FACE Systems for Studying the Impacts of Greenhouse Gases on Forest Ecosystems

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Free-air CO_2 and/or O_3 enrichment (FACE) systems offer unprecedented opportunities for studying the impacts of greenhouse gases on forest ecosystems. With FACE systems, it is now possible to expose reliably large stands of forest trees and to examine forest ecosystems from seedling establishment phases until harvest or biological maturity. Ecosystem processes, such as nutrient and water cycling, can now be studied as well as community and stand dynamics under systems that are relatively free of the artificial influences that have plagued growth chamber, branch chamber, greenhouse and open-top chamber studies. This chapter documents the historical developments of FACE systems, describes seven FACE systems that are currently studying impacts of greenhouse gases on forest ecosystems, and outlines major remaining research questions in which FACE studies can help provide insights into future forest ecosystems under elevated greenhouse gases.

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10.1 Introduction

Experimental research on tree responses to CO_2 over past decades can be characterized by a gradual increase in the scale of complexity of investigations as researchers have moved from laboratory chambers towards field chambers (Fig. 10.1), from small seedlings to larger trees, and from simple, single-factor studies to more complex, multiple-factor studies (Mooney *et al.*, 1991; Körner, 1995). In this logical progression to larger scales, it has only been fairly recently that studies of the entire forest ecosystem and of complete trees of any size can be examined through the advent of free-air CO_2 enrichment (FACE) systems. This chapter outlines the origins of FACE technology development for tree studies, presents and describes the suite of current FACE projects dealing with forest ecosystems, details some early results from forest FACE studies, and speculates about the long-term benefits in research anticipated from these studies.

10.1.1 Historical development of FACE systems for trees

Chamberless fumigation systems for exposing large numbers of young forest trees to various environmental pollutants were first developed in Europe (McLeod *et al.*, 1985; McLeod, 1995). This early 50–60 m diameter system (Fig. 10.2) was the basis of the Liphook Forest Fumigation project which examined the impacts of sulphur dioxide (SO_2) and ozone (O_3) on Scots pine (*Pinus sylvestris*), Corsican pine (*Pinus nigra*), Norway spruce (*Picea abies*) and Sitka spruce (*Picea sitchensis*) over a 7-year period (Holland *et al.*, 1995). This system was later modified for use with CO_2 (Walklate *et al.*, 1996).

Wulff *et al.* (1992) developed a second type of open-air exposure system for exposing young forest trees to O_3 (Fig. 10.3). This system provided a chamberless open-air fumigation area of approximately 3.5 m in diameter with a natural microclimate and excellent control of O_3 during day and night fumigation. This facility has been used extensively for examining the effects of O_3 on birch (*Betula* spp.) (Paakkonen *et al.*, 1993, 1995, 1996, 1997, 1998a,b,c; Lavola *et al.*, 1994; Oksanen and Saleem, 1999). Both the Liphook and Finnish systems allowed for relatively large numbers of trees to be tested in conditions free of chamber effects. However, both of these systems are restricted to trees below a maximum height of a few metres.

In the mid-1980s, Brookhaven National Laboratory scientists developed their free-air CO_2 exposure (FACE) system (Hendrey *et al.*, 1992; Lewin *et al.*, 1994) for emitting CO_2 into ring-shaped plots of 20–30 m in diameter. The BNL-design FACE system was then scaled up for use with large trees with the onset of the loblolly pine (*Pinus taeda*) study at Duke Forest in North Carolina, USA (Hendrey *et al.*, 1999). This BNL system served as the basis for forest ecosystem studies with aspen (*Populus tremuloides*), birch (*Betula papyrifera*) and maple (*Acer rubrum*) in northern Wisconsin (Karnosky *et al.*, 1999; Dickson *et al.*, 2000), with sweetgum

Fig. 10.1. Open-top chambers (first designed by Heagle *et al.* (1973) for agricultural crop studies), as shown here being used for studies of O_3 and/or CO_2 effects on eastern white pine (*Pinus strobus*) (left) and trembling aspen (*Populus tremuloides*) (right), continue to be useful for studies of the impacts of greenhouse gases on forest trees. While these chambers provided more realistic growth conditions than did greenhouse or laboratory chambers, the ambient environment of open-top chambers has been characterized as being significantly different from the environmental conditions outside these chambers (Olszyk *et al.*, 1980; Heagle *et al.*, 1988; Janous *et al.*, 1996; Van Oijen *et al.*, 1999).

(*Liquidambar styraciflua*) in Tennessee, USA (Gunderson *et al.*, 1999; Norby, 1999), and tree plantations in Panama (Potvin, personal communication).

Three additional FACE systems have been subsequently developed in Europe. Miglietta *et al.* (1997) developed a mini FACE system (8 m diameter) in Italy, which has been used for studies of CO_2 effects on agricultural crops and for studies of small trees (Tognetti *et al.*, 1999). The second recent FACE design is that of the POPFACE, also in Viterbo, Italy, which is being used for studies of CO_2 effects on hybrid poplars (Scarascia-Mugnozza, unpublished). The third European FACE system is that developed near Munich, Germany, for study of O_3 impacts on mature European beech (*Fagus sylvatica*) and *P. abies* (Haeberle *et al.*, 1999).

10.1.2 Greenhouse gases and forests: 'FACING' the future

We are in the midst of a global experiment with forest ecosystems, as CO_2 and other greenhouse gases are increasing in approximately the same fashion as the world's population. Because most studies of tree responses to elevated concen-

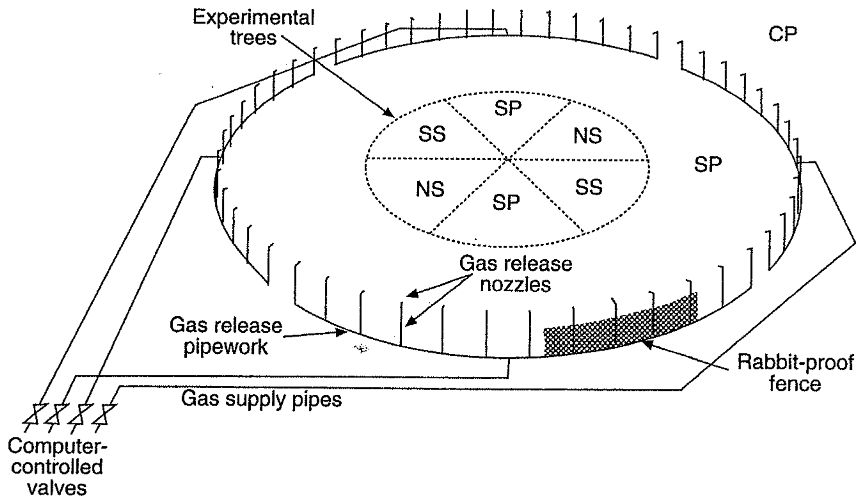


Fig. 10.2. A schematic diagram of one of the first open-air exposure systems designed to accommodate trees. This system was used in the Liphook studies in Europe for examining the impacts of SO_2 and O_3 on forest trees (McLeod *et al.*, 1985, 1992; McLeod, 1995). (From: McLeod *et al.*, 1992.)

