An Historical Perspective on Elevated CO_2 Research:

Early insights guiding today's research agenda

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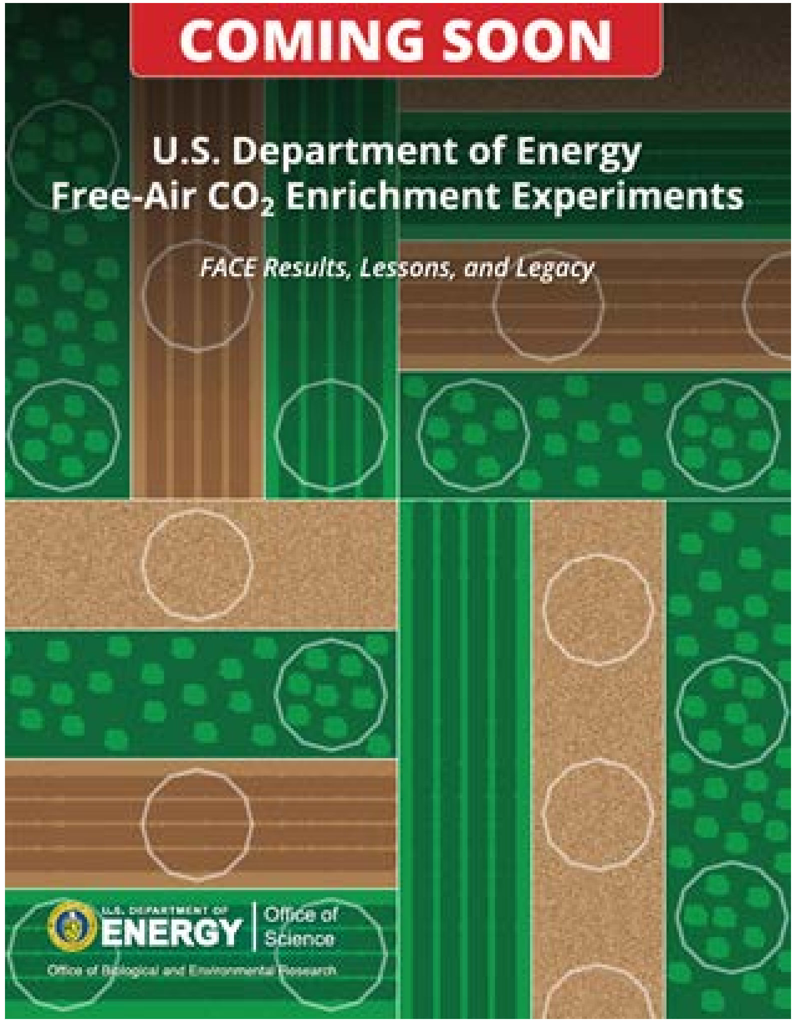
ESS PI Virtual Meeting
May 20, 2020

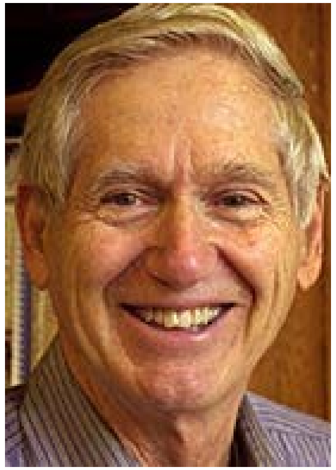


U.S. DOE. 2020. *U.S. Department of Energy Free-Air CO_2 Enrichment Experiments: FACE Results, Lessons, and Legacy*, DOI: 10.2172/1615612. https://tes.science.energy.gov/face/facereport.shtml

- Historical perspective to DOE's carbon-climate-vegetation research that has evolved significantly over the past 40 years to address some of the nation's most pressing energy and scientific challenges
- Insight to the experimental design logic and challenges to experimental manipulation studies
- A guide for lessons learned operating first of a kind ecosystem manipulation experiments

A history of CO_2 research… where should we start?

With a focus on the role of CO_2 fertilization in the global carbon cycle, 1958 is a good place to start.



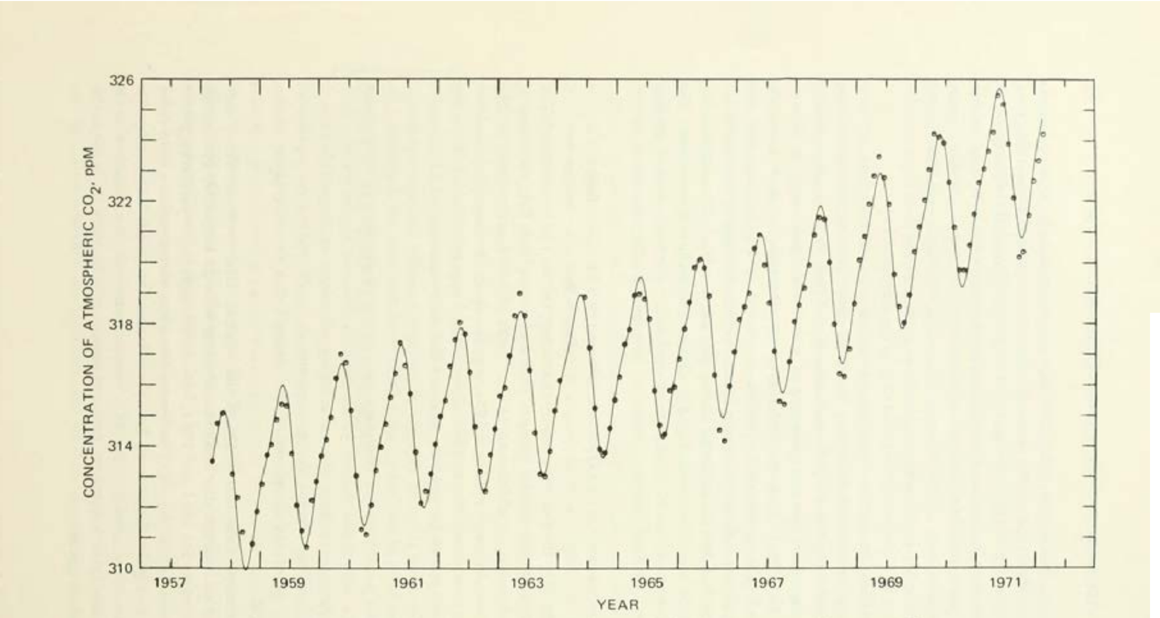


Fig. 1 Long-term variation in the concentration of atmospheric CO_2 at Mauna Loa Observatory. The circles indicate the observed monthly average concentration. The oscillatory curve is a least-squares fit to these averages of an empirical equation containing 6- and 12-month cyclic terms and a cubic-trend function, chosen to contain powers of time up to the third.

Carl A. Ekdahl and Charles D. Keeling. 1973. In Carbon and the Biosphere, Woodwell and Pecan, ed.

