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Impacts of Rising Atmospheric Carbon Dioxide Levels on Agricultural Growing Seasons and Crop Water Use Efficiencies

Volume II, Part 8 of Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change

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Impacts of Rising Atmospheric Carbon Dioxide Levels on Agricultural Growing Seasons and Crop Water Use Efficiencies

Volume II, Part 8 of
Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change

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Under Contract No. DE-AS01-79EV10019

NOTE

The paper which follows was commissioned as part of the project to produce A Research Agenda on Environmental and Societal Consequences of a Possible CO2-Induced Climate Change. Volume I (published December 1980 by the U.S. Department of Energy, publication DOE/EV/10019-01) summarizes the project's recommendations, and is based on the work of nearly 500 authors, co-authors, workshop participants, other experts consulted, and reviewers.

The papers commissioned as part of this project are:

1. Response of the West Antarctic Ice Sheet to CO2-Induced Climatic Warming: A Research Plan: Charles F. Bentley

2. Arctic Sea Ice Research in Support of Studying the Potential Effects of a CO2-Induced Global Warming: N. Untersteiner

3. Influence of Short-Term Climatic Fluctuations on Permafrost Terrain: Jerry Brown and John T. Andrews

4. Potential Effects on Ocean Dynamics of an Increase in Atmospheric Carbon Dioxide: Some Scientific Issues and Research Approaches: Michael McCartney and Henry Lansford

5. Effect of Increased CO2 on Ocean Biota: Osmund Holm-Hansen

6. Effects of Increased CO2 on Photosynthesis and Agricultural Productivity: Donald N. Baker, L. Hartwell Allen, Jr. and Jerry R. Lambert

7. Direct Effects of Increased Concentration of Atmospheric Carbon Dioxide on Managed Forests: Larry W. Tombaugh, Donald I. Dickmann and Douglas G. Sprugel

8. Impacts of Rising Atmospheric Carbon Dioxide Levels on Agricultural Growing Seasons and Crop Water Use Efficiencies: James E. Newman

9. Alleviation of Environmental Stress on Renewable Resource Productivity: Gordon S. Howell

10. Effects on Agricultural Plant Pests: Dean L. Haynes

11. Effects of Climate Change on Animal Agriculture: H. Allen Tucker

12. Response of "Unmanaged" Ecosystems: Boyd R. Strain and Thomas V. Armentano

13. Ecological Consequences of a CO2-Induced Climatic Change on Forest Ecosystems: W. Carter Johnson and David M. Sharpe

14. Research Needed to Determine the Present Carbon Balance of Northern Ecosystems and the Potential Effect of Carbon Dioxide Induced Climate Change: Philip C. Miller

15. Effects of CO2-Induced Climate Change on Freshwater Ecosystems: Charles C. Coutant

16. Research Issues in Grazinglands Under Changing Climate: Dennis F. Pendleton and George M. Van Dyne

17. The Use of Paleoclimatic Data in Understanding and Possibly Predicting How CO2-Induced Climatic Change May Affect the Natural Biosphere: Thompson Webb III

18. Climate Change and Agricultural Production in Non-Industrialized Countries: Lloyd Slater

19. CO2 and Climate Change: Anthropological Perspectives: William I. Torry

20. Responding to CO2-Induced Climate Change: Opportunities for Research: Richard A. Warrick and William E. Riebsame

21. Climate and Society in History: Theodore K. Rabb

22. Research on Political Institutions and Their Response to the Problem of Increasing CO2 in the Atmosphere: Dean E. Mann

23. International, Legal and Institutional Implications of an Increase in Carbon Dioxide: Edith Brown Weiss

24. Psychological Dimensions of Climatic Change: Baruch Fischhoff and Lita Furby

25. Interdisciplinary Research and Integration: The CO2 Problem: Robert S. Chen

26. Effects of Climate Change on Health: Melinda Meade

27. Theoretical and Empirical Aspects of Optimal Control Strategies: William D. Nordhaus

28. A Conceptual Framework for Research About the Likelihood of a "Greenhouse Effect": Mancur Olson

29. Adaptive Aproaches to the CO2 Problem: Roger G. Noll

30. Planning for Climate Change: Dennis Epple and Lester Lave

Contributed Paper: The Potential Response of Antarctic Sea Ice to Climatic Change Induced by Atmospheric CO2 Increases: S. F. Ackley

