step, the document outlines the establishment of a National Free-Air CO_2 Enrichment (FACE) experiment on annual broadacre cropping systems.

2.
Risks of Climate Change to Australia's Grains Industry

The Australian grains industry is an important part of the Australian economy and farm sector, with total production worth $8 billion in 2001/2002 and around $6.3 billion in 2004–2005. Wheat is the greatest contributor to grain production in Australia, with high quality standards leading to Australia's strong position in the global wheat market. Australia is the fourth largest wheat exporter in the world, with an average of 17 million tonnes per year over the last 5 years.

Because of the impacts on the productivity of terrestrial vegetation and on climate change, increasing atmospheric CO_2 concentrations will have far-reaching effects on the viability and profitability of the grains industry. In particular, the largely rain-fed wheat industry will be highly sensitive to projected changes in water availability associated with climate change (Figure 2). Major shifts in rain patterns and overall decreases in water availability in eastern and southern Australia have already taken place over the last 50 years

However, increasing atmospheric CO_2 is also known to enhance photosynthesis and water use efficiency in plants under a wide range of artificially induced environmental conditions (Steffen and Canadell 2005). This provides potential opportunities to the cropping industry for coping with climate change, if appropriate adaptive strategies can be implemented. The increased water-use efficiency that cropping systems may enjoy in a future CO_2-rich world could help to compensate to some extent the negative effects of reduced water availability in some regions, provided other factors are not limiting.

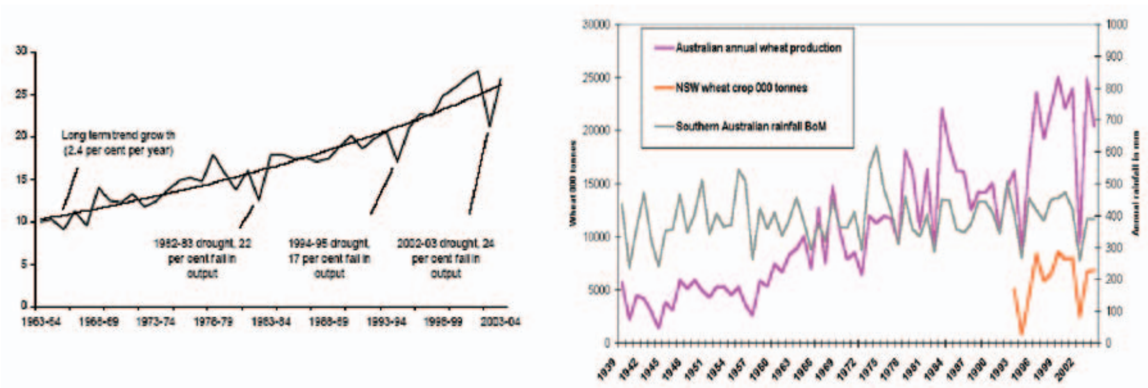


Figure 2. Trends in Australian agricultural output (value-added, $ billion, constant 2002-03 prices) (left) and wheat production (right) over several decades, with a strong influence exerted by changes in water availability (Source: Productivity Commission 2005)

The potential impacts and opportunities brought by climate change relate to:

- Risk management across all aspects of Australia's annual cropping industry
- Long-term sustainability of annual cropping in different regions of Australia
- Adaptation to maximise yield benefits and reduce negative impacts (e.g. lower protein content)
- Diversification and intensification of cropping systems
- Long-term planning for expansion in the cropping area
- Planning of major infrastructure investment
- Impacts of extreme climatic events (e.g. waterlogging, drought)
- Regional development and local governments' ability to raise revenue to provide essential services in these areas.

In order to manage the risks and maximise the opportunitiesfaced by the grains industry under projected climate change, it is essential to develop a more reliable and accurate understanding of how climate change and increasing concentrations of atmospheric CO_2 will affect annual grain cropping in Australia.

3. Why is a National Annual Cropping FACE Experiment Needed?

Over the last two decades, dozens of studies have been conducted around the world to understand the effects of elevated CO_2 on yield for a number of annual crops (e.g. Amthor 2001 for a review on wheat). Most were conducted in laboratory conditions and a few in the field. Of these experiments, there have been only 3 experiments on wheat (as an example), carried out under realistic field conditions using the best CO2 enrichment technology currently available- Free-Air CO2 Enrichment (FACE)- in Arizona, US (Kimball *et al*. 2001;), Italy (Miglietta *et al*. 1996;), and Germany (H.J.Weigel, in preparation). A wealth of modelling experiments have also being undertaken as stand alone studies or to compliment the laboratory and field experiments.