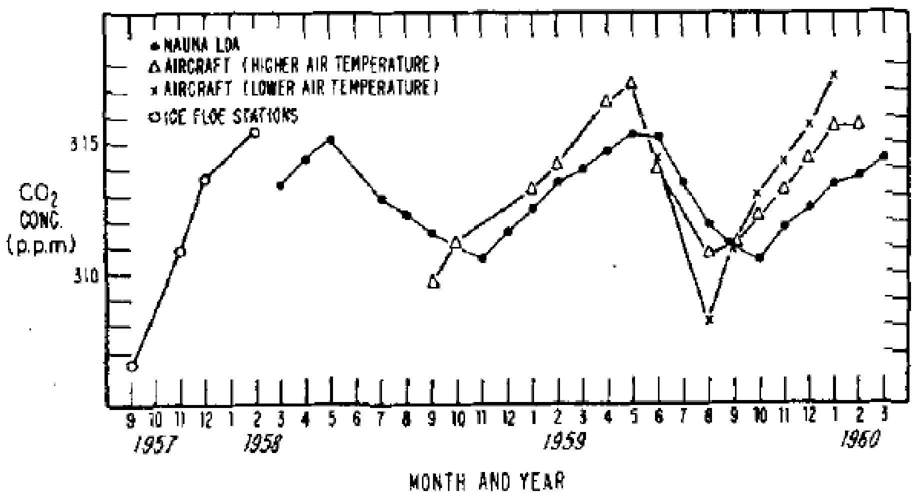


Fig. 1. Variation in concentration of atmospheric carbon dioxide in the Northern Hemisphere.

Tellus XII (1960), 2

The Williamstown Study of Critical Environmental Problems

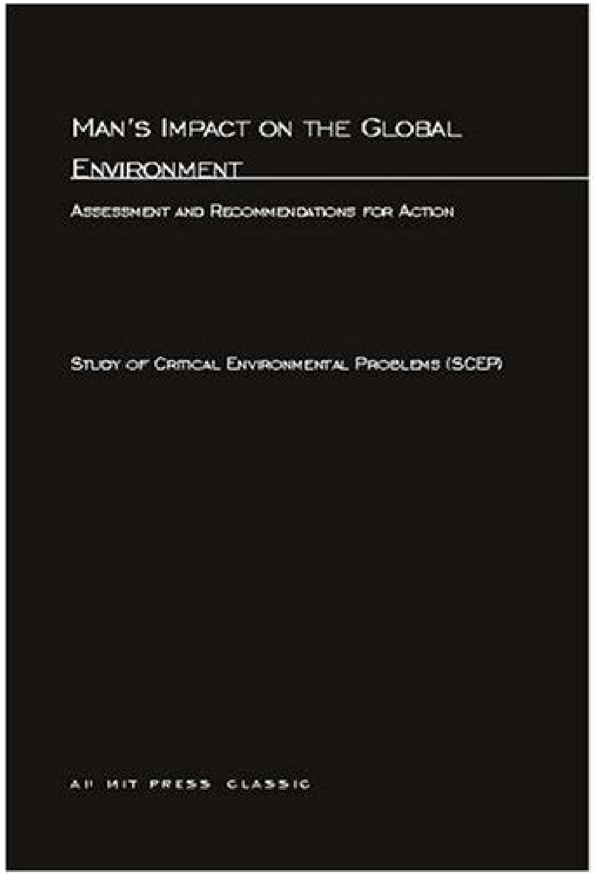
July 1970, 100 scientists conducted a month–long Study of Critical Environmental Problems (SCEP)

Considered effects of increases in CO_2 resulting from fossil fuel combustion to the year 2000 and the risk of long-term warming of the planet

"SCEP believes that the likelihood of direct climate change in this century resulting from CO_2 is small, but its long term potential consequences are so large that much more must be learned about future trends of climate change if society is to have time to adjust to changes which may be necessary."

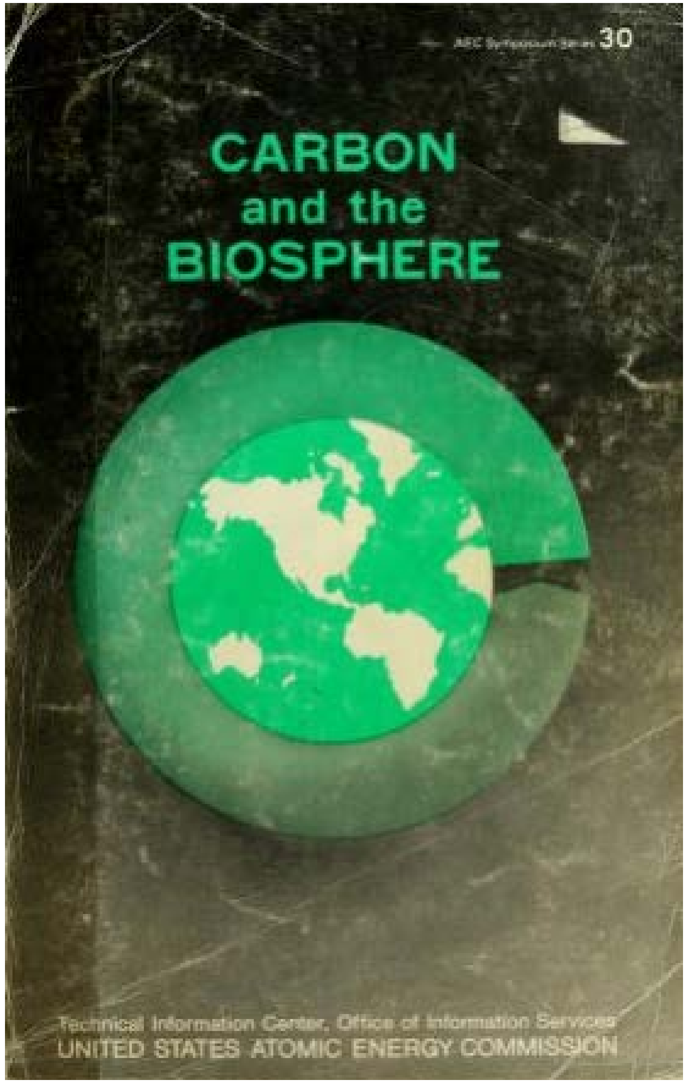
Recommendations:

- Improve estimates of future fossil fuel combustions and emissions
- Study changes in mass of living matter and decaying products
- Continue Mauna Loa measurements and additional stations
- Systematic study of the partition of CO_2 between the atmosphere, oceans, and biomass
- Develop comprehensive computer models of atmosphere dynamics and ocean-atmosphere interactions for expected CO_2 levels.



Bulletin of the Atomic Scientists (1970), 26: 24-30

The Biota Growth Factor -- β



Bacastow and Keeling, 1973

Introduces the biota growth factor (β) as an adjustable parameter that reflects the degree of CO_2 fertilization needed to balance global C budget

"In our model we assume that the land biota responds to gaseous CO_2 approximately as do individual plants grown in glass houses with adequate light, water, and nutrients. If this assumption holds, the land biota may nearly double by 2070."

They recognize this is unrealistic and rather assumed that plant growth will not be able to keep pace with fossil fuel consumption.