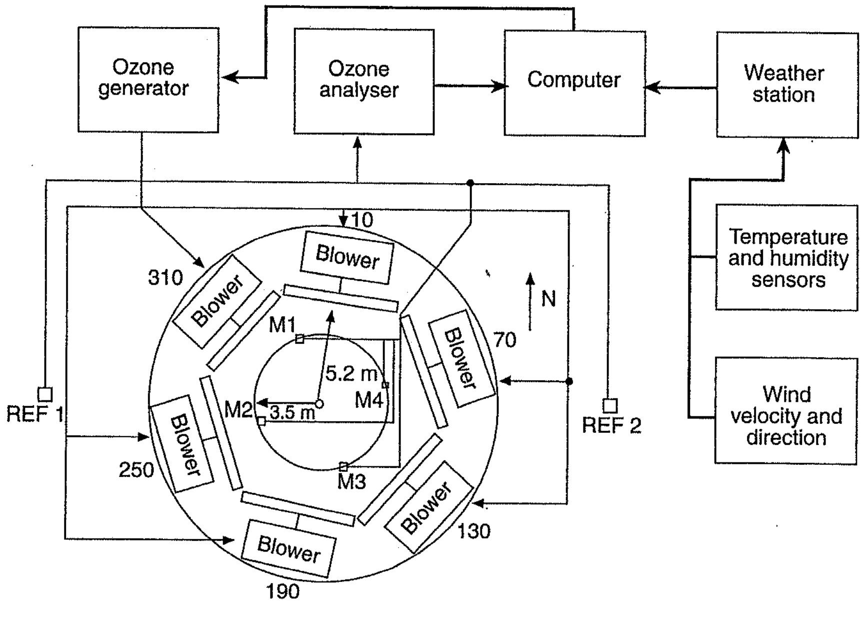


Fig. 10.3. A schematic diagram of the open-air exposure system developed by Wulff *et al.* (1992) for study of the impacts of O_3 on birch (*Betula pendula*) trees in Finland. (From: McLeod *et al.*, 1992.)

trations of greenhouse gases have been done with young trees and in chambers with artificial environments, it is very difficult to predict the impacts of elevated greenhouse gases on forest ecosystems. Because of the design flexibility of FACE systems, scientists can now expose whole stands of mature forest trees and we are not limited to studying seedlings. Similarly, because of the large spatial scales of the FACE rings (diameters of 20–30 m or more are possible), scientists can now address stand and community-level studies of forest ecosystems exposed to experimentally manipulated atmospheric chemistry. Finally, for the first time, scientists have a realistic vehicle for testing hypotheses about carbon and nutrient cycling, water movement and litter decomposition on intact forest systems, *in situ*. Thus, the FACE systems are allowing a 'window' into the future chemical climate to which forests will be exposed.

A second major research area that FACE technology can address is carbon sequestration. With the increasing interest in carbon credits related to tree planting, it is quite startling how little we know about the capacity of forests to sequester carbon. For example, at what age do new plantations change from being carbon sources to sinks? Will carbon sequestration in forests increase or decrease in response to greenhouse gases? Will stresses related to insects, diseases, drought, temperature changes or pollution overwhelm the generally positive growth responses demonstrated by forest trees growing in elevated CO_2? FACE studies will allow scientists to answer these questions, as this approach enables the analysis of whole-tree and system responses under the characteristic multifactorial scenarios of typical forest sites.

10.1.3 Current FACE systems being used for forest ecosystem studies

Currently, there are seven operational FACE systems of various types and sizes in use for the study of the impacts of greenhouse gases on forest trees (Table 10.1). The longest running free-air exposure system is in Finland, where the impacts of O_3 on young *B. pendula*, *P. sylvestris* and *P. abies* trees have been studied for the past 8 years (Wulff *et al.*, 1992; Paakkonen *et al.*, 1993). The main purpose of this facility was to examine the impacts of O_3 on trees growing in an environment closely mimicking the natural forest (Paakkonen *et al.*, 1993).

A second system to study the O_3 impacts on forest trees has recently been developed in Germany (Haeberle *et al.*, 1999). In contrast to other FACE sites, this German system uses thin-walled diffusion tubes for gas dispersal in the canopy of a mixed forest stand of 40–60-year-old (about 25 m high) trees of *P. abies* and *F. sylvatica* trees (Fig. 10.4).

The first FACE/forest system in North America was developed to study the impacts of elevated CO_2 on large (15-year-old) trees of a nearly pure *P. taeda* stand in the Duke Forest, North Carolina (Fig. 10.5; Hendrey *et al.*, 1999). This system has three rings of elevated atmospheric CO_2 (200 p.p.m. over ambient) that is administered 24 hours per day and year around.

Table 10.1. Summary of ongoing FACE/forest ecosystem studies.

	FACTS-I	FACTS-II (Aspen FACE)	Oak Ridge	POPFACE	Panama FACE	O_3 FACE, Finland	'Free-Air' O_3 fumigation experiment
Location	Duke Forest, North Carolina, USA	Rhinelander, Wisconsin, USA	Tennessee, USA	Tuscania, Viterbo, Italy	Sardinilla, Panama	Kuopio, Finland	Kranzberg Forest, Germany
Site co-ordinates and elevation	35° 58′ N, 79° 05′ W; elevation = 174 m	45° 40′ N, 89° 37′ W; elevation = 490 m	35° 54′ N, 84° 20′ W	42° 37′ 04″ N, 11° 80′ 87″ E; elevation = 150 m	9° 19′ N, 79° 38′ W; elevation = 90 m		48° 25′ 08″ N, 11° 39′ 41″ E; elevation = 485 m
Species	*Pinus taeda* (loblolly pine) forest (height = 12–13 m)	Aspen (*Populus tremuloides*); birch (*Betula papyrifera*); sugar maple (*Acer saccharum*)	Sweetgum (*Liquidambar styraciflua*), closed canopy (height = 12 m)	*Populus alba* '2AS-11', *Populus nigra* 'Jean Pourtet', *P.* × *euramericana* 'I-214'	Rainforest half multiple species plantations, half teak plantation	*Betula pendula*, *Pinus sylvestris*, *Picea abies*	*Fagus sylvatica*, *Picea abies* mixed forest (height = 25 m)
Age at start of treatment	14 years	<1 year	10 years	<1 year		1 year	40–60 years old
Density/ plant distance	2.4 × 2.4 m	1 × 1 m					Managed forest, few metres distance
Replicates	3 elevated CO_2 rings, injection of	3 elevated CO_2 CO_2 rings, 3 elevated O_3	2 elevated CO_2 rings, 2 ambient rings	3 elevated CO_2 rings, 3 ambient rings	2 elevated CO_2 rings, 2 ambient	2 fumigation blocks	5 neighbouring individuals per species each

