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Forest Atmosphere Carbon Transfer and Storage (FACTS–II) The Aspen Free-air CO_2 and O_3 Enrichment (FACE) Project: An Overview

R.E. Dickson, K.F. Lewin, J.G. Isebrands, M.D. Coleman, W.E. Heilman, D.E. Riemenschneider, J. Sober, G.E. Host, D.R. Zak, G.R. Hendrey, K.S. Pregitzer, and D.F. Karnosky

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I. EXECUTIVE SUMMARY

Human activities have modified regional environments for thousands of years. These activities are now increasing at such a rate and over such large areas that there is genuine concern that not only regional environments, but also the global environment will be affected. The Intergovernmental Panel on Climate Change (IPCC) has concluded that over the past 150 years, significant climate change has taken place and that human activities have significantly contributed to these changes. Indicators of past atmospheric conditions and climate change found in Greenland and Antarctic ice cores and in deep sea sediments show that for the past 160,000 years, global temperatures and the concentrations of atmospheric greenhouse gases were closely correlated. During this long period, atmospheric carbon dioxide concentrations rarely exceeded 300 $\mu l l^{-1}$ and commonly ranged between 180 and 250 $\mu l l^{-1}$. Since the middle of the 19th century, however, atmospheric carbon dioxide (CO_2) concentrations have increased from about 280 $\mu l l^{-1}$ to the current 360 $\mu l l^{-1}$, largely from burning fossil fuels (coal, oil, gas) and from burning and converting forests to grasslands and croplands. Average global temperature has also increased by about 0.5^{o}C. At the current rate of increase, concentrations of atmospheric CO_2 and other greenhouse gases are expected to double in the next 100 to 150 years, and global temperatures are expected to increase by 1^{o} to 4^{o}C. Regional responses may be even greater. In addition, there may be significant changes in agricultural and natural ecosystem productivity, biogeochemical cycling, and availability of water resources, as well as increases in weather extremes, shifts in plant hardiness zones, and a rise in sea level. Such changes in regional and global climate could have severe impacts on world economies and public health.

Forest and woodland ecosystems contain a major portion of the world's biomass and are significant contributors to biosphere-atmosphere CO_2 cycling and carbon storage. Information on forest responses to different factors associated with climate change will be critical

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for fine-tuning global climate change scenarios and modeling efforts. Of particular importance is tree response to tropospheric CO_2 and ozone (O_3), both of which are increasing in concentration and will continue to do so well into the future. Increasing atmospheric CO_2 concentrations have the potential to increase forest productivity because photosynthetic rates are limited by current CO_2 concentrations. In contrast, O_3 is a phytotoxic gas that is reactive at very low concentrations. Current ambient O_3 concentrations over large portions of the Eastern United States may already be decreasing growth and productivity of O_3-sensitive tree species. Because elevated CO_2 exposure may increase photosynthetic rates and resistance to other environmental stresses, it is generally believed that increasing atmospheric CO_2 concentrations will offset the detrimental effects of increasing O_3 concentrations. However, results of recent studies on the interacting effects of CO_2 and O_3 are contradictory; some show amelioration, others show no effect of increased CO_2 or even an increase in the O_3 response.

There is a huge amount of research information about the response of plants to increased CO_2 concentrations and increased O_3 concentrations, but relatively little information about CO_2 and O_3 interactions. Most of this information comes from studies on plants in greenhouses, growth chambers, or field enclosures. Chamber effects are always present in these systems, and the size of these systems usually require experiments with potted seedlings or small plants. Pots restrict root growth, and seedling response may differ from that of large trees. Long-term studies (3 to 4 years) of larger plants in open-top chambers more closely approximate natural conditions, but chamber effects are still present. Because of these limitations, results from extrapolating chamber responses of seedlings to large trees in forest stands are questionable.

The need for large-scale field experiments to evaluate the response of plants growing in the open under natural conditions has been recognized for some time. However, the technology to control the concentration of CO_2 and other trace atmospheric gases throughout large areas of big plants has only recently been developed. Free-Air Carbon dioxide Enrichment (FACE) systems provide the experimental means to control CO_2 concentrations over large areas (up to 30-m-diameter circles) without appreciable changes in other environmental factors. Within the last 10 years, FACE systems have been developed for agricultural crops, tall-grass prairie, desert scrub and grasses, southern pines, southern hardwoods, and northern hardwoods. The overall goal is to study the response of widely different ecosystems to elevated CO_2 and other trace gases and to minimize duplication of effort with these large and expensive experimental systems. FACE systems, although expensive to install and operate, provide economies of scale such that costs per unit of ground area or of experimental plant material are significantly lower than those of other enrichment systems, such as open-top chambers. In addition, the large experimental area and large amount of plant material provide opportunities for cooperation among investigators with widely different expertise and for studies that range in scale from cellular to ecosystem processes. Our Aspen FACE project at Rhinelander, Wisconsin, is unique because of its large size (twelve 30-m diameter rings), the combination of both CO_2 and O_3 exposures, exposure of the plant material to elevated CO_2 and O_3 from the seedling stage to maturity, and the inclusion of three tree species (trembling aspen, paper birch, and sugar maple) and five aspen clones known to differ in response to CO_2 and O_3.

This publication:

- Briefly reviews the rationale for studying the response of forest stands to increasing concentrations of CO_2 and O_3;
- Describes the development of FACTS-II, the Aspen FACE project;
- Outlines the experimental variables currently being measured;
- Credits our research and funding partners;
- Describes the CO_2 and O_3 delivery and control systems; and
- Examines some of the database management and statistical considerations involved.

We hope that this publication will be the primary reference source for the Aspen FACE Project and that it will be useful for all our research partners in publishing their individual research results.

II. INTRODUCTION

A. Atmospheric Carbon Dioxide

Changes in atmospheric chemistry and the potential changes in global climate resulting from anthropogenic inputs to the atmosphere may have serious ecological, economic, and social consequences. These changes and consequences were carefully documented in recent reports by the Intergovernmental Panel on Climate Change (IPCC 1996, 1998). Because these changes will not be uniform over the world and specific regional changes will have greater degrees of uncertainty (Shriner and Street 1998), vigorous debates have arisen concerning all aspects of projected global change. Certain facts and projections, however, leave little room for debate (Mahlman 1997). Atmospheric CO_2 concentration varied over the past 160,000 years, and global temperatures were closely correlated with changes in CO_2 concentration (fig. 1) (Barnola *et al.* 1995, Raynaud *et al.* 1993). During this long period, atmospheric CO_2 concentrations rarely exceeded 300 μll^{-1} and commonly ranged between 180 and 250 μll^{-1}, although recent evidence indicates that short-term increases may have been present since the last ice age (Wagner *et al.* 1999). In the last 150 years, however, CO_2 concentrations have increased from about 280 μll^{-1} to the current 360 μll^{-1}, largely from burning fossil fuels (coal, oil, gas) and burning biomass from forests and grasslands (fig. 2) (Friedli *et al.* 1986, Keeling *et al.* 1995). These anthropogenic sources produce about 7 Pg carbon per year (1 Pg = 10^{15}g) of which roughly 2 Pg is absorbed by oceans, 2 Pg is stored by land vegetation, and about 3 Pg remains in the atmosphere (Amthor 1995, Schimel *et al.* 1996). This 3 Pg of carbon is equivalent to about 1.5 μll^{-1}, which is the current annual rate of CO_2 increase in the atmosphere. Depending on anthropogenic CO_2 emissions in the future, the CO_2 concentration in the atmosphere will probably double to over 700 μll^{-1} within the next 100 to 150 years. This doubling of the CO_2 concentration will have significant effects on global and regional climate and on plant growth and competition. Global mean temperature has increased about 0.5^{o}C within the last 100 years as CO_2 concentrations have increased from 290 to 360 μll^{-1} (fig. 3) (Schneider 1990). Doubling of the current atmospheric CO_2 concentration may increase global temperatures by 1^{o} to 5^{o}C and elevate regional temperatures even more (Mahlman 1997, Schimel *et al.* 1996). Despite vigorous argument as to the extent of the greenhouse effect, radiative forcing of global temperature from increasing concentrations of atmospheric gases is a physical fact, and there is no reason to expect that global temperature will not track CO_2 concentrations in the future, just as it did in the past (fig. 1).

B. Carbon Dioxide Effects on Plants

Plants and soils of terrestrial ecosystems are major global carbon pools. Although estimates differ considerably and all plant and organic components may not be included in these estimates (see Amthor 1995), terrestrial plants contain 490 to 760 Pg carbon and soil organic matter contains 1,500 to 2,100 Pg carbon, compared to 760 Pg carbon in the atmosphere. Annually, plants photosynthetically fix about 15 percent of the atmospheric carbon pool, while respiration and decomposition return similar amounts of CO_2 to the atmosphere (note the annual cycling of CO_2 in the atmosphere in figure 2). Because of uncertainties in the estimation of soil organic carbon pools, and the effect of increasing atmospheric CO_2 concentration on these pools, the amount of soil organic carbon is a major concern in calculations of global carbon budgets. Because most soil organic carbon originates from living plants, differences in plant response to increasing atmospheric CO_2 concentrations and the proportion of fixed carbon entering root and soil pools are very important research topics.

Carbon dioxide at twice the current atmospheric concentration has the potential to increase productivity in many agricultural crops and forest trees by 20 to 50 percent (Ceulemans and Mousseau 1994, Eamus and Jarvis 1989, Wittwer 1990). Increased productivity is expected because photosynthetic rate in most plants is limited by current atmospheric CO_2 concentrations, and increasing CO_2 concentrations also may increase water-use efficiency, nitrogen fixation, and mycorrhizal symbiotic effectiveness. In addition, increased CO_2 concentrations may ameliorate other environmental stresses (e.g., low nutrient availability, mild water stress, and O_3 impacts). Photosynthetic rates of C_3 plants may increase by 10 to 100 percent with a doubling of atmospheric CO_2 concentration (Kirschbaum 1994). However, leaf and whole-tree canopy responses will differ, and the actual photosynthetic

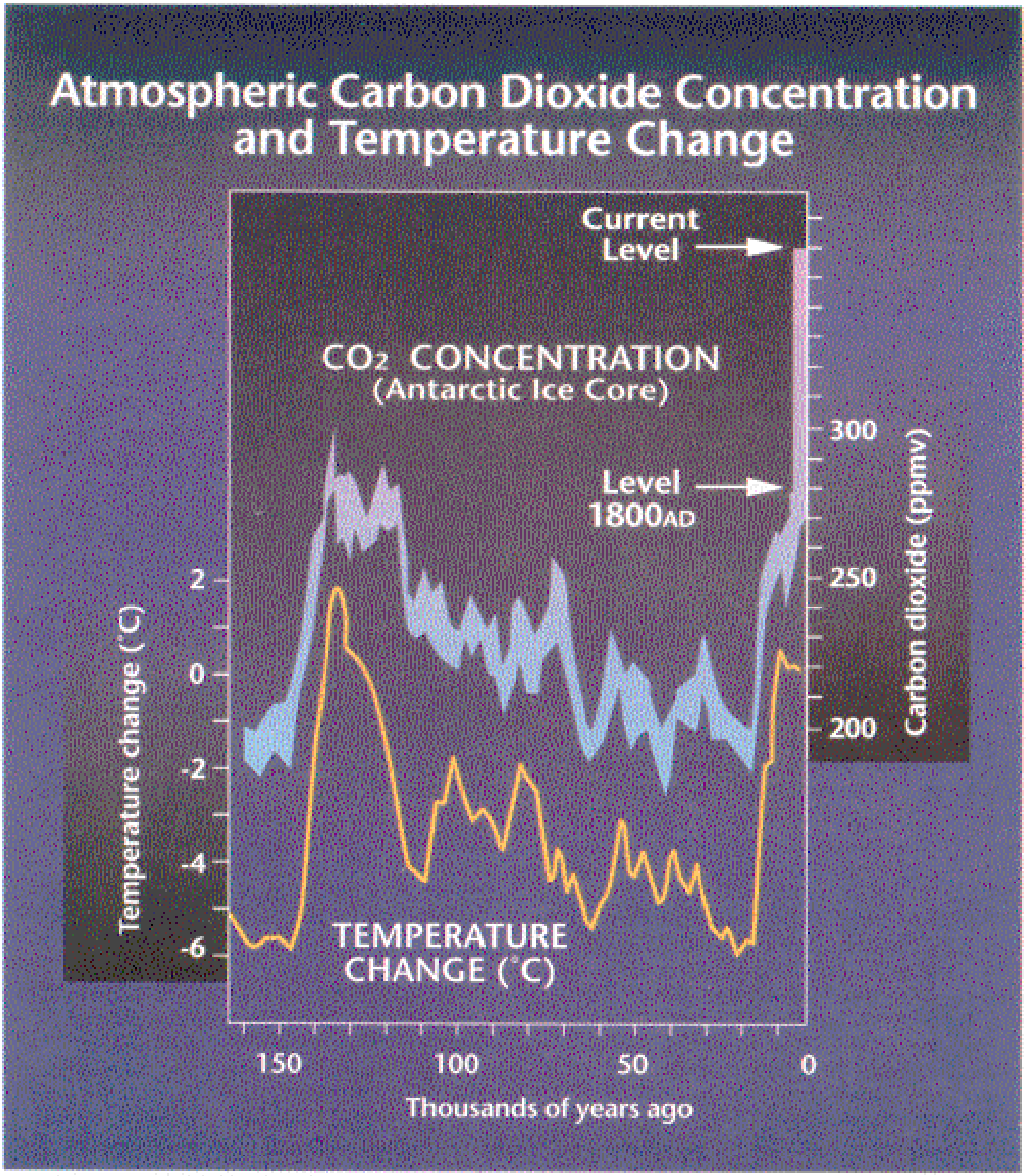


Figure 1.—Atmospheric CO_2 concentrations and global temperatures. Fluctuations in CO_2 concentrations and global temperature were closely correlated for the past 160,000 years (Anonymous 1997).

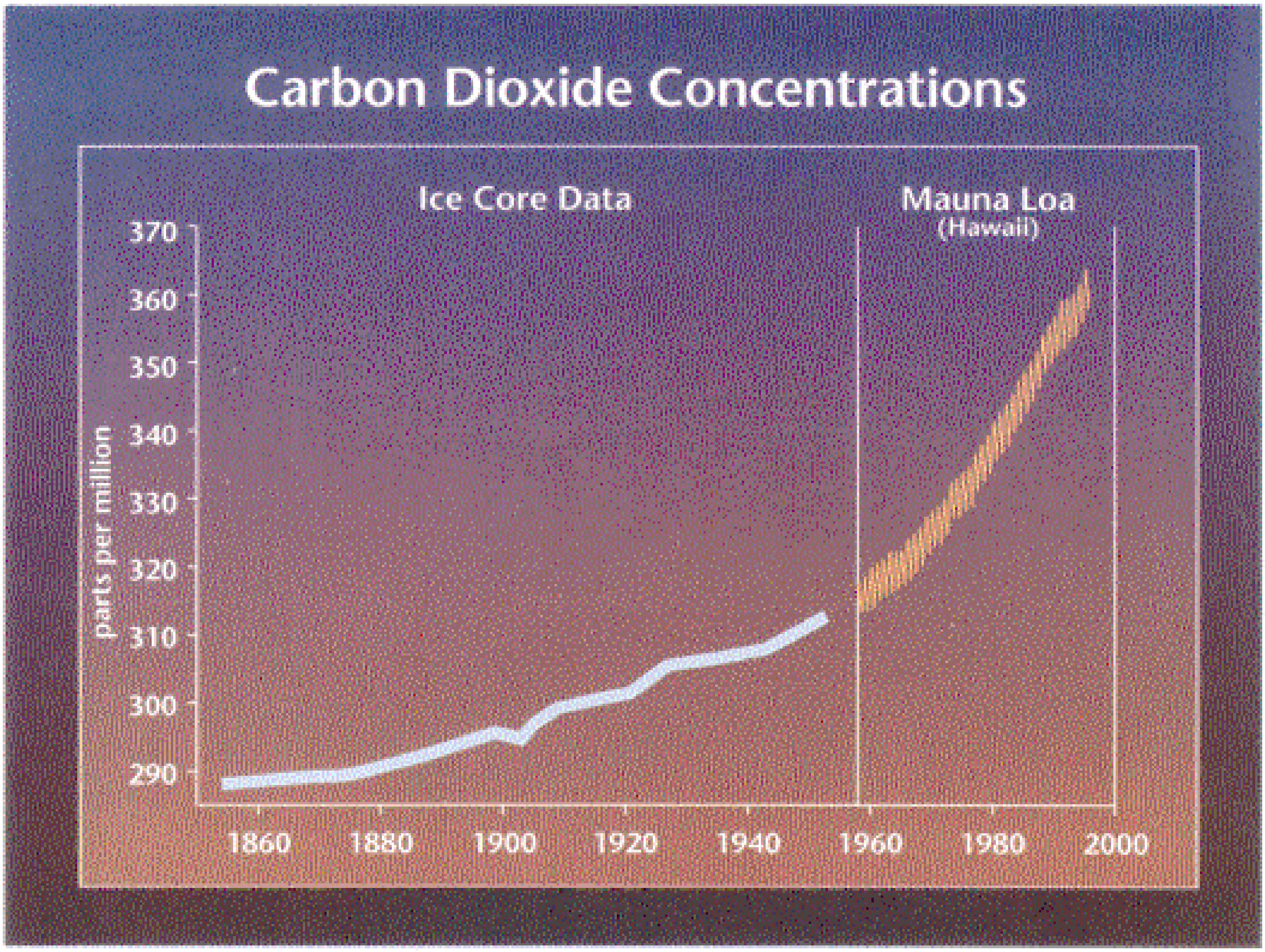


Figure 2.—*Atmospheric CO_2 concentration change during the past 150 years. CO_2 concentrations have increased from about 280 µl l[-1] to the current 360 µl l[-1]. Seasonal cycles in CO_2 concentration (1960 to date) result from seasonal uptake and release of CO_2 by vegetation in the Northern Hemisphere (Anonymous 1997).*

response is influenced by many other environmental factors such as nutrient and water supply, temperature, and light. Many studies show that plants may acclimate (decrease photosynthetic rates) in response to elevated CO_2 concentration (Gunderson and Wullschleger 1994, Sage 1994). Such acclimation may result from down-regulation or a decrease in Rubisco and other photosynthetic enzymes (Jacob *et al.* 1995, Webber *et al.* 1994) or from active feedback inhibition induced by the accumulation of nonstructural carbohydrates in leaves (Foyer 1988, Webber *et al.* 1994). Most CO_2 enrichment studies use plants or tree seedlings grown in pots in controlled environments or open-top chambers for relatively short periods. It is not at all clear how much photosynthetic acclimation will take place in trees growing in the field for long periods of time under natural conditions. No acclimation was found for yellow poplar (*Liriodendron tulipifera* L.) and white oak (*Quercus alba* L.) after three growing seasons in open-top chambers (Norby *et al.* 1996), for large loblolly pine (*Pinus taeda* L.) trees in the field (Ellsworth 1999, Teskey 1997), or for field-grown cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.) (Pinter *et al.* 1996).

Increased photosynthetic response to elevated CO_2 should be reflected in increased plant

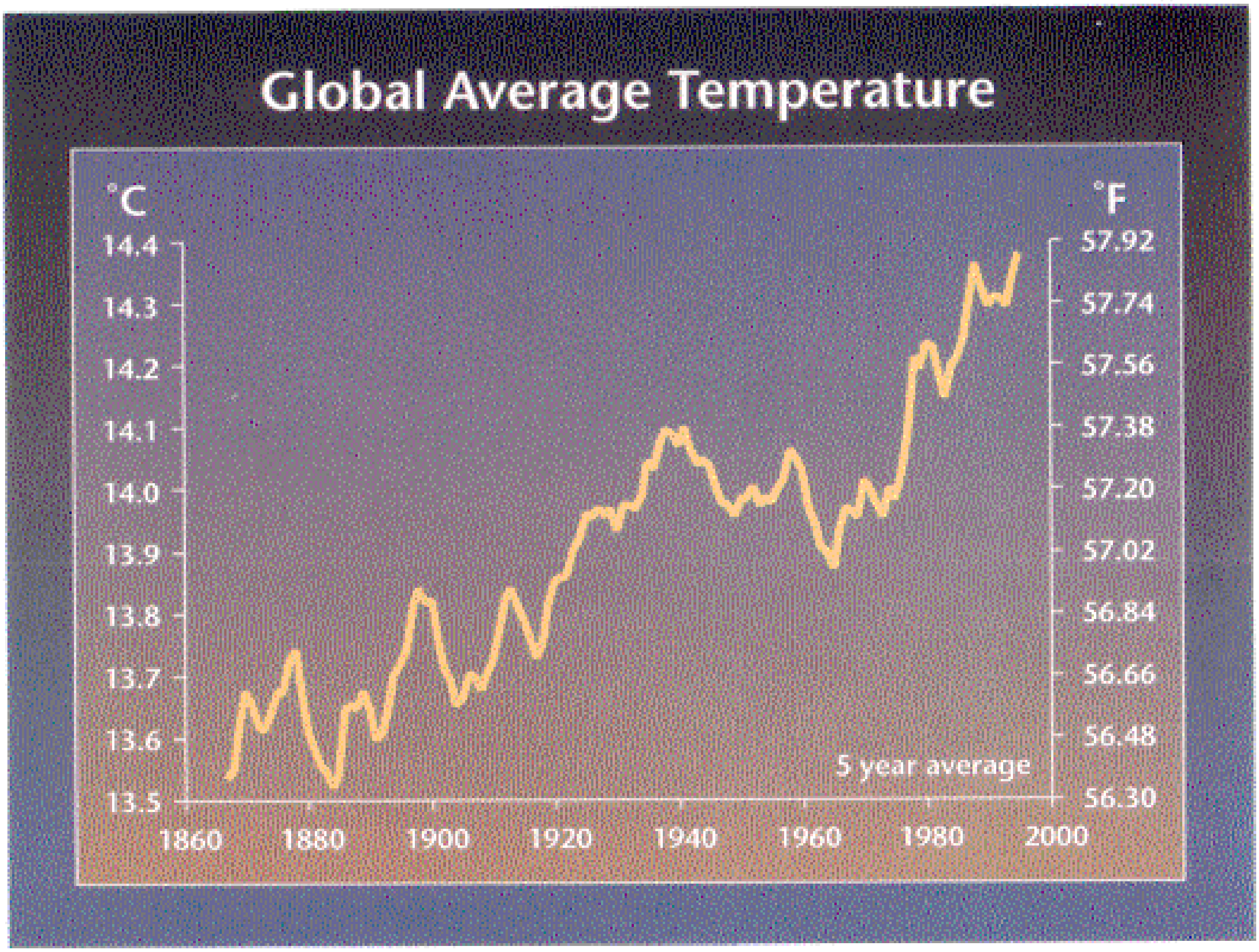


Figure 3.—*Average global temperature change during the past 100 years. Global temperature increased by about 0.5°C (1°F) during the 20th century (Anonymous 1997).*

growth because excess photosynthate is available and respiration rates often decrease (Wullschleger *et al.* 1994). In fact, an increase in plant biomass may be a more sensitive indicator of positive response than photosynthesis because small increases in carbon fixation may compound over time. In a review of tree response to CO_2, Eamus and Jarvis (1989) found that average tree growth increased by about 40 percent (range 20 to 120 percent) with increased CO_2 concentration. However, individual species responses can differ widely. Norby *et al.* (1996) found no increase in dry weight of yellow poplar seedlings after 4 years' exposure to plus 300 $\mu l l^{-1}$ CO_2, but white oak dry weight increased by 134 percent. These growth responses cannot be projected to large trees or forest stands because increased growth rates may not be sustained in larger trees as canopies close and competition within stands increases (Loehle 1996, Norby *et al.* 1999).

It is important to distinguish between relative and absolute response to increasing CO_2. Relative response, the proportional increase in productivity compared to the ambient control [(elevated-ambient/ambient) x 100], is often greater under conditions that limit growth (e.g., water stress, low nutrients, and high temperature) and can also be greater for slower growing species (Ceulemans *et al.* 1996, Radoglou and Jarvis 1990). Under such conditions, elevated CO_2 may partially alleviate the environmental stress responsible for decreasing growth. Absolute response (i.e., elevated-ambient) is often greater than relative response under optimal conditions for growth and for faster growing species. Consideration of both responses is important because relative response may provide information on the interactions between increasing CO_2 and other environmental variables, while absolute response provides information on potential productivity increases in highly productive systems that are major factors in global net primary production and carbon storage. Information on carbon flux and carbon storage in productive forest ecosystems, such as northern hardwoods and aspen stands, is critical for understanding forest responses to global climate change.

To further complicate the picture, an increase in photosynthesis or net carbon fixation may not be reflected in aboveground increases in dry weight because changes in carbon allocation may favor belowground components such as roots, mycorrhizae, and other rhizosphere organisms (Curtis *et al.* 1996, Hodge 1996, Jones *et al.* 1998, Körner and Arnone 1992, Loehle 1996). However, inputs to soil organic carbon pools should be positively related to increased productivity or increased carbon fixation. Quantitative estimates of changes in soil carbon storage are problematic because little information is available about changes in the various input components (e.g., litter, fine root production and turnover, carbon allocation to soil organisms, and direct exudation into the rhizosphere) (Metting *et al.* 1999). Although difficult, these questions about productivity and the fate of fixed carbon can be answered with long-term field experiments with elevated CO_2 and natural ecosystems. Such information is critical for the development of carbon budgets and potential responses of terrestrial ecosystems.