The potential role of CO_2 fertilization in the global carbon cycle is questioned

Possibly severe consequences of growing CO_2 releases from fossil fuels require a much better understanding of the carbon cycle, climate change, and the resulting impacts on the atmosphere

"Another effect to be considered is the enhanced rate of photosynthetic production that might be caused by the increasing concentration of CO_2 in the atmosphere…. *however, its importance in the carbon cycle is presently unclear*."

Baes et al.. Carbon dioxide and climate: The uncontrolled experiment. *American Scientis*t, 1977.

Model of atmospheric CO_2 levels driven primarily by fossil fuel emissions and ocean uptake.

Assumed biospheric growth factor and deforestation compensated each other.

Siegenthaler & Oeschger. Predicting future atmospheric carbon dioxide levels. *Science,* 27 January 1978

The increase of biomass atmospheric carbon dioxide may partly be due to the expansion of forestry and agriculture. Will CO_2 fertilization compensate for the land source (deforestation and cultivation)? *It seems unlikely to be complete because of nutrient limitation*.

Bolin B. Changes of land biota and their importance for the carbon cycle. *Science*, 1977.

The biosphere is a net source of CO_2 to the atmosphere. *The potential increase in NPP due to increasing CO_2 is too small to compensate for the release of CO_2 from fossil fuels and forest clearing.*

Woodwell et al. The biota and the world carbon budget. *Science,* 13 January 1978.

The case of the missing sink

Ocean flux + deforestation + increase in atmospheric CO_2 $\neq$ anthropogenic CO_2 release…

…there must be a ‘**missing sink**’

Science News

Scientists Close In On Missing Carbon Sink

from research organizations

Date: June 22, 2007

Source: National Center for Atmospheric Re…

Summary: Forests in the United States … playing a smaller role in … a new study appear… carbon sink. …pper-latitude regions are …usly thought, according to … so-called missing

NATURE | NEWS FEATURE

The hunt for the world's missing carbon

Researchers are racing to determine whether forests will continue to act as a brake on climate change by soaking up more carbon.

Gabriel Popkin

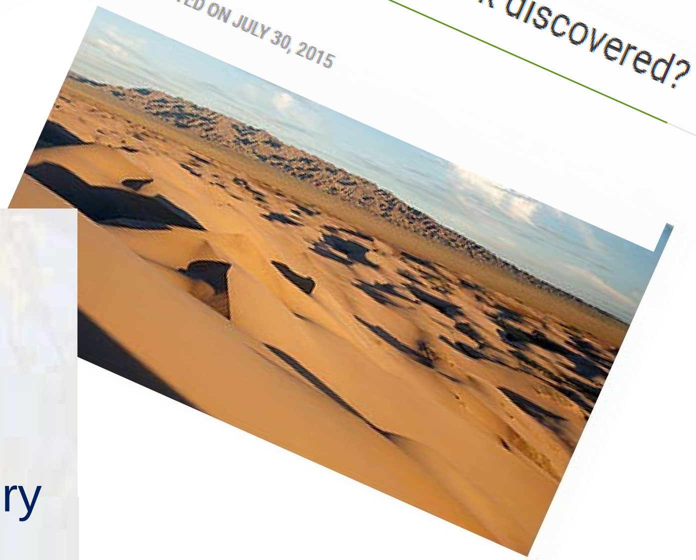
30 June 2015 | Corrected: 02 July 2015

Where is the missing carbon?

A giant hole in the global carbon budget may be plugged by an unlikely source: fish guts.

Missing carbon sink discovered?

POSTED ON JULY 30, 2015

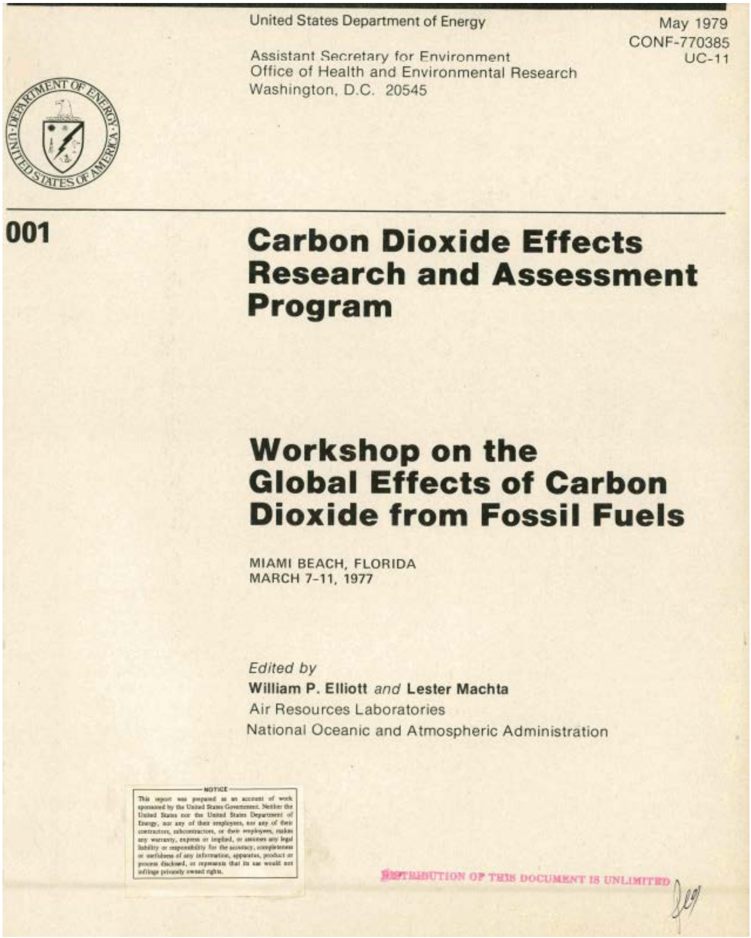


The Missing Sink

October 13, 2015/ Bill Schlesinger

The search for the missing sink—the Holy grail of biogeochemistry—may very well end in forest.

DOE program development began with a series of workshops


United States Department of Energy
Assistant Secretary for Environment
Office of Health and Environmental Research
Washington, D.C. 20545

May 1979
CONF-770385
UC-11

001

Carbon Dioxide Effects Research and Assessment Program

Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels

MIAMI BEACH, FLORIDA
MARCH 7-11, 1977

Edited by
William P. Elliott *and* Lester Machta
Air Resources Laboratories
National Oceanic and Atmospheric Administration

NOTICE

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"The key problem for national and international policy making as to the CO_2 question is uncertainty itself; **uncertainty that must be reduced through research**."

1977

Miami Beach workshop to "discuss the current knowledge of the CO_2 cycle and the consequences of increases in CO_2 content."

"Research will be required on the role of nutrient availability, water availability, and sunlight on the effect of CO_2 increases on plant productivity, particularly on trees."

"Modeling teams must be closely coupled with field researchers."