	CO_2-enriched air at vertical vent pipes. 3 ambient rings (blower) control)	rings, 3 elevated $CO_2 + O_3$ rings, 3 ambient rings (blower control), 2 ambient rings	(blower control), 2 ambient rings		rings (blower control), 2 ambient rings	2 ambient fumigation blocks	under the ambient (control) and 2× ambient ozone regimes
FACE technology	BNL design	BNL design, injection of CO_2-enriched air at vertical vent pipes with modifications for O_3 (Dickson *et al.*, 2000)	BNL design, injection of CO_2-enriched air at vertical vent pipes	IATA-CNR design, pure CO_2 injection from laser-drilled holes through flexible pipes	BNL design, injection of CO_2-enriched air at vertical vent pipes	O_3 release from perforated vertical vent pipes	O_3 release from perforated Teflon tubes, being suspended through the canopy (developed and operated by Werner and Fabian, unpublished)
Plot diameter	30 m	30 m	25 m	22 m	24 m	3.5 m	15 m
Enrichment	Ambient + 200 p.p.m; 24 h day^{-1}	560 p.p.m. (day only)	565 p.p.m. (day) and 645 p.p.m. (night)	550 p.p.m. (day only)	550 p.p.m.	1.6–1.7 × ambient	2 × ambient; ($O_3 \leq 150$ p.p.b.)
Start of fumigation	August 1996	August 1997 (CO_2); May 1998 (all treatments)	April 1998	June 1999	March–April 1999; running of prototype FACE ring	Numerous studies, started in 1991	April 2000

Continued

Table 10.1. *Continued.*

	FACTS-I	FACTS-II (Aspen FACE)	Oak Ridge	POPFACE	Panama FACE	O_3 FACE, Finland	'Free-Air' O_3 fumigation experiment
Interaction		O_3				Drought, fertility	
Soil type	Ultic alfisol of the Enon series	Sandy loam	Silty clay loam	Heavy loam		Soil mix (pots)	
Site management		Overhead irrigation for first two growing seasons		Drip irrigation			
References	Hendrey *et al.* (1999)	Karnosky *et al.* (1999); Dickson *et al.* (2000)	Norby (1999); Gunderson *et al.* (1999)	Gielen *et al.* (2000); Scarascia-Mugnozza, unpublished	Potvin, unpublished	Wulff *et al.* (1992)	Haeberle *et al.* (1999)

Websites:
FACTS-I: http://www.face.bnl.gov/FACTS/facts1.html
FACTS-II: http://www.nrri.umn.edu/aspenface
Oak Ridge: http://gcte-focus1.org/activities/activity_11/Task_111/CO2%20sites/ornl/ornl
POPFACE: http://www.unitus.it/relcult/popface/home.htm
Panama FACE: http://www.mcgill.ca/Biology/faculty/potvin
'Free-Air' O_3 fumigation experiment: http://www.forst.uni-muenchen.de/LST/BOTANIK/PROJEKTE/SFB/sfbb4.htm

The Oak Ridge, Tennessee, USA FACE experiment was constructed in a 10-year-old *L. styraciflua* stand (Fig. 10.6). This study uses the BNL design modified by having 24 vertical vent pipes (VVPs) around the periphery instead of the 36 VVPs as used in the Duke Forest, and is examining the impacts of elevated CO_2 on this closed-canopy deciduous forest. Fumigations are done during the growing season at ambient plus 565 p.p.m. during the day and 645 p.p.m. at night (Gunderson *et al.*, 1999; Norby, 1999).

The only current CO_2 FACE study of forest trees in Europe is the POPFACE study initiated in 1999 (coordinated by Scarascia-Mugnozza *et al.*, unpublished). This European Union project, located in Viterbo, Italy, is examining the impacts of elevated atmospheric CO_2 on different poplar clones in an agroforestry system. The aim is to quantify the sequestration capacity of high-density forest plantations within Europe. Enrichment of the elevated rings is made during the growing season with daytime-only fumigations at 550 p.p.m. In contrast to other CO_2 FACE projects that have initiated CO_2 fumigation in the midst of a normal harvest rotation, this study is exposing the trees to elevated or ambient CO_2 for the entire rotation (Fig. 10.7).

The first FACE site under development in the Tropics is located in Central Panama where a prototype CO_2 FACE ring was established and tested for 1 month in 1999 (Fig. 10.8). This system used the BNL design and was functional even under high wind speeds (winds averaged 4.5 m s^{-1} with peaks up to 9 m s^{-1}).

The largest FACE facility, and the only one to include a full factorial experiment with elevation of two greenhouse gases (CO_2 and O_3), is the FACTS-II (Aspen FACE) project located at Rhinelander, Wisconsin (Karnosky *et al.*, 1999; Dickson *et al.*, 2000; Fig. 10.9). This study uses the BNL FACE design modified to include larger exit ports on the vertical vent pipes, emission of gases in the opposite direction of the rings, and baffles to redirect the gases into the rings. The baffles were modified from Walklate *et al.* (1996). The modifications were made to accommodate O_3 dispensing from the vertical vent pipes, as some dilution was necessary so that trees near the vertical vent pipes were not killed by the high O_3 levels.

10.2 Early FACE/Forest results

10.2.1 FACE performance

Micrometeorological measurements made at FACE facilities suggest that FACE systems provide a microclimate very similar to that of the surrounding plant communities (Heilman *et al.*, 2000; Pinter *et al.*, 2000). Furthermore, CO_2 and/or O_3 dispensed from a FACE ring is nearly undetectable 100 m downwind of the treatment ring (Karnosky *et al.*, 2000; Stoughton *et al.*, 2000). Stoughton *et al.* (2000) suggested that the highest contamination of control rings at the Duke Forest FACTS-I experimental site was no more than 1% of its total carbon flux. Karnosky *et al.* (2000) consistently measured background O_3 levels at 100 m downwind of their FACTS-II (Aspen FACE) rings where O_3 was emitted.

