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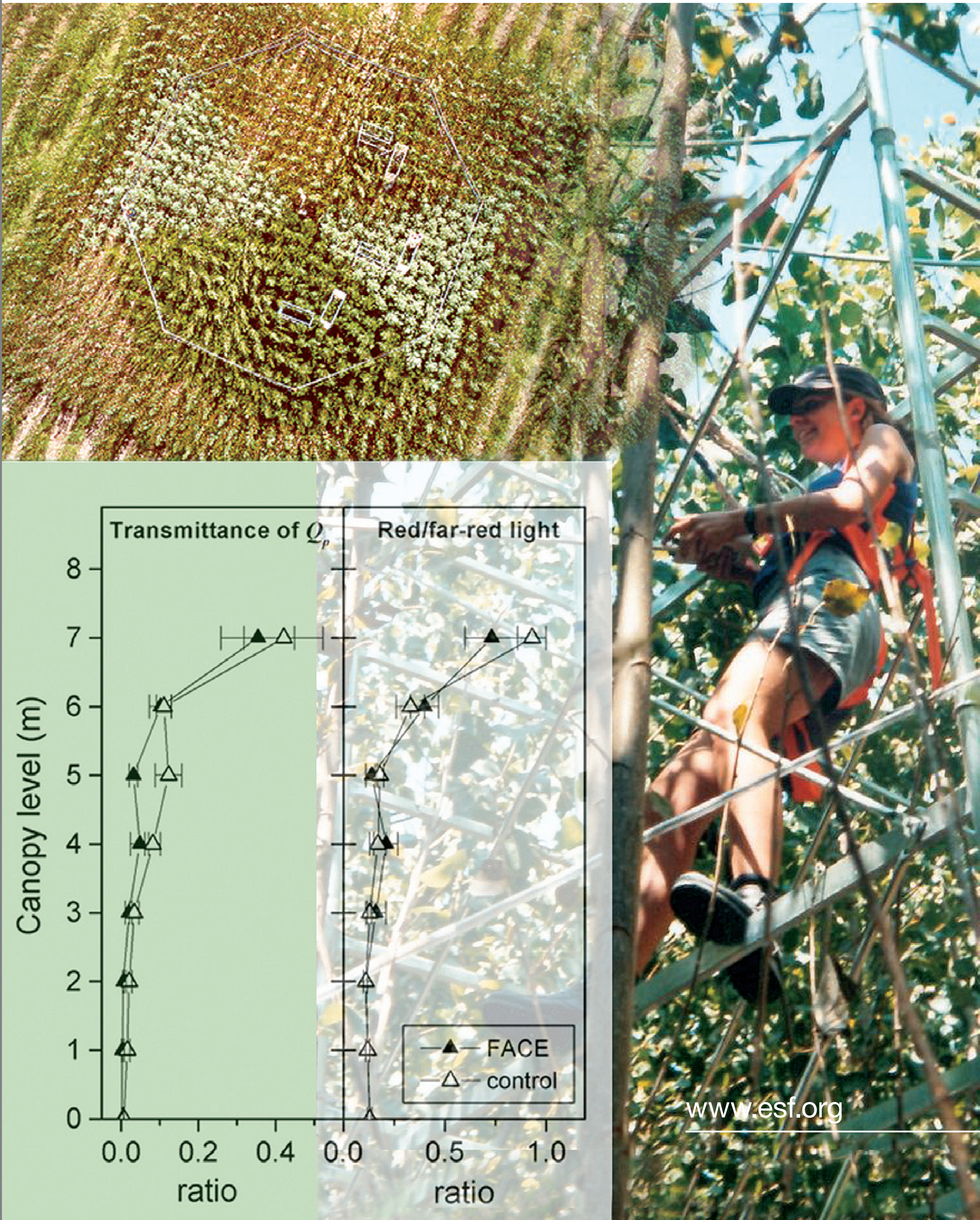
LESC-PESC SCIENCE POSITION PAPER

FACEing the Future:
Planning the Next Generation of Elevated CO_2 Experiments on Crops and Ecosystems



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Cover: Field measurements of canopy profiles
in the EUROFACE experiment with fast-growing poplars
in Central Italy.

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The Science Position Paper results from an ESF-INIF workshop meeting held in the Academia Belgica in Rome (Italy) in December 2007.

Foreword

One of the most pressing challenges facing mankind is to understand the causes and dynamics of global climate change, to predict their extent and scope, and to develop strategies to limit their impact. There is correspondingly a massive investment of financial resources and scientific activity in climate change research.

Climate change is driven mainly by the release of greenhouse gases caused by human activities. One of these gases is carbon dioxide (CO_2). The response of plants to rising CO_2 plays a crucial role in determining how fast and how far atmospheric CO_2 levels will rise. This response in combination with changes in climate will determine how ecosystems and agricultural land systems are affected. A better understanding of the response of vegetation and its interaction with the global biogeochemical cycles would clarify some of the major uncertainties in current predictions of climate change.

The response of agricultural land systems and terrestrial ecosystems to future atmospheric CO_2 concentrations is studied in Free Air Carbon dioxide Enrichment (FACE) facilities. These are large open-air experiments, in which the atmospheric CO_2 concentration is locally elevated to the levels expected in the future. FACE sites are "big science". They are used jointly by teams of scientists from many different disciplines, including plant physiology, crop science, ecology, soil chemistry, hydrology, plant-microbe interactions and soil microbiology, microclimatology, and plant and ecosystem modelling. FACE facilities require considerable investment in site hardware and running costs, making them very expensive compared to most other biological and ecological research. Clearly, strategic planning is required to ensure that they are designed and used to address the most pressing scientific goals.

In the past, the main aim of FACE studies was to provide a basic description of the response of different crop systems and entire ecosystems to elevated CO_2. They did not include interactions with the nutrient supply and climatic variables like temperature and water, and did not address questions of genetic variation. These studies are now drawing to a close.