However, and in spite of the large body of scientific literature generated by these studies, there have been no experiments carried out under realistic field conditions that would be relevant to the environment and practices of the annual cropping industry in Australia. The experiments mentioned above were carried out under watering and heavy fertilisation treatments, and they tested genotypic differences not necessarily relevant to Australian conditions.

Consequently the working *Research Hypothesis* for the proposed National Annual Cropping FACE experiment, particularly when focusing on the rain-fed wheat industry, is:

> Increasing atmospheric CO_2 will increase crop water use efficiency and so increase overall productivity and partially alleviate the negative effects of low water availability, including droughts.

The research questions to be tested will address a wide range of critical processes, combinations of environmental conditions and management practices, and genotypes. Whilst the specific experimental research questions will clearly emerge once the site(s) selection is complete, some of the high level research questions are:

- Will elevated CO_2 concentrations partially alleviate water stress and the effects of increased climate variability in a future warmer climate?
- Will higher yields in a rich-CO_2 world come at a financial cost? (e.g. need for larger nitrogen additions to maintain grain protein content)
- Are there significant differences in the CO_2 responses from different genotypes that could be utilised to maximise productivity?

These research questions will help to evaluate the key interactions between 4 critical factors (Figure 3):

- Yield responses under increasing CO_2 concentrations
- Water avaliability (resulting from climate, climate variability, and soil properties)
- Nutrient availability resulting from soil properties and different levels of fertilisation
- Genotype differences (to identify those most suitable under future conditions)

Water	Nutrients
Genotypes	CO_2

Figure 3. The four critical factors of the proposed experimental design.

4. Rationale for Experimental Concept and Site(s) Selection

There are three main agro-ecological regions for grain cropping in Australia: Northern Region (Queensland/Northern NSW), Southern Region (New South Wales, Victoria and South Australia), and Western Region (Western Australia) (GRDC, 2005). The proposed National FACE Experiment will address the unique climatic envelopes and soil characteristics of these three regions (Figure 4), with emphasis on water-limiting environments.

The National experiment could have one or more FACE facilities testing the unique characteristics of climate and soil conditions in different parts of Australia. In all cases, it is emphasised that each experiment must include a multi-factorial approach to gain maximum statistical power. Water manipulations (and more difficult temperature manipulations) at the experimental site(s) may reproduce, to some extent, environmental conditions relevant to other regions.

Figure 4. Wheat cropping areas in Australia (Source: GRDC, 2005)

The selection of site(s) for successful FACE experiment(s) in Australia must meet a number of key site criteria. Essentially these criteria set out the most desired characteristics for a site from an industry, research, and Government perspective. If these requirements are fulfilled there is likely to be a higher level of stakeholder collaboration and acceptance of project outcomes. The following criteria have been identified by the Steering Committee as being essential in the delivery of high value science outputs from FACE experiments in Australia. Once established the site(s) would provide a hub for both national and international collaboration and science exchange within the global FACE network.

The preferred location for FACE experimentation in Australia should:

- fit with one of the agroecologoical zones identified in Australia
- be able to attract a critical mass of scientists from different disciplines
- have ready access to research teams
- have ready access to universities (therefore students and Australian Research Council funding)
- consider a multi-disciplinary approach (modeling, agronomy, natural resources, etc.)
- have effective engagement with industry and state government stakeholders
- have ready access to a good supply of CO_2
- be secure
- be accessible to interstate and international visitors
- have ready access to essential infrastructure requirements (e.g. electric power, water).

5. Basic Elements of the Experimental Design

The decision on the final experimental design will be undertaken by the field research team and modeling group that will be involved in the experiment(s). This section presents some of the components that will be critical in guiding the final design. The initial four critical research components of the experiment are i) CO_2, ii) water, iii) fertiliser, and iv) genotypes.

There is already a wealth of understanding on the interactions between water and fertiliser availability, which will be used to guide the choice of specific treatments and treatment combinations. The proposed design also emphasises the need to address responses, at various CO_2 levels, given the saturation nature of plant responses (Figure 5).