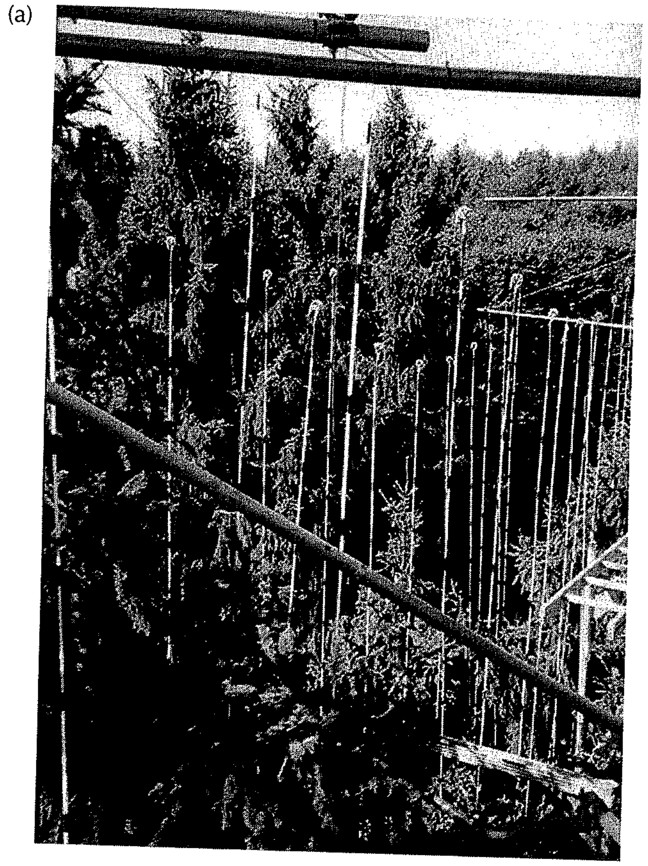
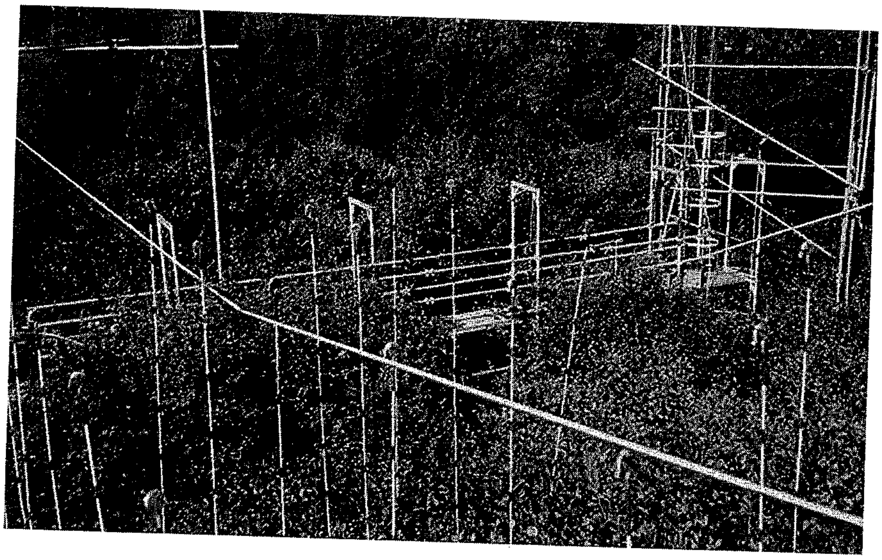


Fig. 10.4. The German free-air system for examining the impacts of O_3 on mature forest trees. Diffusion tubes dispense O_3 into crowns of European beech (*Fagus sylvatica*) (a) and Norway spruce (*Picea abies*) (b, opposite). The canopy is accessed via a system of towers (c, opposite) and catwalks between the towers. This system is also designed for eventually dispensing CO_2 as well as O_3.

Temporal and spatial distribution patterns inside FACE rings suggest that FACE systems can produce reliable, repeatable and spatially similar concentrations of CO_2 (Walklate *et al.*, 1996; Hendrey *et al.*, 1999; Dickson *et al.*, 2000; Karnosky *et al.*, 2000) and other pollutants (McLeod *et al.*, 1985; Wulff *et al.*, 1992; McLeod, 1995; Dickson *et al.*, 2000; Karnosky *et al.*, 2000). These systems are capable of delivering CO_2, O_3 and SO_2 reliably, at values within 20% for 90–95% of the time or more (Hendrey *et al.*, 1999; Dickson *et al.*, 2000). The spatial distribution in all FACE systems results in higher gas concentrations near the gas-dispensing vents. However, in all systems, a large core area is available that is similar to the central control points (McLeod *et al.*, 1985; Wulff *et al.*, 1992; McLeod, 1995; Hendrey *et al.*, 1999).

(b)



(c)

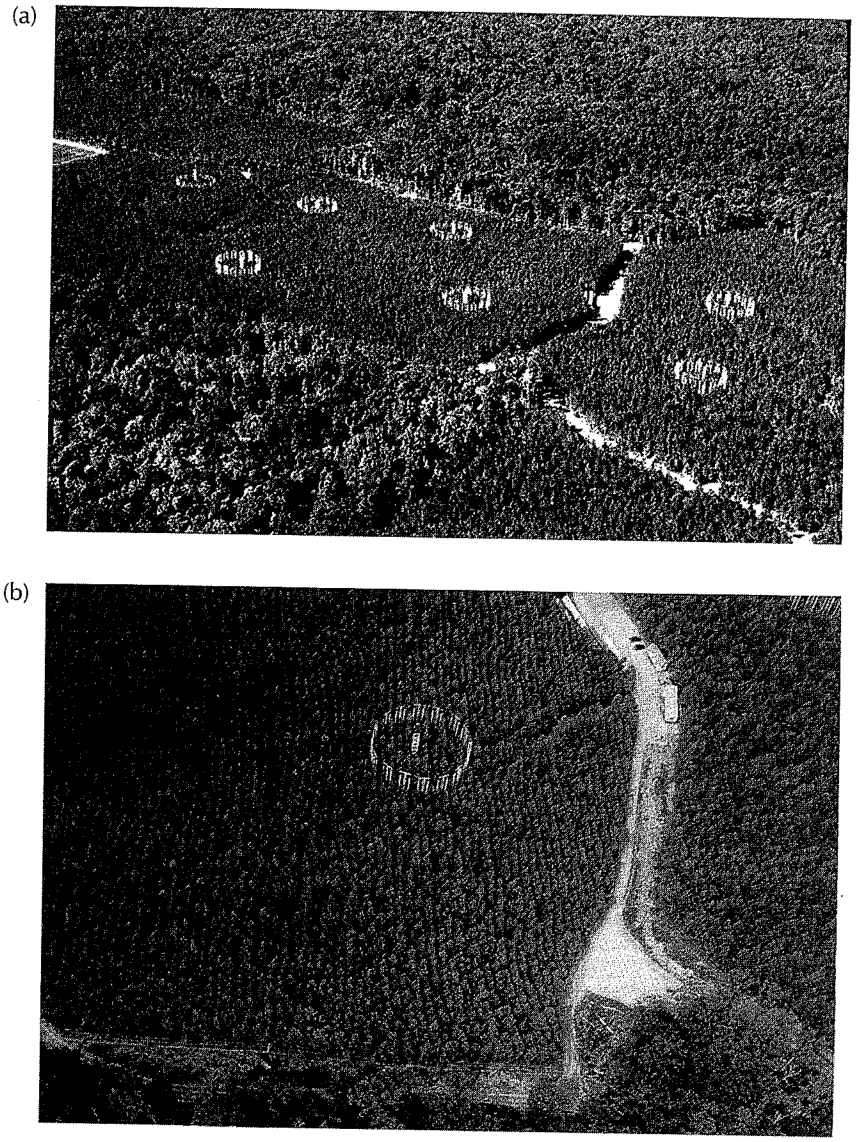
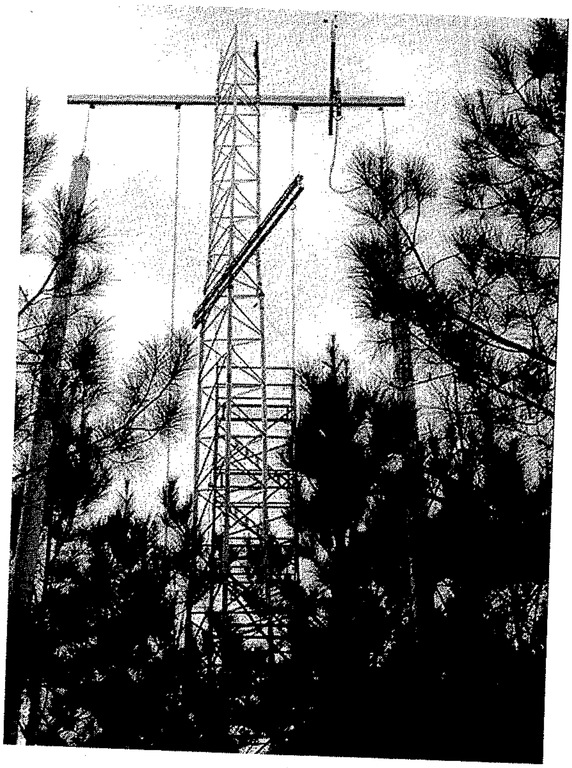


