CLIMATE CHANGE: A CONTROLLED EXPERIMENT

Scientists have carefully manipulated grasslands and forests to see how precipitation, carbon dioxide and temperature changes affect the biosphere, allowing them to forecast the future

By Stan D. Wullschleger and Maya Strahl

KEY CONCEPTS

- Researchers are altering temperature, carbon dioxide and precipitation levels across plots of forests, grasses and crops to see how plant life responds.
- Warmer temperatures and higher CO_2 concentrations generally result in more leaf growth or crop yield, but these factors can also raise insect infestation and weaken plants' ability to ward off pests and disease.
- Future field experiments that can manipulate all three conditions at once will lead to better models of how long-term climate changes will affect ecosystems worldwide.

—The Editors

Thirty years ago Charles F. Baes, Jr., a chemist at the U.S. Department of Energy's Oak Ridge National Laboratory, wrote that the earth was undergoing a great "uncontrolled experiment," one that would soon reveal the global consequences of rising greenhouse gas concentrations. Today scientists know that deforestation, land use and the burning of fossil fuels are warming our planet. We are less certain, however, about how climate change will alter forests and grasslands, as well as the goods and services these ecosystems provide society.

Much of the climate change news in the mass media comes not from experiments but observations. Scientists monitor Arctic sea ice, glaciers and natural events such as the timing of leaf appearance and inform the public when changes fall outside normal expectations. Recording this kind of information over time is important. But rather than waiting to see how an evolving climate slowly alters the biosphere, climate change biologists are conducting field experiments, often at large scales, to see how ecosystems will respond to more or less precipitation, rising concentrations of carbon dioxide (CO_2) and warming temperatures. Experimental data are key to determining if and to what extent ecosystems will be affected by climate change in 10, 50 or 100 years and how those changes might feed back to further advance change. The results can help separate fact from fiction in the climate debate, one that is charged with emotion.

For years researchers investigated how single plants—typically grown for several months inside climate-controlled chambers—responded to varied conditions. Understanding mechanisms at this scale is necessary. But we must also study plants in their proper context: actual ecosystems. Largely unknown to the public, several sizable outdoor experiments involving altered precipitation and CO_2 concentrations have been under way for more than a decade, including those that are described in boxes on the following pages. Temperature experiments have begun as well. Enough data have now been generated to improve models that predict climate and vegetation changes, providing a more accurate picture of how woodlands, prairies and agricultural crops may change in an increasingly warmer world that is subject to different precipitation patterns and blanketed in more CO_2.

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MONDOLITHIC STUDIOS

[WATER]

PRECIPITATION: TIMING IS EVERYTHING

Issue: Although temperature and CO_2 levels will generally rise worldwide, climate models predict that precipitation increases and decreases will vary much more from place to place in coming decades.

Experiment: Scientists have built a variety of structures to lower or raise the amount of water that reaches plants in grasslands, forests and croplands, as well as the treeless tundra in northern latitudes. Domed canopies or troughs are most often used. The water can be sent off-site or redistributed across a nearby site to test greater precipitation there. Some shelters can be moved or retracted. Barriers or trenches can be built into the soil to prevent surface water from creeping into the study plots and prevent plant roots from accessing water outside the plots.

Projects such as the Throughfall Displacement Experiment (TDE) near Oak Ridge, Tenn., employ elaborate trough and gutter systems in the understory of a forest to create dry and wet soil conditions [*see photograph* and *illustration*]. As many as 1,900 troughs may be distributed across zones the size of football fields. Similar designs can be placed between trees that are widely spaced, for example, in piñon-juniper woodlands of New Mexico, where Nathan McDowell of Los Alamos National Laboratory is studying the role of drought and insects in tree mortality.

TROUGHS at the Throughfall Displacement Experiment simulate drought by preventing rainfall from reaching the ground.

Results: On the Konza Prairie, studied by Kansas State University, some grasses have tolerated shifting precipitation patterns better than others. Competition between plants for water could rise in a warming world.

In temperate forests, such as the one being studied by Paul Hanson in his 13-year-long TDE project, mature trees with deep roots have withstood sustained reductions in precipitation. But many saplings and seedlings with shallow roots have died. This experiment has also revealed that trees are harmed more by excessively dry intervals during certain seasons; reduced rainfall during active stem expansion in early spring retarded growth more dramatically than reduced rainfall did at other times. Late-season droughts occurring after trees had stopped growing were of little consequence, as long as soil-water supplies were fully recharged before the subsequent growing season. In contrast, some large trees in the Amazon rain forests of Brazil perished during the fourth year of a drought created by researchers from the Woods Hole Research Center in Massachusetts. Yet saplings and small-diameter trees were less affected. Blocking 60 percent of the rainfall dried deep soils, but surface soils remained fairly moist, the opposite of TDE results. It is clear that complex interactions must be understood before models can faithfully represent climate change effects.