Outline of Commission Paper
entitled
Impacts of Rising Atmospheric Carbon Dioxide Levels on Agricultural Growing Seasons and Crop Water Use Efficiencies

I. Scope of Research Area

The researchable areas addressed in this commission paper relate to the possible impacts of climate change on agricultural growing seasons and crop adaptation responses on a global basis. The assumed climate change is that of a global warming related to increasing atmospheric CO_2 concentrations. However, the research proposed herein is also relevant under a scenario of global cooling or no change, since the ever increasing demand for food, fiber and other renewable resources will be present as long as human populations continue to increase around the world.

The research activities proposed are divided into two main areas of investigation; one, anticipated climate change impacts on the physical environmental characteristics[1] of the agricultural growing seasons and two, the most probable food crop responses to the possible changes in atmospheric CO_2 levels in plant environments. The main physical environmental impacts to be considered are the changes in temperature, or more directly, thermal energy levels and the growing season evapotranspiration-precipitation balances. The resulting food crop, commercial forest and rangeland species response impacts to be addressed relate to potential geographical shifts in agricultural growing seasons as determined by the length in days of the frost free period, thermal energy changes and water balance changes. In addition, the interaction of possible changes in plant water use efficiencies during the growing season in relationship to changing atmospheric CO_2 concentrations, is a central biological response impact to be considered under the scenario of global warming due to increases in atmospheric CO_2 concentration. These proposed research investigations are to be followed by adaptive response evaluations. Therefore, the scope of the research set forth in this commission paper should produce an important assessment contribution to the question of increased atmospheric CO_2 induced climate change impacts on food, fiber and other renewable resources.

II. The Relationship of Research Proposed on Previous Efforts

This is not a literature survey. Rather, it is a briefly summarized statement of pertinent findings that relate to the impact and assessment studies proposed.

During the 1950's, 60's, and 70's many individuals and several national teams of agricultural scientists attempted to increase crop production by the application of enriched CO_2 environments. Many experiments were carried out in growth chambers, greenhouses and under open field conditions. Some successes were achieved, particularly in growth chambers and greenhouses (Wittwer and Robb 1964). The successes under field conditions were less spectacular.[2] But, investigations under open field environments did reveal considerable diurnal variations in atmospheric CO_2 concentrations above and within well developed vegetative canopies of crop monocultures (Rosenberg and Verma 1976). Some idealized CO_2 profiles are illustrated within and above maize canopies in Figure 1. Such experimentation revealed that well developed vegetative canopies can be strong sinks for CO_2 during very active photosynthesis and light wind thus causing considerable diurnal variations in CO_2 profiles (Harper 1973). As much as 50 ppm in diurnal variations in crop canopy profiles have been reported under managed biospheric conditions (Allen 1971). Diurnal variations, illustrated in Figure 2, coupled with well known annual variations, as illustrated in Figure 3, suggest that CO_2 concentrations within a well developed agricultural region could vary as much as 50 to 100 ppm over an annual growing season. These variations are fully twice the reported increases in atmospheric CO_2 concentrations over the past century (Keeling 1976). This possible regionality of diurnal and seasonal variations in CO_2 concentrations over well developed agricultural and forested areas is illustrated by Figure 4 (Verma and Rosenberg 1976).

Review comment by R. H. Shaw

Denmead 1966, showed changes of over 200 ppm CO_2 from early morning to midday at 10 cms. above a wheat crop (Proceedings of WMO Seminar on Agricultural Meteorology, Melbourne, Australia). Such open field diurnal variations raise the question, as global atmospheric CO_2 levels increase, at what level above a given base or average global level would atmospheric CO_2 levels be maintained during periods of rapid photosynthesis above and within food crop monocultures. This would probably be the most meaningful values in predicting food crop-CO_2-climate change impacts. As has been pointed out, the daily and seasonal variations are much greater than many of the CO_2 increases monitored as global background measurements.

The C_3 VS C_4 Plant Groups

Two groups of plant species with different photosynthetic systems have been recognized during the last two decades. One group is known as C_3 plants while the other is knowns as C_4 plants. The C_3 species fix 3 carbon carboxylic acid as an early product of photosynthesis; thus the C_3 designation. In contrast, the C_4 species fix 4 carbon dicarboxylic acid as an early product of photosynthesis; thus the C_4 designation.