Now is the time to redefine the scientific goals and organisation of future FACE facilities. It is important to close present gaps in understanding, define new questions and, more generally, to maximise the generation of knowledge. This will support and inform ecosystem and global modelling to obtain more reliable predictions of climate change, and allow us to develop strategies to mitigate some of the feared negative aspects of the future climate.

This LESC-PESC Science Position Paper was produced at an Interdisciplinary New Initiative Fund (INIF) workshop, "FACEing the Future: Planning the Next Generation of Elevated CO_2 Experiments on Crops and Ecosystems". The workshop – organised by Reinhart Ceulemans and Mark Stitt – was held in Rome, Italy on 5-7 December 2007 and was financed by the European Science Foundation (ESF). The aim was to promote a dialogue between engineers and scientists who have been involved in research on how plants respond to elevated CO_2, and a wider circle of plant scientists, ecosystem researchers and modellers. They were asked to identify the main questions that must be tackled in the future, and assess what the implications are for the design and implementation of future FACE facilities. The ESF-INIF workshop emphasised that a new generation of expanded FACE facilities for crop and natural ecosystems is needed, in which experiments can be performed that provide a predictive understanding of the response of crop plants and natural ecosystems to elevated CO_2. These experiments will make it possible to explore whether genetic diversity affects this response, and to lay the foundation for crop improvement to maximise the potential gain in yield in the next century. They should also initiate dissecting interactions between elevated CO_2 and other environmental factors, and contribute to modelling future responses of managed and natural ecosystems, including short-rotation forestry systems.

This LESC-PESC Science Position Paper has undergone external international peer review and has been approved by the ESF Standing Committees for the Life, Earth and Environmental Sciences (LESC) and for the Physical and Engineering Sciences (PESC).

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Introduction

Terrestrial and aquatic plants play a central role in the response of the global carbon cycle to anthropogenic release of the greenhouse gas, CO_2. They perform oxygenic photosynthesis, converting CO_2 into organic carbon, and provide a short-term negative feedback to increasing levels of the atmospheric CO_2 concentration.

Research has over the last 50 years laid a solid basis to understand and model the immediate impact of a rising CO_2 concentration on the rate of photosynthesis. However, **we need to understand much more about the fate of the additional assimilated carbon**. How is the additional carbon utilised in the plant? Will plants grow faster, and if so, by how much? Will more carbon be sequestered in living plant biomass? How will carbon sequestration be affected in the soil and other components of the ecosystem? Does "CO_2 fertilisation" affect the requirements for and modify the circulation of water and nutrients? What are the similarities and differences between agricultural systems and natural ecosystems?

Innumerable experiments have been performed in the last 30 years to address these questions. They started with experiments in simple systems where plants were grown in pots in growth chambers and greenhouses, and exposed to elevated CO_2. These were followed by increasingly realistic – but more complex and expensive – studies in which open top chambers or Free Air Carbon dioxide Enrichment (FACE) facilities were used to elevate the CO_2 concentration in arable field systems or in natural ecosystems.

The key lessons from these earlier studies are outlined in the following two sections. Briefly, although our knowledge is advancing, **we still do not yet understand enough about plant growth and the interactions between plants and ecosystems to predict how growth and carbon cycling will respond to rising atmospheric CO_2 concentrations**.

The first generation of FACE sites is currently being wound down. At this time, to our knowledge, there are no plans for a next generation of sites in Europe. The development of FACE in the USA is presently a topic of discussions in the Office of Science of the US Department of Energy.

FACE facilities require a substantial investment in hardware and have high running costs, due to the need for continual maintenance and control, and the cost of CO_2. It is timely and important to develop a coordinated strategy for "next-generation" FACE experiments. This will require that discussions of FACE design, costs and logistics are integrated with a fresh discussion of scientific priorities. This Science Position Paper summarises what has been learnt from the first generation of FACE experiments (primarily in Europe and the USA) and defines key questions that have to be answered using the next generation of FACE sites. It then considers whether current FACE technology will allow these questions to be tackled, and what changes this will require in the design and scope of the experimental design and approach, and the operation of the sites.

One of the working groups at the ESF-INIF workshop held in the Academia Belgica in Rome (Italy) in December 2007.

FACEing the Future

Pressing questions in crop systems

Over the last 50 years, a rising global demand for feed and food has been matched by a large increase in agronomic productivity. This increase in productivity was driven by advances in plant breeding and changes in agronomic practice, including the use of fertilisers. Global grain stocks nevertheless recently fell to their lowest level for 30 years. Demand for food and feed will continue to increase, and an increasing part of the available land area will probably be used for bio-energy crops.

There is therefore an **urgent need to maintain or increase yield, while simultaneously increasing sustainability and minimising negative impacts on the environment.**

Current projections by the International Panel for Climate Change (IPCC) predict that rising temperature and changes in water availability will have detrimental effects on the future global food supply. Current projections also hope that these losses may be offset by the fertilisation effect of rising CO_2. These projections are based on theoretical considerations and on consolidated scientific results. The scientific data that were available for these IPCC projections were derived mainly from chamber experiments. These indicated that there may be a potential yield gain of over 30% as the atmospheric CO_2 concentration is increased from present-day levels up to 550 ppm CO_2, which is the projected level in 2050. During the last 15 years, FACE studies with many crops, including tree plantations, at different locations around the world have confirmed that there is a stimulation of photosynthesis of ca. 30%, which is in line with predictions from photosynthesis models. As plant growth is quasi-exponential, this stimulation of photosynthesis should translate into an even larger increase in yield. However, the average yield gain shown in FACE experiments was only around 14%. As science continues to evolve, novel information emerges and continuous reassessment will be needed in forthcoming IPCC reports.

These new results raise the important question: how can we identify and overcome the genetic and agronomic constraints that prevent the potential gain from being realised on the farm?