Increased atmospheric CO_2 concentrations not only may increase growth, but also impact plant populations and community interactions. Many studies show that the physiological response of individual species treated in isolation does not reflect their response in competitive situations (Ackerly and Bazzaz 1995, Bazzaz *et al.* 1996, Groninger *et al.* 1995, Körner 1996, Mooney *et al.* 1991, Ward and Strain 1999). The majority of plants in both temperate and tropical ecosystems, and essentially all forest tree species, use the C_3 pathway of photosynthetic carbon fixation (Bowes 1993). Growth response to elevated CO_2 of C_3 plants should be greater than response of C_4 plants because photosynthetic rates of C_3 plants are limited by current CO_2 concentrations, while C_4 plants are near photosynthetic saturation (Bazzaz 1990, Bowes 1993, Kirschbaum 1994). However, some C_4 plants may respond to elevated CO_2 with increased photosynthetic rates and increased growth (LeCain and Morgan 1998, Ziska *et al.* 1999). An increase in growth of C_3 plants compared to C_4 plants could have significant consequences for species composition in ecosystems containing both kinds of plants. Superior growth of C_3 plants is by no means certain because other environmental factors (e.g., water stress, higher temperatures) may favor the growth of C_4 plants (Amthor 1995). Potential C_3/C_4 responses are widely discussed in the literature, but ecosystems composed largely of such competitors are of minor importance in global net primary production. Ecosystems dominated by C_3 species, such as temperate and tropical forests, are far more important in both area and response to increasing CO_2 than other biomes (Wilsey 1996), and competition among C_3 species is more significant when changes in populations and loss of biodiversity are considered. Competitive advantages among C_3 species are difficult to predict because different growth strategies, reproductive strategies, and allometric plasticity interact with CO_2 and other environmental stresses (Ackerly and Bazzaz 1995, Farnsworth and Bazzaz 1995, Groninger *et al.* 1995, Hunt *et al.* 1993, Mousseau *et al.* 1996). Indeterminate or semideterminate flushing species capable of rapid growth in rich environments may respond more rapidly to increasing CO_2 than determinate species. In contrast, determinate species with more conservative growth strategies may be favored on nutrient poor or droughty sites. Vegetative response, however, may not be a good predictor of competitive ability because reproductive responses may also be important for determining species fitness with changing climates (Farnsworth and Bazzaz 1995).

C. Atmospheric Ozone

Atmospheric O_3 is largely confined to two distinct layers of the atmosphere, the troposphere, and the stratosphere. The troposphere extends upward 10 to 15 km (6 to 10 miles) from the Earth's surface. The stratosphere extends upward about 40 km above the troposphere. These two parts (they are not distinct layers because there is much mixing between them) of the atmosphere are defined by their temperature gradients. Temperature in the troposphere decreases with altitude from about

18°C at the Earth's surface to –56°C at the boundary with the stratosphere (the tropopause). In contrast, temperature in the stratosphere increases with altitude from –56°C to about 0°C at the top of the stratosphere (the stratopause) (Seinfeld and Pandis 1998). These temperature gradients repeat in the mesosphere and thermosphere, which are two more layers that extend the atmosphere outward by an additional 100 km (60 miles). To put the entire atmosphere into perspective, it is but a thin (90 to 160 km thick) shell around the Earth that measures about 1 percent of the diameter of the Earth (12,900 km). Tropospheric thickness is about 0.1 percent of the diameter of the Earth, and most humans (and other animals) live in the lowest 5 km (3 miles) of the troposphere. This thin envelope of gas, which we use as a dumping ground for all manner of pollutants, is all that protects us, our crops and animals, and other natural ecosystems from rapid death from intense ultraviolet (UV) radiation from the sun, and it is all that maintains a livable surface temperature.

The temperature gradients in the troposphere and stratosphere are very important global climate factors. The troposphere contains about 80 percent of the mass in the atmosphere and is very chemically active. It contains water (liquid and gas), other gases (nitrogen, oxygen, carbon dioxide, volatile organic compounds, nitrogen oxides, ozone, and other trace gases) and particulate matter (smoke, dust, soot, salt particles), all of which provide many potential chemical reactions and sites for chemical reactions. The troposphere is characterized by a temperature gradient that decreases with height at about 6°C km^{-1}, corresponding to a temperature decrease of about 70° to 90°C between the Earth's surface and the tropopause. This temperature decrease with height in the troposphere, coupled with episodes of significant surface heating, leads to rapid vertical movement of air parcels. Furthermore, vertical movement of air and horizontal temperature gradients in the troposphere also lead to horizontal winds and turbulent mixing. Particularly important in energy, gas, and particulate movement is the turbulent Earth-surface atmosphere boundary layer that fluctuates diurnally and extends upward from a few meters at night to several kilometers during the day when high surface temperatures increase turbulent vertical mixing (Dabberdt *et al.* 1993). In contrast, the stratospheric temperature gradient, which increases with height, inhibits vertical mixing, except in the tropopause. This temperature gradient in the stratosphere results largely from the production of O_3 and absorption of UV radiation by O_3.

Differences in tropospheric and stratospheric O_3 concentrations are cause for much public confusion. Ozone in the troposphere (bad O_3—harmful to plants and animals) ranges from 10 to 80 nll^{-1} in pristine areas and may increase to 150 to 200 nll^{-1} in certain urban areas (Miller *et al.* 1994, Taylor 1994). In contrast, O_3 in the stratosphere (good O_3—protects plants and animals by absorbing harmful UV radiation) increases rapidly from about 40 nll^{-1} in the upper troposphere to over 10 μll^{-1} (10,000 nll^{-1}) in the lower stratosphere, then decreases to near zero concentration in the upper stratosphere (Seinfeld and Pandis 1998). The stratosphere contains about 90 percent of the atmospheric O_3, and the peak concentrations in the lower stratosphere result from the interactions of O_3 precursors and UV radiation. Catalytic destruction of O_3 by halogens and nitrogen oxides in the stratosphere has created the seasonal ozone holes over the poles and decreased mid-latitude O_3 concentrations in the last 30 years by about 15 percent (Prather *et al.* 1996, Seinfeld and Pandis 1998).

The production and destruction of O_3 in the atmosphere is extremely complex and cannot be covered in any detail here. (For discussion of O_3 chemistry and various control strategies, see Derwent and Davies 1994, Krupa and Manning 1988, Milford *et al.* 1994, Seinfeld and Pandis 1998, Wolff 1993). In the simplest of terms, O_3 is produced in the presence of sunlight at wavelengths less than 424 nm and various nitrogen, oxygen, organic, and inorganic compounds. Nitrogen oxides are the major catalysts in the formation or destruction of O_3. For example, nitrogen dioxide in the presence of sunlight (hv) may produce the following reactions:

$NO_2 + \underline{hv} = NO + O$
$O + O_2 = O_3 + M$

and the back reaction that destroys O_3

$O_3 + NO = NO_2 + O_2$

M may be N_2, O_2, or any other molecule that catalyzes or stabilizes O_3 formation. Many other volatile organic compounds (VOC's) and nitrogen oxides (NO_x) react with sunlight and O_2 to form O_3. Although a large proportion of VOC's may come from natural vegetation in some areas (Chameides *et al.* 1988), most VOC's and NO_x's result from human activity.

D. Ozone Effects on Plants

Diurnal background O_3 concentrations in pristine areas currently range from 20 to 40 $nl\,l^{-1}$ during the growing season but may increase to 60 to 80 $nl\,l^{-1}$ for short periods of time. Summer daytime values of 50 to 70 $nl\,l^{-1}$ (seasonal 70 to 100 $\mu l\,l^{-1}$-h) are common over much of the Eastern and Southeastern United States (Hogsett *et al.* 1997, Taylor 1994) and Southeastern Canada (fig. 4) (Fuentes and Dann 1994). Measurements from mountain stations in Western Europe indicate that O_3 concentrations are increasing by about 1 to 2 percent per year (fig. 5) (Marenco *et al.* 1994). More pessimistic estimates based on potential regional NO_x production (Eastern U.S., Europe, China, and Japan) indicate that O_3 concentrations may triple within the next 30 to 40 years (Chameides *et al.* 1994). These projections are consistent with the estimated tripling of the average growing-season O_3 concentration over

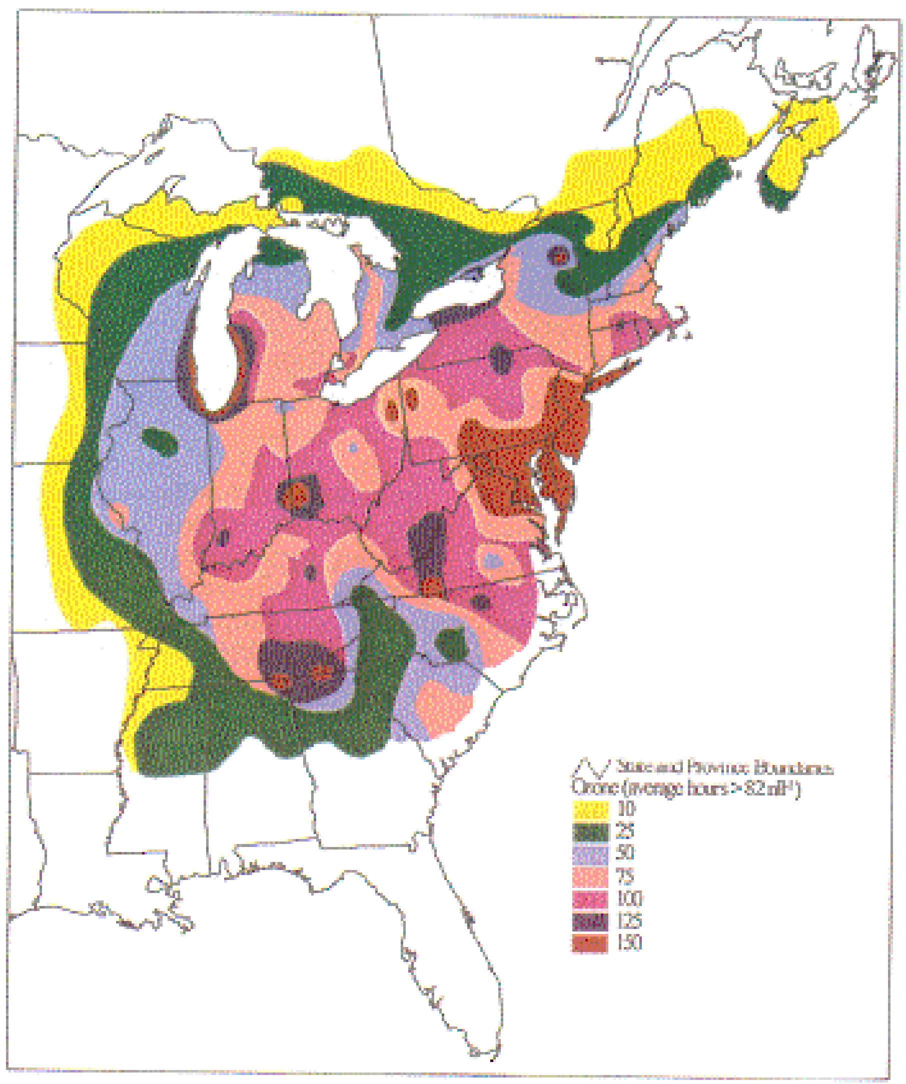


Figure 4.—*Distribution of O_3 over Eastern North America. Color contours show the spatial distribution of the average number of hours (1986 to 1993) with O_3 concentrations greater than 82 $nl\,l^{-1}$. Figure redrawn from Dann and Summers (1997).*

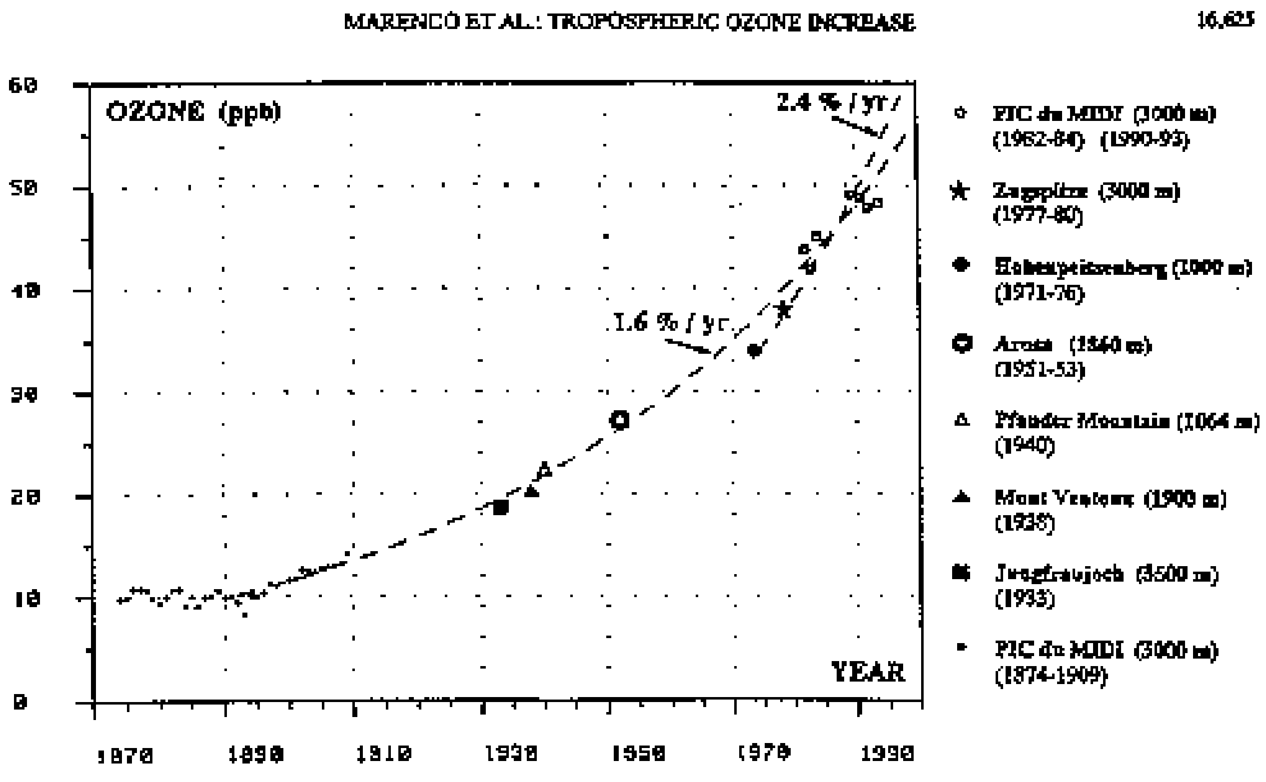


Figure 5.—*Increasing O_3 concentrations in the troposphere during the 20th century. Measurements from Pic du Midi, Southwestern France, and other western European high altitude (average 2200m) stations. Data indicate that the ambient yearly average O_3 concentrations at these relatively pristine stations are increasing by 1.6 to 2.4 percent per year. Figure redrawn from Marenco* et al. *1994.*

the last century in some regions (Finlayson-Pitts and Pitts 1997, Marenco *et al.* 1994, Taylor *et al.* 1994, Volz and Kley 1988). Growing season tropospheric O_3 concentrations may be increasing in some regions, but whether or not there are worldwide or continental increases is controversial (Lefohn *et al.* 1992). Long-term trends in O_3 concentrations are a function of the time period and data selected for analysis, and the method of analysis. There is currently no standard method for trend analysis. Nevertheless, tropospheric ozone is a potent atmospheric pollutant that causes widespread damage to plants. Damage estimates based on current O_3 concentrations indicate billions of dollars in agriculture crop losses annually (Adams *et al.* 1989) and significant impacts on forest tree productivity (Pye 1988, Taylor *et al.* 1994). However, decreases in yield of forest trees from O_3 impacts are not well documented. Estimates for major regional forest ecosystems are highly variable, but on average range from a 2- to 15-percent yearly decrease in growth (de Steiguer *et al.* 1990). Estimates for sensitive species such as aspen (*Populus tremuloides* Michx.) and black cherry (*Prunus serotina* Ehrh.) range from a 14- to 33-percent loss in yearly productivity over 50 percent of their range in years of high O_3 impact (e.g., 1988 and 1995 were years with high summer O_3 concentrations) (Hogsett *et al.* 1997). After one season of O_3 exposure, we have found decreases in total dry weight as great as 45 percent in sensitive aspen clones (Karnosky *et al.* 1996) and 46 percent in *Populus* hybrids (Dickson *et al.* 1998).

Response to atmospheric pollutants varies among species and genotypes within species. Current damage estimates are usually based on broad species classifications such as northern hardwoods or southern pines (de Steiguer *et al.* 1990), or on average species responses based on seedling populations (Pye 1988). However, these estimates do not account for the potentially large impact on sensitive genotypes within a species. Sensitive genotypes have been identified in both agricultural crops and forest trees (Ballach 1997, Karnosky *et al.* 1996, Kozlowski and Constantinidou 1986, Taylor 1994, Wittwer 1990).

E. Carbon Dioxide and Ozone Interactions

Because elevated CO_2 exposure usually increases photosynthetic rates, decreases stomatal conductance, and increases resistance to other environmental stresses, it is generally believed that increasing atmospheric CO_2 concentrations will offset the detrimental effects of increasing O_3 concentrations (Allen 1990). Results of recent studies on the interacting effects of CO_2 and O_3, however, are contradictory. Studies with several different species show that exposure to elevated concentrations of CO_2 may counteract decreases in photosynthesis and growth caused by O_3 (Dickson *et al.* 1998, McKee *et al.* 1995, Mortensen 1995, Volin and Reich 1996). In contrast, other studies show that elevated CO_2 did not protect against O_3 (Balaguer *et al.* 1995, Barnes *et al.* 1995). Most of these studies involved average responses of general plant populations and did not examine genotypic responses. However, there is a strong genotypic response in *Populus* to both CO_2 (Ceulemans *et al.* 1996) and O_3 exposure (Karnosky *et al.* 1996, 1998; Kull *et al.* 1996). In the latter study, added CO_2 did not ameliorate the detrimental effects of O_3 on photosynthetic parameters of two aspen clones differing in sensitivity to O_3. In fact, the O_3-tolerant clone appeared more sensitive to O_3 (Kull *et al.* 1996). Even in cases where added CO_2 may counteract the negative impact of O_3 and increase growth back to the control level, the added O_3 negated increased growth from CO_2 (Dickson *et al.* 1998).

F. The Importance of FACE Systems

It has been recognized for some time that existing information and experimental techniques are not adequate for developing accurate predictions of ecosystem response to global climate change (Mooney *et al.* 1991). There is a critical need for large-scale experiments that examine all of the interactions and feedbacks involved in total ecosystem response to increasing CO_2 (Körner 1996, Lee and Jarvis 1995, Mooney and Koch 1994) and other atmospheric gases such as O_3 (Heck *et al.* 1998). It is even more important that these large-scale experiments involve ecosystems, such as temperate forests, that are major factors in global carbon cycles and sustainable economic systems.

The large amount of data about CO_2 responses generated with individual species in restricted experimental settings has provided much useful basic biological and physiological information. Short-term physiological measurements on individual species, however, cannot be used to predict long-term species or ecosystem response. Long-term measurements of individual species response in competitive environments are necessary for predicting ecosystem response. While ecosystem responses are very complex and highly variable in space and time (Bazzaz *et al.* 1996, Körner 1996, Mooney 1996), techniques are available to study species response within a community or ecosystem context. Open-top chambers are useful for studying communities of relatively small plant species, but chamber effects are always present and complicate application to natural systems (McLeod and Long 1999, Olszyk *et al.* 1986a, b). Open-air field systems for exposure of different agricultural crops with air pollutants such as sulfur dioxide (SO_2) developed rapidly during the 1980's (McLeod *et al.* 1985, 1991) and were soon applied to forest tree species (McLeod and Skeffington 1995). These concepts were rapidly adopted for CO_2 exposure of both agricultural crops and natural ecosystems (Hendrey 1992, Hendrey and Kimball 1994). These FACE systems (Free Air Carbon dioxide Enrichment) are large enough that the many complex interactions of water, gas, and energy fluxes; biological responses; and biogeochemical cycles can be studied simultaneously to determine realistic gas exchanges and resource balances. Such studies are necessary if we are to move from understanding individual plant responses to understanding ecosystem responses to global climate change.

The rationale for FACE technology, development of exposure systems, performance analysis, relative costs, and early plant responses were recently reviewed and discussed in some detail (Allen 1992, Hendrey 1992, Hendrey and Kimball 1994, Hendrey *et al.* 1999, Kimball 1992, Koch and Mooney 1996, Lewin *et al.* 1994, McLeod and Long 1999, Mooney 1996, Nagy *et al.* 1994, Pinter *et al.* 1996). The FACE technology initially developed in 1986 and deployed in agricultural field trials in 1988 and 1990 by George Hendrey's group at

Brookhaven National Laboratory has been used in several agricultural systems around the world. However, only three FACE experimental systems involve forest trees. The FACTS-I (Forest-Atmosphere Carbon Transfer and Storage) experiment is in a loblolly pine (*Pinus taeda* L.) plantation in the Duke University forest near Durham, North Carolina. The prototype of this system was tested in 1993 and began operation in 1994 (Ellsworth *et al.* 1995). FACTS-II is a FACE system designed to examine the interacting effects of elevated CO_2 and O_3, alone and in combination, on the productivity, competitive interactions, and carbon and nitrogen fluxes in a regenerating northern hardwood ecosystem. This system, near Rhinelander, Wisconsin, was constructed in 1995 and 1996 and tested in 1997, and it began full operation in May 1998. The FACTS-II, Aspen FACE system is designed to test the response of aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), and sugar maple (*Acer saccharum* Marsh.) during development from seedling to mature tree. Additional FACE systems are being developed at Oak Ridge National Laboratory in a sweet gum (*Liquidambar styraciflua* L.) stand and in a plantation of hybrid poplars (*Populus* spp.) near Viterbo, Italy.

To be effective, FACE experiments must continue for enough time to clearly separate response to treatment from response to seasonal environmental changes. Experiments should continue for two to three life cycles of annual plants, 3 to 5 years for perennial grasslands, and 10 to 15 years or longer for forest stands (Hendrey 1992). FACE systems provide a technique for treatment of large areas (over 700 m^2 for each ring at Rhinelander) essentially free of any chamber or changed microclimatic effect, in which large numbers of plants (660 trees per ring at Rhinelander) can interact with their associated micro- and macro-biological agents such as mycorrhizae and insect herbivores in a community response that closely simulates a natural ecosystem. Initial construction costs and yearly operating costs for a large FACE system are very high, but because of the large area and large number of plants involved, costs per square meter or per plant are much less than with other exposure systems such as open-top chambers (Kimball 1992). For example, the area of one ring at Rhinelander is about 100 times the area of a standard open-top chamber (700 m^2 vs. 7 m^2). Such large areas of treated plant material produce huge economies of scale for both scientific output and plant material production costs.

G. Unique Characteristics of the Aspen FACE Project at Rhinelander

The Aspen FACE project has four characteristics that set it well apart from all other forest FACE projects:

1. It is large. Twelve 30-m diameter rings are spaced 100 m apart within a fenced 32-ha site. Each ring contains 700 m^2 of treatment area for a total experimental area of 8,400 m^2 (2,100 m^2 per treatment).
2. The Aspen FACE project is the only one in the world that combines CO_2 and O_3 exposures. The experiment is a full factorial design with three control rings, three CO_2 rings, three O_3 rings, and three CO_2 + O_3 rings.
3. The trees will be exposed to the CO_2 and O_3 treatments throughout the experiment from small, 1-year-old plants to mature trees. Exposures throughout the lifetime of the plants and associated organisms contrast with both the Duke and Oak Ridge FACE programs, which began CO_2 enrichments on large trees that had developed under ambient CO_2 concentrations.
4. The experiment contains three tree species common to the Lake States forests (trembling aspen, paper birch, sugar maple), including five clones of aspen that differ in response to CO_2 and O_3. Thus, the experiment contains a wide range of species and genotypes that can be assessed for their response to treatment and competitive interactions.

H. Multidisciplinary Approach

Research designed to answer questions about ecosystem physiology provides the opportunity for and, in fact, requires collaboration of scientists from many disciplines who normally do not work closely together. The simultaneous study of individual plant and leaf responses (photosynthesis, stomatal conductance, and carbon allocation) in addition to whole system responses (soil CO_2, stand water loss, energy exchange, and nitrogen dynamics) requires expertise in many areas. The large number of factors in ecosystem physiology that must be considered (see, for example, table 3.1 in Körner 1996 and fig. 2.1 in Mooney 1996) if CO_2 responses, water and energy fluxes, and soil processes are adequately addressed, requires such teamwork. Currently, at the Aspen FACE site, 30 scientists are involved in various aspects of CO_2, O_3, plant, insect, soil, and meteorological interactions, and there is room for many more. In addition, the site provides an opportunity for training and hands-on research experience for research associates, undergraduate students, and graduate students in a wide variety of research areas. The economy of scale, and the close cooperation and sharing of mutually useful data will increase scientific output per unit of research time and funds spent.

I. Aspen: Genetic Variation and Economic Importance

Quaking or trembling aspen is the most widely distributed native tree species in North America. It ranges east to west from Newfoundland and Labrador to Alaska and south to the mountains of Mexico. A similar species, the Eurasian aspen (*Populus tremula* L.), ranges from Britain across Europe and Asia to the Pacific Ocean (Barnes and Han 1993). Thus, two very similar species of aspen circle the entire globe. Not only is trembling aspen the widest ranging tree species, it may also contain the oldest and largest individual plant known (Mitton and Grant 1996). A single clone in Utah is estimated to weigh more than 6 million kg and be more than 1 million years old. Trembling aspen (and perhaps also *P. tremula*) may be the most genetically variable plant ever studied (Barnes and Han 1993, Mitton and Grant 1996). Such genetic diversity allows aspen to survive from sea level to tree line in a variety of plant communities, from quite dry to very wet sites, and from shrubs 0.5 m tall to trees 30 m tall. Response to atmospheric pollutants also differs among genotypes. Ozone-sensitive and ozone-tolerant clones have been found, and these clones are very useful for studying growth and mechanistic responses to O_3 exposure (Karnosky *et al.* 1996) and as bioindicators of regional pollutants (Ballach 1997, Karnosky *et al.* 1999). Aspen is also an excellent indicator of ecological integrity and forms communities of high biodiversity. Many birds and animals depend on aspen ecosystems for survival (Alban *et al.* 1991, Kay 1997). Aspen stands in the West provide many benefits, such as forage for livestock and wildlife, watershed protection, recreational sites, aesthetics, landscape diversity, and wood fiber (Bartos and Campbell 1998). Aspen-birch stands are major components of the Lake States forests, making up about 5.3 million ha or 16 percent of the commercial forest lands. The Northeast contains an additional 1.3 million ha. Aspen-birch and maple make up about one-third of the growing stock in the Lake States region and provide about 70 percent of the roundwood harvest (Hackett and Piva 1994, Piva 1996). In addition, these productive forests play an important role in carbon sequestration (Alban and Perala 1992). Aspen-birch-maple stands are also important aesthetic components of northern forests, and their vibrant yellow, gold, and red leaves are major contributors to the fall color parade. Given the major importance of these northern forest ecosystems, any impact on productivity and biodiversity from atmospheric pollutants will have severe ramifications throughout the Eastern U.S.