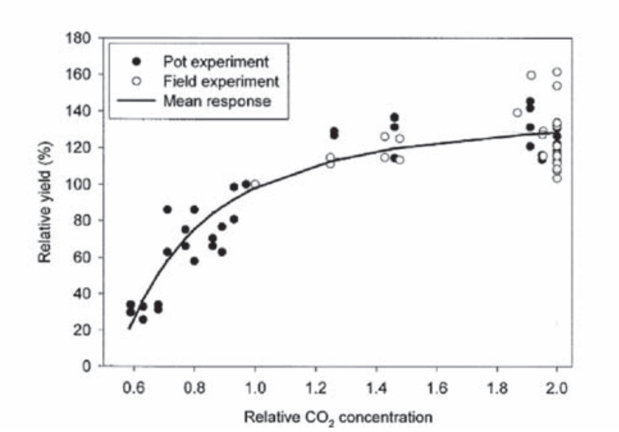


Figure 5. Wheat yield responses to multiple levels of atmospheric CO_2 (Source: Olesen and Bindi 2002)

One of the critical elements of the experiment will be the analyses of different genotype responses because they will be a key component in designing adaptive strategies for future environmental conditions. To give maximum statistical power to testing for genotype differences (i.e. number of independent treatment replicates), the recommended approach is to have genotype treatments inside of the plots, while water and nutrients may be tested using different plots. This approach will also reduce cross-contamination among treatments (e.g. of water and nutrients inside of the plot).

Given the overriding importance of water availability for rain-fed wheat cropping, water treatments and add-on water experiments should be part of the experimental portfolio. The experimental design should have the capacity to measure water use through the profile to determine water availability and utilisation at depth to ascertain if there are any environmental positives or negatives. This will also provide another avenue to determine efficiency of CO_2 use with the crops depending on water availability at different depths and times during the growing season (it may be that CO_2 by water availability may only increase leaf index/crop growth but not actually contribute to grain yield).

Rain-out shelter methodologies to manipulate water availability are well-developed and encouraged to be used in this study. It is also recommended that water manipulation experiments be established to reproduce to reproduce similar yield responses to those from elevated CO_2, as the most important CO_2 effects are expected to take place through increased water availability. These are inexpensive experiments with the potential to add substantial information on yield responses to multiple levels of CO_2 concentrations. Ultimately, these experiments could be used in different regions as inexpensive but valuable surrogates for understanding yield responses to elevated CO_2.

In summary, the final experiment design should include a focus on:

- Largest statistical power on genotype x CO_2 (~adaptation)
- Response trends to increasing atmospheric CO_2 (e.g. 500 ppm, 600 ppm)
- Nitrogen interactions as fully factorial in the experiment and/or relying on existing knowledge.
- Water relations enhanced through water manipulations (e.g. rain-out shelters)

6. CO_2 Enrichment Technology and Plot Size

The technology of choice to create a high-CO_2 environment in the experimental plot is the "Free Air CO_2 Enrichment" (FACE) technology consisting of a ring with vertical pipes or tubing around the plot that releases CO_2 at high concentrations (Hely *et al*. 2005). The release of CO_2 is directionally controlled to maximise CO_2 transport by wind inside the plot.

If the source of CO_2 is pure and highly pressurised, a passive delivery system (without blowers) is recommended as described in technical reports for the Mini-FACE technology (e.g. Miglietta *et al*. 2001). If a less concentrated source of CO_2 is available, the system will require an air blower with a more complex control system.

There is a balance to be found between having multiple independent treatment-plots and a cost-effective use of CO_2/area covered. An analysis of different options suggests that the most suitable FACE system for the experimental design described above is a Meso-scale FACE. This involves, plots of 8 m in diameter although bigger sizes up to 15 m can be considered in the final design (Figure 6). Smaller plot size is not recommended given the edge and island effect on water relations.