1. **We need to screen a very wide range of germplasm for our major crops to determine whether there is genetic variation for the economic yield response to elevated CO_2, and identify traits that may be linked to a strong positive response.** While existing small-scale studies of wheat and soybean show that there is genetic variation in responsiveness to CO_2, this has not been investigated on a large scale, nor have genetic tools been explicitly used to dissect the complex trait of elevated CO_2 response. As maize, wheat, rice and soybean are the world's major food crops, they should be the primary targets for this new generation of elevated CO_2 experiments on crops.
2. **We need to determine whether the benefits of elevated CO_2 will still be valid when they are combined with other aspects of global climate change.** These include warmer temperatures, increased drought stress, rising tropospheric ozone and altered nutrient availability. Elevated CO_2 is not the only global change. Understanding the interaction with further global change drivers and responses, such as rising temperatures, altered precipitation patterns and rising tropospheric ozone concentrations, is imperative.
3. **We need to understand the performance of the whole cropping system in relation to elevated CO_2, including feedbacks on the atmosphere and environment.** A further research priority is to understand the feedback of the cropping system on global carbon, nitrogen and water cycles, as well as the feedback on surface temperature. Crops occupy more than 10% of the terrestrial land surface. As simple and tractable systems, they provide an important test-bed for general hypotheses about ecosystem response to global change.
4. **We need to learn if future CO_2 levels will make it possible to maintain yield while modifying agronomic practice to decrease negative impacts on the environment.** This may be the case for some parameters; for example, an increase of water-use efficiency in elevated CO_2 may allow decreased use of water in irrigated field systems. However, it is also possible that full exploitation of the potential gain in yield will require intensive inputs, for example, large amounts of fertiliser. It is also well known that there is a strong genetic component in plant-environment interactions. This raises the question whether plant breeding can provide new genotypes that maximise yield and minimise negative impacts on the environment.

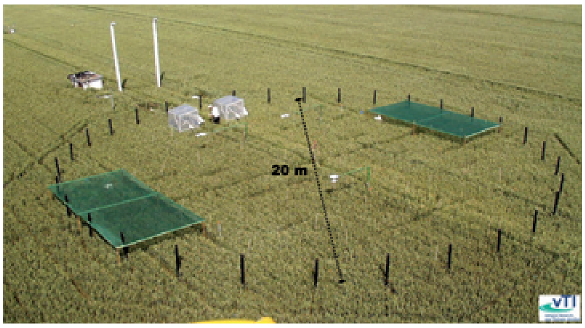
A new generation of crop elevated CO_2 experiments are urgently needed to answer these pressing questions. They will require a new series of large, replicated FACE experiments, located in the major production areas for these crops. These facilities must be international, collaborative facilities, with the capacity to screen 100 to 200 genotypes in a replicated manner. The research goals will only be achieved by the collaboration of international experts in the areas of crop genetics, molecular biology, physiology, agronomy and micro-meteorology.

Pressing questions in natural ecosystems

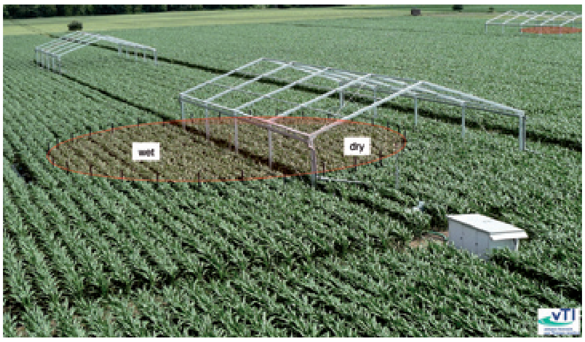
FACE experiments in forests, grasslands, and other non-crop (or "natural") ecosystems have been extremely valuable. They have identified critical process-level responses to elevated CO_2, provided process-level understanding for ecosystem and global models, and served as test cases for model projections of future productivity and feedbacks to the climate system.

Tree crops will play an important role in biomass and bio-energy production. It will therefore be important to include short-rotation and fast-growing tree crops in future elevated CO_2 and climate change experiments. Forest and biomass plantation systems are therefore implicitly included in the following discussion of natural ecosystems.

As the present generation of ecosystem FACE experiments reaches completion, the research and policy-maker communities need to decide on the questions and locations for the next generation of experiments. There is a clear consensus that next-generation experiments need to manipulate not only CO_2 but also other aspects of atmospheric chemistry and climatic variables. These include increasing temperatures and altering patterns of precipitation, as these have substantial effects on vegetation phenology. They include fire frequency and the potential for carbon sequestration. Another important factor is nutrient deposition. Agricultural use of nitrogen-based fertilisers and fossil fuel combustion increase the amount of reactive nitrogen in the earth's atmosphere. This is subsequently deposited in terrestrial ecosystems and can potentially increase productivity, but may also contribute to the saturation of ecosystem function due to excessive inputs.



FACE in Braunschweig, Germany: 2 rings in a wheat field with canopy CO_2/H_2O gas exchange chambers and shading devices to study CO_2/radiation interactions



FACE in Braunschweig, Germany: ring in a maize field with rain shelters to study CO_2/precipitation interactions (shelters are covered with transparent tarps during rain events)

There is therefore a clear need for multi-factorial experiments with elevated CO_2 that simultaneously modify some combination of temperature, precipitation, nitrogen deposition and fire. Regional analysis should guide which factors and factor levels are applied to a specific system. The set of scientific questions that are considered most important are highly overlapping, and individual experiments should be designed to address multiple questions. Here we identify major research themes (in bold) and candidate questions (non-bold). These scientific priorities are intended to inform the choice of ecosystems for the next-generation studies.