III. GOALS AND OBJECTIVES

Our long-term goal is to examine the interacting effects of elevated CO_2 and O_3, alone and in combination, on the resultant productivity, sustainability, competitive interactions, and carbon and nitrogen fluxes in a regenerating, northern hardwood ecosystem under field conditions over its life history.

The specific objectives of the Aspen FACE project are to:

1. Develop a reliable CO_2 plus O_3 delivery system
2. Examine the interacting effects of elevated CO_2 and O_3, alone and in combination, on aspen, sugar maple, and paper birch:
   a. growth, survival, productivity, and sustainability
   b. carbon and nitrogen allocation and sequestration
   c. competitive interactions among species and genotypes
   d. stress tolerance as regulated by foliar defense compounds
   e. response to insects, diseases, and other stresses

3. Examine ecosystem processes such as litter decomposition, mineral weathering, and carbon and nutrient cycling
4. Parameterize and validate an ecophysiological process model of growth and development to scale individual tree responses to the ecosystem level.

IV. EXPERIMENTAL METHODS

A. Site Description

Location

The Aspen FACE site (32 ha) is located in northern Wisconsin near Rhinelander, Wisconsin (long. 45.6°, lat. 89.5°), on the Harshaw Experimental Farm of the USDA Forest Service. The legal description of the site is SW80, sect. 21, T37N, R7E, Cassian Township, Oneida County, Wisconsin, USA. The site is old agricultural land that was farmed for potatoes and small grains for more than 50 years. The Forest Service purchased the Farm in 1972 for use as a short-rotation intensive culture and mixed-genetics forest research facility. About 80 percent of the 32-ha Aspen FACE site was planted with different hybrid poplar clones and some larch from 1976 to 1990. The remaining area reverted to old-field vegetation. All poplar and larch plantings were cleared from the site in 1996 and 1997, all stumps in the ring areas were pulled, and the rings were disked and planted in rye covercrop in the summer of 1996. Aspen clones, paper birch seedlings, and sugar maple seedlings were planted in the ring areas in early June 1997.

Soil Properties

The Aspen FACE site is level to gently rolling Pandus sandy loam (mixed, frigid, coarse loamy Alfic Haplorthod). The sandy loam topsoil (about 15 cm thick) grades into a plowlayer-clay loam accumulation layer (about 30 cm thick) and then grades back into a sandy loam, stratified sand, and gravel substratum. Occasional clay layers at 30 to 60 cm are found throughout the field, primarily in the northern 16 ha. As a basis for future comparisons, soils within each ring were analyzed in 1997 (table 1). Soil properties differed little among the 12 rings. Of all soil properties measured, only

Table 1.—*Summary of soil properties for the Aspen FACE site for 1997*[1]*. (See detailed table of soil properties in the appendix.)*

Treatment	Control	CO_2	O_3	$CO_2 + O_3$
Soil texture				
% sand	55.1 (3.58)	53.9 (2.60)	58.3 (1.98)	55.0 (2.94)
% silt	36.1 (3.15)	37.7 (2.30)	35.3 (3.74)	37.4 (2.68)
% clay	8.8 (1.31)	8.4 (1.04)	6.4 (1.87)	7.7 (0.72)
Gravimetric moisture content				
(-0.3 bar)	0.163 (0.0215)	0.171 (0.0220)	0.159 (0.0077)	0.166 (0.0091)
(-15 bar)	0.060 (0.0049)	0.066 (0.0147)	0.060 (0.0093)	0.053 (0.0045)
(WHC)	0.102 (0.0183)	0.105 (0.0097)	0.099 (0.0016)	0.114 (0.0052)
D_b (Mg/m^3)	1.27 (0.119)	1.31 (0.089)	1.31 (0.084)	1.43 (0.075)
pH	5.50 (0.263)	5.45 (0.596)	5.57 (0.530)	5.68 (0.425)
NH_4^+-N (µg N/g)	1.03 (0.772)	0.94 (0.450)	0.85 (0.294)	0.56 (0.202)
NO_3^--N (µg N/g)	15.06 (11.392)	15.24 (4.149)	11.83 (5.410)	11.98 (14.748)
Total C (%)	1.54 (0.267)	1.68 (0.327)	1.59 (0.321)	1.31 (0.200)
Total N (%)	0.12 (0.016)	0.14 (0.027)	0.12 (0.028)	0.10 (0.019)
C:N	12.88 (0.779)	12.40 (0.435)	13.58 (0.702)	12.84 (0.654)

[1] Values are treatment means with standard deviations listed in parentheses.

total C and N (%) were significantly different among treatments (Percent C and N averaged slightly higher in the CO_2 rings than in the CO_2 + O_3 rings). There were no significant differences among replications or gradients across the field.

B. Study Design

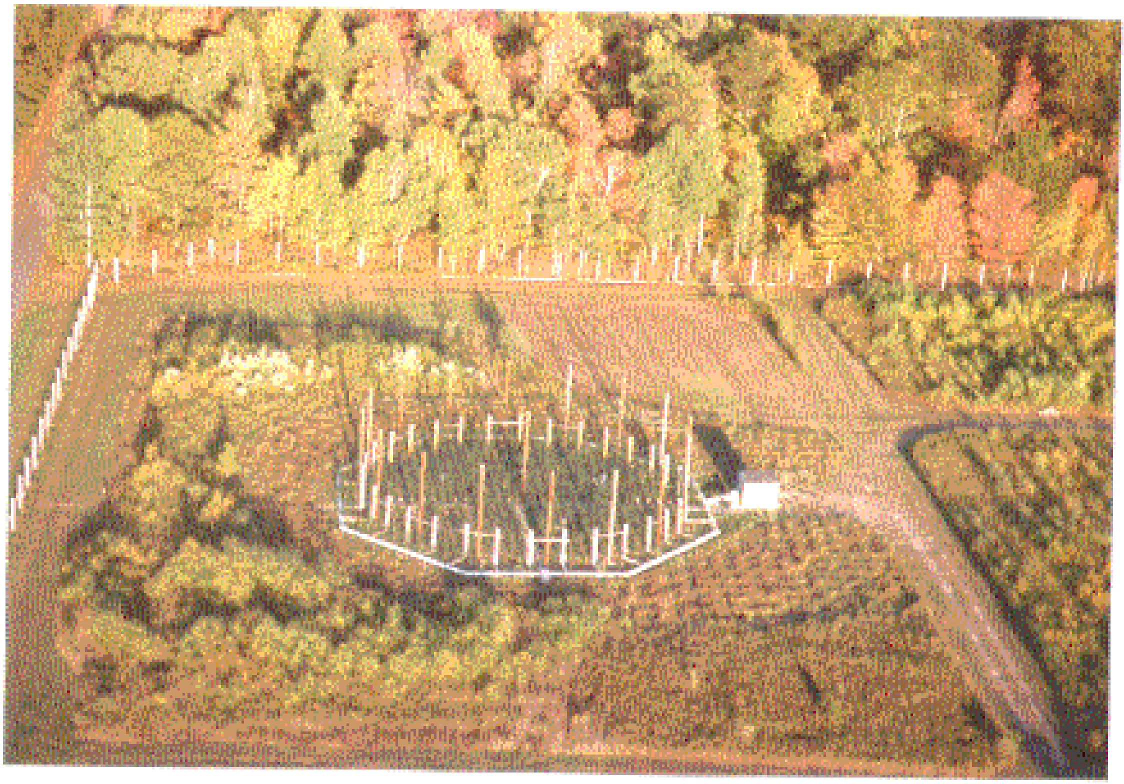
The FACTS-II; Aspen FACE study is located within a fenced 32-ha field (fig. 6A) on the Harshaw Experimental Farm near Rhinelander, Wisconsin. The study contains 12 individual treatment rings (fig. 6B,C), which are 30 m in diameter and spaced 100 m apart to minimize between-ring drift of CO_2 and O_3. The experiment is a full-factorial design with three control rings (no added CO_2 or O_3), three CO_2 rings, three O_3 rings, and three CO_2 + O_3 rings. The treatments are replicated three times in each of three blocks from north to south across the site (fig. 7). Each ring is divided into east and west halves, and the west half is further subdivided into north and south quadrants (fig. 8). The eastern half contains five aspen clones numbered 8L, 42E, 216, 259, and 271 (E216 and E271 were grown with elevated CO_2 from rooting to out planting). The aspen clones are planted at 1-m spacing as randomized pairs within the eastern half of the ring, and the rings are individually randomized so that clonal position within each ring is unique. The northwest quadrant of each ring is planted (1 m x 1 m) with alternating sugar maple and aspen clone 216, and the southwest quadrant is planted (1 m x 1 m) with paper birch and aspen clone 216. Each row is marked with a number from west to east (1 through 29) and a letter or letter combination from north to south (AD, AC through Z) so that each tree has a unique pair of coordinates. For example, 15-C is clone 216, the northern member of that clonal pair (fig. 8). Complete identification would require the ring number, e.g., 1,4 (CO_2 + O_3) (fig. 7), and the number-letter coordinates. In addition, each tree is tagged with a unique number ranging from 1 to 7920.

A

B

Figure 6.—*Aspen FACE Project, Harshaw Experimental Farm, Rhinelander, Wisconsin. A. Aerial view of the 32-ha site, 1998. B. & C. Individual FACE treatment rings.*

C



C. Plant Material, Propagation, and Planting

Plant materials for the Aspen FACE Project were chosen to represent a developing northern hardwood stand common in the northern Lake States of the United States. A completely representative stand would be difficult to develop because of the large number of species commonly found on such sites. Therefore, aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), and sugar maple (*Acer saccharum* Marsh.) were chosen because these species are common competitors on these northern hardwood sites, and are of major economic and aesthetic importance. Together, aspen, birch, and maple make up about one-third of the growing stock in the Lake States and provide over 70 percent of the pulpwood harvested in this area (Piva 1996). The birch and maple seeds came from local northern Michigan sources, and the five aspen clones were selected based on previously determined variable response to O_3 and CO_2. Three aspen clones (216, 259, 271) were selected for their differing sensitivity to O_3 (Karnosky *et al.* 1996), and two aspen clones were selected for early (42E) and late (8L) leaf fall and differing response to elevated CO_2 (Kubiske *et al.* 1998).

The aspen clones (numbered 8L, 42E, 216, 259, 271) were vegetatively propagated from greenwood cuttings (Karnosky *et al.* 1996). Stock plants of the selected clones were grown in 6-l pots with trickle irrigation and time-release fertilizer (3 g/l, Sierra Blend Osmocote 17-6-12 plus minors, 3-4 month formulation, Scotts-Sierra Horticultural Products, Co., Maysville, OH 43041) to achieve rapid growth. Actively growing greenwood shoot cuttings 10 to 15 cm long were trimmed to about 30 cm^2 leaf area and soaked for 15 minutes in Benelate fungicide (2 tbsp/gal water). Then the base of the cut stem was dipped in rooting hormone mixed with fungicide (Rootone 3, Dragon Corp., Roanoke, VA 24019) and inserted into flats containing wet peat-perlite (1:3 v:v) soil mix. Flats with cuttings were placed in an enclosed mist chamber for 6 weeks or until roots appeared on the bottom of the flat. Humidity in the chamber was adjusted to retain moisture on the leaf surface. Following root initiation, cuttings were hardened-off on an

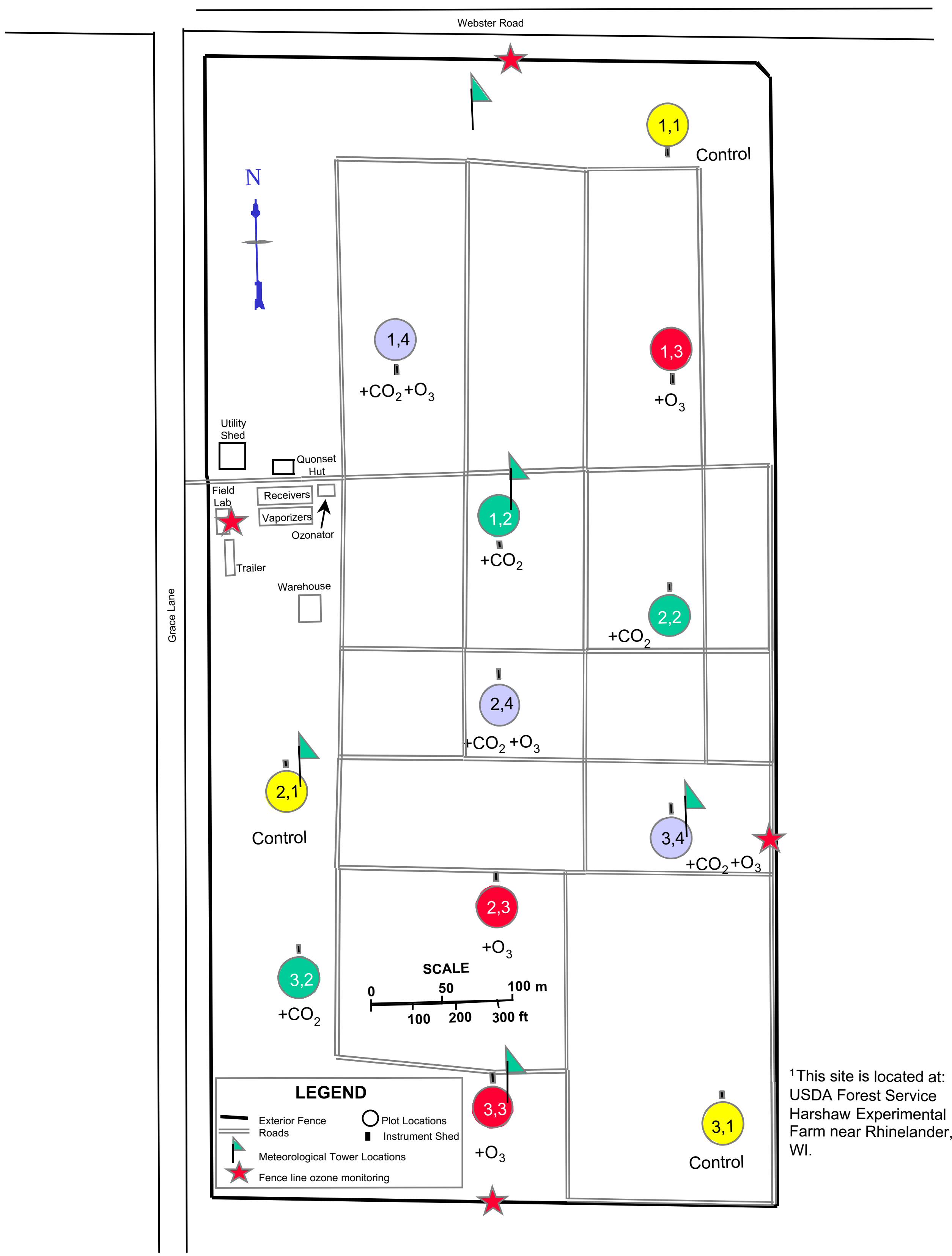


Figure 7.—*Aspen FACE project, location of the individual treatment rings and facilities within the 32-ha site.*

FACE Ring Map

Harshaw Experimental Farm, Rhindander, Wisconsin

N

W

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
AD												A	M	A
AC										M	A	M	A	M
AB								A	M	A	M	A	M	A
AA							A	M	A	M	A	M	A	M
A					M	A	M	A	M	A	M	A	M	A
B					A	M	A	M	A	M	A	M	A	M
C				A	M	A	M	A	M	A	M	A	M	A
D			A	M	A	M	A	M	A	M	A	M	A	M
E			M	A	M	A	M	A	M	A	M	A	M	A
F		M	A	M	A	M	A	M	A	M	A	M	A	M
G		A	M	A	M	A	M	A	M	A	M	A	M	A
H	A	M	A	M	A	M	A	M	A	M	A	M	A	M
I	M	A	M	A	M	A	M	A	M	A	M	A	M	A
J	A	M	A	M	A	M	A	M	A	M	A	M	A	M
L	A	B	A	B	A	B	A	B	A	B	A	B	A	B
M	B	A	B	A	B	A	B	A	B	A	B	A	B	A
N	A	B	A	B	A	B	A	B	A	B	A	B	A	B
O	B	A	B	A	B	A	B	A	B	A	B	A	B	A
P		B	A	B	A	B	A	B	A	B	A	B	A	B
Q		A	B	A	B	A	B	A	B	A	B	A	B	A
R		B	A	B	A	B	A	B	A	B	A	B	A	B
S			B	A	B	A	B	A	B	A	B	A	B	A
T				B	A	B	A	B	A	B	A	B	A	B
U					B	A	B	A	B	A	B	A	B	A
V					A	B	A	B	A	B	A	B	A	B
W						A	B	A	B	A	B	A	B	A
X							A	B	A	B	A	B	A	B
Y									B	A	B	A	B	A
Z												B	A	B
	1	2	3	4	5	6	7	8	9	10	11	12	13	14

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
42E	42E	E271	271												AD
42E	42E	E271	42E	271	E216	E216									AC
E216	271	8L	42E	42E	259	42E	8L	E271							AB
E216	271	8L	42E	42E	259	42E	8L	E271	259						AA
E216	8L	216	42E	271	E271	216	271	216	259	E271					A
E216	8L	216	8L	271	E271	216	271	216	259	E271	8L				B
216	271	271	8L	259	E271	271	E271	42E	259	E216	8L				C
216	271	271	216	259	E271	271	E271	42E	E271	E216	259	E216			D
8L	271	216	216	42E	42E	42E	E216	8L	E271	216	259	E216	8L		E
8L	271	216	E271	42E	42E	42E	E216	8L	216	216	259	E216	271		F
259	42E	216	E271	216	E216	8L	259	E271	216	E216	259	E216	271		G
259	42E	216	271	216	E216	8L	259	E271	216	E216	271	271	E271	8L	H
E271	42E	E216	271	271	8L	8L	E216	E216	216	8L	271	271	E271	271	I
E271	42E	E216	8L	271	8L	8L	E216	E216	8L	8L	259	259	216	271	J
E271	259	E271	8L	259	259	271	271	259	8L	8L	259	259	216	259	K
E271	259	E271	42E	259	259	271	271	259	271	8L	E271	259	E271	259	L
8L	42E	216	42E	216	E216	E271	271	E216	271	216	E271	259	E271		M
8L	42E	216	E216	216	E216	E271	271	E216	42E	216	271	E271	259		N
E271	259	216	E216	E216	259	271	E216	E216	42E	8L	271	E271	259		O
E271	259	216	42E	E216	259	271	E216	E216	216	8L	42E	42E	259		P
8L	271	271	42E	E271	8L	E271	E271	216	216	259	42E	42E	259		Q
8L	271	E216	259	E271	8L	E271	E271	216	216	259	259	8L			R
271	259	216	216	8L	216	42E	E216	259	216	E271	259	8L			S
271	259	216	42E	8L	216	42E	E216	259	42E	E271	E216				T
E216	8L	42E	42E	E216	E271	8L	42E	271	42E	E216					U
E216	8L	42E	216	E216	E271	8L	42E	271	E271						V
42E	E216	216	216	271	216	271	8L	E271							W
42E	E216	216	8L	271	216	271	8L								X
E216	216	E271	8L	42E	42E										Y
E216	216	E271													Z
15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	

E

S

Figure 8.—*A treatment ring tree map showing the location of the different aspen clones in the eastern half of the ring and the aspen-birch and aspen-maple trees in the western half of the ring. Letters and numbers are the x,y coordinates and the heavy line indicates the "sweet spot" or area of most uniform gas concentration. Trees outside the line are considered border trees.*

open greenhouse bench with an overhead water spray for 15 minutes twice a day. After at least a week on the hardening bench, the rooted cuttings were transplanted to 0.5-l containers (Stuewe and Sons, Corvallis, OR 97333). The potting mix was peat-sand-vermiculite (2:1:1, v:v:v) and timed-release fertilizer, Osmocote 17-6-12 (1 g/l). Water was applied overhead for 15 minutes twice a day.

Some of the aspen material (labeled E216 and E271) was raised with elevated CO_2 to test the impact of early exposure on subsequent response. Rooted cuttings of clones 216 and 271 were transplanted into 0.5-l containers and grown with ambient plus 350 μll^{-1} CO_2 in a growth chamber until outplanted. This material was treated as separate planting stock during outplanting.

Maple and birch plants were grown from seed in the same type of containers and soil mix as the rooted aspen cuttings. Birch seed was collected under mature trees in Houghton County, Michigan, during the late summer of 1996. Birch seed was stored dry and sown on top of containerized soil on March 7, 1997. After germination the plants were thinned to one plant per 0.5-l container for subsequent growth in the greenhouse.

Maple seed was collected in Baraga County, Michigan, during autumn and refrigerated moist with Captan fungicide in plastic bags. On March 15, 1997, two to three maple seeds containing live embryos were planted 0.5 cm below the soil surface in each 0.5-l container. Germination of the stratified maple seed was poor, so naturally germinated seed from the same source location was also used. Naturally germinated seed was collected and planted in the containers on April 15, 1997.

Plant material had reached outplanting size by late May 1997. The containerized stock of aspen, birch, and maple was then graded, moved outdoors, and kept under 50 percent shade until planting. Plant material was outplanted into the FACE rings during June 1997. A 10-cm-diameter hand-held gasoline-powered auger was used to drill planting holes. Each plant-root plus soil plug was removed from the container and firmly packed into the planting hole by hand. Immediately after planting, the rings were irrigated. During the establishment season, summer 1997, rainfall was supplemented with irrigation when the soil appeared dry.

D. Site Safety

Safety is a major concern because of the large size of the Aspen FACE site; the large number of investigators, students, and technicians involved; potentially dangerous farm equipment; high pressure cryogenic gases (CO_2 and O_2); and toxic ozone production. General access to the site is controlled with a 3.6-m deer fence around the entire 32 ha and a card-operated electric gate on the access road. Michigan Technological University or Forest Service personnel are present at the site 24 hours each day during the summer operating season. We have developed a safety program that involves written, video, and tailgate instruction that covers areas such as power tools, electrical systems, farm equipment, storm warnings, lightning and wind protection, and Occupational Safety and Health Administration (OSHA) safety data for O_3 and cryogenic gas exposures. Ozone exposure is of special concern because of human toxicity at high O_3 concentrations. The O_3 distribution lines around the site are aboveground and contain about 4 percent (40,000 μll^{-1}) O_3 with the oxygen carrier gas. Direct exposure to such O_3 concentrations via a broken line would be extremely dangerous, if not lethal. Ozone exposure in the experimental FACE rings, however, is much lower because treatment concentrations range from 60 to 100 nll^{-1} in the center of the rings. Ozone concentrations near the vents may be much higher (150 to 250 nll^{-1}). Excess O_3 in the lines is converted to O_2 in a destruct unit and then vented into the air above the control shed. Potential exposure within the rings must be compared to OSHA standards for a realistic assessment of danger. OSHA permissible standards for worker exposures are 100 nll^{-1} averaged for 8 hours and 300 nll^{-1} for 15 minutes. Exposures over 300 nll^{-1} are considered hazardous, particularly for sensitive people and others with chronic lung problems. Based on these standards, O_3 exposure of research personnel in the rings would not be considered harmful. However, all precautions are being taken to minimize O_3 exposure of people working within the O_3 exposure rings.

E. Micrometeorological Monitoring

Within-ring Micrometeorological Measurements

The following meteorological parameters are measured at rings 1,2; 2,1; 3,3; and 3,4 (see figure 7 for ring locations): air and soil temperature, relative humidity, photosynthetically active radiation (PAR), net radiation, wind speed and direction, and soil water content (fig. 9A). Air temperature and relative humidity are measured with Campbell CS500 probes (Campbell Scientific, Inc., Logan, UT 84321) consisting of platinum resistance thermisters and Vaisala capacitive 50-Y intercap humidity sensors (Vaisala, Inc., Woburn, MA 01801). Soil temperatures are measured with 24-gauge copper/constantan thermocouples referenced to a Campbell T107 temperature probe (Fenwal UUT51J1 thermister, Fenwal Electronics, Milford, MA 01757). Wind speed and direction are measured with Young 03001-5 wind sentry sets (R.M. Young Co., Traverse City, MI 49686); PAR with LI-COR LI-1905B quantum sensors (LI-COR, Inc., Lincoln, NE 68504); and net radiation with a Q7.1 net radiometer (Radiation and Energy Balance Co., Bellvue, WA 98006). Soil water content is measured with Campbell CS615 water content reflectometer probes, and precipitation is measured at rings 1, 2, and 3,3 with a TE525 tipping bucket rain gauge (Texas Electronics, Inc., Dallas, TX 75235). Data from all the meteorological equipment are collected with Campbell Scientific CR10X data loggers.