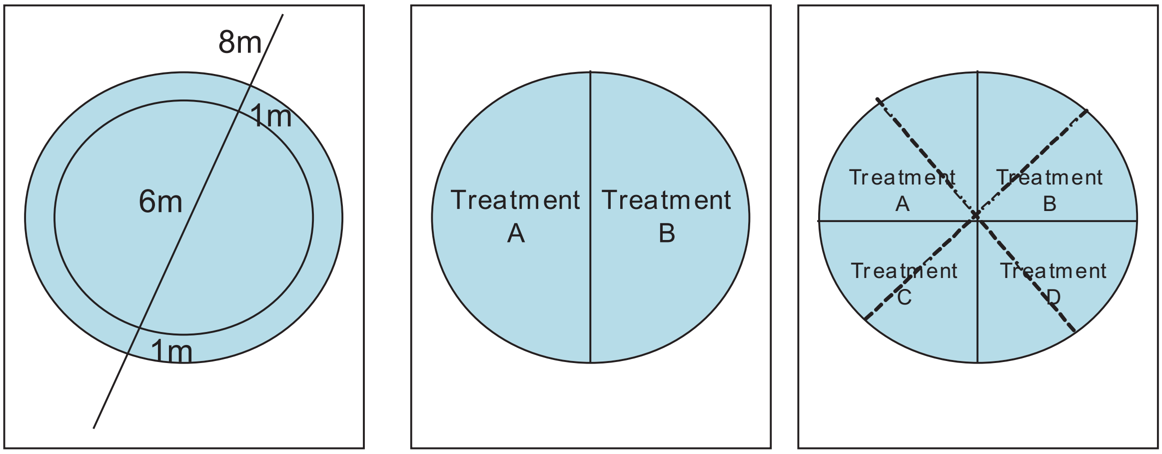


Figure 6. Minimum plot size recommended with internal sub-divisions for multiple treatments

7. Implementation

A modular approach is proposed such that the smallest experimental module (and therefore the minimum investment required to begin with) would already give a high quality experiment from which important scientific information could be generated. Figure 7 shows two possible “minimum” modules below which an experiment is not recommended. The module can be expanded to the module in Figure 8 with higher replication and the addition of a water manipulation experiment. A full experiment is illustrated in Figure 9 with:

3 CO_2 x 2 mitrogen/water x 4 genotypes x 3 replicates =
72 treatments
18 total plots
12 FACE plots

Additional water manipulation experiment:
3 water x 4 genotypes x 3 replicates =
36 treatments
9 total plots
0 FACE plots

Other factorial combinations could be achieved by using treatments within the plots.

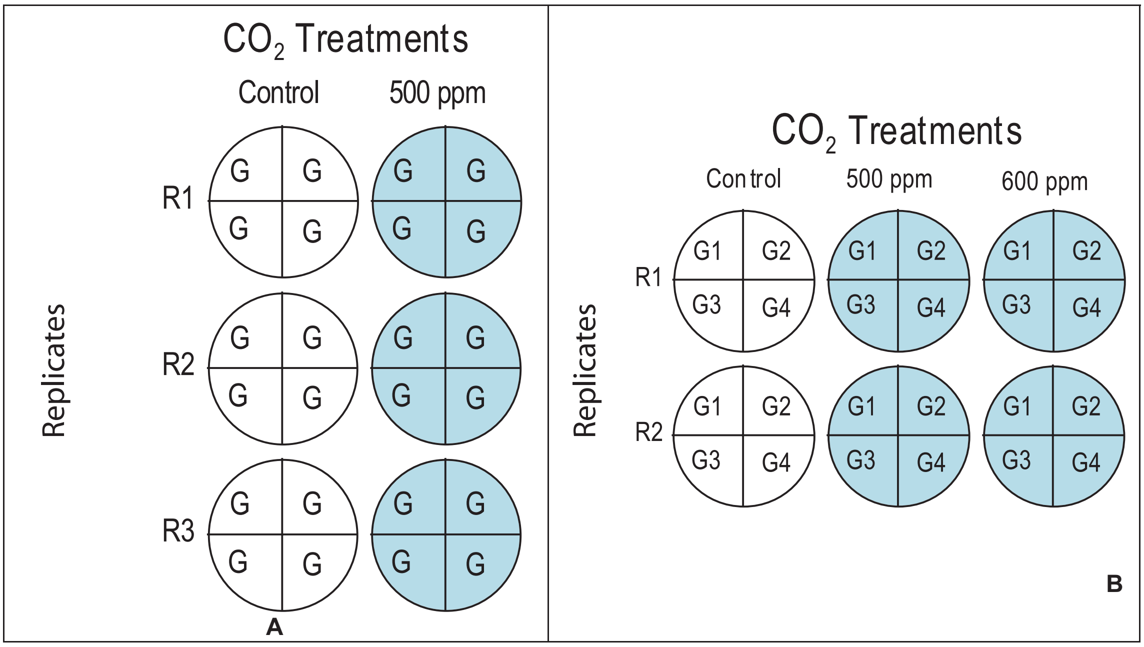


Figure 7. Minimum module of the experimental design. Two options (A, B)