THROUGHFALL DISPLACEMENT EXPERIMENT

COURTESY OF OAK RIDGE NATIONAL LABORATORY (*photograph*); DAVID FIERSTEIN (*illustration*)

[AIR]

CO_2: GREATER GROWTH FOR SOME

Issue: Scientists estimate that the oceans and terrestrial ecosystems soak up at least half of the CO_2 released by burning fossil fuels. Plants do it by using the gas to produce carbohydrates during photosynthesis. But will that conversion continue at higher CO_2 concentrations? And will more CO_2 alter the sugars, carbohydrates and protective compounds in plants, in turn helping or hindering insects and pathogens?

Experiment. The Free-Air CO_2 Enrichment (FACE) experiment has been running at Oak Ridge National Laboratory for more than 10 years, under Richard Norby. It consists of four study areas ringed by vent pipes suspended from towers [*see photograph* and *illustration*]. The pipes release CO_2 such that the trees all receive a selected amount. Similar FACE experiments operate at almost 35 other natural and managed ecosystems worldwide, ranging from one-meter-diameter plots in bogs, 23-meter plots on croplands and 30-meter plots on forest plantations.

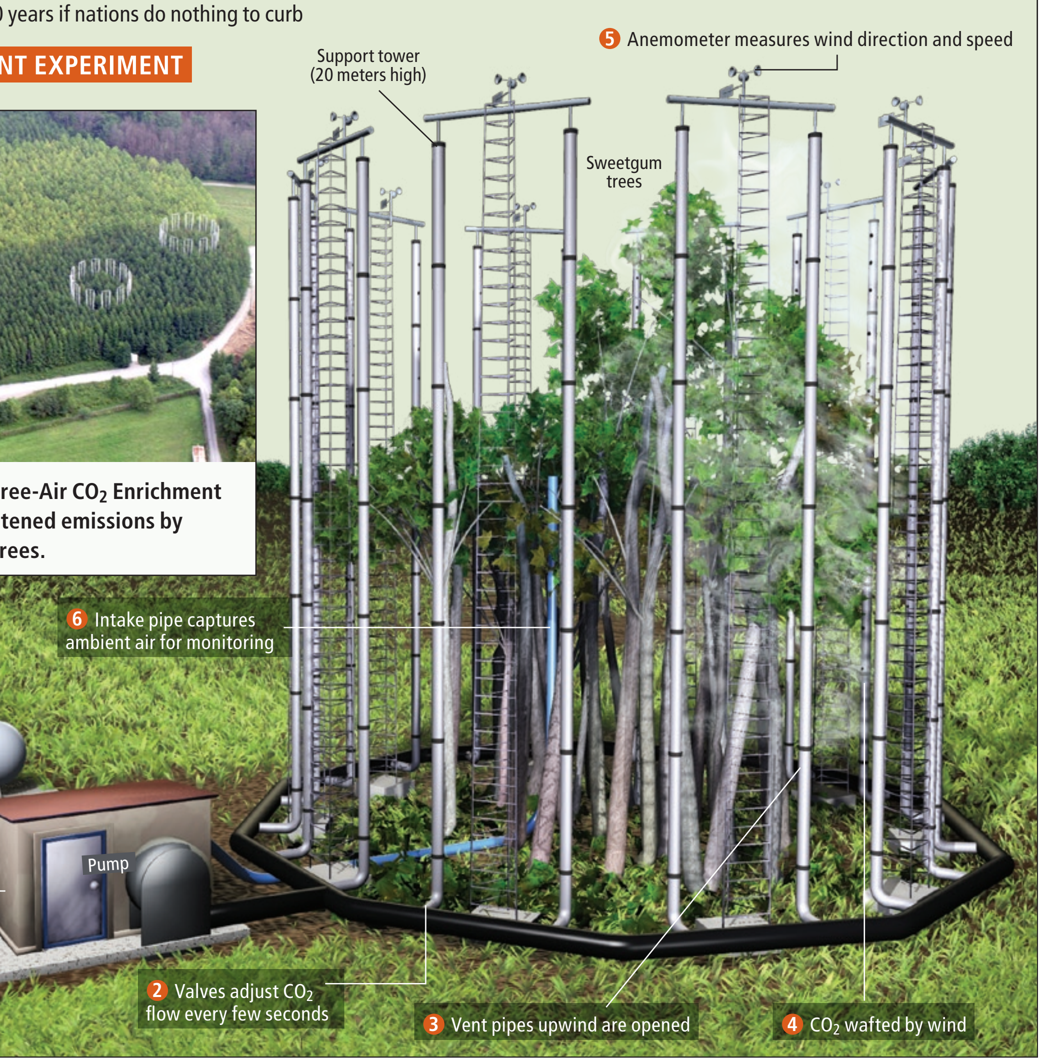
Results: The data confirm that higher CO_2 levels stimulate photosynthesis, which incorporates more carbon into plant tissues. This net primary production (NPP) is also sustained over multiple growing seasons. NPP in forest experiments in Wisconsin, North Carolina, Tennessee and Italy has increased 23 percent annually when CO_2 is raised from the ambient level of 388 parts per million (ppm) to 550 ppm—a level that could arise within 100 years if nations do nothing to curb emissions. Recent modeling results suggest that plants will respond positively to elevated CO_2 levels, although gains may be tempered where soil contains insufficient nutrients such as nitrogen.