The meteorological data are measured, recorded, and reported at different intervals depending on the particular measurement (table 2). Wind speed, wind direction, PAR, and

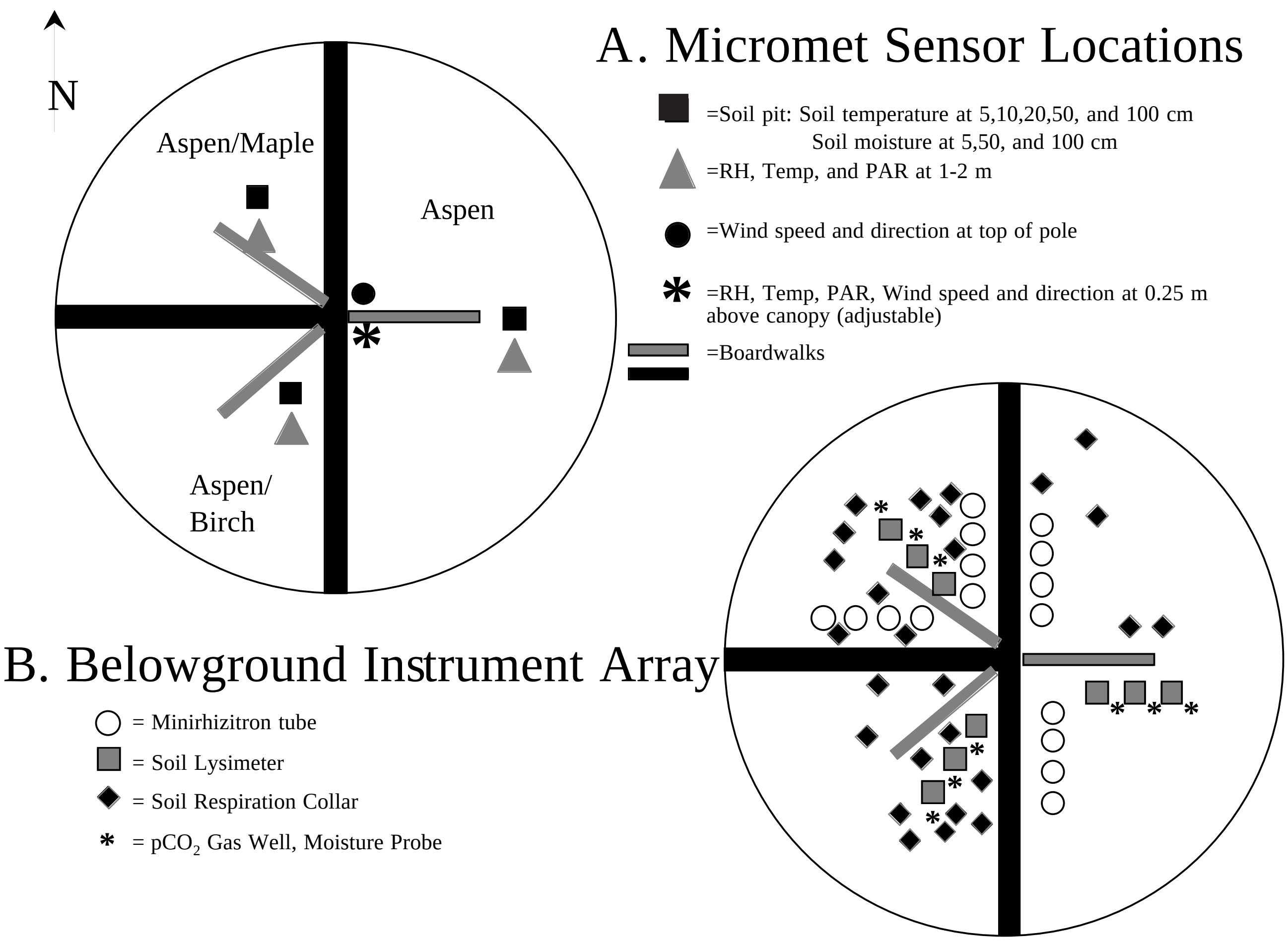


Figure 9.—*A treatment ring map showing the location of micrometeorological equipment and other installed experimental sampling equipment. A. Meteorological monitoring equipment (see table 2). B. Belowground root growth and carbon flux monitoring equipment.*

Table 2.—*Aspen FACE meteorological monitoring (rings 1,2; 2,1; 3.3; 3,4)*

Parameter	Scan interval	I.D. 101[1] report 30 min	I.D. 102 report 2 hr	I.D. 124 report 24 hr	I.D. 8 Acceptable limits	I.D. 8 Out-of-range operation [2)]
Wind speed @ 2 & 10 m	5 sec	Avg		Avg, max (w/time)	0 to 55 ($m\ s^{-1}$)	Set flag
Wind direction @ 2 & 10 m	5 sec	Avg/Stdv		Avg, standard deviation max (w/time)	-10^{o} to 360^{o}	Set flag
PAR @ 2 m 3 reps	5 sec	Avg		Avg, max (w/time) totalized	-.01 to 2.4 (mmoles $m^{-2}s^{-1}$)	Set flag
Net radiation @ 2 m	5 sec	Avg		Avg, max (w/time), min (w/time)	-300 to 1200 ($W\ m^{-2}$)	Set flag
Temperature 3 reps @ 2 m and 10 m	5 min	Avg		Avg, max (w/time), min (w/time)	-50 to 50 (^{o}C)	Set flag
Relative humidity 3 reps @ 2 m and 10 m	5 min	Avg		Avg, max (w/time), min (w/time)	0 to 120 (%)	Set flag Set to 100 if > 100
Soil temp profile (5, 10, 20, 50, 100 cm) 3 reps	5 min	Avg		Avg, max (w/time), min (w/time)	-50 to 50 (^{o}C)	Set flag
Soil moisture profile (water content) 3 reps @ 0-30, 30-60, 100-130 cm	2 hr		Sample	Avg, max (w/time), min (w/time)	0 to 1.1 (%)	Set flag
Precipitation (rings 1,2 and 3,3 only)	Continuous	Total		Total	0 to 254 (mm)	Set flag

[1]Array identifier. The array identifier is the first number in the data array that is coded to identify the array relative to data summary interval and the parameters measured.

[2]Note: Out-of-range flag initiates snapshot of all parameters for first 10 out-of-range events.

net radiation are measured every 5 seconds; soil temperature, air temperature, and relative humidity are measured every 5 minutes. Average values for all parameters are reported every 30 minutes. Soil moisture is measured and reported every 2 hours. Daily reports include average, minimum, and maximum values for all parameters.

Background Meteorological Measurements

For comparison with the within-ring measurements, a 20-m meteorological tower is located in an open field near the north boundary of the experimental site (fig. 10) to provide near-surface, background measurements. The tower site measurements include relative humidity, wind speed and wind direction, PAR and net radiation, air and near-ground surface temperature, soil temperatures, soil moisture, barometric pressure, evaporation, leaf wetness, and rainfall (table 3). For information about these meteorological parameters, consult our FACE website (www.fs.fed.us/nc/face or climate.usfs.msu.edu/face/meteorology.html).

Figure 10.—*Aspen FACE meteorological tower containing instruments to measure site background meteorological parameters (see table 3).*

Table 3.—*Aspen FACE meteorological monitoring (ambient tower)*

Parameter	Scan interval	I.D. 201[1] report 30 min	I.D. 202 report 2 hr	I.D. 224 report 24 hr	I.D. 10 acceptable limits	I.D. 10 out-of-range operation[2]
Wind speed @ 2, 5, 10, 15, 20 m	5 sec	Avg		Avg, max (w/time)	0 to 55 ($m\ s^{-1}$)	Set flag
Wind direction @ 2, 5, 10, 15, 20 m	5 sec	Avg/Stdv		Avg, standard deviation max (w/time)	-10^{o} to 360^{0}	Set flag
PAR @ 2 m	5 sec	Avg		Avg, max (w/time) totalized	-.01 to 2.4 (mmoles $m^{-2}s^{-1}$)	Set flag
Net radiation @ 2 m	5 sec	Avg		Avg, max (w/time), min (w/time)	-300 to 1200 ($W\ m^{-2}$)	Set flag
Air temperature @ 2, 5, 10, 15, 20 m soil temperatures @ surface, 0.25, 0.5, 0.75, 1.0, 2.0 m	5 min	Avg		Avg, max (w/time), min (w/time)	-50 to 50 (^{0}C)	Set flag
Relative humidity @ 2, 5, 10, 15, 20 m	5 min	Avg		Avg, max (w/time), min (w/time)	0 to 120 (%)	Set flag Set to 100 if > 100
Soil temp profile @ 5, 10, 20, 50, 100 cm	5 min	Avg		Avg, max (w/time), min (w/time)	-50 to 50 (^{0}C)	Set flag
Leaf wetness @ 2 m	5 min	Sample			0 to 99999 (K ohms)	Set flag
Soil moisture profile (water content) 1 rep @ 0-30, 30-60, 100-130 cm	2 hr		Sample	Avg, max (w/time), min (w/time)	0 to 1.1 (%)	Set flag
Precipitation	Continuous	Total		Total	0 to 254 (mm)	Set flag
Evaporation gauge (pan)	5 min	Sample		Sample	0 to 254 (mm)	Set flag
Barometric pressure	30 min	Sample		Avg, max (w/time), min (w/time)	600 to 1060 (mb)	Set flag

[1]Array identifier. The array identifier is the first number in the data array that is coded to identify the array relative to data summary interval and the parameters measured.

[2]Note: Out-of-range flag initiates snapshot of all parameters for first 10 out-of-range events.

Belowground Instrument Array

In addition to the meteorological measuring instruments, a large array of equipment was also installed within each ring to measure belowground processes (fig. 9B). The mechanisms that regulate carbon transformation and the time-steps and flux rates of belowground carbon and nitrogen are largely unknown (Vitousek 1994) and are a major component of the Aspen FACE project. Thirty soil respiration collars were randomly placed in each ring (10 in each quadrant) while the minirhizotron tubes (16 per ring), soil tension lysimeters, pCO_2 gas wells, and TDR soil moisture probes (9 each per ring) were systematically placed along the boardwalks within the treatment rings for easy access and to minimize foot traffic on the soil within the rings. The exact ring coordinates of all belowground carbon flux instruments and meteorological instruments are included in the overall Aspen FACE digital site maps (see the Aspen FACE web site, www.fs.fed.us/nc/face, and George Host at the Natural Resource Research Institute (NRRI), www.nrri.umn.edu/aspenface).

F. Experimental Variables Measured

Because of the large size of the Aspen FACE project, the high construction and operating costs, and the large number of investigations involved (see Section II: G and H), it is very important to measure as many experimental variables as possible. The many experiments involved have been separated into aboveground and belowground studies primarily for simplification (table 4). However, several study areas have both aboveground and belowground components. Measuring plant growth, competition, and carbon and nitrogen fluxes from leaf to ecosystem level requires cooperation among investigators to maximize information gain and minimize duplication of effort.

Five general aboveground study areas and four belowground study areas each contain several individual areas for research. To facilitate research coordination and database management, closely related study areas are combined into subgroups, such as gas exchange and canopy architecture. Scientists from these subgroups meet independently to organize and coordinate future research so they can obtain maximum information with a minimum expenditure of research time and funding (see figures 16 and 17 for examples of these subgroups).

Table 4.—*Experimental variables measured in the Aspen FACE project*

Aboveground studies	Belowground studies
1. Photosynthesis/gas exchange	1. Root growth and turnover
Light response curves within the crown	Soil cores
A/Ci curves	Minirhizotrons
Respiration	
Transpiration	2. Soil carbon fluxes
Stomatal conductance	Soil organic matter
Canopy light environment	Soil respiration
Leaf chemistry	Soil CO_2 concentrations
	Soluble organic and inorganic carbon
2. Canopy architecture and leaf phenology	
Branching characteristics	3. Soil biota-chemistry
Spring bud and leaf development	Microbial processes
Fall bud-set and leaf senescence	Nitrogen fluxes
	Plant nutrients
3. Leaf surface characteristics and cellular antioxidants	Root chemical content
Stomatal density	4. Leaf litter
Leaf wax chemistry	Decomposition rates
Leaf wettability	Chemical content
Antioxidant enzyme systems	
Antioxidant chemical concentrations	
4. Water relations	
Soil moisture	
Plant and soil moisture stress	
Transpiration and water movement in plants	
Hydraulic conductivity	
5. Insects and disease	
Gypsy moth	
White-marked tussock moth	
Aspen-blotch leaf miner	
Forest tent caterpillar	
Poplar branch borer	
Poplar gall-maker	
Aspen gall fly	
Birch leaf miner	
White-spotted poplar aphid	
Smoky-winged poplar aphid	
Birch leaf aphid	
Leaf-produced insect defense compounds	

V. CARBON DIOXIDE/OZONE DELIVERY AND CONTROL SYSTEM

The overall system design for this type of facility, as implemented by Brookhaven National Laboratory, was described in Hendrey *et al.* (1993, 1999) and Lewin *et al.* (1994). The Aspen FACE facility described in this report was modified from these earlier designs. The generic FACE system ring hardware consists of a high-volume blower, a plenum pipe for air distribution, and 32 vertical vent pipes for emitting CO_2 and O_3 into the exposure volume. The major subcomponents of the Aspen FACE facility that will be described in more detail below (including modifications of the design to enable more uniform gas distribution and fumigation with ozone) are (1) the CO_2 and O_3 supply systems, (2) the fan and plenum system, (3) the vertical vent pipe system, and (4) the control system.

The set-point for the CO_2 concentration within the Aspen FACE rings receiving elevated levels of CO_2 during the 1998 and 1999 growing seasons was 560 μll^{-1}, 200 μll^{-1} above ambient CO_2 concentrations and similar to the CO_2 concentrations anticipated by 2060 (IS92f emission scenario, Technical summary, IPCC 1996). A constant set-point was chosen to simplify analysis of system performance, although the system can operate in a mode that maintains a constant increment (e.g., +200 μll^{-1}) above ambient CO_2 concentration. In 1997, initial performance tests and tests of continuous 24-hour operation were conducted. In 1998, the Aspen FACE CO_2-enriched plots were treated from dawn to twilight (when the sun elevation angle exceeded 6^{o} from the horizon) from May 1 to October 13 for 158 out of 166 days. In 1999, CO_2 exposures were from 0700 to 1900 from May 10 to September 30 for 144 days.

The treatment target for the O_3 concentration within the Aspen FACE rings receiving elevated O_3 during the 1998 and 1999 growing season was a daily episodic exposure that followed a diurnal profile based on actual O_3 data collected at Leelenaw, Michigan, during the summer of 1987 (Karnosky *et al.* 1996). These ambient profiles were modified to more closely match regional 6-year averages (1978-1983) described in Pinkerton and Lefohn (1987). Before the start of the experiment, the average shape of the diurnal curve (stepped sine wave) and the frequency classes of daily peak O_3 concentrations were established. A protocol was then devised whereby the site operator picked a peak value at the beginning of each day, based on that day's meteorological conditions and forecast. For example, for hot and sunny days, when O_3 concentrations are normally higher, a diurnal curve with a high maximum O_3 concentration (90 to 100 nll^{-1}) was chosen. For cool and cloudy days, a diurnal profile with low maximum O_3 concentrations (50 to 60 nll^{-1}) was chosen. Plants were not exposed to O_3 during rain or when the leaves were wet with dew. In 1998, the Aspen FACE O_3 plots were treated from May 3 to October 13 for a total exposure (Sum 0) of 97.8 μll^{-1}-h. In 1999, the O_3 plots were treated from May 10 to September 30 for a total exposure of 89.0 μll^{-1}-h.

A. Carbon Dioxide Supply System

Carbon dioxide was obtained as a byproduct of agricultural fertilizer manufactured from methane and atmospheric nitrogen. Food-grade, liquified CO_2 was delivered to the FACE site by truck in 20,000-kg lots and transferred to two insulated receiving tanks with a total storage capacity of 110,000 kg (fig. 11A). Tank pressure was maintained at 1,725 kPa to keep the CO_2 in a liquid state. A refrigeration unit and an electric heater maintained this pressure regardless of demand for CO_2 by the FACE control system. Liquid CO_2 was supplied to a bank of eight ambient-air heat exchangers, which vaporize the CO_2 as needed (fig. 11B). The gaseous CO_2 was routed from the vaporizers to the ring locations through high pressure copper piping (see figure A3 in the appendix). Near each ring, a pressure regulator decreased line pressure to 140 kPa above ambient. The CO_2 gas was piped from the regulator to the FACE ring through 5-cm polyethylene tubing. The CO_2 supply lines were equipped with a manually actuated shut-off valve where they diverged from the main system supply line, and a pneumatically actuated shut-off valve at each FACE ring. Carbon dioxide flow was measured by an electronic flow sensor and throttled by a Kurz rotary ramp metering valve (Model 735, Kurz Instruments, Monterey, CA 93940) that provided an even, linear gradation of gas flow over the range 0 to 1,550 kg hr^{-1}. The metering

Figure 11.—*Central control systems for CO_2, liquid O_2, O_3 production, and gas distribution. A. Liquid CO_2 storage tanks. B. Ambient-air heat exchangers. C. Liquid O_2 storage tank. D. Ozone generation building. E. Carbon dioxide and O_3 gas distribution lines. F. Main computer control building and shops.*

valve was operated directly by the FACE control program (described below). The CO_2 gas was injected into the plenum immediately downstream of the air supply fan.

B. Ozone Supply System

Medical-grade, liquified O_2 was delivered to the FACE site by truck in 15,000-l lots and transferred to an insulated receiving tank with a total storage capacity of 23,000 l (fig. 11C). The O_2 storage tank was equipped with vaporizer coils that maintained tank pressure as O_2 was withdrawn and a relief valve that protected the tank from overpressurization during low O_2 demand. The oxygen gas used to make ozone was routed through a regulator that decreased the pressure to 120 kPa above ambient. This low-pressure oxygen gas was then routed into the ozonator building (fig. 11D) and then into an ozone generator (Model Unizone MZ18X, Praxair-Trailigaz Ozone Co., Cincinnati, OH 45249) capable of producing 16 kg per day of O_3 at a maximum O_3 concentration of 6 percent by weight. The rate of O_3 production could be manually adjusted by varying the flow of O_2 through the generator and by altering the power to the generator electrodes. For this experiment, the flow of O_2 was held constant at the expected maximum usage rate of 2 l min^{-1} per O_3 treatment ring, and the generator power was varied as needed to obtain enough O_3 to supply all the rings. The power setting was adjusted when the site operator found that the O_3 mass-flow controller was operating near its maximum or minimum settings. In practice, we found that this setting did not have to be changed very often. The sum of the independently varying demands of the six treatment rings tended to remain fairly constant over time.

The O_3 in O_2 gas mixture was routed to the treatment rings through stainless steel tubing (fig. 11E) (also see figure A4 in the appendix). At each treatment shed, the supply line branched into two paths. One led to the mass-flow controller that governed the flow of O_3 into the treatment ring; the other led to a back pressure relief regulator, which was set to pass a maximum of just over 2 l min^{-1} if the pressure in the supply line rose above 35 kPa. This excess portion of the O_3-laden oxygen stream was piped through a stainless steel canister filled with magnesium dioxide catalyst, which converted the O_3 back to O_2. This canister was sized to destroy a stream of 6 percent O_3 passing at a rate of 4 l min^{-1}, twice the maximum flow rate that the back pressure regulator could pass.

This arrangement of centralized O_3 production, O_3 distribution control, and O_3 destruction allowed a relatively constant production of O_3 at the source while accommodating a broad range of O_3 demands at the individual rings. At each ring the metering of the O_3 was rapidly and accurately controlled using a mass-flow controller. Locating the O_3 bypass regulators and O_3 conversion units at the end of the supply line for each O_3 treatment ring kept residence time of the O_3 in the supply lines both short and constant, regardless of the O_3 demand at the ring. This stabilized the losses of O_3 as it traveled through the supply piping. We found that the average loss of O_3 as it traversed the piping system from the generator to the furthest treatment ring (over 660 m) was less than 10 percent.

C. Fan and Plenum

An octagon plenum was assembled 2 m outside of the 30-m-diameter circle of vertical vent pipes (VVP's) to minimize the impact of the equipment on vegetation within the study area (fig. 12). The plenum was made of 38-cm-diameter polyvinyl chloride (PVC) pipe connected to the fan at a 'T' by a 2 m-length of the same pipe (fig. 13A). A radial fan (Model 18-BISW-21, Vyron Corporation, Wisconsin Rapids, WI 54494) provided air flow (102 m^3 min^{-1} at 2.0 kPa pressure) around the plenum.

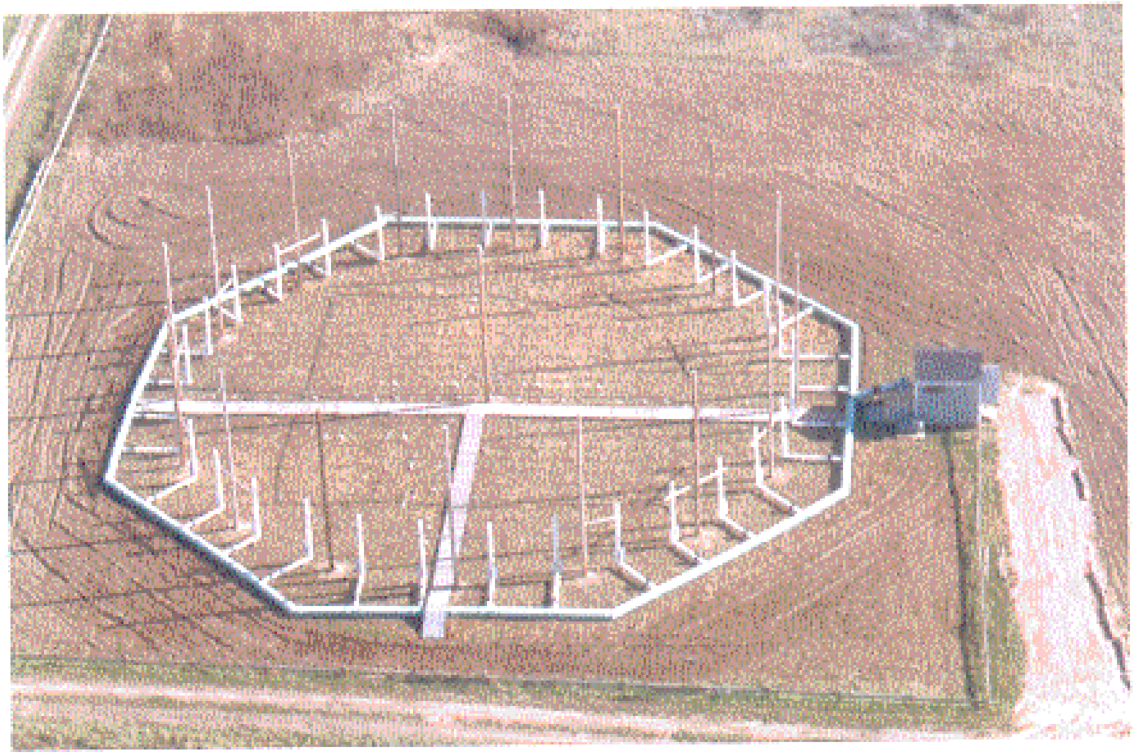
D. Vertical Vent Pipes

Carbon dioxide- or O_3-enriched air was injected into a FACE ring at the vertical vent pipes (VVP's) (figs. 12 and 13). This is the most critical control step in the free-air approach and determines how well gas enrichment is controlled within the FACE ring. The following elements of the system are each adjustable to some degree.

Upwind Control

Thirty-two VVP's constructed from 15-cm-diameter PVC pipe were evenly spaced in a 30-m-diameter circle around the FACE ring (fig.

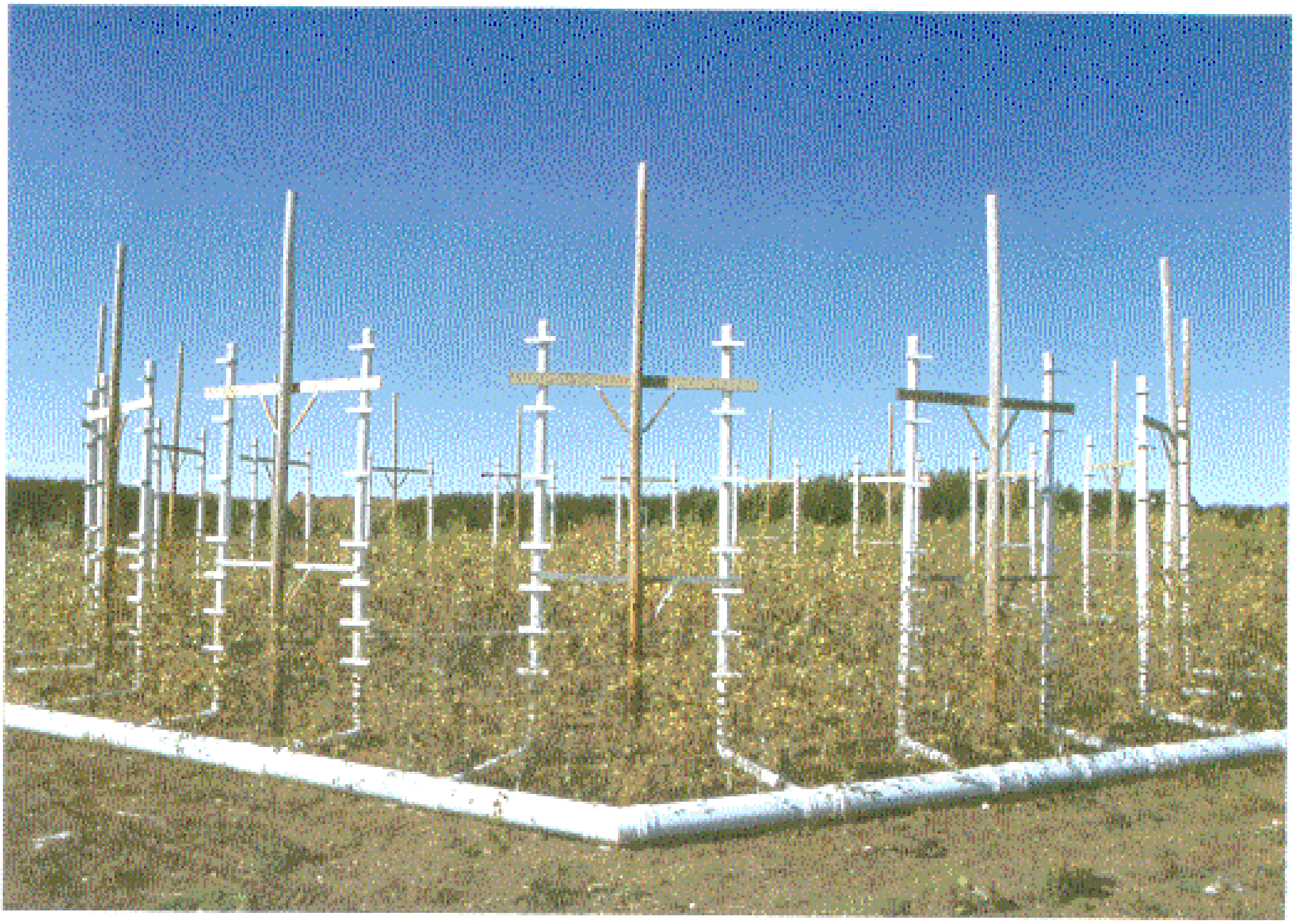
A



B

Figure 12.—*Individual treatment ring configuration in 1997 showing: A. Octagon plenum pipe, vertical vent pipes, support poles, crosswalks, and control shed. B. Octagon plenum pipe, vertical vent pipes, and butterfly control valves. C. Treatment ring in 1999 with increased tree growth and extensions on the vertical vent pipes.*

C



12). Valves at the bases of the VVP's were opened to release CO_2- and O_3-enriched air from the upwind direction only (figs. 12 and 13B). This feature led to less gas loss than would occur if CO_2 or O_3 were released on the downwind side, and it decreased the potential for carryover of injected gasses to adjacent rings. If all 16 VVP's of the upwind semi-circle were opened, excessive CO_2 or O_3 concentrations would occur near the edges of the ring where tangents are about parallel to wind direction. To prevent such high concentrations, CO_2 was released from an arc containing 12 VVP's over 135° of the VVP circle. Furthermore, better concentration control was achieved by closing the second VVP from each end of the arc of 12 upwind VVP's (i.e., only 10 VVP's open). This arrangement was determined from empirical observations of open or closed VVP's that produced the most even spatial distribution of CO_2 concentration under a wide range of wind speed and turbulence conditions (Lewin *et al.* 1994).