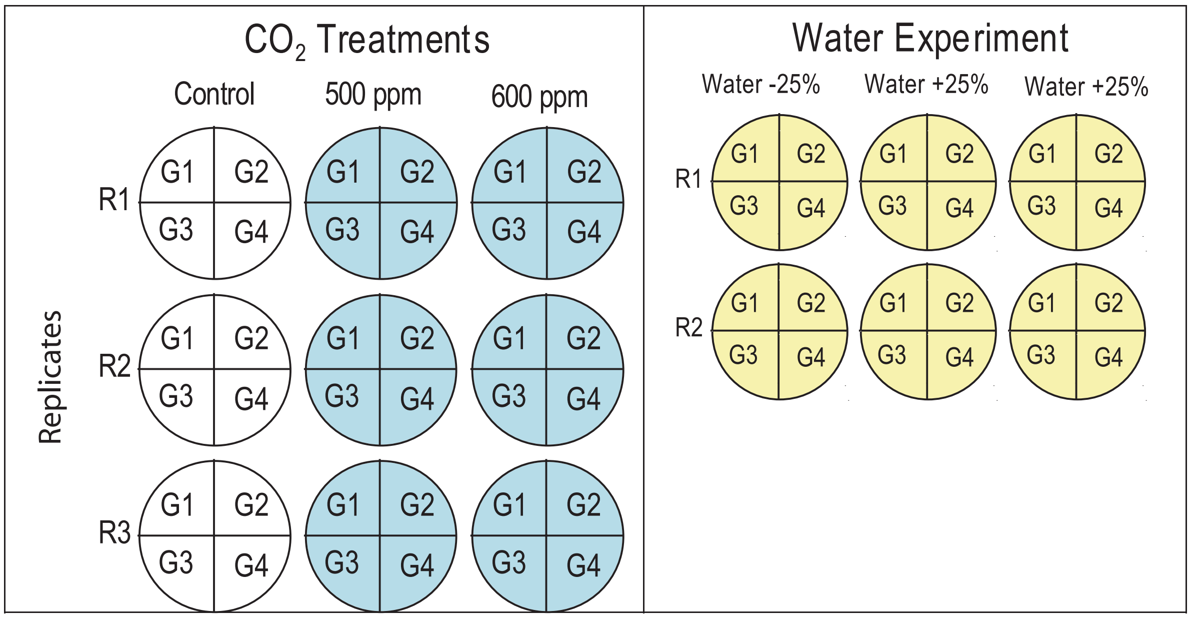


Figure 8. Next module up with increased replication and a complementary water manipulation experiment