Fig. 10.5. The Duke Forest FACE site in North Carolina, USA, consists of six treatment rings (three control and three elevated atmospheric CO_2) and one prototype ring (a) in the midst of a 15-year-old loblolly pine (*Pinus taeda*) stand. A single ring and the adjacent CO_2 supply and control facility are shown in (b). CO_2-enriched air is dispersed throughout the forest from the ground to the top of the crown of the 20 m tall trees from vertical vent pipes, as shown in (c, opposite). Photos (a) and (b) by Will Owens.

(c)



10.2.2 CO_2

The strong stimulation of photosynthesis by elevated atmospheric CO_2, consistently found in chamber studies of young trees and older tree branch chamber studies (Ceulemans and Mousseau, 1994), is holding across forest FACE studies (Table 10.2). While it is too early to tell whether elevated CO_2-induced growth responses are going to continue, it appears as though a significant positive growth response is being seen across FACE sites (Table 10.3). In fact, the growth enhancement for loblolly pine appears to be increasing over time (Fig. 10.10).

The fate of the increased carbon assimilated that cannot be accounted for in increased biomass production under elevated atmospheric CO_2 has largely been a mystery for forest ecosystems. However, recent evidence from Schlesinger and Andrews (2000) suggests that the concentration of CO_2 in the soil pore space and the flux of CO_2 from the soil surface both increased approximately 30% over values seen in ambient conditions. These authors suggested that 30–50% of the increase in soil respiration of CO_2 is derived from root activity, and the remainder is from soil microbes (Bowden *et al.*, 1993; Andrews *et al.*, 1999). Based on their *P. taeda* results, Schlesinger and Andrews (2000) and

King *et al.* (2000) suggested that while plant growth at high CO_2 may add additional carbon to soils, most of it is likely to return to the atmosphere as CO_2. Clearly, the below-ground carbon budget remains largely unknown for other forest ecosystems exposed to elevated atmospheric CO_2.

10.2.3 O_3

The 'free-air' O_3 exposure system developed by Wulff *et al.* (1992) has been used extensively in Finland for examining the impact of O_3 under near ambient O_3 and in natural, non-chambered conditions (Paakkonen *et al.*, 1993, 1995, 1996, 1997, 1998a; Oksanen and Saleem, 1999). This 'free-air' system has also been useful in studies of the interaction of O_3 with other environmental factors, such as drought (Paakkonen *et al.*, 1998b,c). Recently, this scientific team has documented long-term carry-over effects and prolonged biomass decreases from O_3 with *B. pendula* (Oksanen and Saleem, 1999).

Table 10.2. Relative photosynthetic enhancement reported in trees exposed to elevated atmospheric CO_2 in FACE experiments.

Species	Light regime	CO_2 treatment (p.p.m.v.)	Response (%)	Reference
Acer rubrum	Shade	Ambient +200 (24 h)	+59	DeLucia and Thomas (2000)
Carya glabra	Shade	Ambient +200 (24 h)	+80 to 82	DeLucia and Thomas (2000)
Cercis canadensis	Shade	Ambient +200 (24 h)	+159 to 190	DeLucia and Thomas (2000)
Liquidambar styraciflua	Shade	Ambient +200 (24 h)	+74	DeLucia and Thomas (2000)
Liquidambar styraciflua	Sun	Ambient +200 (24 h)	+98	Herrick and Thomas (1999)
Liquidambar styraciflua	Shade	Ambient +200 (24 h)	+41	Herrick and Thomas (1999)
Liquidambar styraciflua	Sun	565 (day) and 645 (night)	+ 30 to 70	Gunderson *et al.* (1999)
Pinus taeda	Sun	Ambient +200 (24 h)	+0 to 52, depending on season	Myers *et al.* (1999)
Populus tremuloides	Sun	560 (day)	+7 to 58, depending on season	Noormets *et al.* (2001a,b), Sober *et al.* (2001)
Populus deltoides	Sun	560 (24 h)	+17.2 to 39.4	Tognetti *et al.* (1999)
Populus hybrid	Sun	560 (24 h)	+20.3 to 45.8	Tognetti *et al.* (1999)