Low Wind Speed Regime

Detection of true wind direction becomes unreliable with wind vanes below a minimum stall velocity (0.4 m s^{-1} for the model used, Climatronics Inc., Bohemia, NY 11716). The control-limiting process under these low-wind conditions is the information feed-forward from the moment of a change in the release rate of CO_2 to the detection of changing CO_2 concentrations at the FACE ring center. At wind speeds below the anemometer stall threshold, it will take at least 40 seconds for CO_2 to traverse the air-handling system, be emitted from the VVP's, carried across the ring, and detected at the control point in the center. Use of a more sensitive anemometer (i.e., sonic anemometer) would not improve control over the CO_2 concentration. Therefore, when wind speed dropped below 0.4 m s^{-1} for a 20-second period, directional control was terminated, and the fan and CO_2 injection system were shut down until higher wind speeds returned. Low wind speeds

A

B

C

Figure 13.—*Individual treatment ring gas distribution equipment. A. Control shed, gas injection fan, and connecting plenum pipe. B. Butterfly control valves. C. Vertical vent pipe with gas emitter ports and baffles.*

are the biggest problem in maintaining control of gas concentration in a FACE system because (1) transport from the VVP's into the plot is very irregular in all four cardinal directions; (2) low wind speed means slower transport of the enriched air from the VVP's to the sample intake in the center of the ring for the gas analyzer, increasing feedback delay; and (3) parcels of air differentially enriched with CO_2 may move irregularly through the plant canopy and back into the plot.

Support Poles

For CO_2 exposure of tall trees, two VVP's were connected to each of sixteen 10-m-tall wooden poles evenly spaced around the perimeter of the 30-m-diameter ring (fig. 12A). These poles are free-standing and are identical to those commonly used to support electric or telephone lines. Additional sections can be added to the existing VVP's as the trees grow.

Vertical Vent Pipe Valves and Emitters

The VVP's were connected to 15-cm-diameter butterfly valves (Model 323-79U, Keystone Valves and Controls, Inc., Houston, TX 77040), which were directly connected to the plenum pipe by a short length of 15-cm-diameter PVC pipe (figs. 12B and 13B). The valves were pneumatically actuated, and each was separately controlled by the computer-operated control system. These valves opened or closed according to wind direction averaged over a 10-second period. Each valve was connected to a manifold of 32 pneumatic valves actuated by the control program (described below) via 24-volt AC solenoids. The pneumatic system was pressurized at 620 kPa with air from an air compressor (model 7Z030, W. W. Grainger, Inc., Green Bay, WI 54304) and storage tank located in the control building at each ring.

The CO_2- or O_3-enriched air was emitted from horizontally slotted ports cut into the VVP's (fig. 13C). The ports were 2.5 cm high and 16 cm wide, covering an included angle of 120°, and the center of the slot pointed directly away from the center of the ring. The air stream leaving the slot was directed against a baffle plate positioned 10 cm away from the pipe. The baffle system was modified from the enhanced local mixing (ELM) system described by Walklate *et al.* (1996). The baffle plate was made from a strip of aluminum sheet (15 cm wide by 50 cm long) bent in a right angle along the center line of its width. This was mounted horizontally in an inverted "L" orientation with the top leg of the "L" pointing back towards the vent pipe. This baffle redirected the air stream coming from the emitter port so that it moved horizontally and downwards along the periphery of the ring. At the start of the experiment, five emitter ports were cut into each vent pipe, spaced at 25-cm vertical intervals from about 0.5 to 1.5 m above the ground. As the trees increased in height, additional ports and baffles were placed higher up on the pipe, and some of the lower ports were closed to match the release rates at differing heights above the ground with the vertical wind profile. In 1998, the aluminum baffles were replaced with PVC rain-gutter sections cut in half and positioned to direct the gas flow downward as described above.

This emitter design differs from that used in prior FACE systems designed by personnel at the Brookhaven National Laboratory. The purpose of this design was to more rapidly mix the CO_2 and O_3 from the jets with the ambient air passing by the vent pipes as it moved into the ring. Due to the phytotoxicity of O_3, the concentration of gas had to be decreased as rapidly as possible. However, it appears that this emitter and baffle arrangement increased the variability of the gas concentrations within the rings. Further studies are needed to quantify and, if possible, correct this increased variability.

E. Gas Enrichment Control System

Regulation of CO_2 and O_3 concentrations within the treatment rings as well as registration and logging of all pertinent data were achieved via three fully integrated subsystems: (1) wind and gas (CO_2 and O_3) concentration detectors; (2) a central data acquisition and control system; and (3) a gas enrichment control program. Because of the number of rings in this experiment, the site was run by three parallel control systems, each monitoring four rings. Separate sampling systems were used to monitor the spatial uniformity of the enriched gases within the rings.

Wind and Gas Concentration Detectors

Wind speed was measured at the center of each ring, near the top of the canopy, by a sensitive cup anemometer (Model 100075, Climatronics, Bohemia, NY 11716) and wind direction with a wind vane (Climatronics model 100076) mounted on a support pole in the center of each ring. The minimum detectable wind speed was 0.3 m s^{-1}, and the wind vane was reliable at wind speeds above 0.4 m s^{-1}.

Carbon dioxide concentration within the canopy at the center of each ring was continuously monitored with a non-dispersive infrared gas analyzer, or IRGA (Model LI-6252, Li-Cor, Inc., Lincoln, NE 68504) placed within the ring instrument shed (figs. 6C and 13A). Air was sampled from a control point at the center of the ring and the inlet port was set just above the main portion of the canopy. The sampled air was pumped at 15 l min^{-1} through approximately 20 m of 4.3-mm-diameter polypropylene tubing to the analyzer. Just before entering the analyzer, air flow was restricted to 0.8 l min^{-1} for CO_2 analysis and the remainder was diverted to waste. Tubing used for all CO_2 monitoring was made from opaque, black polypropylene (black Impolene tubing, Burns Industrial Supply Inc., Whitewater, WI 53190) with low CO_2 absorptivity and permeability, and high resistance to ultraviolet radiation.

Ozone concentration within the canopy at the center of each ring was continuously monitored with a UV absorption gas analyzer (Models 49 and 49C, Thermo Environmental Instruments, Inc., Franklin, MA 02038). Sample air was pulled at 31 min^{-1} through 4.3-mm-diameter Teflon tubing by a pump connected to the exhaust side of the analyzer detector cell. The analyzer automatically compensated for the vacuum applied to the detector and gave a new O_3 reading every 10 seconds. As a check on the possibility that the O_3 released in the plots might leave the site in phytotoxic concentrations, separate measurements of ambient O_3 were made at four points on the periphery of the research site close to rings where O_3 was being released (fig. 7). Air for O_3 analysis was pumped through 1.2-cm-diameter Teflon tubing from intakes on the fence line to a separate O_3 analyzer (Model 8810, Monitor Labs, Inc., San Diego, CA 92131) in the control sheds.

The CO_2 and O_3 analyzers were read at 1-second intervals. However, due to smearing of the sample within the 20-m-long sample tubes and the averaging occurring in the detector cells and analyzer electronics, the 1-second values were reported as “grab-samples,” representing an averaging time of less than 4 seconds for CO_2 and 10 seconds for O_3.

Data Acquisition and Control System

The data acquisition and control subsystems were located in a small shed adjacent to the FACE ring (figs. 6C and 13A). These subsystems processed commands received on a fiber optic link from the central control computer (see following section). The commands either requested measurements from sensors (input) or changed the state of a device (output). Inputs included CO_2 or O_3 at the control point, wind speed and direction, CO_2 or O_3 mass-flow rate, air temperature, atmospheric pressure, and photosynthetically active radiation (PAR). Other inputs included the status of power supplies, fan operation, and VVP valve actuation air pressure. Command signals were converted from analog to digital and digital to analog, by IOP-AD and IOP-D “I/OPLEXER” modules (DuTec, Inc., Jackson, MI 49264).

Gas flow to the individual VVP’s was controlled with a bi-directional DC motor controller that positioned the Kurz CO_2 flow-metering valve (Model 735, Kurz Instruments, Inc., Monterey, CA 93940). Digital output signals turned the CO_2 feedline quarter-turn valve (Model S90-WCB, Flow-Tek, Inc., Columbia, SC 29201) on or off and actuated 32 pneumatic pilot valves (Mac Valves, Inc., Wixom, MI 48096), which, in turn, opened or closed the 15-cm butterfly valves (Model 323-79U), Keystone Valves and Controls, Inc., Houston, TX 77040) at the base of each VVP (figs. 12B and 13B). The mass-flow of CO_2 was measured with a Kurz Instruments model 452 flow sensor (Kurtz Instruments, Inc., Monterey. CA 93940). With O_3, the gas flow was monitored and controlled with a stainless steel mass-flow controller (Model 840, Sierra Instruments, Monterey, CA 93940).

Gas Enrichment Control Program

Due to several factors, it was not possible to control gas enrichment by simply making the gas release directly proportional to wind velocity. Principal causes of variation in transport and mixing are air turbulence, low wind speed, and other factors, such as time delays in the system. For this reason, a custom control program was written to accommodate complex interactions between the sampling and control hardware. To optimize the operation of the control program, an extensive operator interface was provided that allows the system operator to view both the present and historical operation of the system in either textual or graphic modes. This interface allows the operator to adjust the integrating and weighting functions of the control algorithm from the computer keyboard, so that the system can be fine tuned as needed while the control system is operating. Provisions were also made for backing up data on removable media, reporting alarms, and accessing the control program from a remote terminal.

The FACE operation programs were controlled by three Intel Pentium processor-based personal computers located in the main control building at the edge of the research site (fig. 11F). A duplex fiber optic serial cable network using eight-channel multiplexed fiber to RS-232 converters (Model TC2800, TC Communication, Inc., Irvine, CA 92606) was the only data link between the FACE control computers and the field (see figure A5 in the appendix). The primary purpose for using fiber optics was to electrically isolate the control building and computers from the FACE rings and to isolate the rings from each other in event of lightning strikes. The multiplexed converters allowed several data streams to coexist on the same fiber pair and added fault tolerance and troubleshooting capability to the fiber network. Each computer controlled the amount of CO_2 and/or O_3 metered into the air stream entering the plenums of four treatment rings based on wind speed and gas concentration sampled at the center of each ring. An empirically derived, proportional-integrative-differential (PID) control algorithm, described in Hendrey *et al.* (1999), adjusts the amount of CO_2 introduced into the plenum. Another algorithm, monitoring both wind direction and wind speed, controls which VVP's emit CO_2-enriched air (Lewin *et al.* 1994). These two algorithms work together to maintain the desired concentration within the central area of the FACE ring while minimizing CO_2 and O_3 usage.

CO_2 concentration control within the rings was quite satisfactory with the new vent pipe emitter design. Seasonal 1-minute average CO_2 concentration was within 10 percent of the 560 $\mu l l^{-1}$ target concentration 80 percent of the time and within 20 percent of target concentration 96 percent of the time (table 5). Control performance was not as good as that previously reported (within 10 percent of the 550 $\mu l l^{-1}$ 90 percent of the time and within 20 percent of target 98 percent of the time) by Nagy *et al.* (1994) and Hendry *et al.* (1999). Control performance of the Aspen FACE system tended to decrease as the summer progressed and to increase with wind speed as was found previously (Nagy *et al.* 1994).

Ozone concentration control performance was not as good as that found with CO_2 but averaged within 10 percent of the target concentration 66 percent of the time and within 20 percent of target 83 percent of the time (table 6). This degradation of control was probably related to the very low O_3 target concentration (50 to 100 $nl l^{-1}$) and to the daily difference in O_3 target concentration imposed by the episodic treatment regime. Ozone monitors, sampling air on the site perimeter fence (fig. 7) and at a Wisconsin Department of Natural Resources air monitoring station at Trout Lake, Wisconsin, provided hourly average ambient O_3 concentrations for comparison with ring treatment concentrations. Plots of daily average 1-hour maximum O_3 concentrations clearly showed that daily target O_3 exposures within the treatment rings were not detected at the fenceline, and that fenceline O_3 concentrations were the same as that at Trout Lake, indicating that the fenceline measurements were similar to regional ambient O_3 concentrations (fig. 14).

Monthly average O_3 concentrations and Sum 0 values for the Aspen FACE project for 1998 also showed that the fenceline exposures did not differ from regional ambient exposures, and that the seasonal exposures within the treatment rings (Sum 0 values, 97.8 $\mu l l^{-1}$-h vs. 65.3 $\mu l l^{-1}$-h) were close to the 1.5x ambient O_3 target exposure originally planned (table 7). More detailed O_3 exposures were compiled for the

Table 5.—*Carbon dioxide concentration control performance by month in 1998 for the Aspen FACE project*

	CO_2 and CO_2 plus O_3 treatment rings					
	1,2[1]	1,4	2,2	2,4	3,2	3,4
	- - - - - - - - - -	- -	Percent	- -	- - - - - - - - - -	
May	81.7[2]	82.7	85.0	83.8	80.5	82.6
June	—[3]	83.9	87.1	84.5	82.0	84.5
July	88.5	81.4	82.9	79.3	74.0	79.3
August	79.6	79.8	80.7	78.0	67.5	77.9
September	80.1	79.7	83.3	78.9	71.3	80.0
October	79.8	77.8	77.2	77.4	64.9	74.7
Seasonal average within 10%	81.6	81.4	83.6	80.8	74.7	80.6
Seasonal average within 20%	96.1	96.0	96.5	95.3	94.2	95.8

[1] 1= North replicate, 2 = Center replicate, 3 = South replicate; 2 = CO_2 exposure ring, 4 = CO_2 plus O_3 exposure ring.

[2] Percentage of time the 1-minute average CO_2 concentration was within 10 percent of the 560 $\mu l1^{-1}$ target concentration.

[3] Ring 1,2 was out of service in June because the control shed was destroyed by fire.

1999 exposure season (table 8). Maximum daily mean O_3 exposures tended to decrease during the growing season, because the number of hours each day with high O_3 target concentrations decreased. Maximum 1-hour means were similar throughout the growing season because there were always several days during the month with high (90 to 100 nll^{-1}) O_3 target concentrations. Seasonal Sum 0 exposures (0700-1900) for ambient and the treatment rings were 61.9 μll^{-1}-h and 89.0 μll^{-1}-h respectively. The seasonal ring average Sum 40 and Sum 80 exposures were 31.9 μll^{-1}-h and 3.6 μll^{-1}-h, respectively (table 8). An example of daily diurnal O_3 exposures (1-hour means) is given in the appendix (table A3).

Within-Ring Gas Distribution

A computer-controlled, multiple-port, selectable-sequencing sampler (MP3S) (Hendrey *et al.* 1993, 1999) was set up in CO_2 enrichment ring 1,2 to collect CO_2 data from 32 sample ports arranged in two layers (0.5 and 1.5 m aboveground) within the controlled experimental area. This array sampled a cylindrical volume of 1,062 m^3 (2 m height, 26 m diameter). Another sampler, made from stainless steel and Teflon with 23 sampling ports arranged in a single layer 1.5 m aboveground, was installed in an O_3 enrichment ring (1,4). The outer 2-m zone of the 30-m-diameter FACE rings did not contain sample ports because this area was considered a mixing zone in which experimental CO_2 and O_3 concentrations were not controlled. Samples were drawn sequentially from each port through the valve manifold

Table 6.—*Ozone concentration control performance by month in 1998 for the Aspen FACE project*

	O_3 and O_3 plus CO_2 treatment rings					
	1,3[1]	1,4	2,3	2,4	3,3	3,4
	Percent					
May	64.1[2]	69.5	63.9	67.6	66.2	60.2
June	72.3	78.4	72.3	76.0	70.0	67.4
July	63.1	74.2	67.7	73.0	64.4	59.0
August	67.8	61.1	62.1	62.0	69.6	65.0
September	61.8	67.5	60.8	66.4	63.0	60.9
October	62.4	77.4	66.0	70.8	63.9	61.6
Seasonal average within 10%	62.2	71.4	65.5	69.3	66.2	62.4
Seasonal average within 20%	84.0	83.9	82.6	83.7	83.1	83.5

[1]1 = North replicate, 2 = Center replicate, 3 = South replicate; 3 = O_3 exposure ring, 4 = CO_2 plus O_3 exposure ring.

[2]Percentage of time the 1-minute average O_3 concentration was within 10 percent of the target concentration.

and sent to the CO_2 or O_3 analyzer. A 15-second purge time was used between sequential samples, followed by a 45-second observation period. Information collected from these samplers was used to document the spatial uniformity of the CO_2 and O_3 concentrations within the rings.

Gas concentrations within the rings increased from the target concentration (560 µll^{-1} CO_2) at the ring center or CO_2 control point out to the VVP's (fig. 15). In this example of CO_2 concentration contours, CO_2 increased from 560 µll^{-1} at the center of the 26-m experimental area to 640 µll^{-1} near the outer borders. This was an increase over target concentration of about 14 percent across the ring, although a small portion of the experimental area (northeast quadrant) was more than 20 percent higher than the target concentration. The CO_2 contour plots are generally bowl shaped with higher concentrations near the VVP's. Daily, weekly, and monthly spatial uniformity varied because of variability in wind speed and direction, temperature, and solar radiation—all factors that affect atmospheric stability (Nagy *et al.* 1994).

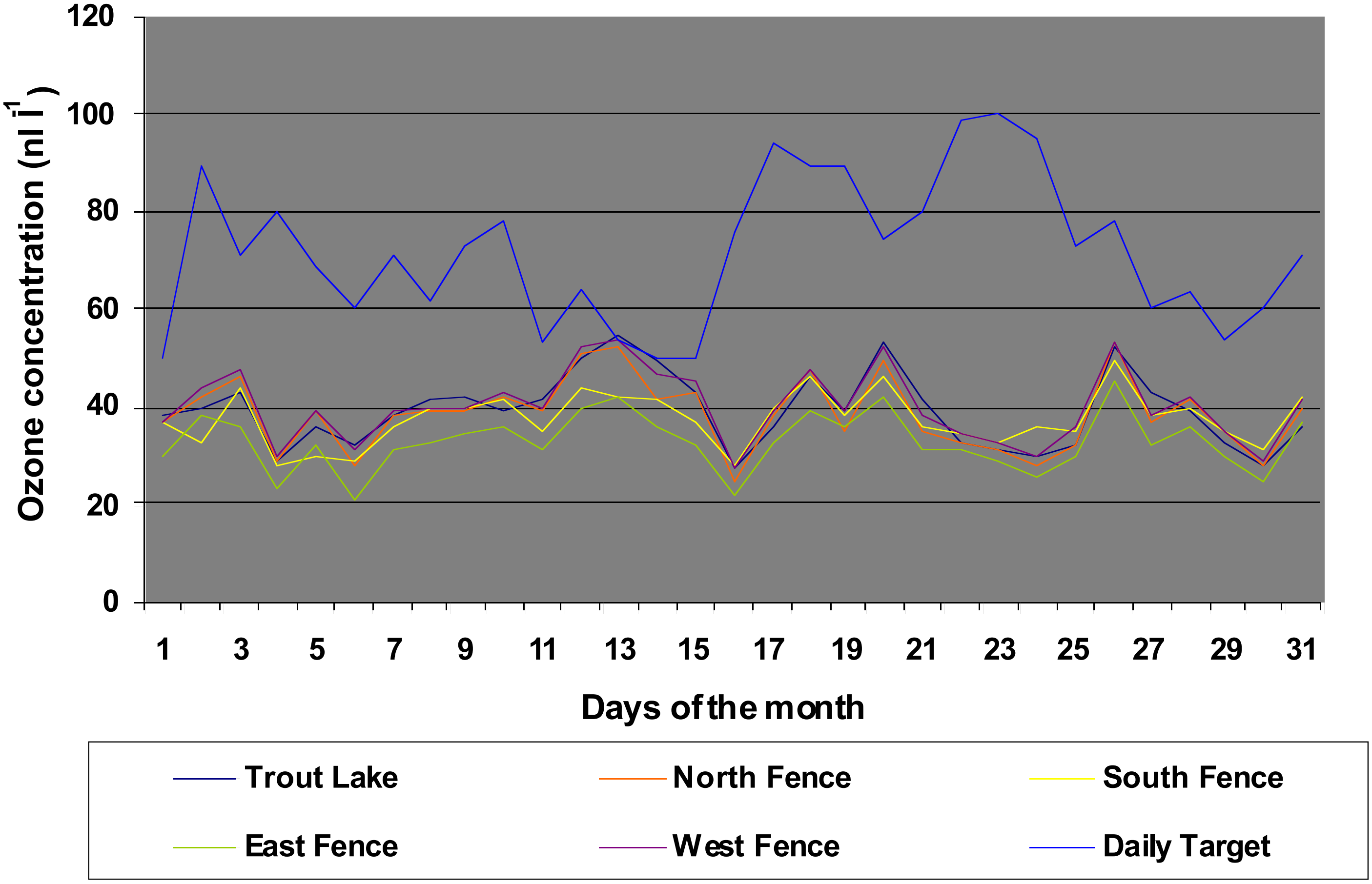


Figure 14.—*Comparison of fenceline and regional ambient O_3 concentrations with daily O_3 treatment concentrations for July 1998. Data lines show maximum 1-hr average O_3 concentrations for each day. Trout Lake and the west fence are Wisconsin Department of Natural Resources regional air quality test stations.*

Table 7.—*Monthly average O_3 concentration and Sum 0 values for the Aspen FACE project during the 1998 exposure season (ambient O_3 concentrations are compared to the O_3 exposures within the treatment rings)*

	May		June		July		Aug		Sep		Oct		1998 Season	
	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h	Mean $nl l^{-1}$	Sum 0 $\mu l l^{-1}$-h
Ambient fenceline														
North	45	16.6	35	12.5	32	11.9	44	13.6	41	11.1	29	2.1	37.7	67.8
South	42	15.6	32	11.7	31	11.5	41	12.6	35	9.3	25	1.8	34.0	62.5
East	44	16.4	31	11.3	27	10.0	37	11.4	34	9.2	24	1.8	32.8	60.1
West	48	17.8	36	13.0	32	12.0	43	13.4	41	11.0	29	2.1	38.2	69.3
Trout Lake	47	17.4	34	12.3	32	12.0	41	12.7	38	10.2	28	2.0	36.7	66.6
													mean	65.3
Ring														
1,3	52	17.9	55	19.7	57	21.2	59	18.4	64	17.3	38	2.8	54.2	97.3
1,4	52	17.2	55	19.9	55	20.5	64	19.8	64	17.3	38	2.8	54.7	97.5
2,3	54	18.6	57	20.5	58	21.6	58	18.0	65	17.6	39	2.8	55.2	99.1
2,4	53	18.3	57	20.3	57	21.2	62	19.1	65	17.6	39	2.8	55.5	99.3
3,3	53	18.1	55	19.7	56	20.8	59	18.3	65	17.6	37	2.8	54.2	97.3
3,4	50	17.5	55	19.7	57	21.2	57	17.8	63	17.0	38	2.8	53.3	96.0
													mean	97.8

Ozone means and sums are for the treatment – time interval: May, June, July : 0700-1900; August: 0900-1900; September: 1000-1900; October 1-12: 1000-1900. Start-time of the O_3 treatment was delayed late in the season because of dew on the leaf surfaces.

Table 8.—*Maximum daily and hourly mean O_3 concentration for each month of the 1999 exposure season. Sum 40 and Sum 80 O_3 exposures are also given for each month.*

Ring		Month of O_3 exposure: May	June	July	August	September	Total
	Maximum daily mean[1]	69	81	64	50	76	($\mu l1^{-1}h$)
1,3	Maximum 1-h mean	91	99	91	91	100	
	Sum 40[2] (μll^{-1}-h)	5.2	9.5	8.2	6.5	3.3	32.8
	Sum 80 (nll^{-1}-h)	296	1,492	810	746	320	3.7
	Maximum daily mean	72	81	56	54	78	
1,4	Maximum 1-h mean	91	99	116	92	100	
	Sum 40	5.1	9.7	5.9	6.8	3.4	30.9
	Sum 80	267	1,513	382	641	293	3.1
	Maximum daily mean	75	82	64	53	78	
2,3	Maximum 1-h mean	93	101	91	92	100	
	Sum 40	5.3	9.7	7.8	6.3	3.4	32.5
	Sum 80	304	1,501	834	806	361	3.8
	Maximum daily mean	73	80	65	53	78	
2,4	Maximum 1-h mean	90	99	95	91	100	
	Sum 40	5.2	9.8	8.5	6.8	3.4	33.8
	Sum 80	273	1,557	875	741	327	3.8
	Maximum daily mean	68	78	60	53	76	
3,3	Maximum 1-h mean	91	99	106	95	100	
	Sum 40	5.1	9.2	5.2	5.5	3.1	28.2
	Sum 80	333	1,546	758	837	290	3.8
	Maximum daily mean	72	81	65	53	78	
3,4	Maximum 1-h mean	90	101	90	91	100	
	Sum 40	5.2	9.7	8.4	6.8	3.4	33.4
	Sum 80	296	1,516	780	667	317	3.6
						Sum 40 ring mean	31.9
						Sum 80 ring mean	3.6

[1]The maximum daily mean O_3 concentration (nll^{-1}) is the average of 24 one-hour means for one day in any particular month. The day-of-the month with maximum O_3 concentration may differ because the episodic O_3 treatment differed from day to day.

[2]Sum 40 (μll^{-1}-h) and Sum 80 (nll^{-1}-h) are the total hourly mean O_3 concentration over 40 and 80 nll^{-1}, respectively. 1999 seasonal Sum 0 exposures (0700 to 1900) for fenceline and regional ambient, and for the treatment rings were 61.9 μll^{-1}-h, and 89.0 μll^{-1}-h.