1. **What are the fundamental responses of ecosystems to elevated CO_2 and climate change, including simultaneous changes of CO_2 and other environmental variables?** Are there threshold responses in carbon storage that are altered by elevated CO_2 and changes in climate? How do species diversity and trophic interactions vary as a function of CO_2 and climate? How are growing season length and carbon storage affected by CO_2 and climate? How is carbon allocation affected by changes in CO_2, climate and atmospheric N deposition? To what extent can species and ecosystems adapt and which evolutionary constraints exist?
2. **How does forest or rangeland management interact with elevated CO_2 and climate change?**
3. **How is carbon storage in terrestrial ecosystems modified by feedbacks between rising CO_2, changing climate and biogeochemical cycles of water and nutrients?** Are short-term responses representative of long-term responses to rising CO_2 and climate change? If yes, how does this affect the selection of sites? If not, how does this affect the selection of sites that remain operational?
4. **Are there evolutionary constraints that limit the extent to which species adapt to rising CO_2 and climate change?**
5. **What are the region-specific vulnerabilities of greatest concern in a world with rising CO_2 con-**

centrations and changing climate?** Are certain areas more susceptible to increased water stress as a result of biosphere-atmosphere feedbacks? Can forest productivity be expected to increase significantly more in some areas than others?

6. At the present time there is increasing interest in biofuels, including tree crops for biomass and bioenergy. Converting land presently used to produce food, feed or fibre (or even non-managed ecosystems) to biofuels may affect carbon sequestration, energy and water balance. This might be one of the most uncertain areas in projecting carbon sequestration potential and biosphere feedback to climate change. **How will bio-energy crops respond to rising CO_2 concentrations and changing climate? What are the likely effects of converting to various potential biofuels on carbon sequestration, both in terms of soil storage and in replacement of fossil fuels?**

The greatest priority should be given to experimental systems that are likely to deliver high-quality, process-level data that can be directly incorporated in ecosystem models.

The technology is available to answer these questions

Most current FACE sites (in Europe, the USA and Japan) release CO_2 from a series of pipes or tubes located in a ring around the experimental area. The rate of release of CO_2 from the individual pipes is automatically adjusted, based on the wind direction and strength and measurements of the CO_2 concentration inside the ring.

Current FACE technology is adequate and appropriate for applications of CO_2, O_3 or other trace gases to crops, and other low-stature vegetation. Current sites are typically 15-25 m in diameter, which is equivalent to an area of 130-350 m^2. Whether existing FACE technology needs a radical extension will depend on the number of cultivars that need to be studied, and on the area needed per cultivar. For example, for cereals like wheat or rice and using a singe plot size per cultivar of ca. 0.5 m^2, current site design (allowing unused areas for access and instrumentation) would allow up to 400-500 individual plots per ring, which would allow an internally well-replicated experiment with 100 genotypes in each ring. For crops like soybean, where the plants are larger, the area will not suffice.

There is no inherent advantage to building much larger rings. The efficiency of gas use decreases, and there is a loss of control over the temporal and spatial concentration when circumferential gas release is used

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Field measurements of light interception and leaf area index in the EUROFACE experiment with fast-growing poplars in Central Italy.

on larger plots. If the growth area required needs to be increased compared to previous sites, the simplest strategy would be just to use more rings, rather than to increase the size of the individual rings. This would anyway increase statistical power, at least for crops where enough space is available to allow a randomised distribution of replicate plots in each ring.

If large individual areas need to be treated with elevated CO_2, it may be possible to use arrays or networks of gridded CO_2 emitter tubes. These offer the potential to minimise variation and gas use. It will be necessary to develop an algorithm to control emission rate from individual nodes using feedback from multiple, distributed gas-concentration sampling points. These new techniques are being modelled, but have not yet been prototyped.

For application to forests of 40 m height, such as tropical forests, the current FACE technology will need to be extended. One way to achieve this is by using a circular array of light-weight or telescopic towers, which are guyed to each other and to points outside the central plot in order to avoid damage inside the plot. An alternative is to use networks of emitter tubes strung within trees. The latter will require frequent maintenance of emitter placement within the top of the canopy. In both cases, a canopy crane will be required to provide sampling access to the crowns of the trees. These technologies need to be optimised and evaluated.

With respect to combining CO_2 and temperature treatments, several possibilities are being examined for low-stature vegetation in 3-5 m diameter plots. These include down-welling radiant heaters, translocation of monolithic soil blocks with vegetation from cooler to warmer sites, applying FACE to sites across natural temperature gradients, planting at different times of the season to modify the warming, or covering the crop with a horizontal curtain at night. The only practical approach for a tall forest would currently be to build sites across a natural temperature gradient.

The output from FACE should be optimised with respect to predictive power

The high cost of FACE sites makes it important to maximise the predictive power of the information that is gained for as many processes as possible. This requires that many parameters are investigated in the context of a well-structured and replicated experimental design. The investigated parameters will include plant biomass production, allocation and yield, plant architecture and phenology, soil structure, and soil microbes and fauna. Genomics profiling platforms can provide data on the levels of individual nutrients, metabolites and, where needed, enzyme activities, proteins and transcripts. Analyses of stable isotopes and soil parameters like water and nutrient content will be needed to place the response of the plants in the context of the ecosystem. Where possible, it will be important to use non-destructive technologies. It is vital that FACE studies measure parameters that are required to support scaling activities, and the formulation and validation of models.

In crop FACE systems, physiological and molecular phenotyping technologies should be used to analyse large populations of genetically diverse and genotypically characterised plants. This is a crucial advance compared to the past, where at best only small numbers of genotypes were compared. This provided descriptive information but did not allow rigorous genetic dissection and analysis of inherited variation in response to elevated CO_2.

Goal 1: Functional genomics and quantitative genetics with large populations of plants will allow us to **causally dissect the complex multi-factorial network that controls carbon allocation, growth and yield.** This will open up new perspectives to understand the genetic and molecular basis of the response of plant growth to elevated CO_2 (see box, Goal 1).

Goal 2: On a pragmatic level, questions can be addressed relating to **selection of germplasm and, in a broader sense, the exploitation of biodiversity to maximise crop yield in a future, elevated CO_2 world** (see box, Goal 2).

In ecosystem FACE systems, fine-grained information should be collected about the composition and physiological status of plants and the status of the soil. This will provide important insights into resource acquisition, allocation and utilisation competition between individuals and species.