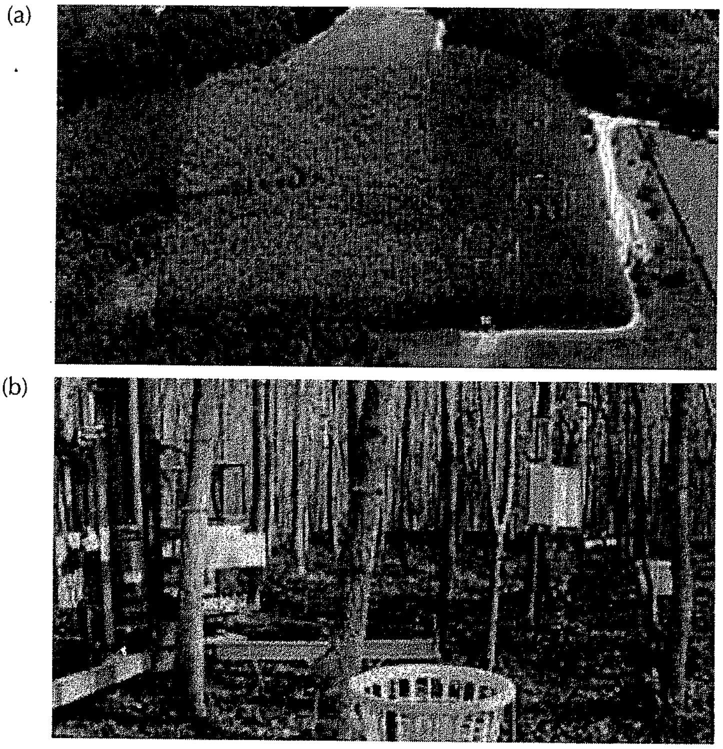


Fig. 10.6. The Oak Ridge, Tennessee, USA, FACE experiment is shown in (a). Within each of the four rings (two with elevated atmospheric CO_2 and two with ambient CO_2), the stand is being carefully monitored for growth, litter fall, water use and carbon and nutrient cycling (b).

At the Kranzberg site in Germany, installation work of the 'free-air' O_3 fumigation system has been completed and test runs are presently under way, so that a first continuous canopy exposure to an elevated O_3 regime occurred for the growing season of the year 2000. A group of 10 trees (five *P. abies* and F. *sylvatica* individuals each) was exposed to a twice-ambient O_3 regime, confining peak values, however, to below 150 p.p.b. A corresponding group of tree individuals under the unchanged ambient O_3 regime of the forest site served as a control. Each of the 20 trees are regarded, in the analysis, as an individual case study, examining a broad spectrum of assessed physiological and structural responses for consistency patterns, and scaling findings across the levels of cells, organs and the whole tree. The exposure experiment is planned to continue for several years. A prototype system has shown, for a smaller group of trees, that a doubling of O_3 levels in the canopy is technically feasible through computer-processed feedback control, based on on-line O_3 monitoring at several canopy positions and a large number of passive O_3 samplers for dose analysis by weekly intervals (Werner and Fabian, Munich, 2000, personal communication).

Table 10.3. Relative growth enhancement reported in trees exposed to elevated atmospheric CO_2 in FACE experiments.

Species	CO_2 treatment (p.p.m.v.)	Growth measure	Growth response (%)	Reference
Betula papyrifera	560 (day)	d^2h	+38	Karnosky *et al.* (2001)
Liquidambar styraciflua	565 (day) and 645 (night)	Basal area increment and taper	+19	Norby (1999)
		Dry mass calculated from basal area increment and taper	+32	Norby (1999)
Pinus taeda	Ambient +200 (24 h)	Basal area increment	+25	DeLucia *et al.* (1999)
Populus alba	550 (day)	d^2h	+64	Gielen *et al.* (2001)
Populus × *euramericana*	550 (day)	d^2h	+102	Gielen *et al.* (2001)
Populus nigra	550 (day)	d^2h	+99	Gielen *et al.* (2001)
Populus tremuloides	560 (day)	d^2h	+34	Karnosky *et al.* (2001) Isebrands *et al.* (2001)
Populus deltoides	560 (24 h)	d^2h	+6	Tognetti *et al.* (1999)
Populus hybrid	560 (24 h)	d^2h	+40	Tognetti *et al.* (1999)

10.2.4 CO_2/O_3 interactions

Globally, the concentrations of the greenhouse gases CO_2 and tropospheric O_3 are increasing at a rate of 1–2% per year (Mohnen *et al.*, 1993; Keeling *et al.*, 1995). There will surely be large areas of forest ecosystems exposed during the coming century to both elevated CO_2 and O_3. As these two gases tend to cause diametrically different responses – largely positive growth responses by elevated CO_2 (see reviews by Ceulemans and Mousseau, 1994; Körner, 1995; Norby *et al.*, 1999) and negative growth responses by elevated O_3 (see reviews by Barnard *et al.*, 1990; Chappelka and Samuelson, 1998; Matyssek and Innes, 1999) – and as they also act oppositely on whole-tree carbon allocation, which may have consequences for competitiveness and fitness (see Saxe *et al.* (1998) for a review of CO_2 responses and Matyssek and Innes (1999) for a review of O_3 responses; and see Fig. 10.11), it is very difficult to predict the responses of forest ecosystems to the combination of these two gases.

Early results from the Aspen FACE project suggest that the positive growth response induced by elevated CO_2 is largely lost when O_3 is present, even in relatively low doses (Isebrands *et al.*, 2000; Karnosky *et al.*, 2000). In fact, some aspen clones appear to have an increased susceptibility to O_3 when grown under elevated atmospheric CO_2 (Kull *et al.*, 1996). Significant interactions between CO_2 and O_3 have also been found at the Aspen FACE project for the degradation of epicuticular waxes (Karnosky *et al.*, 1999) and for the occurrence of various insect and disease pests.

10.3 Remaining key FACE/Forest research needs

Enrichment studies conducted so far using controlled environment chambers, branch bags, or open-top chambers have not enabled the prediction of responses of entire forest stands or ecosystems to changing CO_2 conditions. The failure to deal with specific scaling issues is another inevitable limitation of all these experimental studies. Therefore, new experiments had to be conducted at a larger scale (McLeod and Long, 1999). FACE studies can move beyond many of the limitations of open-top chamber experiments (Hendrey, 1992; Norby *et al.*, 1999): (i) the basic unit of response can be a stand or ecosystem rather than an individual plant or tree; (ii) the components of the plant–soil nutrient cycle are fully integrated; (iii) there can be a fully developed forest canopy; and (iv) different species can compete for resources.

Early growth-enhancement results from elevated atmospheric CO_2 studies at FACE sites suggest that the response of young (1–2-year-old) trees at the Aspen FACE and POPFACE sites is similar to that of 10–15-year-old trees at the Oak Ridge and Duke Forest FACE sites. Whether these trees will continue to show growth enhancement over time, or at what rate the enhancement will decline, are interesting research questions (Loehle, 1995; Ceulemans *et al.*, 1999; McLeod and Long, 1999). The fate of the carbon that cannot be accounted for in increased biomass production under elevated CO_2 also remains to be determined. Similarly, little is known about long-term nutrient cycling under elevated CO_2 (Andrews *et al.*, 1999), trophic interactions and plant–pest population dynamics, or interactions with other stresses.