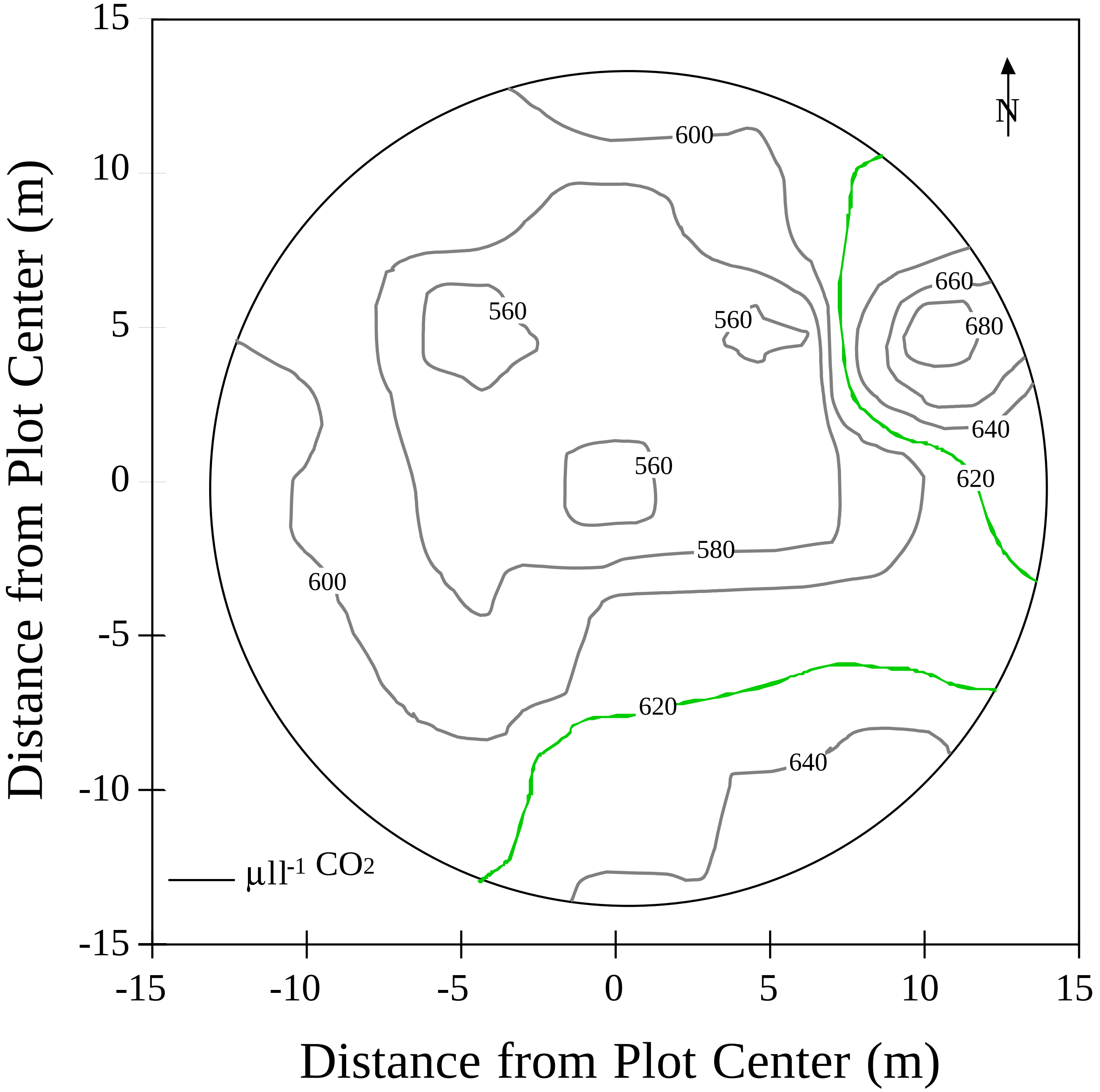


Figure 15.—*Isolines of CO_2 concentrations within the multiport-equipped CO_2 treatment ring. Isoline contours show the spatial variability of CO_2 within the ring at 1.5 m above the ground. Contours begin (circle in the figure) at 2 m inward from the vertical vent pipes. Data are average concentrations from sunrise to sunset for August 3 to September 26, 1998.*

VI. FUNDING PARTNERS, RESEARCH COOPERATION, AND RESEARCH APPROACH

FACE programs that attempt to study ecosystem processes require large exposure rings, some minimum amount of replication (three replications for the FACTS-II, Aspen FACE project) for statistical analysis, and a large number of cooperating scientists from different disciplines. Initial construction costs and yearly operating costs for such large systems are too great to be covered by any one government agency out of research funds allocated to ecosystem or global change studies. Research personnel from Michigan Technological University (MTU); Rhinelander Forestry Sciences Lab of the U.S. Department of Agriculture, Forest Service, North Central Research Station (USDA FS NCRS); Brookhaven National Laboratory (BNL); the University of Wisconsin; and the University of Michigan developed the initial research proposal that was funded with a Terrestrial Ecology and Global Change (TECO) grant, a joint program with backing from the National Science Foundation (NSF)/Department of Energy (DOE)/USDA/National Aeronautics and Space Administration (NASA). These funds provided startup money for the Aspen FACE project and generated several other funding partners (fig. 16). Major continuing supporters of the Aspen FACE project, in addition to the USDA FS NCRS, MTU, and BNL, are DOE, the USDA FS Northern Global Change Program and the Canadian Forest Service (CFS).

The Aspen FACE project is the largest FACE system in the world. It is unique because it involves both CO_2 and O_3 exposures and three species of northern hardwood trees from

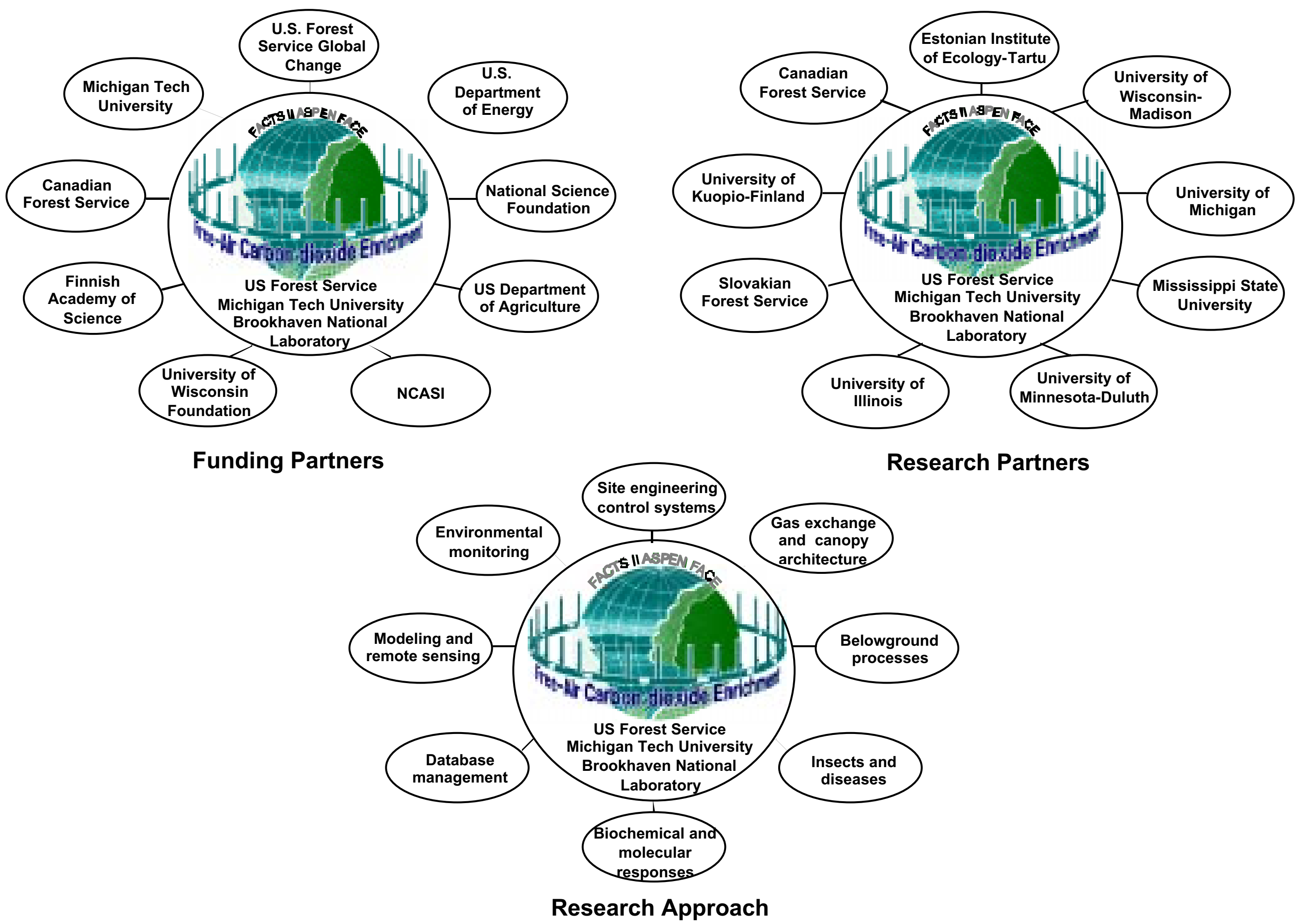


Figure 16.—*Funding partners, research partners, and research approach of the Aspen FACE project.*

genera (*Populus*, *Betula*, and *Acer*) with worldwide distribution. Such a large and complex research project requires, and has attracted, regional and international research cooperators (fig. 16). Currently more than 30 scientists are involved in studying various aspects of gas exchange, plant, insect, soil, experimental system control, and meteorological interactions. Because we are interested in many processes that range in scale from the molecular to the ecosystem level, a number of cooperating subgroups were formed to improve management of the overall project (see research approach, fig. 16). These subgroups, in turn, may contain many different scientists, different research studies, and different experimental techniques (table 4).

VII. DATABASE MANAGEMENT

The numerous investigators working at the Aspen FACE site accumulate massive amounts of data on an annual basis. It is therefore critical that we have an efficient and well-documented system for managing and archiving data. In most cases, investigators use specific data, management, and analysis techniques in their respective disciplines, but also recognize the need to have data stored in common and well-documented data formats to allow for effective archiving and use by other scientists. For this reason, we have adopted a relational database format that allows data sets to be maintained in separate files, but be linked through a series of index fields. The key index field in the data management system is a tree identifier that provides a unique integer for each tree in the study. This tree index number is linked to both locational information and biological data collected on leaves, branches, roots, physiological processes, phenology, and other variables of interest.

The database management system (DBMS) is linked with a geographic information system (GIS) that maintains the real-world coordinates of each tree in the Aspen FACE project. The coordinate system allows for spatial analyses, such as the detection of trends in growth or disease that may be related to tree location within the ring. The GIS database maintains the trees by point coverage, (e.g., identified by x, y coordinates). This database also stores information on site infrastructure, such as locations of buildings, electrical systems, pipes, and roads, and on the locations of specific experiments, such as the location of litterbags or minirhizotron tubes within the ring. By linking the GIS database to the DBMS described above, we can provide maps of trees within the ring coded by height, diameter, or other response variables.

A database management advisory committee is responsible for developing strategies for maintaining data and metadata for the facility and for overseeing the database management plan (fig. 17). The database of the Aspen FACE project consists of four components: 1) site data, 2) meteorological data, 3) operational performance data, and 4) biological data from the science team subgroups (fig. 18). The primary responsibility for the site data rests with D. Zak at the University of Michigan; meteorological data with W. Heilman at NCRS FSL, E. Lansing; operational performance data with G. Hendrey at BNL. Responsibility for the different biological data sets rests with each principal investigator within the science team subgroups. The modeling subgroup has the responsibility for integrating the overall data sets of the experiment (fig. 18). The Aspen FACE website is maintained by G. Host of the Natural Resource Research Institute (NRRI) in Duluth, Minnesota. The purpose of the website is to keep the general public and other investigators informed and updated on Aspen FACE progress and results. The web address is: www.nrri.umn.edu/aspenface or www.fs.fed.us/nc/face.

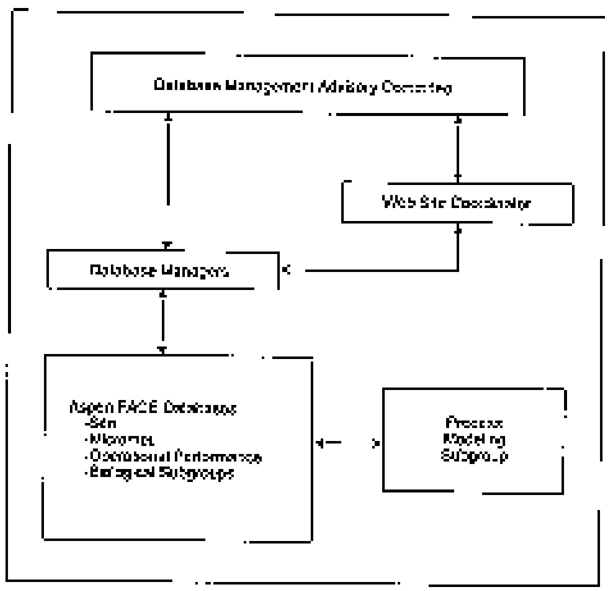


Figure 17.—*Database management organizational structure for the Aspen FACE project.*

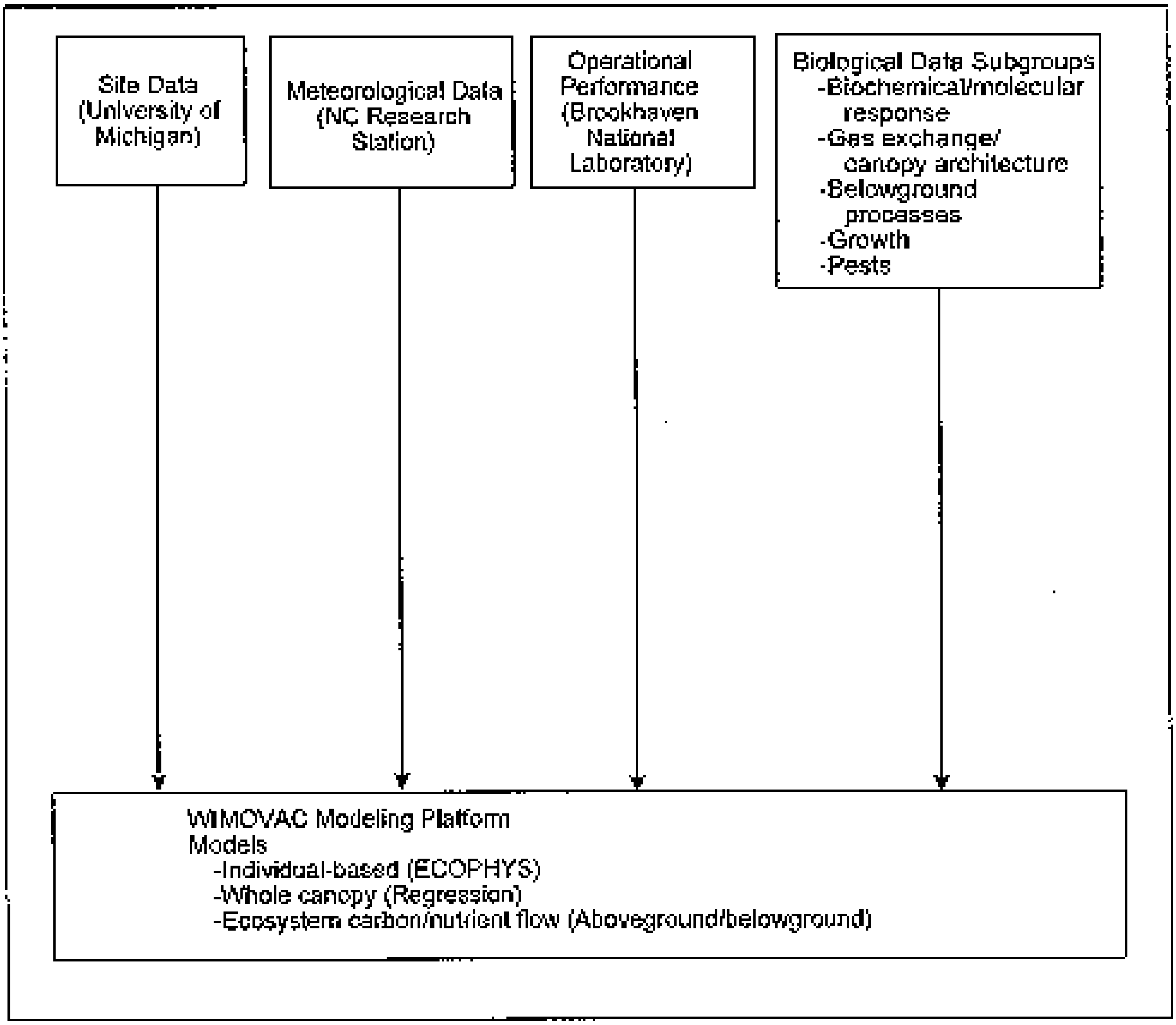


Figure 18.—*Primary data flow-diagram and modeling framework of database management for the Aspen FACE project.*

A. Site Data

The site data consist of all soil properties of the experimental site at the beginning of treatment (1997) including soil texture, moisture, NH_4 and NO_3 content, as well as percent total carbon and nitrogen (see Section IV, A, table 1 and table A2). Site data will be updated as new information becomes available, and will be available through the Aspen FACE website (www.fs.fed.us/nc/face).

B. Meteorological Data Collection and Processing

Meteorological instruments were placed in 4 of the 12 rings at the FACE site, and a 20-m tower also was erected and instrumented at the FACE site to monitor ambient atmospheric conditions at five specific heights (see Section IV, E for details).

Data collected with the ring and tower instrumentation are logged via Campbell data-loggers located at each ring and tower site. The data-loggers are programmed to provide preliminary quality control on the collected data. Currently, data are manually transferred biweekly from the data-logger storage modules at the FACE site to a desktop personal computer at the NCRS, FSL, Rhinelander, where preliminary quality checks are made. This manual downloading of meteorological data will eventually be replaced with automated electronic downloading of data from the data-loggers to personal computers at the FACE study site via a fiber optics line, followed by a manual transfer of the data to a desktop personal computer at the Rhinelander FSL at the end of each month.

At the Rhinelander FSL, ASCII data files specific to each month, ring/tower, and set of meteorological variables are created and then transferred via file transfer protocol (FTP) to the East Lansing FSL. There, the ASCII data files are reformatted and subjected to an additional quality control process involving the flagging of missing data and removal of data outliers using Visual Basic macros within Microsoft Excel. The final meteorological data files in Microsoft Excel 7.0 format are then placed on a Forest Service FTP server that is accessible to other principal investigators via the world wide web for the Aspen FACE (www.fs.fed.us/nc/face) or for direct meteorological information (climate.usfs.msu.edu/face/meteorology.html). A data directory hierarchy has been established that organizes the data files by year, month, and ring number or tower site. Users of the meteorological data files can download specific files from the web site by clicking the appropriate file icons. Information on the file names, file formats, and directory structure for the FTP site is being developed in the form of a README file that can also be downloaded by users as needed.

C. Operational Performance Data

The operational performance data at the Aspen FACE site is managed by BNL personnel as part of the overall FACE Database Management Plan under the direction of G. Hendrey. The Data Manager is BNL's Internet gateway to all FACE databases and is available online at (www.face.bnl.gov).

The BNL web site provides real time performance *Quickbooks*: FACE data archive compact disks; data reduction pathways; quality assurance issues and procedures; long term archive at the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee; and fair use policy. That policy states that the data sets available in this site are provided as a courtesy as part of our ongoing commitment to provide experimental systems, software tools, and data sources for the research community.

We have adopted the fair use policy suggested by CDIAC and the Ameriflux scientific community, namely,

> *"Kindly inform the appropriate Principal Investigators of how you are using site data and of any publication plans. If the Principal Investigators feel that they should be acknowledged or offered participation as authors, they will let you know and we assume that an agreement on such matters will be reached prior to publishing and/or use of the data for publication. If your work directly competes with the Principal Investigator's analysis, they may ask that they have the opportunity to submit a manuscript before you submit the one that uses their data. In addition, when publishing, please acknowledge the agency that supported the research."*

D. Biological Data

Biological data from investigators in the science team subgroups is maintained in an experimental format designed by each investigator. Data sharing, quality assurance, and statistical analysis also are the responsibility of each Principal Investigator. Sharing of data and fair use of other's data are strongly encouraged to maximize interpretation of interactions between environmental variables, and to maximize scientific information obtained from the Aspen FACE project.

VIII. PROCESS MODELING AT THE ASPEN FACE SITE

The modeling efforts at the Aspen FACE site provide for an integration of the meteorological, biological, and operational data collected in the experiment. The fundamental purpose of process modeling work is to allow us to extrapolate the results of the study beyond the range of conditions used in the experimental design. The target O_3 concentrations, for example, are not extraordinarily high—they are equivalent or below typical O_3 concentrations during temperature inversions in Midwestern cities. It would therefore be important to extrapolate the information on growth responses and alterations of competitive relationships at O_3 and CO_2 concentrations beyond those used at the Aspen FACE site. Mechanistically based process models allow these extrapolations (Isebrands and Burk 1992).

Our modeling work is centered on the WIMOVAC model, a flexible modeling platform that provides for management of environmental data, process modeling at various spatial scales, and prediction of plant responses to climate and atmospheric change (fig. 19) (Humphries and Long 1995). The program allows users to vary parameters, numerical assumptions, vegetation, and climate and

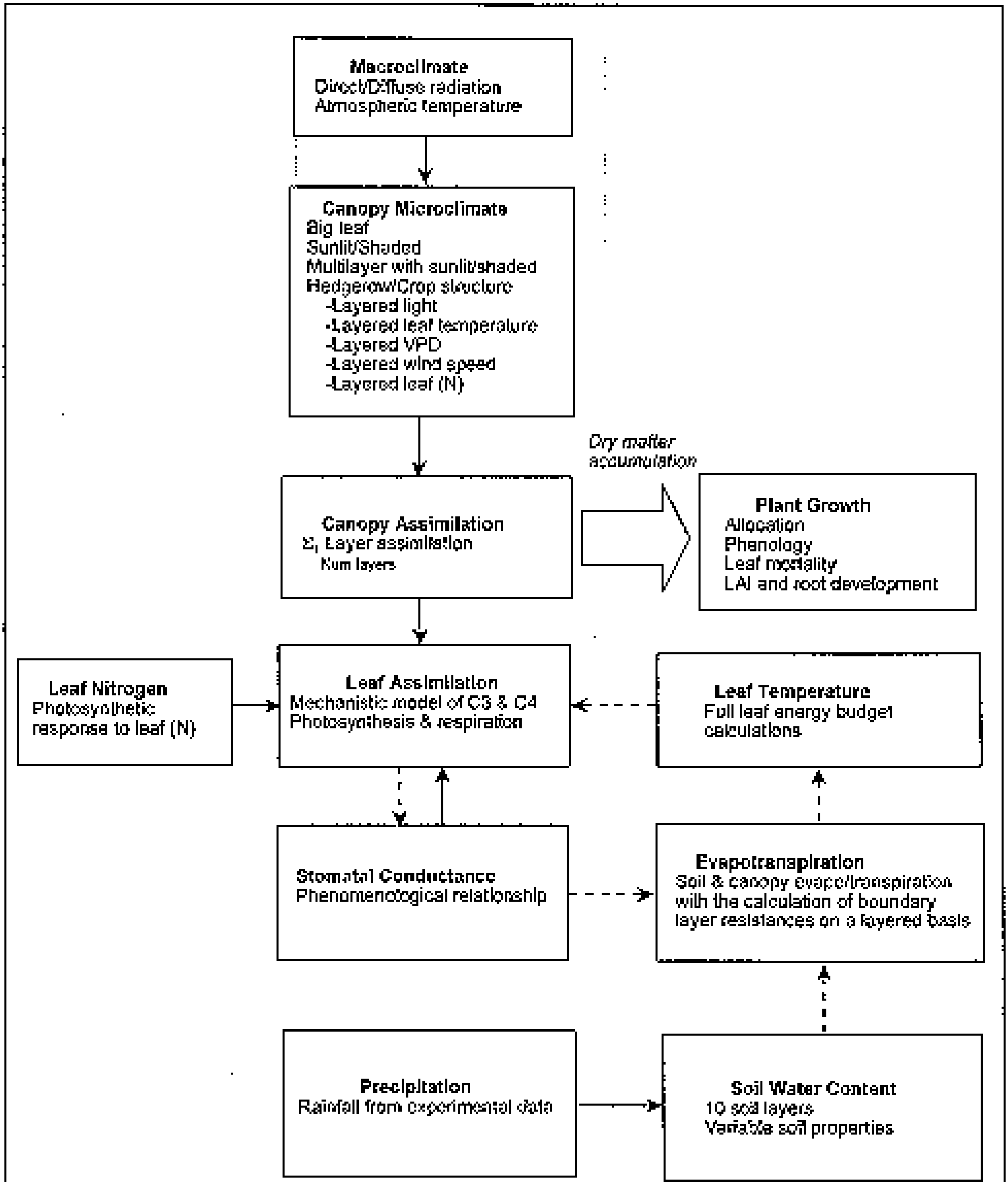


Figure 19.—*The WIMOVAC model schematic showing the main sub-model components. These components are available as separately interactive sub-model dialogues and as integrated functions within the whole-plant canopy model (Humphries and Long 1995).*

atmospheric variables, and visualize their outcomes in a straightforward way. The flexibility and highly interactive nature of controls adopted by WIMOVAC makes it well suited as a platform for both managing data and conducting canopy-level simulations of FACE sites.

WIMOVAC effectively simulates multilayer homogeneous vegetation canopies. Under the multispecies and structurally heterogeneous conditions imposed at the Aspen FACE site, however, the differences in initial plant architecture and differential responses to treatments among clones require a more detailed simulation of the plant canopy. For this reason, we are integrating elements of the ECOPHYS growth process model into the modeling platform. ECOPHYS is an individual-based process model that uses parallel computing strategies to calculate photosynthesis of individual leaves within a structurally heterogeneous forest canopy. It allows for different clonal architectures, differential response to trace gases, and competitive interactions among trees (Host *et al.* 1996, Isebrands *et al.* 2000). Both ECOPHYS and WIMOVAC are adapting Component Object Model (COM) protocols that allow models written in different languages and residing on different computers to communicate. These two modeling strategies are highly complementary and provide for both "bottom-up" (i.e., individual-based) and "top-down" (aggregation-based) modeling approaches.