Goal 3: Use information from FACE systems to **support interpretation of the more complex interactions in ecosystems, and aid scaling from plants to ecosystems** (see box, Goal 3).

Goal 1: Causally dissect the complex multi-factorial network that determines how elevated CO_2 affects biomass production and yield.
The proposed approach will generate a homogenous data set that documents the response of yield and many (probably several hundred) physiological and molecular parameters across a large population of genotypes in elevated CO_2. This will be a powerful resource to develop plant growth models, and to perform multivariate data analysis to identify parameters that influence the relation between elevated CO_2 and growth. It will pinpoint hypotheses about the underlying mechanisms, which can be tested by detailed analyses of small sets of plants, including lines with isogenic changes. It will support quantitative trait loci (QTL) mapping, either via association mapping or in combination with the use of inbred populations. As an example, measurements of isotope discrimination, soil water and metabolites that are known to be involved in water-deficit responses could provide key insights into the contribution of the changes in water-use efficiency to the yield gain in elevated CO_2. Analogous combinations of parameters could be used to probe the relation between nutrient acquisition, utilisation and yield in elevated CO_2.

Goal 2: Identify and validate physiological and molecular parameters that can be measured at ambient CO_2 and that predict the yield response to elevated CO_2, and used in the selection of germplasm and, in a broader sense, the exploitation of biodiversity to maximise crop yield in a future, elevated CO_2 world.
Plant breeding uses phenotypic characters and genetic information to identify useful germplasm, which is crossed to create populations that are then grown and scored for important traits. Breeders are unable, however, to identify or select material that responds well to elevated CO_2, because they have to grow their material at current CO_2. One important aim will be to learn whether any of the traits that breeders currently select affect the response to elevated CO_2. We also need strategies to prioritise lines for screening in elevated CO_2. A novel approach can be proposed, which builds on the multi-layered data sets that will be generated in FACE facilities. The results from a test population (50 -100 genetically diverse genotypes) could be analysed by multivariate statistical methods to identify *parameters whose values in ambient CO_2* correlate with the *yield response in elevated CO_2*. These parameters can be used to survey large genetic populations and predict which genotypes should show a particularly strong or weak response to elevated CO_2. In an iterative cycle, they would be grown under elevated CO_2 in the FACE system to test the quality of the predictions and refine the parameter set that is used for the prediction. For this goal, it will be necessary to concentrate on parameters that can be measured cheaply and easily, for example, plant architecture and phenology, stable isotopes and nutrient and metabolite levels. Integrative parameters should be included that are measured by plant breeders, like yield in different agronomic regimes at ambient CO_2 (e.g. altered fertilisation, water supply or temperature). This would increase the speed with which large populations can be presorted and cycled through FACE facilities to assess their response to future CO_2 regimes. In addition to developing predictors for a given crop, this approach will also reveal similarities and differences between species.

Goal 3: Provide crucial fine-grained information to support interpretation of the more complex interactions in ecosystem FACE systems, and aid scaling from plants to ecosystems.
Detailed analyses of metabolites and nutrients will provide insights into the physiological status of plants, which go far beyond those provided by analyses of total nutrient or carbon content. They will deepen our understanding of resource acquisition, allocation and utilisation in plants themselves and also the resource flow through ecosystems, especially if they are combined with information about changes of water, nutrients, microbes and fauna in the soil. They could be combined with genotyping to provide information about intra-species variation. In the context of inter-species comparisons, they would allow us to experimentally assess and refine existing definitions of plant functional types, which play a major role in higher-level modelling.

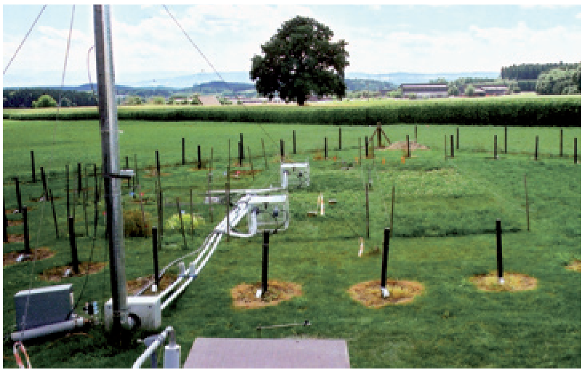
Multi-factorial experiments

Climate change involves changes in many other factors, in addition to CO_2. The resulting interactions will affect ecosystems and plant production in a manner that cannot be predicted from experiments that manipulate individual factors.

Multi-factorial experiments are needed to increase our understanding of the overall climate change impacts, and to improve and test mathematical models. Future experiments should generally combine CO_2 with temperature and precipitation manipulation. O_3 will also be an important factor because its negative effects can cancel the positive effects of CO_2. Locally other factors such as nutrients, N deposition, management, humidity, biotic factors (competition, pests, diseases, biodiversity), and extreme events would also be of interest.

Multi-factorial experiments will benefit from involving modellers to provide guidance about which manipulations and information are most important to them for improving and testing models. The manipulated factors must to some extent be balanced to match the expected reality (e.g. most studies involving warming do not increase the temperature as much as predictions suggest will actually occur in the future). The specific technical design of the experiments must be solved case by case to optimise the quality and interactions among the combined treatments and to minimise artefacts.

Multi-factorial experiments require strategies to cope with organisation, costs and the complexity of multi-dimensional data sets. Studies comparing FACE and chamber technologies would give a better understanding of how and when we can compare results derived from these different technologies and when we can use less expensive chamber studies instead of FACE experiments to study specific processes. Natural variation of factors like rainfall and temperature provides another valuable tool. Multi-year studies or studies along natural gradients, eventually including transplanting soil cores or mesocosms from one site to another, may aid comparison and evaluation of interactions between different factors.



View of the Eschlikon FACE experiment.