Increased NPP has been consistent across the FACE plots worldwide. But NPP indicates only the amount of carbon added to a plant; it does not reflect the long-term fate of that carbon. In the North Carolina loblolly pine forest, the additional carbon was stored primarily in stems and branches, where it might persist for decades. In Tennessee's sweetgum forest, however, the carbon appeared mostly in new, small roots. Such roots are advantageous, of course, but live for only a few weeks to a year; much of the carbon returns to the atmosphere as microbes decompose the roots. Scientists are trying to understand what drives carbon to one destination or another; we will learn more as trees are harvested and soils are excavated in the coming months at various sites.

FACE experiments have already paid off. James Randerson of the University of California, Irvine, and scientists at Oak Ridge, the National Center for Atmospheric Research in Boulder, Colo., and other institutions have used the data to evaluate and improve the Community Climate System Model, which simulates the physical, chemical and biological processes that drive the earth's climate system.

FREE-AIR CO_2 ENRICHMENT EXPERIMENT

RINGS of vent pipes at the Free-Air CO_2 Enrichment experiment simulate heightened emissions by pumping the gas through trees.



COURTESY OF OAK RIDGE NATIONAL LABORATORY (*photograph*); DAVID FIERSTEIN (*illustration*)

[HEAT]

TEMPERATURE: HIGHS AND LOWS

Issue: Future warming will vary by geographic location. By 2100 North America will be 3.8 to 5.9 degrees Celsius warmer in winter and 2.8 to 3.3 degrees C warmer in summer. The changes will affect plant metabolism as well as water and nutrient availability in soil, competition among plants, and the voracity of herbivores, insects and pathogens.

Experiment: Researchers have tried various ways to warm very small plots, including infrared-emitting lamps, electrical heating tapes in the soil and open-top chambers—cylindrical frames wrapped in transparent plastic and fitted with warm-air blowers. These approaches have proved useful but also have drawbacks. Most can heat only a small area, and many have heated only parts of the ecosystem. Heating tapes create unnatural hot spots in soils. Passively warmed chambers depend on time of day and season, and they influence rainfall, wind and sunlight in ways that complicate interpretation of outcomes.