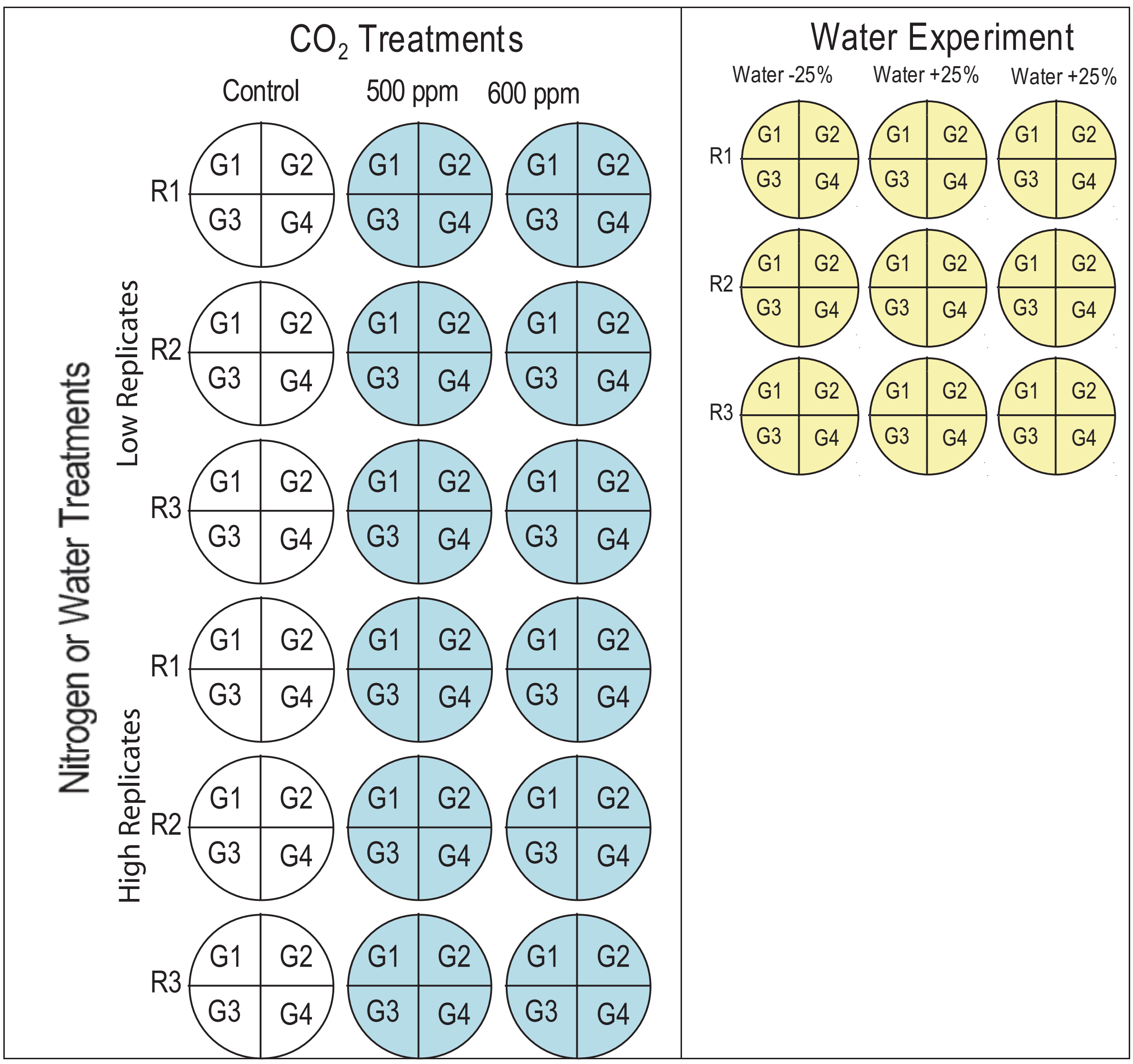


Figure 9. A full multi-factorial experiment with a complementary water experiment

Modeling. experimental manipulations in the field and modeling are two fundamental components of the proposed National FACE experiment. Some of the experimental results are not expected to provide information on realistic wheat yields in a future CO_2-rich world, but will provide insights to specific processes and dynamics critical for model development, validation, and applications to farms, regions, and nation-wide assessments. It is the modeling results, with the appropriate testing and use of data generated from the experiments, that will ultimately provide the answers on grain yield and cropping suitability at the appropriate spatial and temporal scales, relevant to farmers, regions, and the industry as a whole. The models will also need to use the wealth of information avaliable on temperature effects (e.g. daily, seasonal) on wheat yield development and to explore the interactions with elevated CO_2. This will be particularly important because FACE experiments will probably not test interactions with temperature unless a heating treatment is included (e.g. infrared heaters).

8.
Estimated Cost

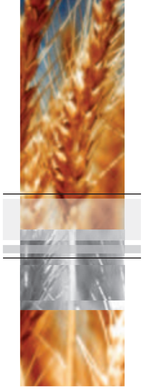
The costs for operating and maintenance of FACE rings will very much depend upon the size and number of enrichment rings being used at the site(s).

An estimate of costs using Bruce Kimball's Brookhaven design with 8 enriched rings of 23 m in diameter and requiring 1,200 tons of CO_2 over a 6 month growing season period is as follows:

- Installation of CO_2 gas cylinder tank, vaporiser, electricity weather station and 8 rings $352,000
- Supply of CO_2 for 6 months $240,000 - $600,000 depending upon cost of CO_2 ($200 - $500/ton
- On-going maintenance at site including 3 staff $292,000
- Total cost of setting up (site and maintaining for 1st year $650,000 - $900,000 with annual costs of $300,000 - $550,000)
- This budget does not include any costs associated with experimental measures, analyses and modeling.

The cost of operating a smaller Miglietta style of twelve 8-10m enrichment rings would include:

- Setup costs of between $110,000 - $270,000
- 2- 3 staff ($150,000 - $200,000)
- Operating costs of between $160,000 - $460,000
- Total cost: $420,000 – $930,000
- This budget does not include any costs associated with experimental measures, analyses and modeling.



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