In addition to simulation modeling, we are using regression and other statistically based approaches to scale information from the individual leaf to the canopy. These sample-based approaches provide a means of describing whole-tree phenomena by instantaneous data with information on specific leaf area, total leaf area, and numbers of leaves. This morphometric approach to scaling will allow us to compare biological responses among clones, treatment, and other factors within the experiment.

Lastly, there is an ecosystem scale of modeling that incorporates aboveground and belowground responses to treatments, such as competitive interactions among trees, alterations to carbon and nutrient cycles, and the response of soil and microbial pools. This ecosystem approach will be important for addressing long-term questions on nutrient cycling, carbon sequestration, and plant-insect interactions under global change conditions.

IX. STATISTICAL CONSIDERATIONS AND DATA ANALYSIS

The method of analysis chosen depends on the physical design of an experiment, the selection of treatments and levels of treatments, the sampling of experimental units for measurement, and the questions (hypotheses) we choose to ask. Not all of the aforementioned factors are defined during the design of an experiment, especially an experiment as large and complex as the Aspen FACE project. For example, when trees within treatment combinations are selected for measurement of physiological characteristics, are the same trees measured each time or is each measurement made on a different random sample of individuals within plots? This choice, which determines whether data need to be treated as repeated measures or as independent random samples, is commonly made after the experiment is designed and is often made differently by different investigators. Other examples exist, all of them leading to the conclusion that no single method of analysis will be rigorously applicable to all data and the questions that are asked of those data. Having said that, however, we put forth in this section some overall considerations that will probably hold true over the life of the study. Within that framework, we also include a sample analysis of early chlorophyll meter (SPAD) measurements.

The Aspen FACE experimental design, at the whole-plot level, is three replications of a randomized complete block design with four treatment combinations. Subplots are established within whole plots and include mixtures of species (aspen, birch, maple) and mixtures of genotypes of the same species (clones of aspen). We assume it will be of interest to test for significant effects of whole-plot treatments (CO_2, O_3), whole-plot interactions (CO_2 x O_3), subplot treatments (clones—considering the aspen subplots), and interactions between subplots and whole-plot treatments (i.e., clone x CO_2 x O_3) on various dependent variables. This suggests that the application of analysis of variance, in some form, is appropriate (Steel and Torrie 1980). To apply analysis of variance, we assume that replications are a random effect, treatments are fixed effects (exposure concentrations were clearly not chosen at random from all possible concentrations), and clones are fixed effects (again, not chosen at random from all possible genotypes within the

Table 9.—*Sample data analysis of chlorophyll meter (SPAD) observations made on several trees of each clone within the aspen subplots*

Source of variation	Sum of squares	Degrees of freedom	Mean squares	f-ratios	Expected mean squares
Whole-plots					
Replications	140.42	2	70.21	0.48^{ns}	$\sigma_{e(b)}^2 + 43.44\ \sigma_{e(a)}^2 + 173.77\ \sigma_r^2$
Treatments	1,871.77	3	623.92	4.76^{*}	$\sigma_{e(b)}^2 + 39.05\ \sigma_{e(a)}^2 + Q_3\ k_t^2$
CO_2	256.96	1	256.96	1.96^{ns}	
O_3	1,511.41	1	1,511.41	11.53^{*}	
CO_2 x O_3	92.61	1	92.61	0.71^{ns}	
Error (a)	871.88	6	145.31	7.99^{**}	$\sigma_{e(b)}^2 + 43.99\ \sigma_{e(a)}^2$
Subplots					
Clones	944.72	4	236.18	12.98^{**}	$\sigma_{e(b)}^2 + Q_2\ k_c^2$
Clones x Treatments	388.71	12	32.39	1.78^{*}	$\sigma_{e(b)}^2 + Q_1\ k_{ct}^2$
Clone x CO_2	71.62	4	17.91	0.98^{ns}	
Clone x O_3	271.82	4	67.96	3.73^{**}	
Clone x CO_2 x O_3	51.28	4	12.82	0.70^{ns}	
Error (b)	9,189.68	505	18.20		$\sigma_{e(b)}^2$

Notes: Overall analysis by general linear models procedure (PROC GLM, SAS® Institute Inc., 1988) with replications, treatments, replications x treatments (*Error* (a)), clones, and clones x treatments specified in the “mode.” Replications, replications x treatments, *Error* (a) and *Error* (b) were assumed random; all other effects were assumed fixed. *Error* (b) is a pooled term containing variation due to replication x subplot effect interactions and variation due to subsampling (leaf positions and ages). Variation due to CO_2, O_3, and CO_2 x O_3 effects was estimated by linear contrasts. Interactions between clone and treatment combinations were also estimated by linear contrasts. F-ratios for subplot effects and *Error* (a) all used *Error* (b) as the denominator. F-ratios for whole-plot treatments are Satterthwaite approximations because of unequal coefficients associated with $\mathbf{s}_{e(a)}^2$ in the replication and treatment expected mean squares. F-ratios for whole-plot treatment combinations (single degree of freedom orthogonal linear contrasts) use the same synthesized denominator as the F-ratio for treatments (synthesized denominator 131.05 with tests on 1 and 6.19 degrees of freedom). ** = probability of f due to chance < 0.01, * = probability of f due to chance > 0.01 and < 0.05, ^{ns} = probability of f due to chance > 0.05.

species). In the data analysis sample (table 9), we consider SPAD readings taken from several trees of each clone within the aspen suplots of each whole plot. The model for the analysis is:

$$X_{ijk} = m + R_i + T_j + RT_{ij} + C_k + CT_{jk} + e_{ijk}$$

where X_{ijk} is an observation, m is the experimental mean, R_i is the effect of the i^{th} replication, T_j is the effect of the j^{th} treatment, RT_{ij} is the interaction between the i^{th} replication and the j^{th} treatment (whole-plot error or *Error* (a)), C_k is the effect of the k^{th} clone, CT_{jk} is the interaction between the j^{th} treatment and the k^{th} clone, and e_{ijk} is a pooled subplot error (*Error* (b)).

Error (a) is a pooled component containing variation attributable to replications x CO_2, replications x O_3, and replications x CO_2 x O_3. *Error* (b) is also a pooled estimate containing variation attributable to replications x clones and to variation among trees within clone-treatment-replication combinations. It would also be valid to extend the model by one term to divide *Error* (b) into replication x clone and subsampling terms.

We further test for effects of various treatments and their interactions, and for interactions between clone and various treatment combinations by extracting appropriate sums of squares by orthogonal linear contrasts. Appropriate f-tests are clearly identifiable by inspection of expected mean squares and utilize the Satterthwaite approximation where needed because of imbalance in sampling (Steel and Torrie 1980).

For analyses that do not involve comparisons among effects within rings, block effects can be treated as fixed or random according to the particular considerations of the individual investigator. For mixed model analyses utilizing the split-plot design with random block effects and fixed treatment effects, block x treatment variation should be evaluated to determine the appropriate error structure of the model with regard to pooling or partitioning of the *Error* (a) term. The PROC Mixed component within the SAS® System software (SAS Institute, 1989-1996) is ideal for analysis of mixed model designs and can readily incorporate covariance, repeated measures, and spatial statistics components (Littell *et al.* 1996). PROC Mixed is preferred for split-plot designs as it automatically calculates correct error terms and degrees of freedom, and adjusts for sampling imbalance. For models with entirely fixed effects, the PROC GLM component of the SAS® software is appropriate.

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XI. ACKNOWLEDGMENTS

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XII. APPENDICES

Table A1.—*Relationships between soil matric potential and gravimetric water content for the Aspen FACE site*

Matric potential (-MPa)		Gravimetric[1] moisture content (%)	Standard deviation
0		38.2	3.18
0.006		34.7	2.46
0.010		30.3	2.39
0.030	Field capacity	16.5	1.48
0.100		5.6	0.63
0.690		5.0	0.91
1.500	Wilting point	4.7	0.81
1.780		4.4	0.72
Water holding capacity (FC-WP)		11.8	0.90

[1]Site mean gravimetric water contents at each matric potential are presented because values did not differ significantly among treatments or among blocks. The moisture contents indicate the Aspen FACE site is a fairly uniform fine sandy loam to loam soil.

Table A2.—*Detailed soil properties for the Aspen FACE site for 1997. Values are ring means with standard deviations listed in parenthesis*

	Control			$+CO_2$			$+O_3$			$+CO_2$, $+O_3$				
Treatment ring	**1,1**	**2,1**	**3,1**	**1,2**	**2,2**	**3,2**	**1,3**	**2,3**	**3,3**	**1,4**	**2,4**	**3,4**	**MEAN**	***n***
Soil texture														
% sand	52.9	53.2	59.3	51.1	56.3	54.3	57.9	56.5	60.5	57.3	55.9	51.7	55.6 (2.99)	12
% silt	39.0	36.5	32.8	40.4	36.5	36.4	36.9	37.9	31.0	34.8	37.2	40.1	36.6 (2.79)	12
% clay	8.0	10.3	7.9	8.5	7.3	9.4	5.1	5.5	8.5	7.9	6.9	8.2	7.8 (1.52)	12
Gravimetric moisture content														
$\theta_{(-0.3\ bar)}$	0.178	0.172	0.138	0.196	0.154	0.164	0.151	0.167	0.159	0.158	0.166	0.176	0.164 (0.015)	12
$\theta_{(-15\ bar)}$	0.066	0.058	0.057	0.083	0.060	0.056	0.050	0.069	0.059	0.050	0.051	0.058	0.059 (0.010)	12
$\theta_{(WHC)}$	0.112	0.114	0.081	0.113	0.094	0.108	0.101	0.098	0.100	0.108	0.115	0.118	0.104 (0.011)	13
D_b (Mg/m^3)	1.25 (0.114)	1.16 (0.104)	1.40 (0.059)	1.21 (0.090)	1.32 (0.120)	1.38 (0.105)	1.41 (0.134)	1.28 (0.073)	1.26 (0.179)	1.52 (0.096)	1.41 (0.043)	1.37 (0.103)	1.31 (0.141)	120
pH	5.76 (0.189)	5.47 (0.090)	5.25 (0.180)	5.73 (0.227)	5.42 (1.004)	5.20 (0.100)	5.94 (0.181)	5.79 (0.083)	5.00 (0.552)	6.13 (0.135)	5.64 (0.161)	5.16 (0.160)	5.55 (0.467)	59
NH_4^+-N (μgN/g)	1.99 (0.516)	0.71 (0.173)	0.40 (0.115)	1.23 (0.252)	1.09 (0.463)	0.49 (0.217)	1.06 (0.315)	0.62 (0.087)	0.88 (0.267)	0.50 (0.169)	0.59 (0.188)	0.60 (0.264)	0.85 (0.501)	60
NO_3^--N (μg N/g)	12.26 (4.536)	14.47 (10.843)	18.44 (17.076)	16.87 (2.224)	16.97 (4.116)	11.86 (4.127)	12.27 (6.359)	8.97 (2.951)	14.23 (5.967)	7.74 (1.454)	6.47 (4.571)	21.73 (23.643)	13.52 (9.804)	60
Extractable P (μg P/g)	161.22 (8.965)	103.80 (7.939)	107.52 (6.983)	175.54 (22.361)	144.06 (14.513)	144.43 (20.053)	141.12 (10.528)	124.63 (5.206)	131.54 (37.959)	149.22 (12.952)	122.38 (1.289)	136.22 (20.747)	136.81 (25.208)	60
Total C (%)	1.79 (0.229)	1.56 (0.120)	1.27 (0.114)	2.09 (0.104)	1.46 (0.094)	1.48 (0.183)	1.24 (0.111)	1.80 (0.198)	1.77 (0.244)	1.115 (0.111)	1.23 (0.058)	1.55 (0.101)	1.53 (0.308)	59
Total N (%)	0.13 (0.017)	0.12 (0.008)	0.11 (0.009)	0.17 (0.008)	0.11 (0.007)	0.12 (0.015)	0.09 (0.008)	0.14 (0.015)	0.14 (0.019)	0.08 (0.008)	0.10 (0.003)	0.12 (0.013)	0.12 (0.025)	59

(table A2 continued on next page)

(table A2 continued)

Treatment ring	Control 1,1	2,1	3,1	$+CO_2$ 1,2	2,2	3,2	$+O_3$ 1,3	2,3	3,3	$+CO_2, +O_3$ 1,4	2,4	3,4	MEAN	*n*
C:N	13.49 (0.209)	13.28 (0.213)	11.86 (0.269)	12.29 (0.209)	12.90 (0.197)	12.01 (0.255)	14.42 (0.302)	13.23 (0.163)	12.96 (0.294)	13.63 (0.050)	12.40 (0.240)	12.49 (0.501)	12.49 (0.763)	59
Ca^{2+} (cmol(+)/kg)	0.18 (0.120)	0.13 (0.073)	n/d	0.59 (0.076)	0.09 (0.081)	0.10 (0.085)	0.08 (0.063)	0.01 (0.020)	0.08 (0.068)	0.20 (0.035)	n/d	0.25 (0.083)	0.14 (0.167)	60
Mg^{2+} (cmol(+)/kg)	0.16 (0.074)	0.10 (0.014)	0.07 (0.018)	0.23 (0.033)	0.14 (0.009)	0.08 (0.008)	0.12 (0.020)	0.14 (0.011)	0.11 (0.019)	0.16 (0.022)	0.10 (0.009)	0.08 (0.016)	0.12 (0.050)	60
K^+ (cmol(+)/kg)	0.05 (0.016)	0.04 (0.010)	0.02 (0.010)	0.07 (0.010)	0.04 (0.010)	0.05 (0.009)	0.04 (0.004)	0.04 (0.011)	0.05 (0.010)	0.04 (0.003)	0.02 (0.005)	0.04 (0.009)	0.04 (0.016)	60
NH_4^+ (cmol(+)/kg)	0.01 (0.004)	0.09 (0.001)	<0.01 (0.001)	0.01 (0.002)	0.01 (0.003)	<0.01 (0.002)	0.01 (0.002)	<0.01 (0.001)	0.01 (0.002)	<0.01 (0.001)	<0.01 (0.001)	<0.01 (0.002)	0.01 (0.004)	60
Exchangeable bases (cmol(+)/kg)	0.41 (0.200)	0.27 (0.086)	0.10 (0.028)	0.89 (0.092)	0.27 (0.085)	0.23 (0.089)	0.25 (0.084)	0.20 (0.034)	0.25 (0.084)	0.40 (0.034)	0.12 (0.014)	0.38 (0.103)	0.31 (0.216)	60
Exchangeable acidity (cmol(+)/kg)	0.18 (0.094)	0.27 (0.082)	0.42 (0.180)	0.07 (0.042)	0.17 (0.056)	0.42 (0.049)	0.19 (0.067)	0.11 (0.066)	0.17 (0.089)	0.10 (0.064)	0.16 (0.116)	0.43 (0.141)	0.22 (0.151)	60
Cation exchange capacity (cmol(+)/kg)	0.59 (0.143)	0.54 (0.106)	0.51 (0.163)	0.96 (0.121)	0.45 (0.095)	0.64 (0.100)	0.43 (0.087)	0.31 (0.068)	0.43 (0.063)	0.50 (0.069)	0.28 (0.112)	0.82 (0.088)	0.54 (0.212)	60
% base saturation	66.58 (18.454)	50.51 (12.801)	20.95 (10.097)	92.97 (3.270)	60.30 (10.562)	34.63 (9.419)	56.52 (15.453)	67.46 (17.356)	60.45 (18.865)	80.14 (10.026)	52.20 (29.648)	47.45 (13.208)	57.51 (23.107)	60

On July 22, 1997, 10 soil samples were collected per ring using random azimuths and distances from the center. Soils were collected to a depth of 10 cm using a 3.27 cm diameter core (vol = 218.13 cm^3). Samples were packed on ice, and returned for analysis at University of Michigan's Terrestrial Ecosystem Laboratory. Soil cores were weighed and subsamples were oven-dried for determination of bulk density. Pairs of cores from each ring were composited to yield 5 samples per ring. Subsamples were used for measurement of pH (1:2 soil:deionized water), KC1-extractable ammonium and nitrate (Alpkem RFA 300, Clackamas, OR), dilute acid-fluoride-extractable P (Alpkem RFA 30), exchangeable bases (Perkin-Elmer 403, Norwalk, CT), exchangeable acidity. Soil samples were ground in a roller mill prior to analysis of total soil carbon and nitrogen (CE Elantech, NA 2500 Elemental Analyzer, Lakewood, NJ). Subsamples of each of the five samples per ring were composited (equal weight) prior to determination of soil texture (hydrometer method). Soil moisture desorption curves were constructed using a ceramic pressure plate extractor (Soilmoisture Equipment Corp., Santa Barbara, CA).

Table A3.—*Diurnal ozone concentrations for ring 1,4 of the Aspen FACE site for June 1999 (1-hour averages in nll[-1])*

Day	O_3 day avg	Time at the end of hour (local time) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
01	35	21.0	20.9	20.4	21.3	21.0	21.0	20.1	19.8	19.7	40.7	62.4	67.1	72.2	75.2	73.5	68.7	26.8	27.2	25.0	24.3	22.7	22.8	21.0	15.1
02	40	11.8	11.4	10.0	9.8	10.1	11.4	13.0	20.3	41.8	54.6	60.4	66.9	70.6	74.4	74.3	75.4	75.3	72.5	69.0	43.1	35.7	28.1	16.2	7.6
03	52	8.4	4.4	4.4	4.1		3.6	7.2	15.3	27.1	65.6	79.8	83.3	86.5	90.2	88.4	91.1	89.2	87.7	85.7	49.3	38.5	44.7	53.2	51.7
04	59	46.2	42.8	40.6	42.8	43.4	40.0	37.7	49.4	62.7	71.4	79.3	55.4	57.8	87.4	88.5	92.0	89.4	87.9	84.1	50.4	43.4	39.1	36.1	41.5
05	43	44.8	46.8	52.0	51.7	49.7	48.2	45.2	42.1	37.0	32.4				32.5	45.1	48.2	48.7	50.2	45.4	38.9	41.5	37.0	30.0	28.9
06	47	32.9	38.5	35.3	37.1	35.0	36.3	34.4	32.5	30.3	31.2	31.4	33.2	78.9	88.6	88.7	91.4	84.3	47.7	43.6	42.7	41.2	41.1	38.9	35.6
07	57	32.2	29.3	28.0	27.0	28.2	28.7	28.7	43.9	63.1	72.6	79.0	83.2	87.7	89.3	89.3	89.1	90.4	88.0	82.6	59.1	54.3	38.0	38.2	28.1
08	51	22.5	21.6	23.3	24.7	14.9	9.3	10.8	28.8	36.4	59.9	78.4	81.6	88.8	89.5	89.3	90.9	89.7	87.5	84.2	46.9	31.4	28.9	32.1	46.8
09	56	43.5	32.9	23.5	23.3	23.5	27.1	24.8	36.2	54.0	37.1	39.0	42.1	89.1	95.0	94.1	95.2	94.1	93.3	88.6	66.6	56.7	49.7	50.7	51.4
10	40	53.9	48.9	41.2	32.4	20.9	27.8	29.0	30.6	36.2	37.1	39.5	57.9	94.4	52.3	38.5	40.2	38.7	38.7	38.9	34.6	31.3	28.9	28.9	26
11	45	25.5	22.1	21.3	23.4	27.7	28.2	31.6	38.5	41.0	43.5	51.5	84.0	87.5	89.2	68.1	48.4	52.9	49.0	47.4	40.6	36.9	33.2	39.6	42.2
12	47	39.8	29.0	24.1	23.6	23.6	23.8	22.9	24.4	47.9	64.3	71.1	77.0	78.9	85.7	85.7	84.6	83.9	82.6	77.8	40.3	18.9	13.5	8.5	5.7
13	51	6.2	4.4	4.1	3.3	3.4	3.2	5.6	13.6	29.5	45.6	76.2	81.9	86.4	88.9	90.5	89.2	88.4	87.8	81.7	45.2	41.5	37.3	35.0	35.0
14	33	32.8	30.7	29.1	27.7	27.3	26.5	23.9	27.6	57.9	67.8	77.6	34.8	28.8	31.9	31.6	31.6	32.2	33.0	38.1	37.3	32.0	21.9	9.9	5.1
15	38		6.5	8.0	7.8	7.6	9.0	15.4	19.6	25.4	57.2	68.1	72.3	74.5	67.9	40.7	71.8	80.9	78.6	74.5	31.6	14.3	11.9	10.8	11.2
16	30	9.9	10.5	9.9	9.7	9.1	13.6	20.7	22.5	27.8	26.5	54.9	76.7	83.2	68.4	36.4	36.5	35.9	36.7	37.2	35.8	20.2	13.9	8.6	6.1
17	41	6.4	5.7	4.3	4.8	6.3	3.6	9.3	16.2	25.6	34.1	70.3	77.0	83.3	83.5	86.0	83.2	85.4	83.8	77.6	35.1	20.8	17.5	14.8	14.2
18	48	16.1	11.7	8.6	7.9	6.3	5.4	8.9	26.0	30.4	67.0	77.0	82.6	86.6	88.3	90.4	88.6	89.7	88.0	84.6	50.3	42.6	34.0	32.2	23.6
19	52	22.7	33.1	35.3	27.2	20.8	15.1	18.8	26.5	56.1	71.2	77.6	82.8	87.1	89.6	89.4	89.2	90.3	69.0	43.3	43.6	46.6	40.2	24.4	42.5
20	53	48.8	46.4	44.0	30.0	34.7	34.8	30.6	27.7	33.1	28.9	32.3	37.4	45.1	79.4	90.3	90.5	89.5	89.0	86.2	69.3	47.8	46.9	55.3	56.5
21	73	56.7	59.3	58.3	47.2	41.8	27.6	42.2	65.4	74.0	81.2	86.1	89.1	92.4	94.3	95.2	95.7	94.6	95.2	90.0	81.8	65.4	58.0	71.1	82.1
22	81	86.2	86.8	84.9	83.8	82.0	78.0	71.3	73.9	80.9	87.2	92.2	95.3	97.6	98.8	99	99	99	98.7	66.9	62.8	60.4	55.2	54.7	52.0
23	46	51.0	47.8	45.2	47.3	46.6	44.1	48.8	46.4	45.5	51.4	53.2	54.6	71.0	52.7	51.3	48.4	46.8	46.0	45.1	37.2	33.9	28.2	26.3	27.4
24	48	25.7	22.2	22.3	20.7	17.0	13.7	16.3	23.4	38.5	69.8	74.6	78.8	81.5	85.1	83.8	85.9	84.2	83.8	80.5	45.9	21.4	21.3	26.3	32.5
25	52	30.8	20.8	12.3	10.5	7.9	6.4	8.9	25.8	38.7	63.5	74.8	79.1	81.9	83.9	85.5	85.4	84.0	83.3	79.6	62.1	58.2	51.7	50.9	50.2
26	70	47.7	49.3	48.4	47.4	44.7	45.2	40.4	48.8	64.1	82.9	88.5	91.6	97.5	99.3	99	99	99	97.6	94.3	64.7	56.5	62.1	55.8	53.8
27	60	54.5	48.8	40.0	44.8	45.3	45.0	44.9	42.2	59.2	76.0	81.1	83.6	85.7	88.4	90.9	88.9	91.7	88.1	85.2	33.2	29.0	27.5	28.2	29.2
28	36	26.5	27.1	17.8	23.5	22.1	21.8	21.7	21.1	46.8	76.2	79.7	83.3	89.4	63.4	27.4	21.7	18.9	16.5	22.0	22.4	24.2	26.5	27.5	26.9
29	24	22.0	20.9	17.7	14.8	12.2	11.4	11.7	14.5	18.8	23.8	27.6	30.8	33.6	34.8	36.2	36.4	35.8	37.8	34.9	33.7	19.0	14.5	12.5	13.8
30	32	13.1	12.2	6.5	9.5	11.5	16.9	29.7	29.4	50.1	75.8	30.5	31.5	59.9	31.0	34.2	38.1	38.5	39.7	39.3	33.6	27.2	32.6	37.3	38.8

47.9 nll[-1] is 0_3 average for June for 24 h
60.9 nll[-1] is 0_3 average for June for 0700 to 1900
34.3 µll[-1]-h is 0_3 Sum 0 for June for 24 h
21.9 µll[-1]-h is 0_3 Sum 0 for June for 0700 to 1900