Collection of a set of "core" measurements. The usefulness of multi-factorial experiments (and FACE experiments in general) would be increased if a set of "core" measurements were to be collected at all sites, independent of the focus of the particular experiment/site. All sites should collect a broad set of data in a common format (e.g. main factors being controlled and meteorological data). Changes in species and competition (biodiversity) form a particular area which needs more attention by studying adaptations to climate change in addition to processes already being studied. Development of common design advice, including statistical considerations of substituting true replication with multilevel factors, would improve the value and quality of the sites and collaboration among them.

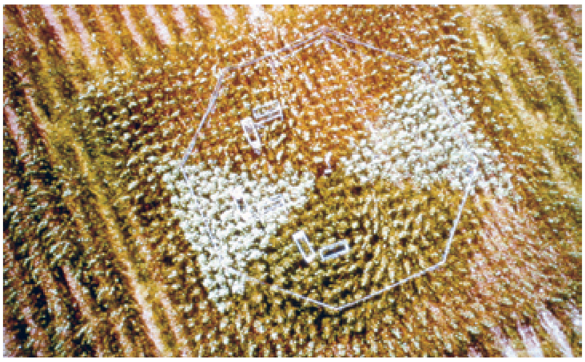
Integration of changes in the soil

A crucial component of the ecosystem's response to elevated CO_2 and climate change is the soil compartment, with all its ongoing processes. The soil represents the largest pool of carbon in terrestrial ecosystems. Some fractions of carbon in the soil represent an important sink, because they have a long residence time (decades to centuries). The soil is also a critical source of water and nutrients. Nutrients are transformed to plant-available forms by the activity of the soil microbial community. The current generation of FACE experiments reveals that there is tremendous variability in the response of the soil to elevated CO_2. The importance of the soil is not only related to the large, mostly unknown capacity to act as a carbon sink, but also to the fact that processes in the soil have a major impact on the CO_2 response.

Elevated CO_2 should increase carbon inputs into the soil. However, while some sites show increasing carbon storage in the soil, others show no change, and some even show a decline of the soil carbon content. There is also variability in the impact on nutrient availability. Soil nutrition is one of the interacting factors which have already been tested in interaction with CO_2 in previous forest FACE studies, although the response has been quite variable due to large differences among sites. Some studies found an increase in the nutrient supply under elevated CO_2, which allowed a sustained enhancement of plant productivity. Other studies have found only a transient enhancement of productivity, and tied this to a decline in the nutrient supply. It is likely that changes in soil, and particularly in soil nutritional status, induced by elevated CO_2 might occur after several growing seasons, especially in the case of old-growth forests with high nutrient stores. Results from both single sites over time and among sites show that soil nutrient availability affects both the total productivity response of a forest to elevated CO_2 and the allocation of the extra carbon among pools of different longevity.

The effect on soil nutrient status is a function of the increase in nutrient demand due to growth enhancement from elevated CO_2 in relation to total nutrient storage in biomass and soil. Interactions of elevated CO_2 could lead to even more complex scenarios. For example, nutrient availability is expected to increase in tundra soils in the future, due to faster mineralisation under warmer conditions and, to a lesser extent, to anthropogenically-induced nitrogen deposition leading to enhanced net primary productivity. However, it is likely that old organic matter in arctic soils may be destabilised under higher nutrient availability due to the simultaneous stimulation of microbial populations, and that carbon stocks will decrease.

New measurements are required to definitively address and understand the reasons for this variability in the response of the soil to elevated CO_2. A greater effort should be put into exploring soil properties as critical components of CO_2 responses and discovering their potential role in the context of carbon balance under elevated CO_2. Key measurements that must be included in future experiments include explicit measurements of the quantity of carbon entering the soil, not only from plant biomass residues but also from mycorrhizal biomass and root exudates, subsequent carbon flow through soil biota, and analysis of C efflux from the soil. This will require explicit characterisation of the soil carbon pool from which the carbon was lost, using isotopic methods and soil fractionation schemes. It will also be necessary to analyse how the turnover of nutrients (e.g. nitrogen) in soil organic matter is affected by changes in below-ground carbon allocation under elevated CO_2.



FACE experiments on bio-energy crops, such as short-rotation poplar plantations will gain on importance in the future. EUROFACE experiment with fast-growing coppiced poplars near Viterbo, Central Italy.

New non-destructive instrumentation is required. Because of substantial spatial variability in the concentration of carbon in the soil, the development of high-frequency, non-destructive techniques could play a major role in improving estimates of soil carbon storage with rising concentrations of atmospheric CO_2.

Spatial and temporal scaling

Scaling helps us to understand how complex interactions at one level lead to changes at higher levels of the system. Examples would be trying to understand how plant carbon uptake by diverse species feeds back to affect atmospheric CO_2, or how water exchange by ecosystems affects climate. Scaling is achieved via modelling. It depends on a better understanding of the processes and functions to improve the model description, and on access to validated parameters and data to test the models. FACE experiments are uniquely placed to explore some issues that are critical in global change, for example, to understand how key physiological and ecological responses to rising atmospheric CO_2, such as stomatal closure, increased photosynthesis and carbohydrate synthesis, and dynamics of species growth propagate to higher scales. Modelling from FACE experiments is central to understanding how these phenomena scale to larger areas, e.g. land water yield and carbon accumulation. Biodiversity loss and species change with elevated CO_2 are of great concern, and results from FACE are important to help move ahead new ideas for up-scaling, particularly with regard to understanding and modelling plant-plant and plant-microbe interactions resulting in changes in species composition of ecosystems in FACE.

FACE experiments are needed to provide information for scaling. The scientific community can gain great confidence in models used at larger scales, by testing them against real-world FACE experiments.

FACE sites should be strategically designed to help us to address the largest uncertainties in modelling processes. In Europe, for example, these could be used to address the strategies of carbon allocation in plants, in order to improve our ability to predict whether and to what extent rising atmospheric CO_2 will be offset by carbon sequestration in ecosystems. There is a special need for new FACE sites that are located in regions that are at a high risk of detrimental global change impacts, and address interactions between elevated CO_2 and water, and CO_2 and temperature.