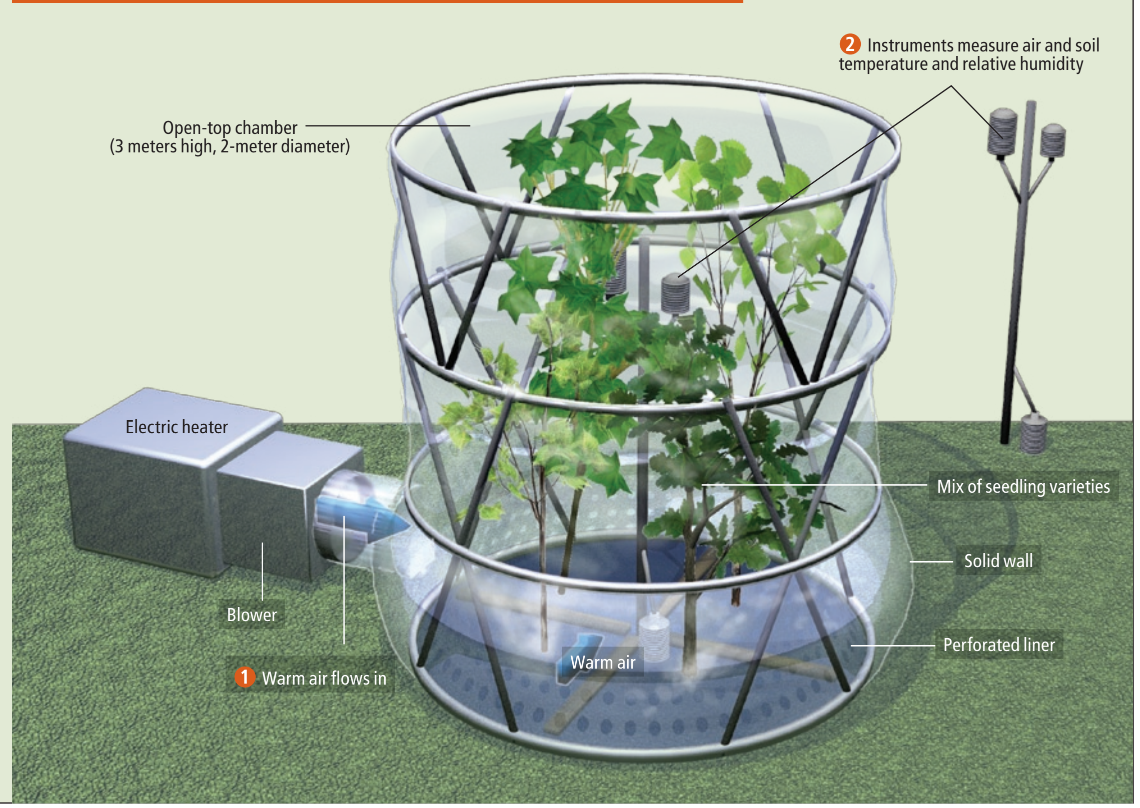
OPEN-TOP CHAMBERS at the Temperature Response and Adjustment Experiment warm saplings and small trees year-round.

Results: Arctic ecosystems and the boreal regions to their immediate south are particularly vulnerable to temperature changes. The International Tundra Experiment, led by Greg Henry of the University of British Columbia, uses passive chambers to warm small plots at more than a dozen sites in various countries. Results thus far show that a one to three degree C increase enhances growth and ground cover of deciduous shrubs and grasses as compared with mosses and lichens. This differential response supports the hypothesis that warming will cause a decline in biodiversity across high-latitude ecosystems. A shift from herbaceous to woody vegetation could also raise the energy absorbed by the earth versus that reflected back into space, further increasing global temperature.

Experiments at other latitudes are offering clues about local extinctions, range migrations and altered species composition. At Oak Ridge National Laboratory, Carla Gunderson has exposed four species of deciduous trees to temperatures up to four degrees C above ambient [*see photograph* and *illustration*]. Seedlings and saplings physiologically adjust, and more often than not they show enhanced growth. Trees produced leaves six to 14 days earlier in the spring, and they retained green leaves later into autumn, lengthening the growing season by up to three weeks. Anecdotal evidence suggests, however, that earlier spring growth might more frequently expose plants to a late, damaging frost.

Despite useful results, it is hard to extrapolate data from small plots to ecosystems. New ways to warm larger areas are needed. Techniques have primarily been powered by electricity, but natural gas or geothermal energy may be better options for remote locations.

TEMPERATURE RESPONSE AND ADJUSTMENT EXPERIMENT



COURTESY OF OAK RIDGE NATIONAL LABORATORY (*photograph*); DAVID FIERSTEIN (*illustration*)

CROPS TESTED, TOO

SITE: Soybean Free-Air CO_2 Enrichment Facility, University of Illinois at Urbana-Champaign
ELEVATED CO_2: 550 ppm
ELEVATED OZONE: 1.2 times ambient
PLOTS: 20-meter-diameter rings
OUTLOOK: Higher levels of CO_2 and ozone are anticipated by midcentury
RESULTS: Soybean plants grew larger than normal but were more ravaged by Japanese beetles

COURTESY OF BRIDGET O'NEILL *Trinity College Dublin* (*beetles*)

[THE AUTHORS]


Stan D. Wullschleger is a climate change biologist and leader of the Plant Systems Biology Group at Oak Ridge National Laboratory in Tennessee. He has conducted experiments exploring the effects of carbon dioxide enrichment, warming and drought on natural forests, plantations and old fields. Currently he is designing and testing warming technology for Arctic tundra and boreal forests. **Maya Strahl** is a plant biologist at Cold Spring Harbor Laboratory in New York and is a former participant in the Higher Education Research Experiences program at Oak Ridge.