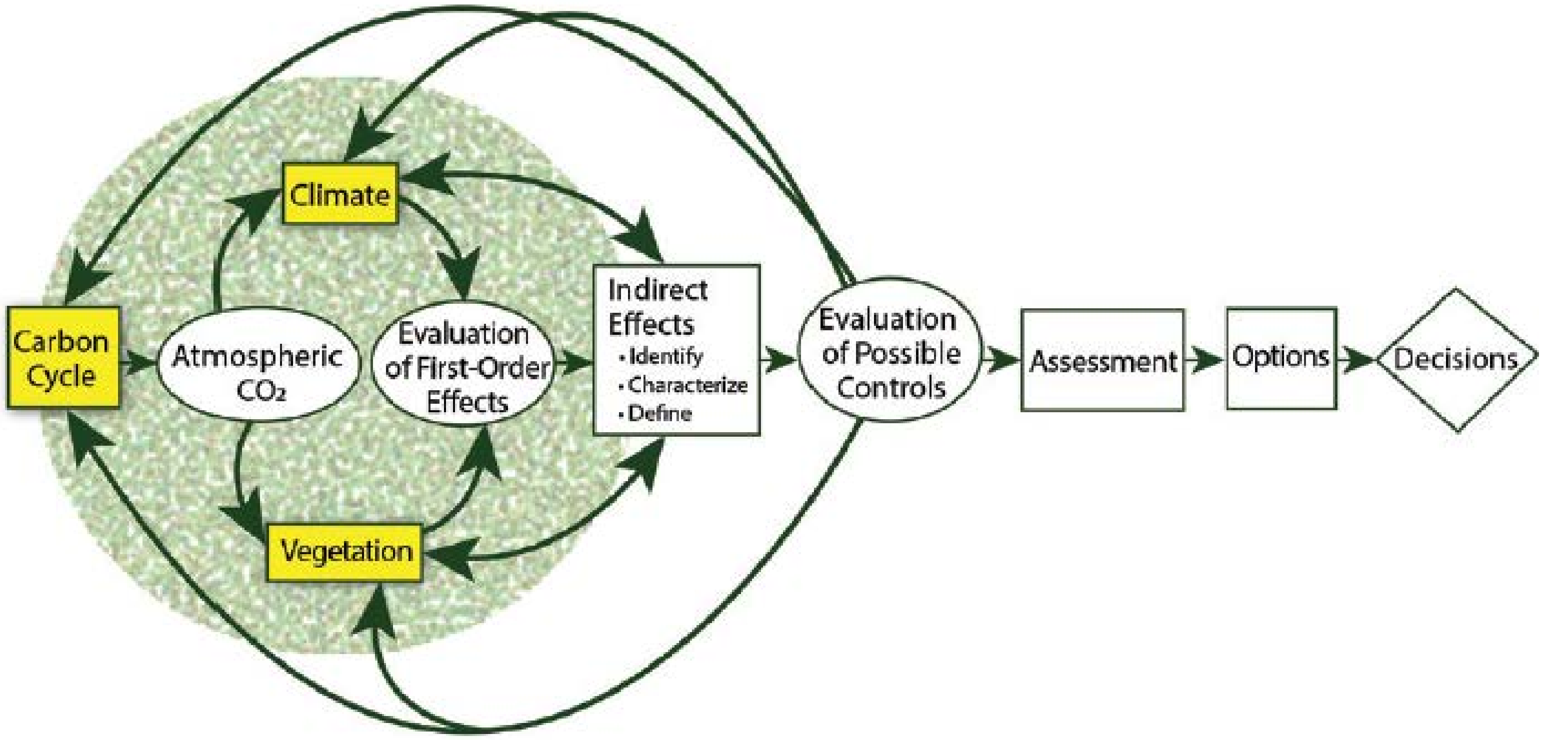
Development of a coordinated research program

The new DOE program focused on three research areas:

global carbon cycle, climate effects, and vegetation effects

Focus of Vegetation Effects:

- Effects of elevated CO_2 and other key variables on yield of major crops
- Fundamental effects of long-term exposure on plant physiology and growth
- Ecosystem responses – productivity plant community composition, carbon change



Roger Dahlman *et al*. 1985. *J. Environ. Qual.* 14: 1-8

Carbon Dioxide Concentration, Photosynthesis, and Dry Matter Production

Paul J. Kramer

BioScience 31:29-33 (1981)

"In nature, the rate of photosynthesis and biomass production probably is limited more often by water and nitrogen deficiency than by the low CO_2 concentration of the air."

"Increasing the CO_2 concentration will have little effect if … the use of photosynthate is limited by lack of nitrogen."

- Forest responses are particularly important
- Evaluation of the role of forests in stabilizing the global CO_2 concentration will require a large, coordinated effort
- Meantime, much useful information can be obtained from small-scale experiments in controlled environments

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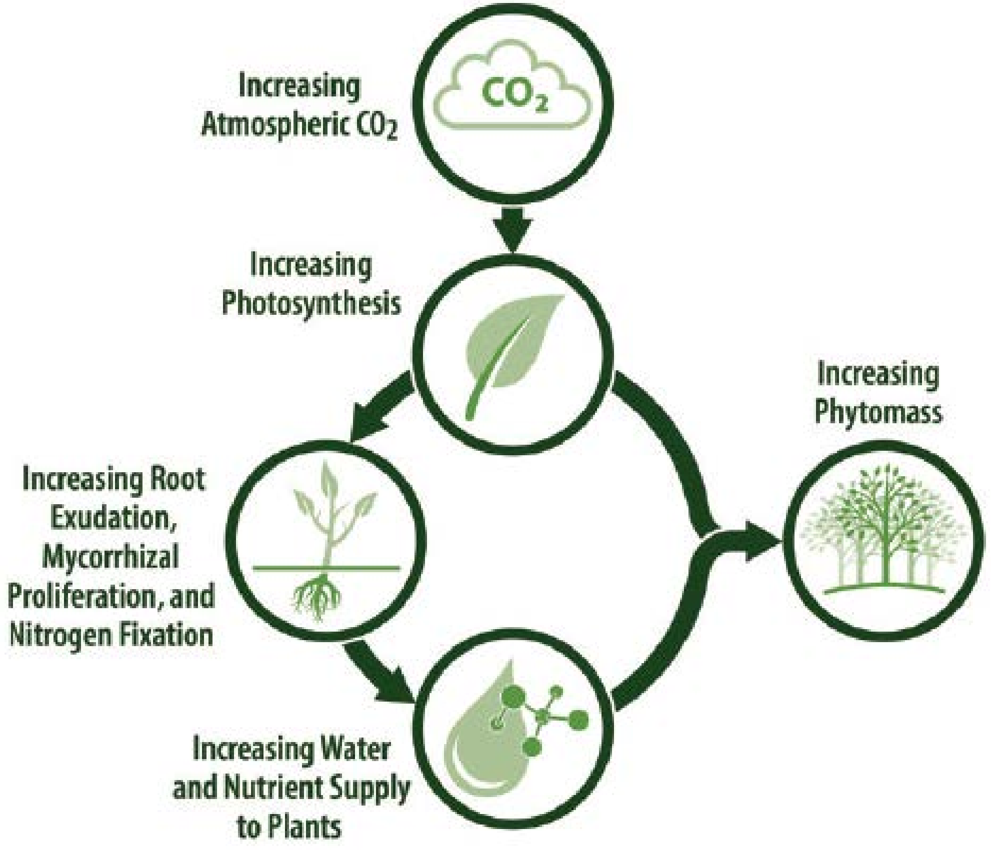
BioScience Vol. 31 No. 9