Modelling and up-scaling are data-intensive activities, and require comprehensive databases. Attention to the quality of these databases is a critical activity that requires funding to support new and synthetic analyses from these experiments, and to place them within a broader context. The databases should include background meteorological and other kinds of data. The FACE databases should be widely accessible for modellers and other researchers. For this purpose, it will be important to establish common databases across many sites within the FACE network.

Databases need to be maintained by a Centre specialised in data archiving. Europe currently lacks such a Centre. It is imperative that sufficient funds are available to generate and maintain database and data-archiving systems consistent across different sites.

Location of future FACE sites

The location of future FACE facilities should be determined by a combination of biological and logistical considerations.

Managed systems (primarily crops) will need large FACE systems in areas with homogeneous soils located near major centres of production. For instance, soybean FACE experiments could be envisaged in the Midwest (USA) or Brazil. Rice is an interesting crop to research the interaction between heating, N-uptake and elevated CO_2. This could for example take place in the Philippines (IRRI). Slash-and-burn and secondary forest systems encompass large areas in Africa, South America and south-east Asia (maize crop – secondary forest systems allow for C_4 – C_3 soil C tracing). In Australia agronomical experiments are already positioned along north-south and east-west transects and focus on water and heat interactions; here, FACE experiments may be added. In some cases, it may be important to locate FACE sites at different latitudes to allow different maturity groups (e.g. with respect to the impact of photoperiod on flowering) of a given crop to be investigated.

For natural ecosystems, including forest and biomass plantations, locations should be chosen to maximise the coverage of existing and future climatic space and along environmental gradients (e.g. increase rates of atmospheric N deposition or precipitation). Temperate ecosystems have been the focus of most research to date, but even for them there are still important unanswered questions, particularly responses over long time scales and interactions between CO_2, climatic warming, and precipitation change. However, there are certain biomes that cover a large part of the globe, but no FACE experiments have been established within them; therefore they should be considered a high priority for future experiments. These include **tropical forests, savannahs, and boreal ecosystems**. Tropical forest functioning is poorly understood in general. Savanna and grassland areas, like those located in northern China and Mongolia, may be especially susceptible to climate shifts due to woody encroachment.

Site location and design should be chosen to allow the production of statistically powerful and predictive information. For low-stature vegetation (e.g. most crops, shrublands, grasslands), relatively more small- to medium-sized (~20 m) rings are needed. For tall-stature vegetation (e.g. forests) there will be a trade-off between plot size and the number of plots that can be affordably maintained. To increase the comparability between experiments and modelling, future experiments may choose to employ regression-based experimental designs rather than ANOVA-based designs. This could be achieved by arraying single FACE plots along gradients in climate or across soil-edaphic gradients where, for example, soil moisture and nutrient availability vary. For natural ecosystems, sites should be developed in areas free of recent soil disturbance to allow below-ground processes to be studied.

FACE facilities should preferably be located in association with other studies. Examples would include co-location with eddy flux-tower facilities (French Guyana, Malaysia, Amazonian basin), or location in areas where biological diversity is actively being manipulated. Future FACE experiments in the USA (primarily temperate) may be linked with the National Ecological Observatory Network (NEON) initiative [1]. The role of Europe should be defined in the future. For instance, Europe needs to play a special role in helping developing countries to be involved in these expensive and sophisticated research facilities. Modern biomass-related research is of great importance for many countries that balance between food and non-food production.

There must be local expertise in operating and managing large science facilities, and easy and cost-effective access to large amounts of clean CO_2. The latter is a major cost factor for FACE studies. Cost is determined not only by CO_2 itself, but also by transport and handling (safety measures). The quality of the CO_2, the reliability of supply and possibilities for CO_2 back-up also need to be considered. CO_2 scrubbed from ambient air may become available, which has the advantage that it is not location-specific; however, quality may pose a problem. In addition, a constant stable isotopic signal ($\delta^{13}C$) value is needed for carbon trace experiments.

1. http://www.neoninc.org

FACE site policy and organisational issues

As already mentioned, FACE sites require a substantial investment in hardware and have high running costs, due to the need for continual maintenance and control, and the cost of CO_2. This makes it vital to maximise output from these sites, which will require that many scientific teams use each site in a coordinated manner. Their activities should not interfere with each other, and the results must be integrated into a common database.

An appropriate management structure must be established. At the outset, an international governance board should be established to provide overall steering. It might be composed of members of the funding agencies. This board would hire a FACE site director. The director would lead the engineering staff responsible for the operation of the FACE and other apparatus, including automated scientific equipment. An internal core of on-site investigators would assist the director in making day-to-day management decisions.

An advisory panel should be established, composed of outside expert scientists. This board would assist the director in assuring overall quality control of the project, reviewing the progress of the project, setting scientific priorities, and adjudicating disputes among researchers with proposed competing or incompatible sampling/measuring activities.

Clearly defined and documented protocols need to be established and enforced. These will be needed to obtain a "core" minimum data set, to assure proper scheduled calibration of equipment, to minimise damage from traffic, to refill soil core holes, etc.

Appropriate storage space needs to be provided. Plant and soil samples from the FACE project are valuable, and frequently irreplaceable, because they are part of a time series.

Data management policies are essential. They need to be established at the outset, including near-immediate back-up, strong enforcement of data-sharing, establishment of a fixed time-frame for a researcher to have exclusive rights to publish his/her data beyond which anyone can publish, encouragement to furnish data to the modellers who in turn must have permission from the author to publish within the fixed time-frame, and adoption of a standard recognised data format.

Data collection, archiving and dissemination need to be secured. An institution needs to be identified which will be responsible for archiving the data and disseminating it to subsequent future users. The institution should also facilitate the collection and assemblage of the data from the many researchers around the world by sending a travelling technician to the various researchers' locations to help convert data into the standard format.