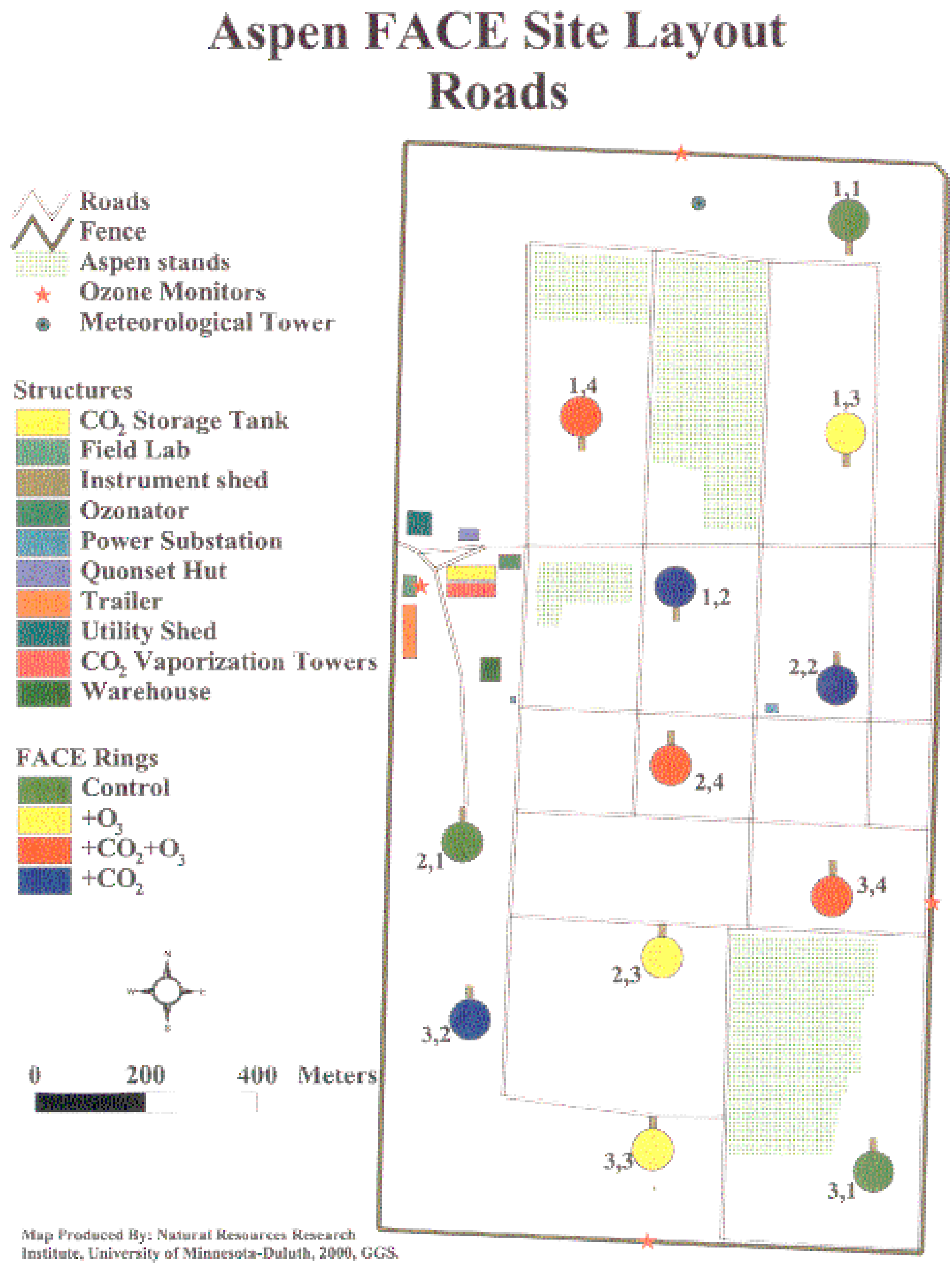

Figure A1.—*Aspen FACE site layout—Roads.*

Aspen FACE Site Layout
Meteorological Stations

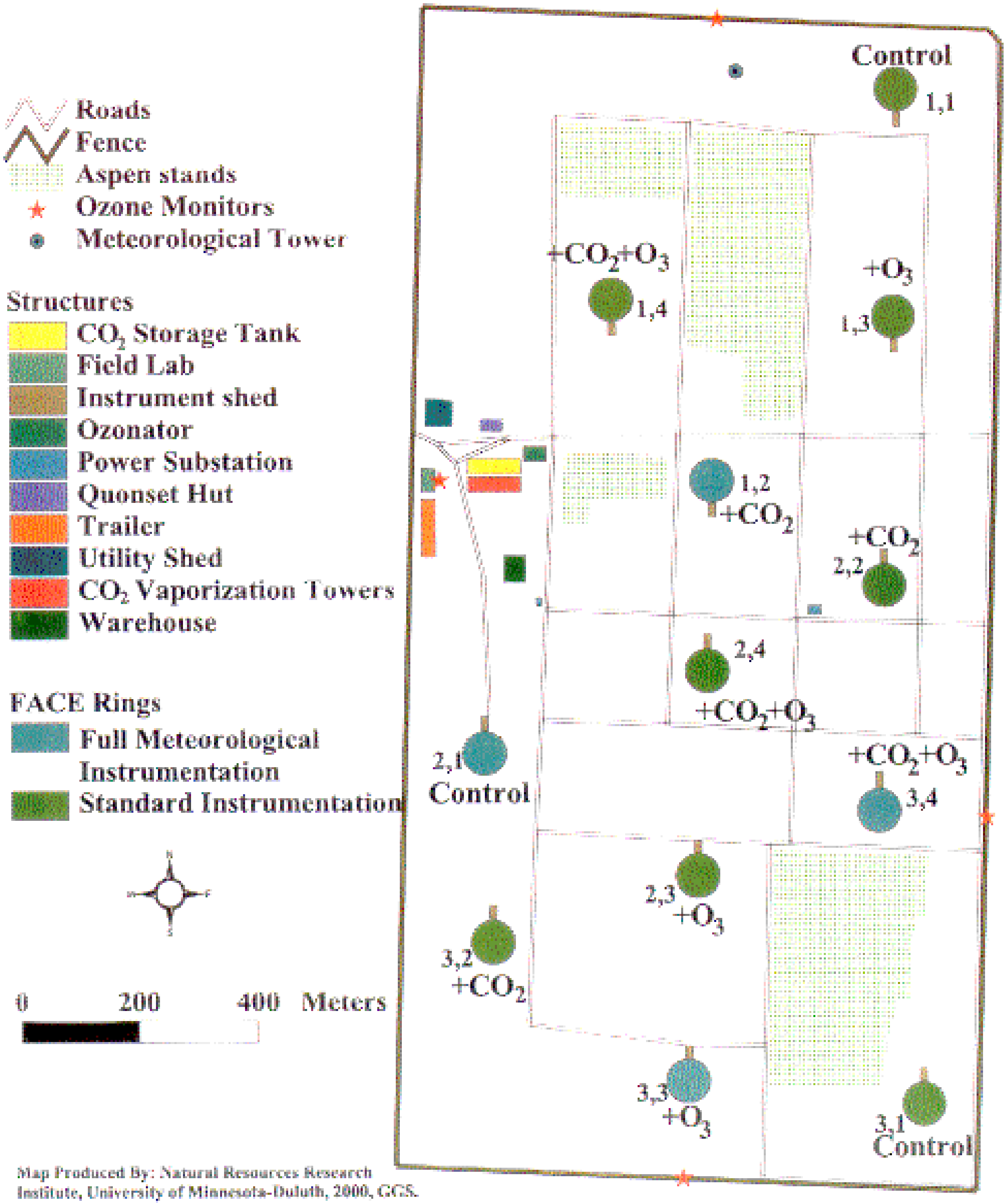

Figure A2.—*Aspen FACE site layout—Meteorological stations.*

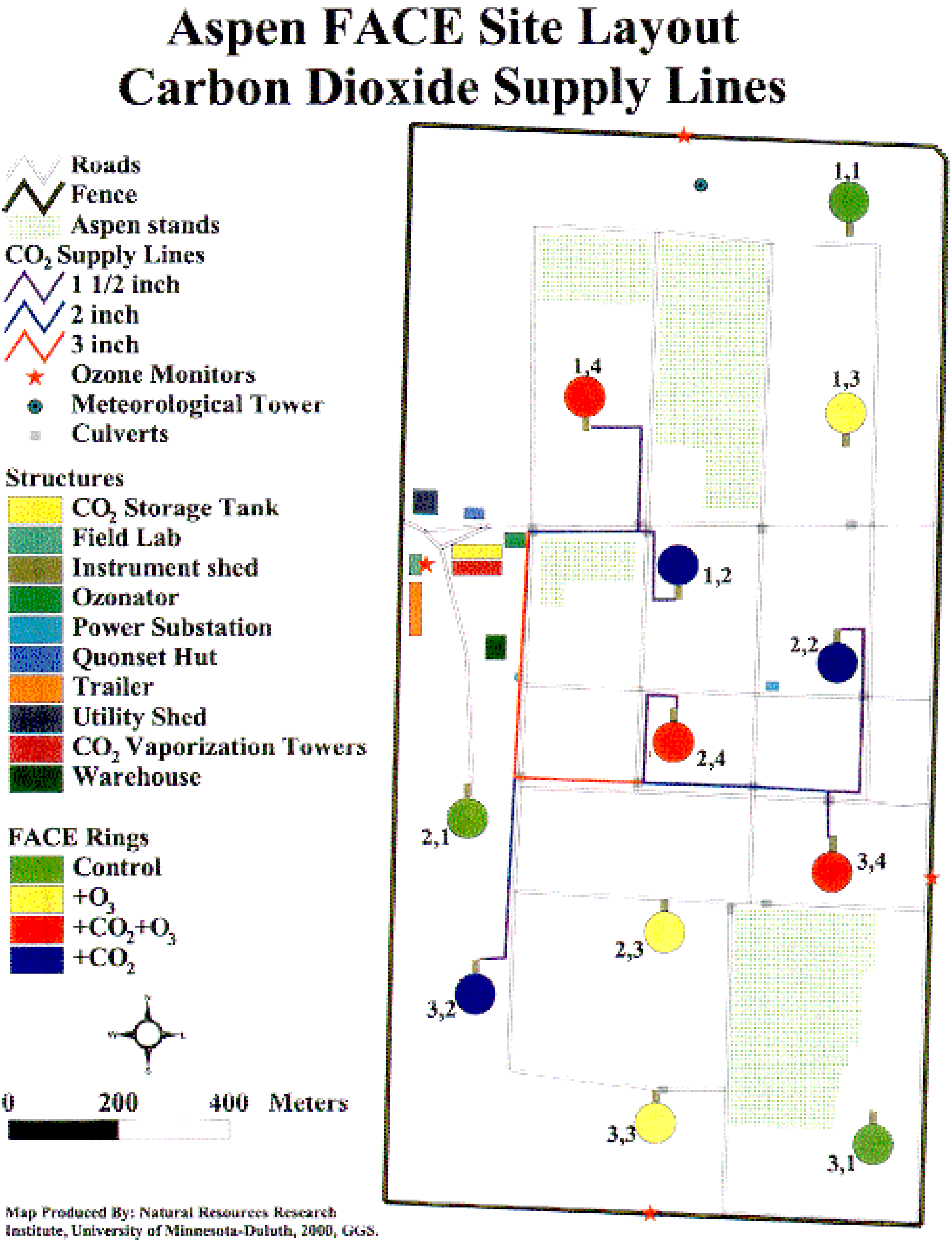

Figure A3.—Aspen FACE site layout—Carbon dioxide supply lines.

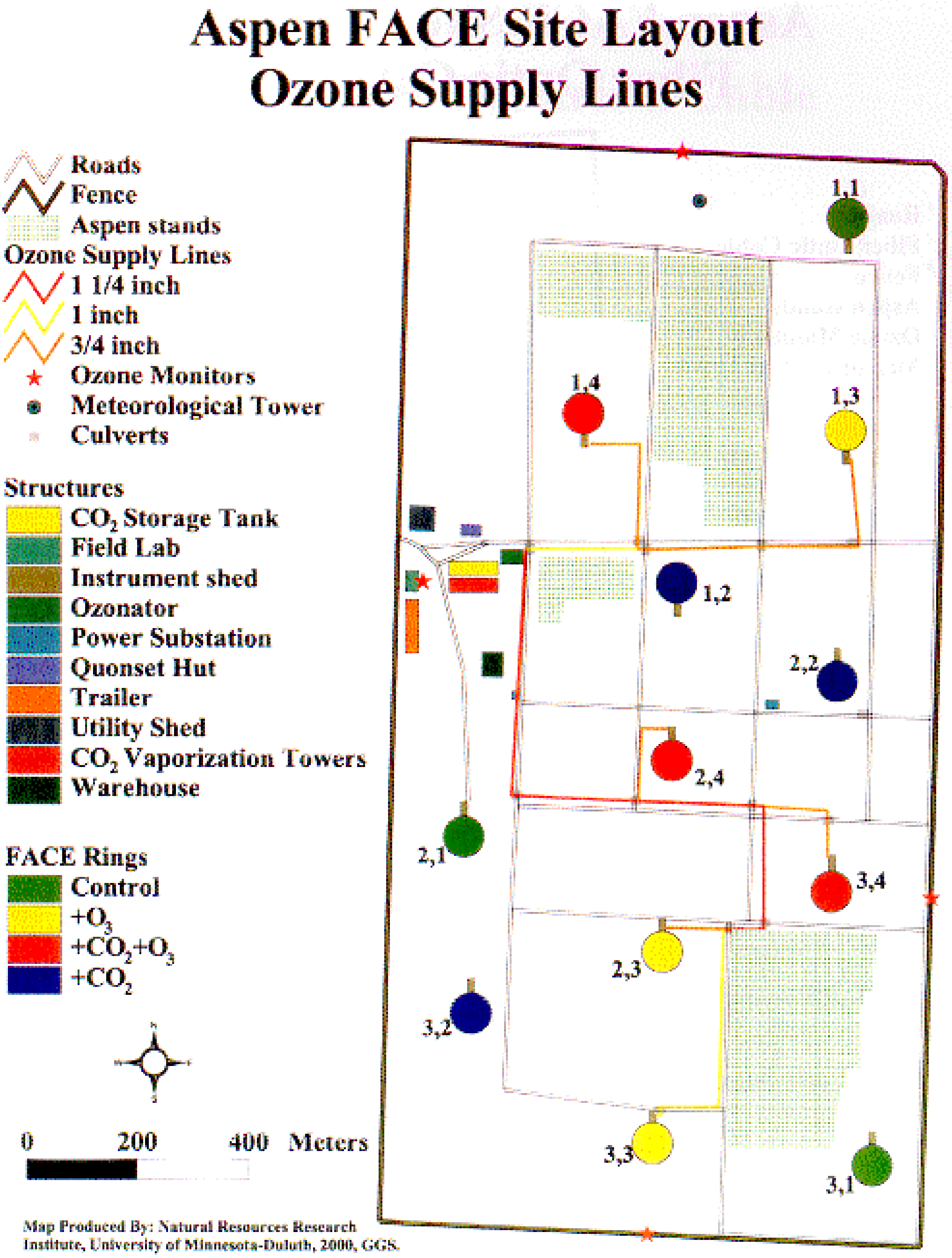

Figure A4.—*Aspen FACE site layout—Oxygen, ozone supply lines.*

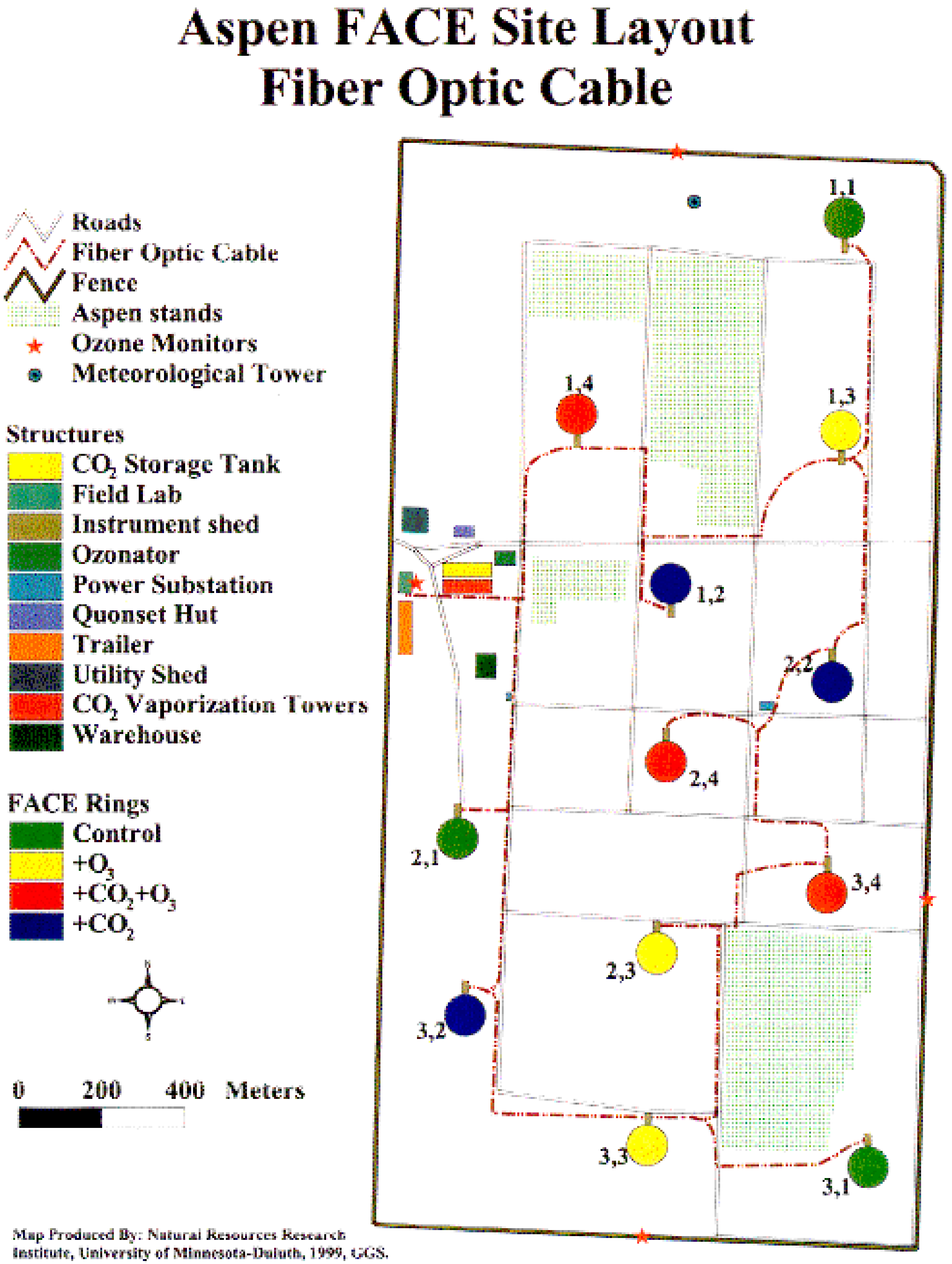

Figure A5.—*Aspen FACE site layout—Fiber optic cable.*

Aspen FACE Site Layout
Underground Electrical Cable

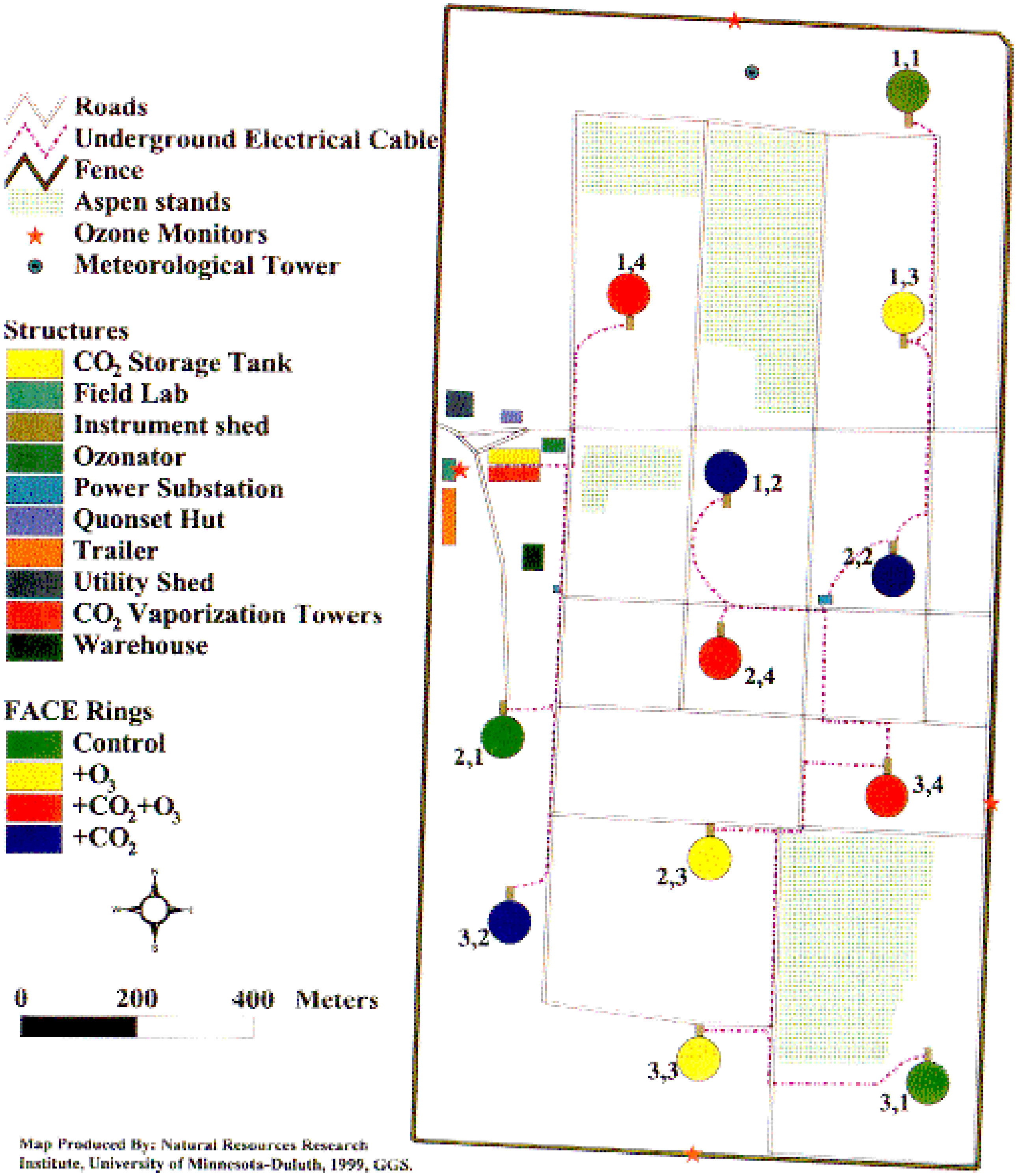

Figure A6.—*Aspen FACE site layout—Underground electrical cable.*

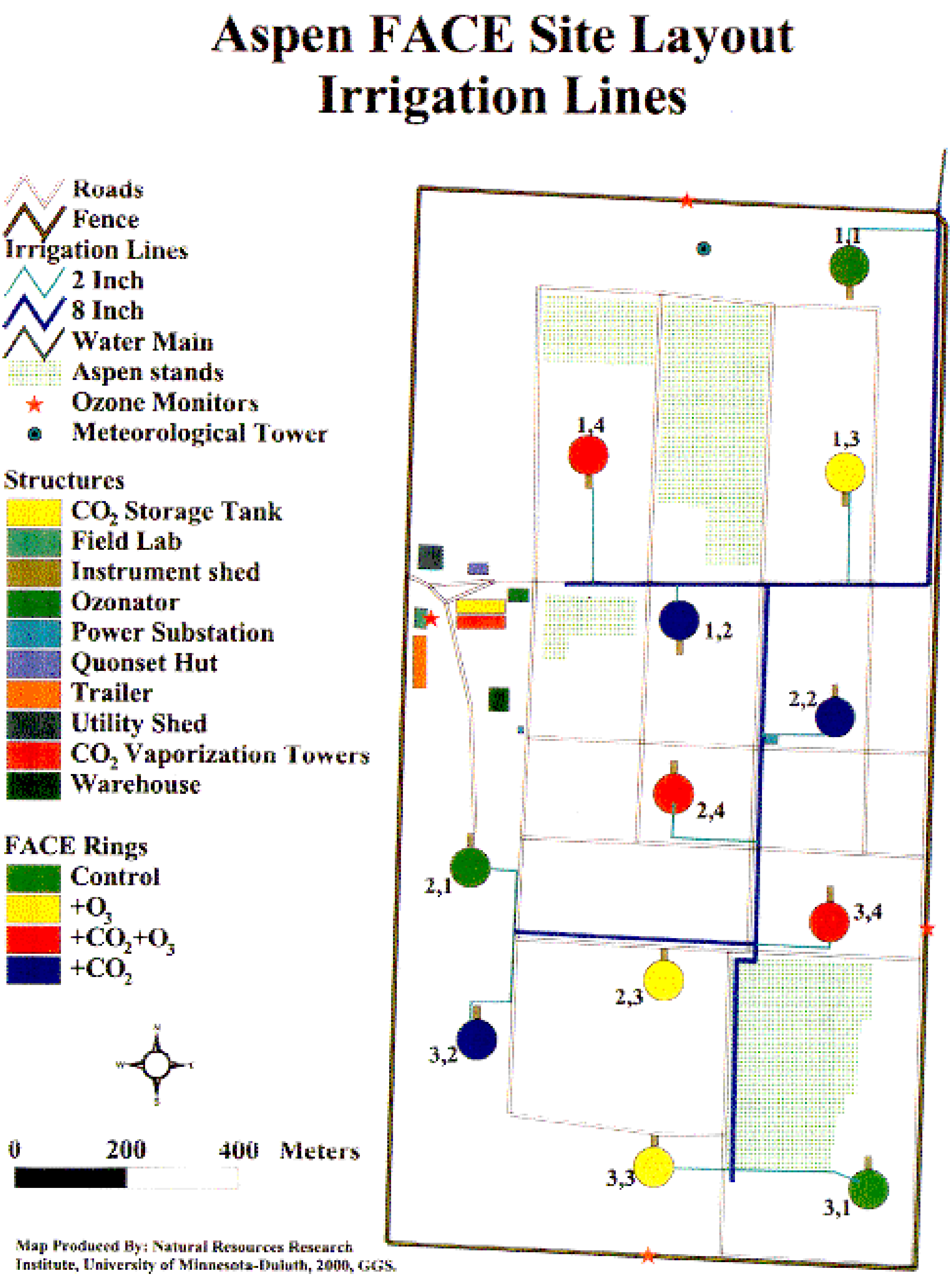

Figure A7.—Aspen FACE site layout—Irrigation lines.

Dickson, R.E.; Lewin, K.F.; Isebrands, J.G.; Coleman, M.D.; Heilman, W.E.; Riemenschneider, D.E.; Sober, J.; Host, G.E.; Zak, D.R.; Hendrey, G.R.; Pregitzer, K.S.; Karnosky, D.F.

2000. **Forest atmosphere carbon transfer and storage (FACTS-II) the aspen Free-air CO_2 and O_3 Enrichment (FACE) project: an overview**. Gen Tech. Rep. NC-214. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 68 p.

This publication briefly reviews the impact of increasing atmospheric carbon dioxide and tropospheric ozone on global climate change, and the response of forest trees to these atmospheric pollutants and their interactions; points out the need for large-scale field experiments to evaluate the response of plants to these environmental stresses; and describes the development, operational parameters, experimental methods, and the potential research scope of the Aspen Free-air Carbon dioxide and ozone Enrichment (FACE) project.

KEY WORDS: Climate change, carbon dioxide, tropospheric ozone, carbon sequestration, carbon-nitrogen cycles, biogeochemical cycles, insect-disease interactions, northern hardwood ecosystems.