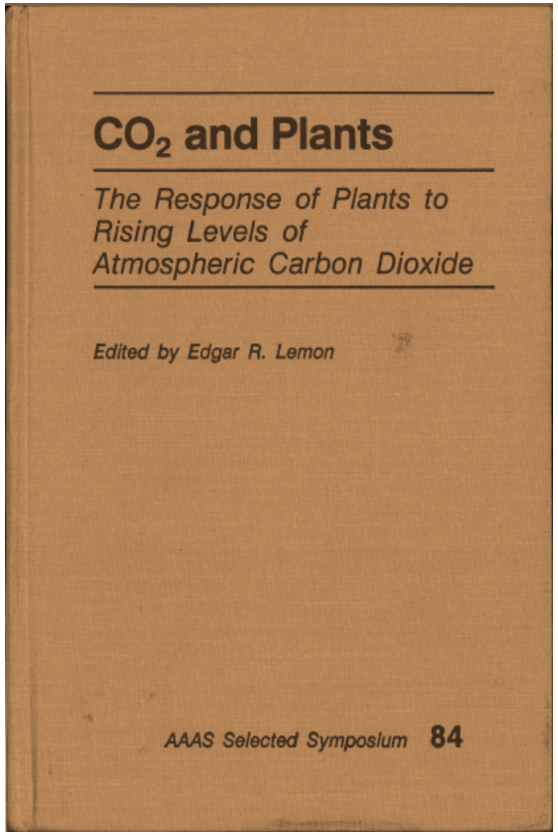
CO_2 and Phytomass

One of Kramer's chief concerns about the plant-CO_2 responses was the limits to growth already set in nature by water and nutrient deficiency.

Thus a key question follows: *Is there any evidence for elevated atmospheric CO_2 alleviating the water and nutrient deficiency of plants?*

"In many temperate forests a large proportion of nutrients occur in soil components, and a shift to preferred nutrient incorporation in vegetation… …*could be the first step to another Carboniferous Age!"*

Rising Atmospheric Carbon Dioxide and Plant Productivity: An International Conference
Athens, Georgia, May 1982 (*DOE and AAAS*)



Objective:

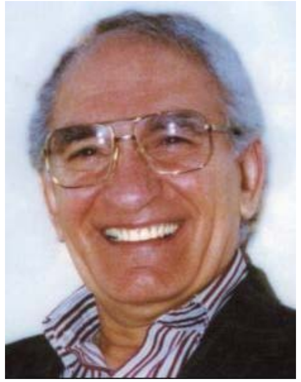
Review what is known about the response of photosynthesizing plants to elevated CO_2, and identify needed research.

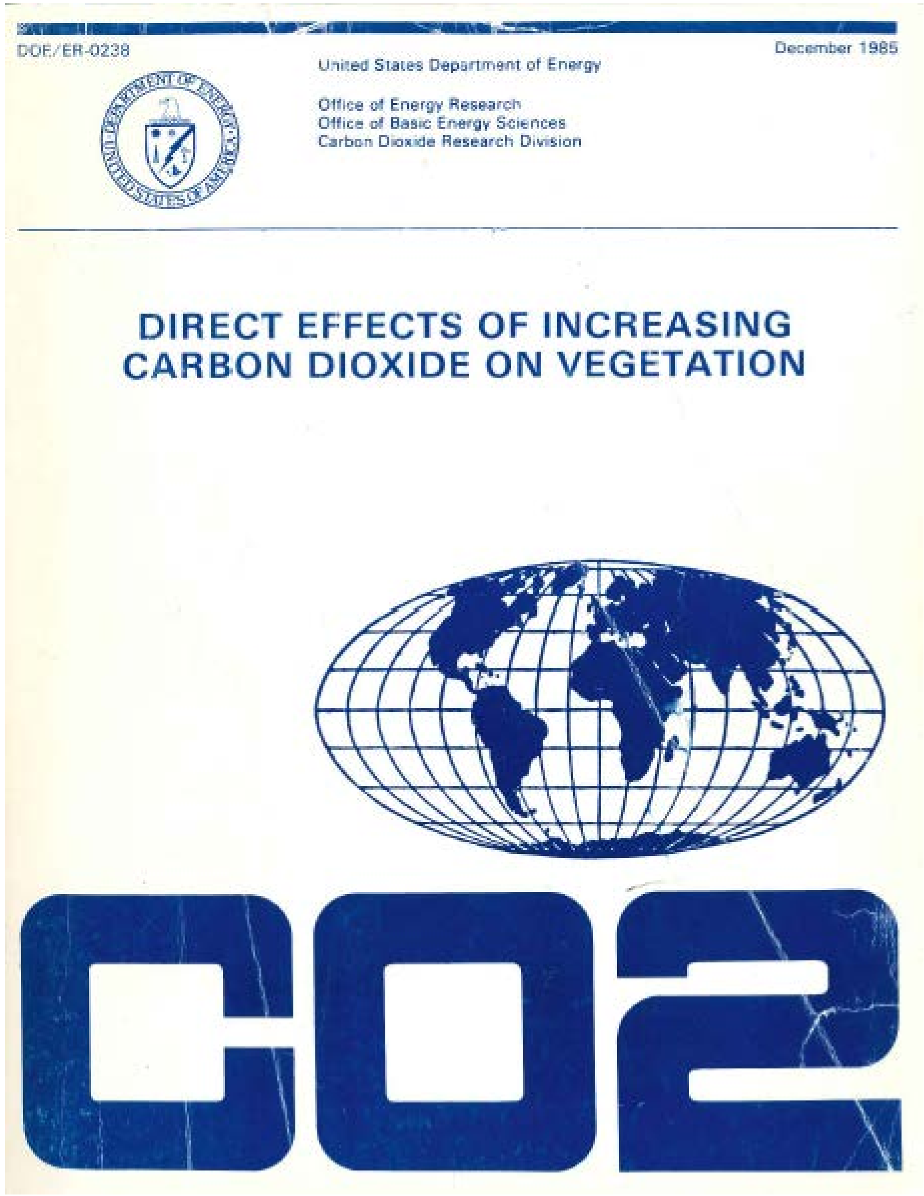
Topics:

Carbon metabolism
Physiological response
Plant growth and development
Microbial effects
Terrestrial plant communities
Aquatic plant communities

Boyd Strain & Fakhri Bazzaz

"…the initial effect of elevated CO_2 will be to increase NPP in most plant communities. …a critical question is the extent to which the increase in NPP will lead to a substantial increase in plant biomass. Alternatively, increased NPP could simply increase the rate of turnover of leaves or roots without changing plant biomass."