Costs

A conventional crop FACE site with an effective usable area of ca. 160 m^2 that is run for 10 years costs ca. 2.5 M€, of which the majority is running costs, especially CO_2. This would require four 20 m diameter plots, which cost about 300-400 k€ to build (including 250 k€ for facilities for storing, vaporising and distributing CO_2, 60 k€ for the ring system and 20 k€ for weather systems) and have running costs of >200 k€ p.a. (including 90 k€ for CO_2 and 80 k€ for salaries for engineers and workers, plus costs associated with renting, crop growth and harvest, storage and transport). There are play-offs between the investment costs in the ring system and the efficiency of use of the CO_2.

Costs would increase for a larger site, e.g. to ca. 10 M€ for a site with a usable area of 650 m^2. If the area were to be increased by using larger rings, construction costs would increase roughly in proportion with the area of a ring, but usage of CO_2 would increase over-proportionately (by about 20-30%) due to the decreased efficiency of CO_2. The use of CO_2 might be more effective if a gridded system were to be used. Estimates, which require testing and verification, indicate a potential saving of almost 2 M€ over 10 years. Options are also available to run large node systems that would allow areas of several hectares to be treated, including the generation of CO_2 gradients. The estimated building costs of such sites would be ca. 2 M€ for the CO_2 release system, plus added investments for CO_2 storage and delivery. **This highlights the importance of modelling and testing alternative CO_2 release systems for experiments that require a large area, for example, with crops for which individual plots >1 m^2 are required.** It also highlights potential financial savings that can be obtained by locating FACE sites close to cheap sources of CO_2.

Increased running costs will also be required for engineering and scientific personnel, infrastructure and data warehousing. Inclusion of parallel studies, in which plants are grown in ambient CO_2 and other parameters are varied, will further increase the total cost, because running costs for land rent and plant growth rise. However, as argued above, this will optimise the investment in FACE sites.

Recommendations

1. FACE studies should proceed beyond descriptive science, and recognise the shift to a mandate to understand and predict the consequences of atmospheric and climatic change on the process and ecosystem level, and to contribute to the design of appropriate strategies to respond to this change.
2. For crops, FACE facilities must be located in major areas of production, with the capacity to screen 100 to 200 genotypes of each crop in a replicated manner.
3. For natural ecosystems, well-replicated FACE sites are needed that maximise the coverage of ecosystems, as well as existing and future climatic space and environmental gradients. Short-rotation bio-energy crops need to be included as their importance will increase in the future.
4. It will be important to model and test alternative CO_2 delivery and release systems for experiments that require a large area, in order to minimise running costs.
5. FACE studies should fully integrate genetics and genomics. These disciplines are needed to understand the complex interactions between plant growth, elevated CO_2 concentrations and climate change, and to design strategies to cope with the consequences.
6. FACE studies should investigate the responses to combinations of future atmospheric and climatic changes, not just elevated CO_2.
7. The design of the sites and experiments and their outputs should be closely integrated with modelling approaches, including systems biology and ecosystem and climate change modelling. This will maximise the predictive power of the data, and further its integration with the formulation and testing of models.
8. A joint plan is needed for crops and natural ecosystems. Despite differences with respect to whether responses in these systems can, and should, be modified, there are many commonalities, including site design, instrumentation, operational protocols (treatment level, treatment times, etc.), control and diagnostic software, which measurements are needed, the theoretical background, and the need to interact with modelling activities.

Further initiatives, further reading

A workshop on "Exploring Science Needs for the Next Generation of Climate Change and Elevated CO_2 Experiments in Terrestrial Ecosystems" was organised from 14-18 April 2008 in Arlington, Virginia (USA). The workshop was operated by the Environmental Sciences Division of Oak Ridge National Laboratory with support from the US Department of Energy, Office of Science, Biological and Environmental Research program. The workshop had very similar objectives and aims to the ESF-INIF workshop which has led to this LESC-PESC Position Paper, although with a clear focus on the situation in the USA. Their conclusions are consistent with the findings of the present Position Paper, and reiterate the need to combine large-scale FACE experimental studies and modelling efforts as a key method for moving global change science forward. The main observations of both initiatives were exchanged in order to optimise cross-fertilisation. A recent paper in *Nature* – published online on 18 November 2008 – entitled "Forestry carbon dioxide projects to close down" warns of the consequences of closing down the US Department of Energy FACE sites without a vision for a next generation of new FACE-based experiments (*Nature* doi:10.1038/456289a).

Two scientific research papers are being produced from the ESF-INIF workshop on the main topic of the workshop. One of the papers has already been published while a second one is in preparation.

- E.A. Ainsworth, C. Beier, C. Calfapietra, R. Ceulemans, M. Durand-Tardif, G.D. Farquhar, D.L. Godbold, G.R. Hendrey, T. Hickler, J. Kaduk, D.F. Karnosky, B.A. Kimball, C. Körner, M. Koornneef, T. Lafarge, A.D.B. Leakey, K.F. Lewin, S.P. Long, R. Manderscheid, D.L. McNeil, T.A. Mies, F. Miglietta, J.A. Morgan, J. Nagy, R.J. Norby, R.M. Norton, K.E. Percy, A. Rogers, J.F. Soussana, M. Stitt, H.J. Weigel and J.W. White (2008) Next generation of elevated CO_2 experiments with crops: a critical investment for feeding the future world. *Plant, Cell and Environment* 31, pp. 1317-1324.
- C. Calfapietra, E.A. Ainsworth, C. Beier, P. De Angelis, D.S. Ellsworth, D.L. Godbold, G.R. Hendrey, T. Hickler, M. Hoosbeek, D.F. Karnosky, J. King, C. Körner, A.D.B. Leakey, K.F. Lewin, M. Liberloo, S.P. Long, M. Lukac, R. Matyssek, F. Miglietta, J. Nagy, R.J. Norby, R. Oren, K.E. Percy, A. Rogers, G. Scarascia-Mugnozza, M. Stitt, G. Taylor and R. Ceulemans (2009) New challenges and priorities in the next generation of elevated CO_2 experiments on forest ecosystems and plantations. In preparation.

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