However, the forests within FACE studies will not replicate the forest of 50–100 years in the future, as the plant material, soil development and land-use history will all be different, and a few small plots of forest cannot be truly representative of an entire region or forest type. Instead, it is appropriate to think of the FACE experiments as experimental systems for testing specific, well-defined hypotheses that will continue to guide the development of ecosystem models of long-term forest responses. As the scientific community awaits the results from FACE experiments, it must be emphasized that predicting long-term ecosystem responses from short-term FACE studies is a difficult challenge (Luan *et al.*, 1999) and patience and persistence of FACE projects are needed to address the long-term responses.

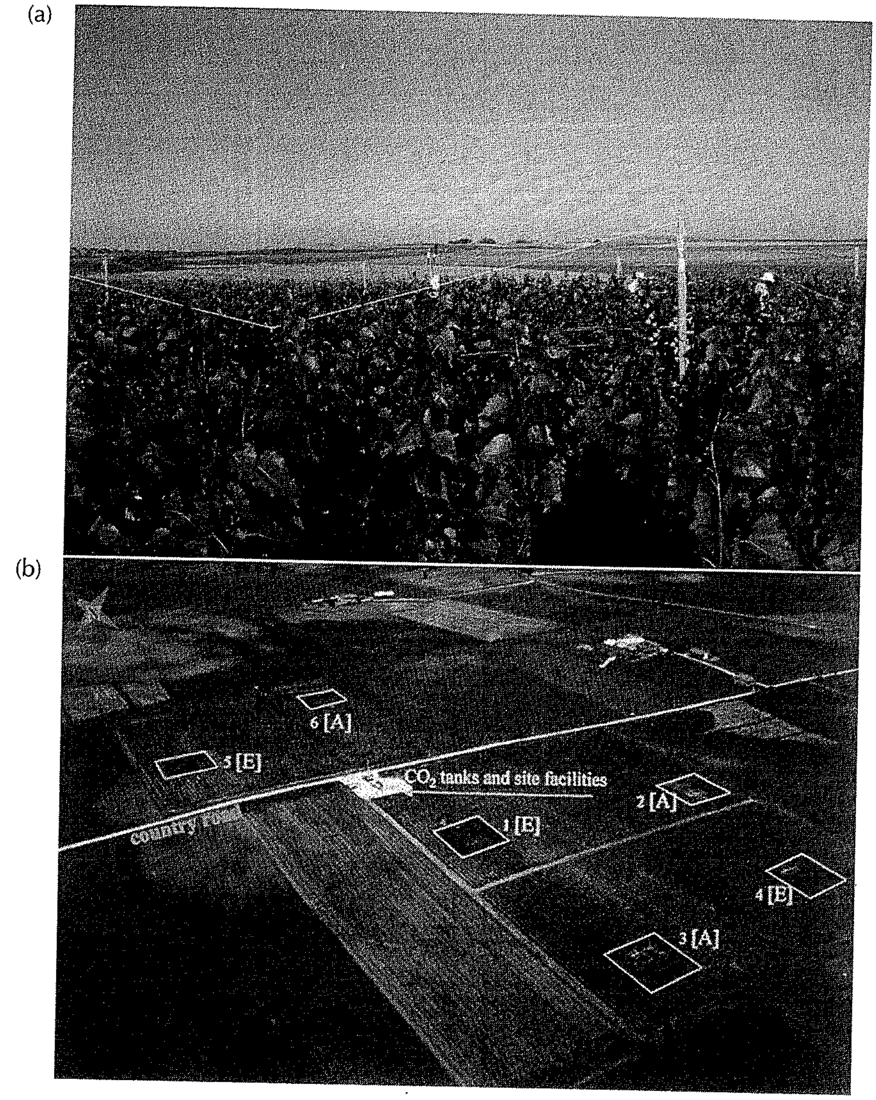
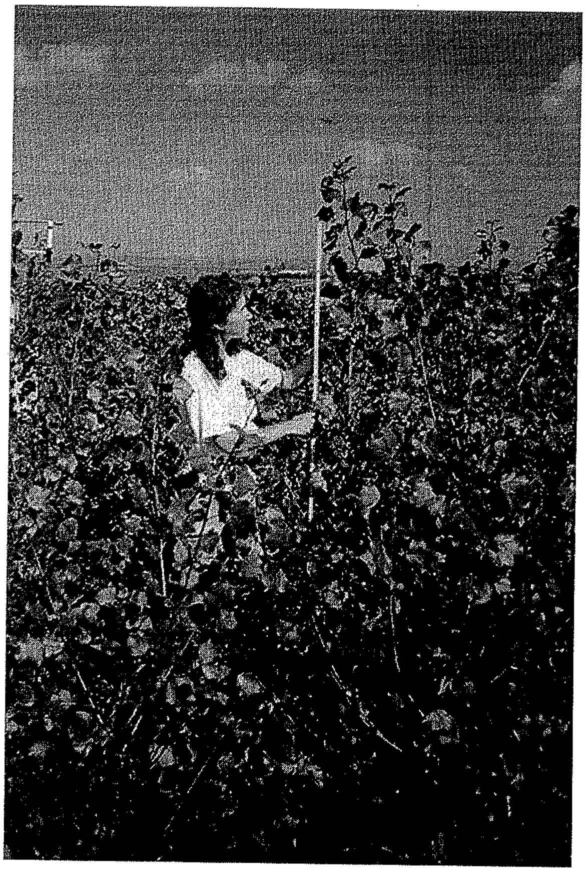


Fig. 10.7. The POPFACE project in Viterbo, Italy. In this project, undiluted CO_2 is emitted through flexible tubes (a). An overview of the POPFACE experiment reveals three elevated [E] atmospheric CO_2 rings and three ambient [A] rings (b). The hybrid poplars in this experiment are planted at close spacing (c, opposite), mimicking a typical poplar short-rotation intensive-culture farm.

(c)



10.4 Conclusions

Free-air CO_2 and/or O_3 enrichment (FACE) systems enable the study of the response of forest trees free of microclimatic artefacts and with natural boundary layers that determine the actual, physiologically relevant pollutant uptake. FACE systems are useful:

1. To study trees under the complex factorial scenarios of typical forest sites, taking into account that plants exposed to a wide array of biotic and abiotic interactions may behave quite differently relative to isolated individuals under controlled conditions;
2. To develop process-based quantitative risk assessment of mature trees and forest ecosystems; and
3. To improve and validate models developed to predict forest tree and forest ecosystem responses to elevated atmospheric CO_2 and/or other pollutants.