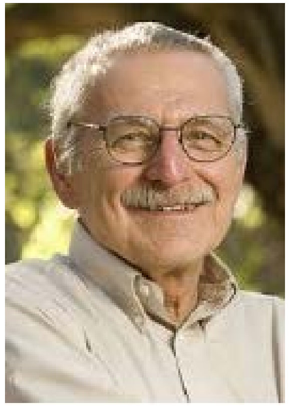


1985 State-of-the-Art Report

Enhanced plant growth and yield from more CO_2 is now widely recognized

Gains in knowledge about a few crop plants, but considerable ignorance remains about responses of native species and ecosystems

Suitable models for evaluating responses of plant communities and ecosystems to elevated CO_2 do not now exist.

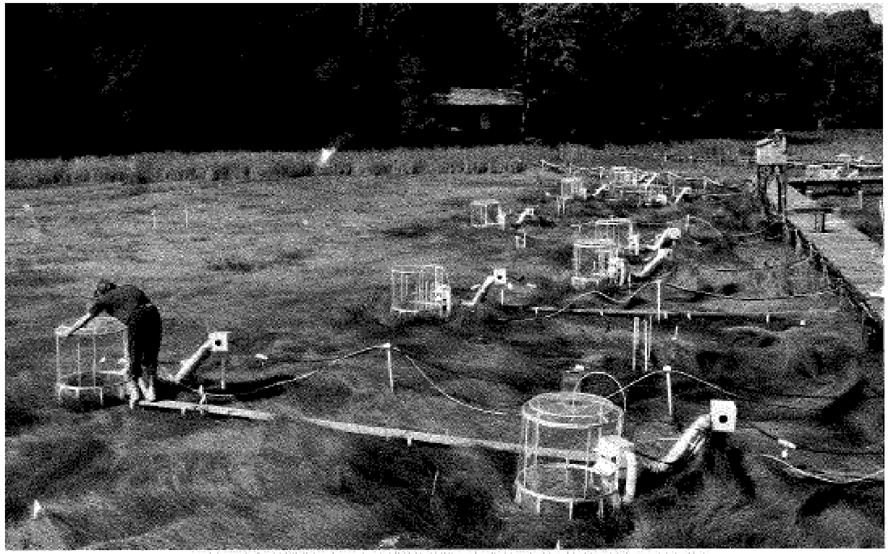


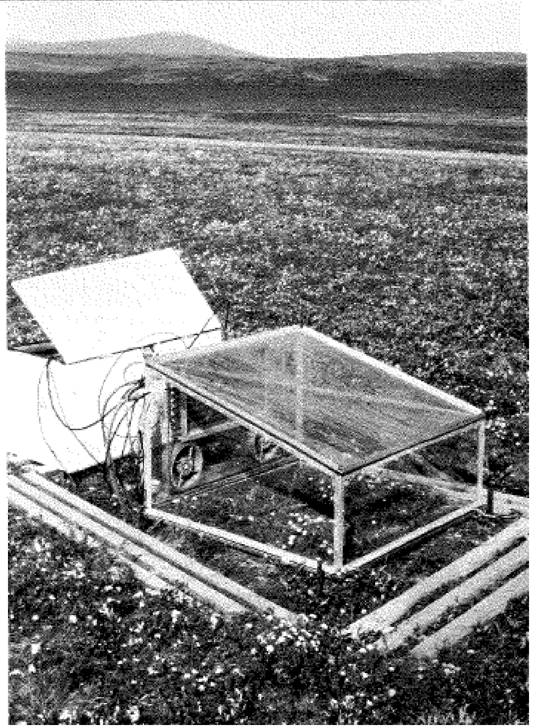
Predicting Ecosystem Responses to Elevated CO_2 Concentrations

What has been learned from laboratory experiments on plant physiology and field observations?

H. A. Mooney, B. G. Drake, R. J. Luxmoore, W. C. Oechel, and L. F. Pitelka

BioScience 41:96-104 (1991)





In 1991 there were just two CO_2 enrichment experiments in intact, natural ecosystems

- Chesapeake Bay salt marsh community (Bert Drake)
- Moist tussock tundra at Toolik Lake, Alaska (Walt Oechel)

The salt marsh was very responsive to elevated CO_2. The tundra was not.

Which is the *correct* response?

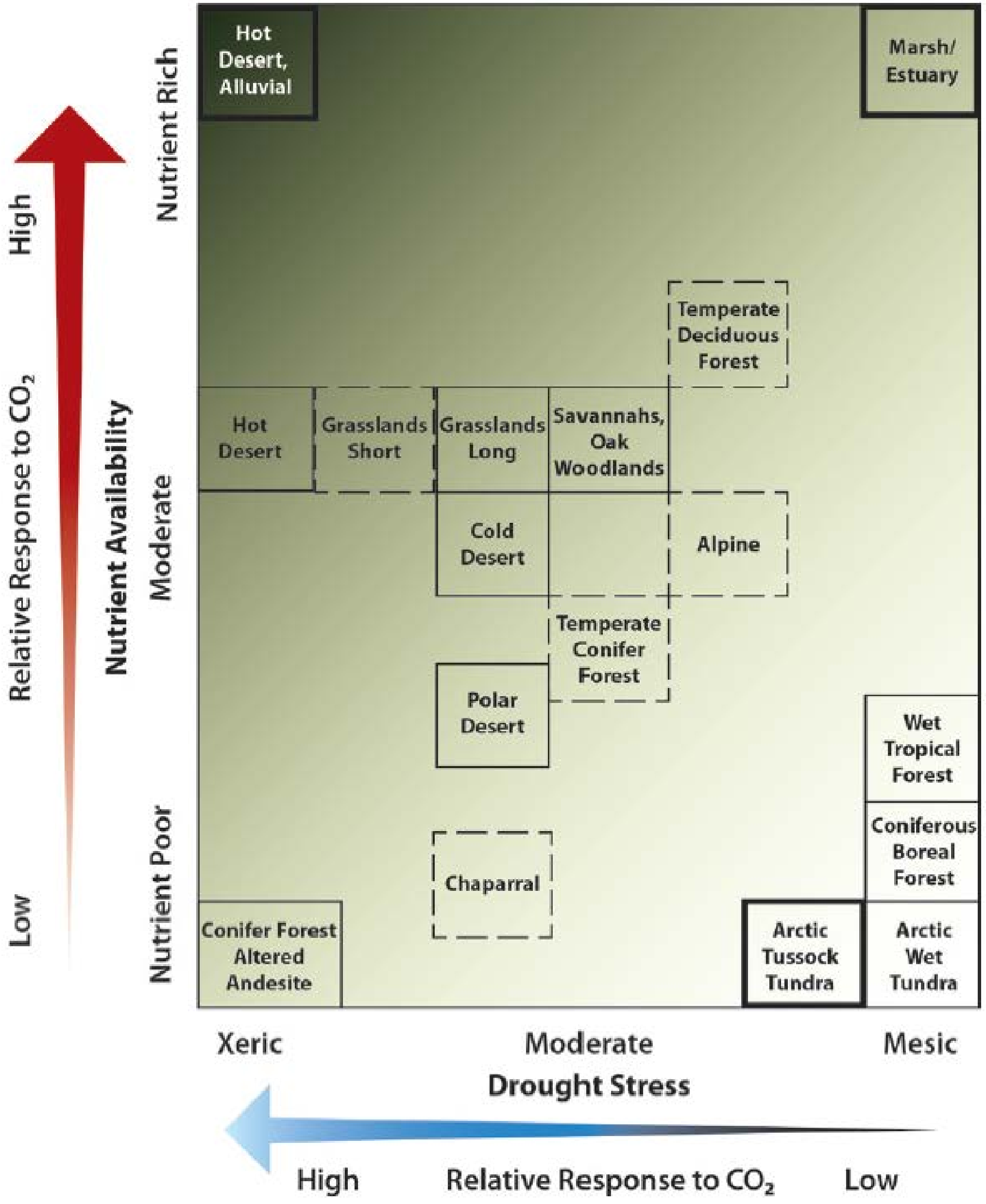
A research framework

"…ecosystems are likely to vary in their response to elevated CO_2."