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Findings around the Globe

Experiments conducted worldwide show that plants and ecosystems possess a remarkable capacity to adjust to new conditions. But scientists expect that thresholds exist beyond which significant and potentially catastrophic responses will occur. As we explore these boundaries, we will find surprises, yet some conclusions informed by field experiment data can already be drawn:

- Higher CO_2 concentrations can enhance yields for commodities such as wheat, rice, barley, soybeans and cotton, but simultaneous warming, and in some locations ozone pollution, may well reduce or negate the "CO_2 fertilization" effect. Climate changes will also alter interactions among crops, weeds, pathogens and insects, with the pests winning out as often as not.
- Deciduous forests in the eastern U.S.—the kind that lose their leaves seasonally—are relatively insensitive to drought. Deep soils hold plenty of water to support the growth of large trees throughout much of the year. But surface soils hold little water and dry out quickly, causing high rates of mortality in young seedlings and small saplings—the forests of the future.
- In a CO_2-enriched atmosphere, greater root growth could provide more nutrients, enhancing the productivity of developing forests. Greater rooting with depth might also benefit plants in arid and dryland ecosystems by increasing access to soil water.
- Global warming and rising CO_2 concentrations could promote the invasiveness of many agricultural weeds, including Canadian thistle, lowering crop yields or demanding more herbicides. Exotic species may also pose problems. For example, recent experiments in the Mojave Desert by Stan Smith of the University of Nevada, Las Vegas, showed that in a year with unusually high rainfall, elevated CO_2 concentration stimulated the spread of *Bromus tectorum*, or cheatgrass, which reduced plant species diversity, modified the food chain and raised the potential for fire.
- Although the invasion of woody plants in world grasslands over the past 200 years has resulted mainly from overgrazing and from fire suppression, rising atmospheric CO_2 concentrations may be contributing to the encroachment of trees and shrubs across the western U.S.
- Future CO_2 concentrations will affect plants in ways that could impact public health, including greater production of pollens that trigger allergies and greater growth and toxicity of poison ivy and other invasive species.

Complex Questions

The results of large outdoor experiments are telling, but most investigations have been conducted at middle latitudes and mostly in the U.S. and Europe. New experiments at a wider range of latitudes are needed to clearly predict the response of boreal, tundra and tropical plants and of ecosystems. Several years will be needed to prepare such experiments because they are likely to be scientifically complicated and located in remote regions. They will require significant engineering to ensure that altered conditions are imposed uniformly and that the infrastructure is robust enough to last for years.

Biologists must also build installations that not only alter CO_2 concentration, temperature or precipitation patterns, but all three factors in combination. We have so far only scratched the surface. A new experiment near Cheyenne, Wyo., is evaluating how plants in a northern mixed-grass prairie will fare given simultaneous changes in CO_2 concentration and temperature. In the first year of the Prairie Heating and CO_2 Enrichment experiment, Jack Morgan of the U.S. Department of Agriculture's Agricultural Research Service has found indications that warming in combination with higher CO_2 concentration may enhance the abundance of warm-season grasses in the Great Plains, at the expense of cool-season grasses.

How best to manipulate multiple factors and how to account for such combinations, as well as possible feedbacks, in models are complex questions. We will need experimentally derived data very soon if we are to help society anticipate, plan and adapt to a climate that is already changing rapidly. ■

MORE TO EXPLORE

Next Generation of Elevated [CO_2] Experiments with Crops: A Critical Investment for Feeding the Future World. Elizabeth A. Ainsworth et al. in *Plant, Cell and Environment,* Vol. 31, pages 1317–1324; 2008.

Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems. Alan K. Knapp et al. in *BioScience,* Vol. 58, No. 9, pages 811–821; October 2008.

Rising CO_2, Climate Change, and Public Health: Exploring the Links to Plant Biology. Lewis H. Ziska et al. in *Environmental Health Perspectives,* Vol. 117, No. 2, pages 155–158; February 2009.