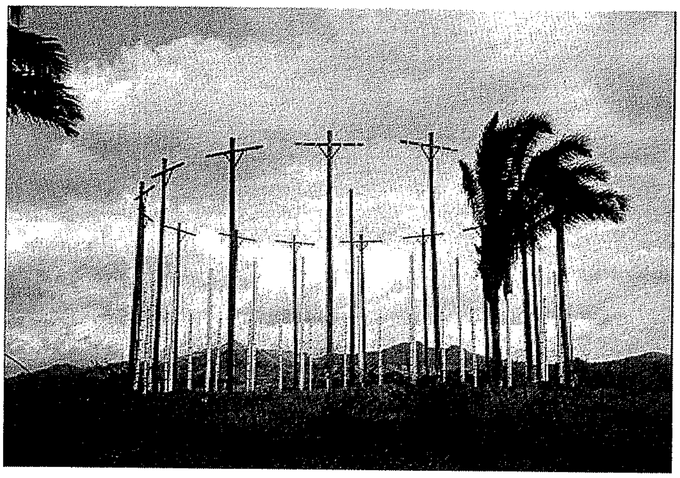


Fig. 10.8. The prototype FACE ring for the only tropical FACE/forest study, located in Central Panama.

Interesting and relevant results will continue to come out of these forest FACE studies in the near future, but some patience is needed before long-term complex ecosystem responses (both above and below ground) can be properly evaluated. We believe these FACE systems should be propagated worldwide in the major forested areas on ecologically and economically relevant forest ecosystems and representative tree species.

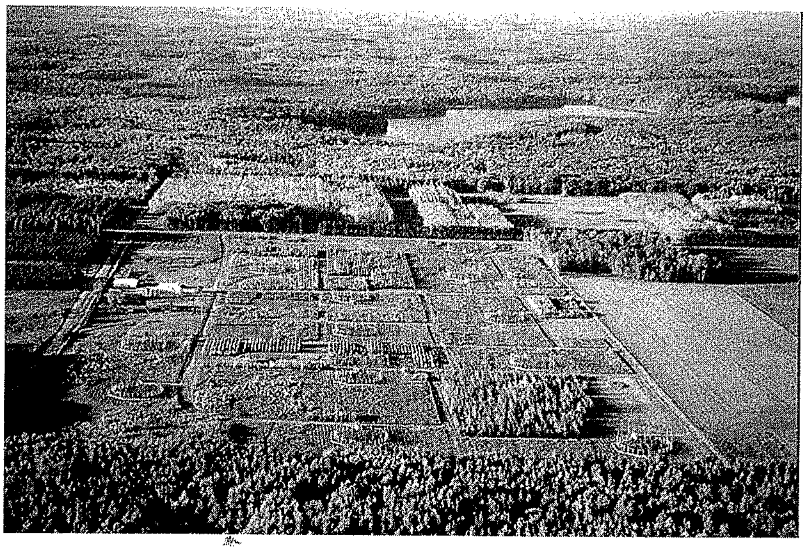


Fig. 10.9. The aspen FACE study site in northern Wisconsin is shown here. (a) An overview of the 12 rings over the 32 ha site; (b, opposite) a ground view of the site; and (c, opposite) the gas dispensing system for the 30 m diameter rings.

(b)

(c)

Not all important questions about forest response are amenable to FACE experiments, and other approaches need to be pursued simultaneously. The value of investigations in forests surrounding natural CO_2 springs has already been demonstrated (Hättenschwiler *et al.*, 1997), and despite their drawbacks (especially the problem of identifying an appropriate control site), the spring sites offer a unique opportunity to explore the long-term implications of the responses observed in shorter-term studies. In a similar fashion, examining trees

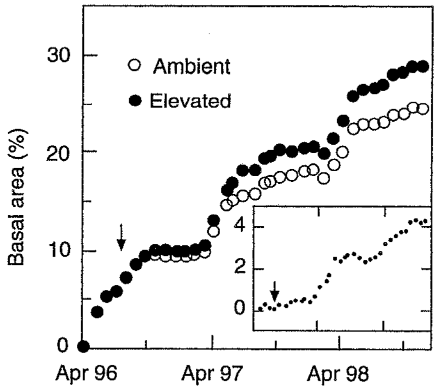


Fig. 10.10. Average basal area (± 1 SE) for loblolly pine (*Pinus taeda*) trees growing in ambient ($N = 102$) and elevated ($N = 101$) CO_2. Values are expressed as the percentage of the initial basal area. The insert shows the absolute difference between the basal area of elevated and ambient trees, and the arrows indicate when the CO_2 fumigation was initiated. (From DeLucia *et al.*, 1999.)

grown under natural pollutant gradients (as demonstrated by Karnosky *et al.*, 1999) can provide valuable insights into forest tree responses to pollutants. Environmental interactions that cannot currently be manipulated at the scale of a FACE experiment (e.g. air temperature) can still be explored in open-top chambers, although all of the scale-dependent limitations and shortcomings

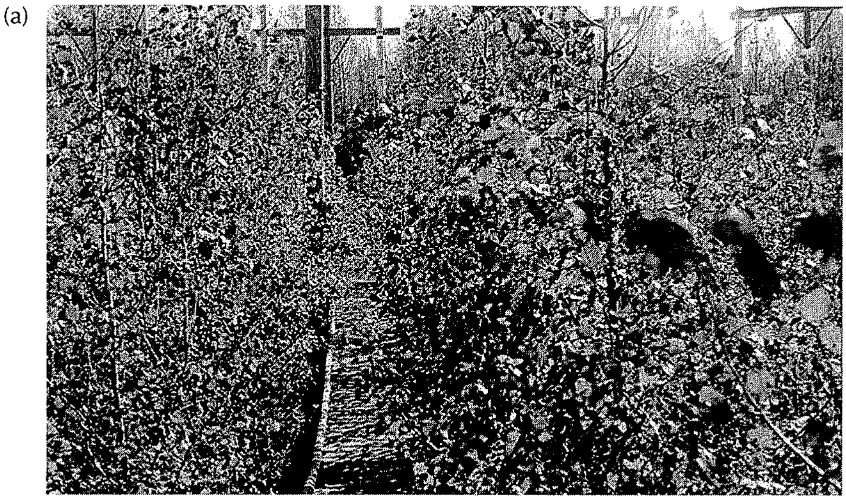


Fig. 10.11. Elevated atmospheric CO_2 and O_3 generally act positively and negatively for growth responses in forest trees. For example, at the FACE site, elevated CO_2 plots (a) hold their foliage 1–2 weeks later in the autumn than do elevated O_3 plots (b, opposite). Thus, it is very difficult to predict future response of forests exposed simultaneously to elevated CO_2 and O_3.

(b)

must be recognized. Similarly, many mechanistic studies are best conducted under conditions of extreme environmental control, such as growth chambers and phytotrons. We view these FACE systems as one more technique available to forest scientists examining the impacts of greenhouse gases on forest trees, and the only experimental approach available for studying effects of changing atmospheric chemistry on intact, forest ecosystems.

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