"Laboratory and field experiments indicate that nutrient availability, water stress, and temperature affect the response, and natural ecosystems vary to the degree that these factors control system function."

"A diverse sampling of ecosystems with different resource limitations… is appropriate."

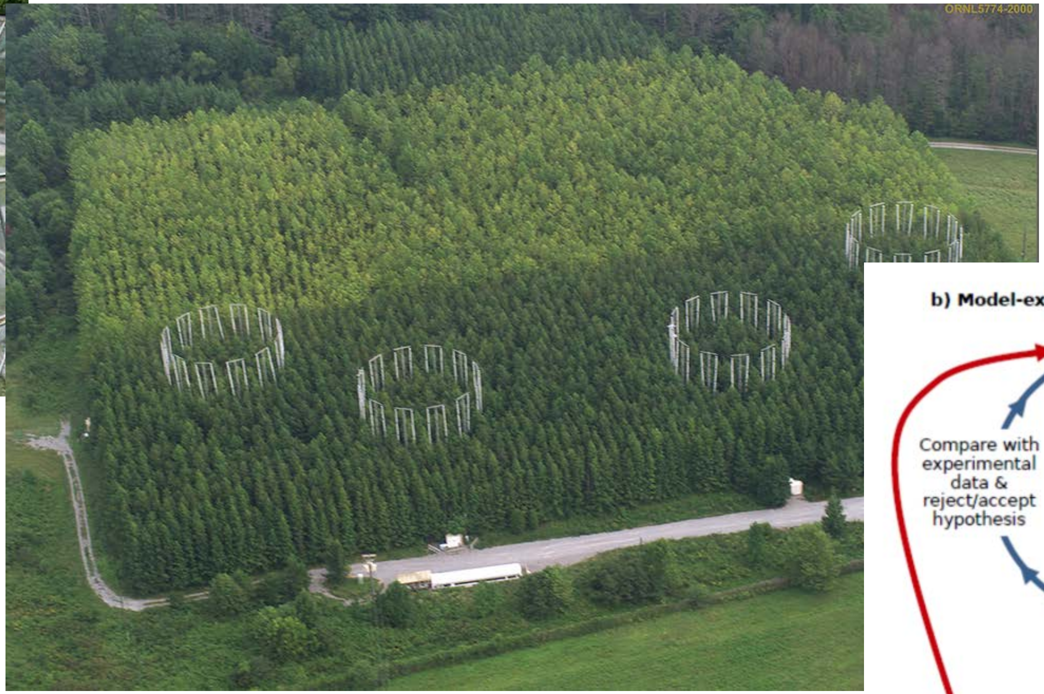
"At minimum, these experiments should be undertaken in each of the world's six major biomes (**tundra, boreal forest, temperate forest, tropical forest, grassland, and desert**)."



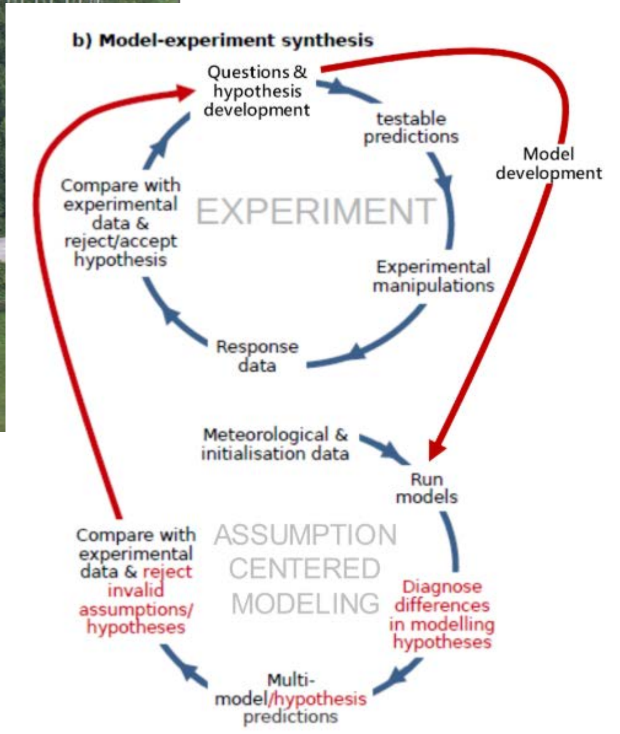
BioScience 41:96-104 (1991)

1982-1988

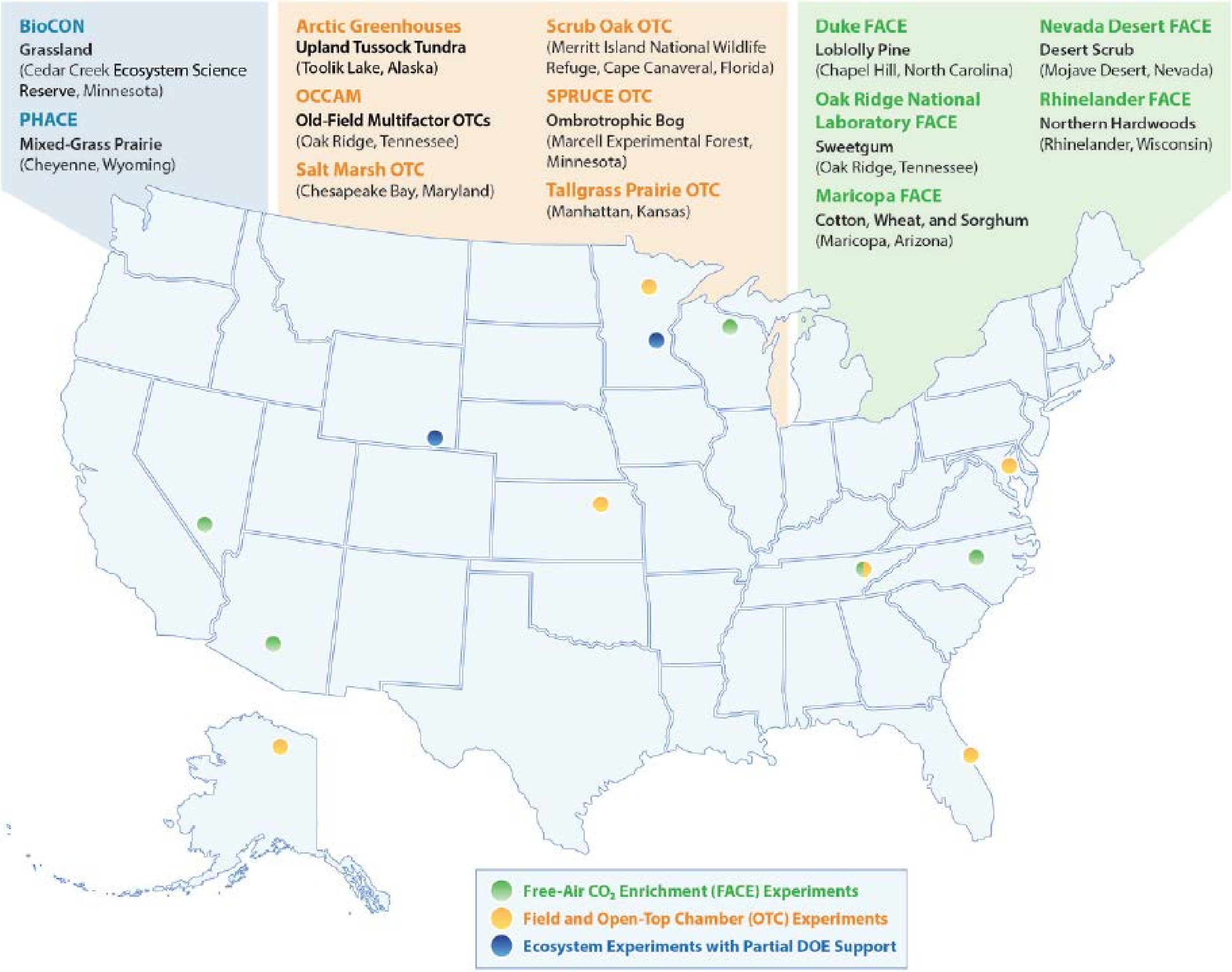
1989-2003



1996-2009



2008-2020+


BioCON
Grassland
(Cedar Creek Ecosystem Science Reserve, Minnesota)
PHACE
Mixed-Grass Prairie
(Cheyenne, Wyoming)
Arctic Greenhouses
Upland Tussock Tundra
(Toolik Lake, Alaska)
OCCAM
Old-Field Multifactor OTCs
(Oak Ridge, Tennessee)
Salt Marsh OTC
(Chesapeake Bay, Maryland)
Scrub Oak OTC
(Merritt Island National Wildlife Refuge, Cape Canaveral, Florida)
SPRUCE OTC
Ombrotrophic Bog
(Marcell Experimental Forest, Minnesota)
Tallgrass Prairie OTC
(Manhattan, Kansas)
Duke FACE
Loblolly Pine
(Chapel Hill, North Carolina)
Oak Ridge National Laboratory FACE
Sweetgum
(Oak Ridge, Tennessee)
Maricopa FACE
Cotton, Wheat, and Sorghum
(Maricopa, Arizona)
Nevada Desert FACE
Desert Scrub
(Mojave Desert, Nevada)
Rhinelander FACE
Northern Hardwoods
(Rhinelander, Wisconsin)
Free-Air CO_2 Enrichment (FACE) Experiments
Field and Open-Top Chamber (OTC) Experiments
Ecosystem Experiments with Partial DOE Support

What did we learn?

- Most of the C3 plants and terrestrial ecosystems studied do respond positively to increased concentrations of atmospheric CO_2.
- Many other environmental factors tend to lessen the effects of CO_2 on plant growth and ecosystem carbon cycling.
- A single, simple conclusion from the entire suite of DOE CO_2 experiments will never be sufficient.
- “Nature is not that simple.” (E. R. Lemon)

Looking forward...
...while looking back

The issues and questions put forward 30-40 years ago are still valid

Do we need new questions?

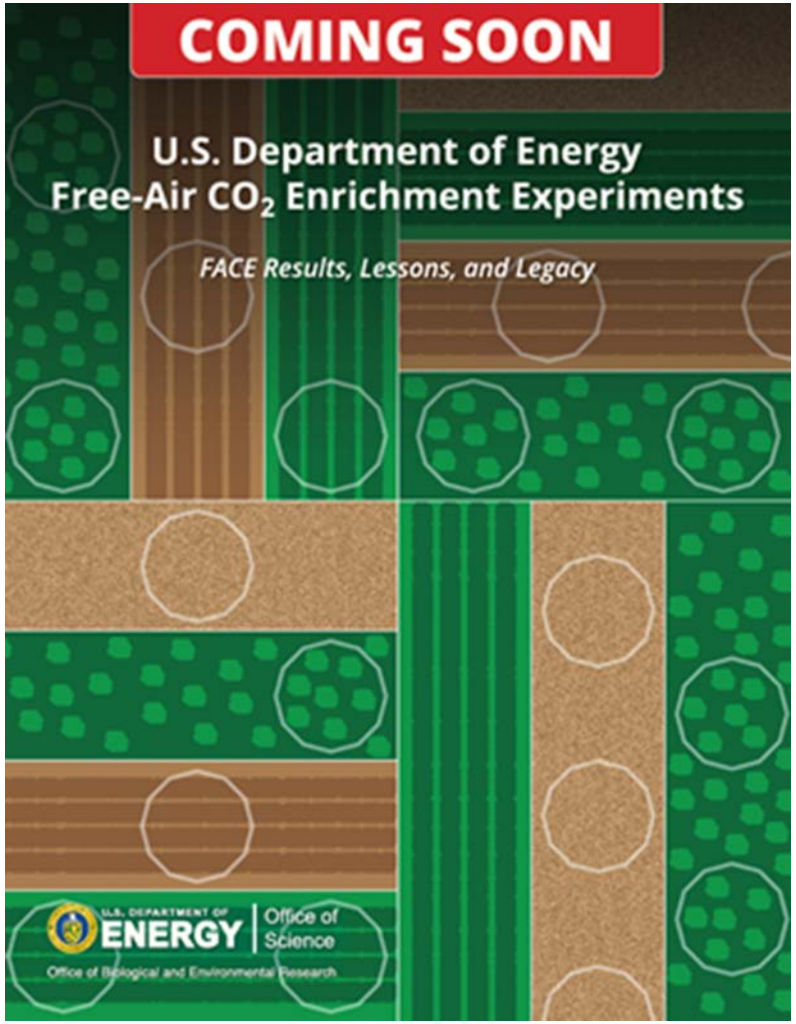
- Allocation, nutrient feedbacks, and plant-soil interactions continue to be important research foci
- A greater range of ecosystems and biomes need to be investigated
- Can we address CO_2 effects on plant community composition?
- New remote sensing tools create new opportunities, especially for scale-related issues

The more we learn, the more complicated the analysis becomes…

but that's the real world!

Lessons and legacy

- A resounding success!
  - 100's of papers, student training, career advancement, public engagement
- Demonstrated importance of model-data interaction
- Inspired and informed DOE's current NGEEs and SFAs
- Provided hypotheses, approaches, and technology for new and proposed FACE experiments in Australia, United Kingdom, and Brazil
- Demonstrated the power of manipulative experiments that encompass the feedbacks between biotic systems and the atmosphere and soil



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