Certain characteristics favor one group over the other. These advantages or disadvantages are related to both physical environmental characteristics as well as to differences in the photosynthetic processes. Therefore, the understanding and the successful management of these differences on a local, regional, national and international level is a paramount issue in coping with future climate change impacts on renewable resource production.

FIGURE 1. IDEALIZED PROFILES OF CARBON DIOXIDE CONTENT OF THE AIR IN AN ACTIVELY PHOTOSNYTHESIZING CORN FIELD AS A FUNCTION OF THE ABOVEGROUND HEIGHT OF VARIOUS PERIODS DURING A SUNNY DAY (AFTER LEMON, 1960).

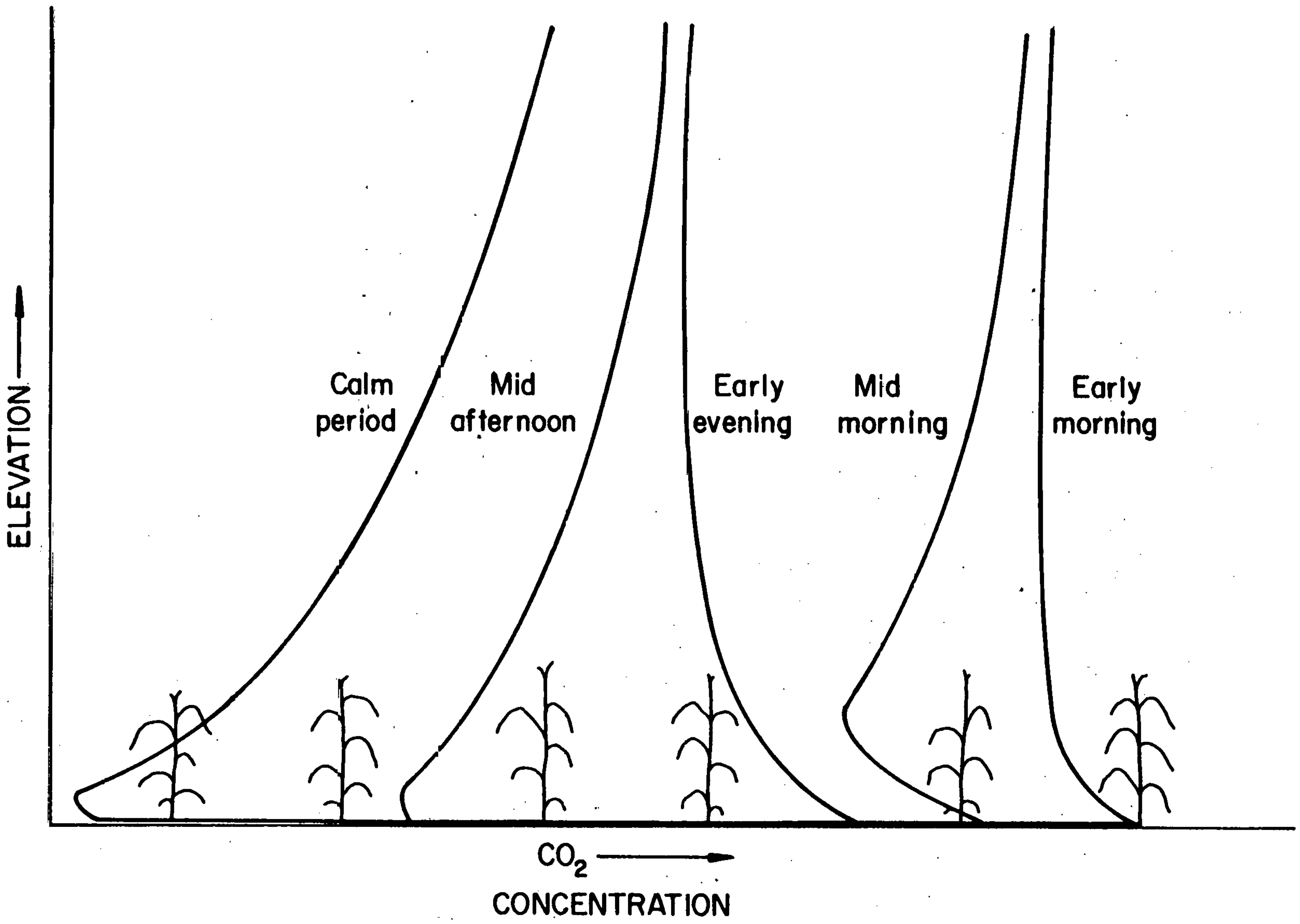


FIGURE 2. TYPICAL DIURNAL PATTERN OF CO_2 CONCENTRATION AT 16 M ABOVE GROUND DURING THE GROWING SEASON AT MEAD, NEBRASKA. (VERMA AND ROSENBERG 1976).

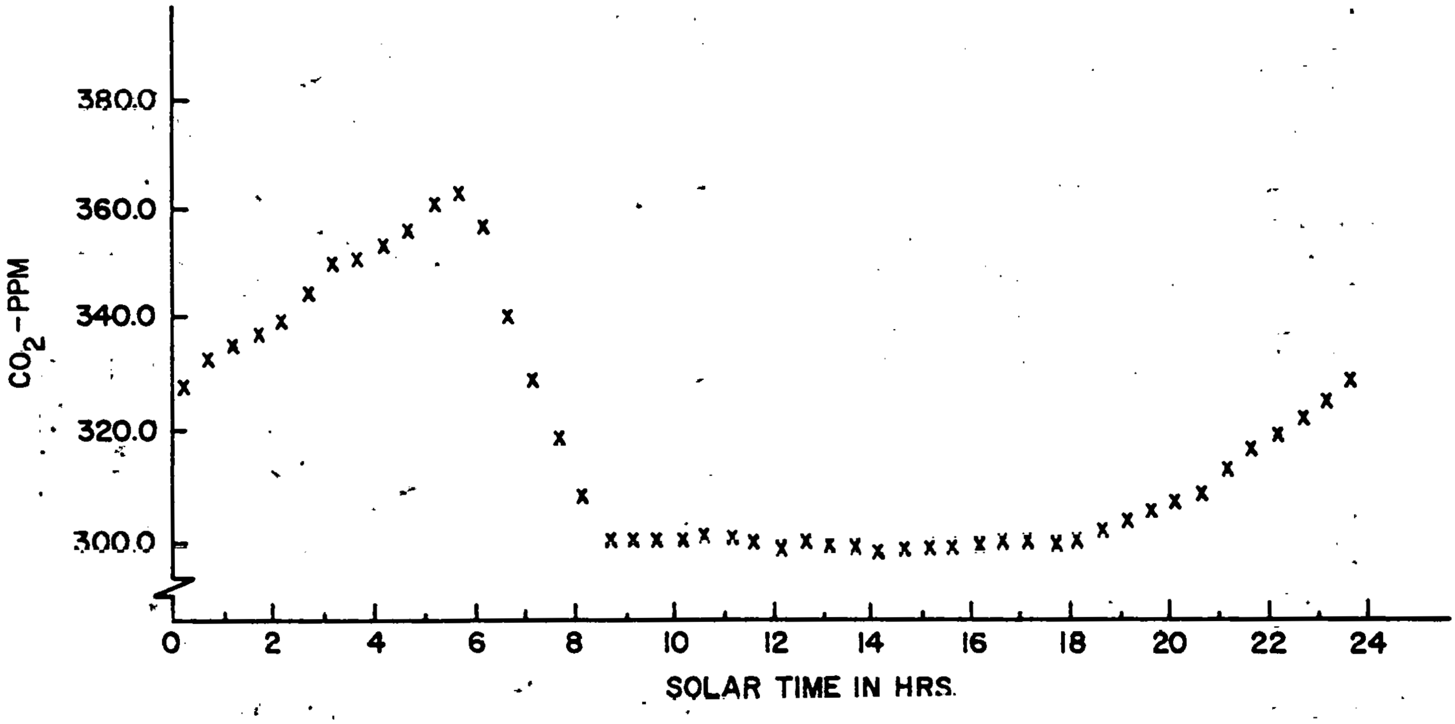


FIGURE 3. SEASONAL VARIATIONS IN THE CARBON DIOXIDE CONTENT OF THE ATMOSPHERE FOR THE REGION NORTH OF LATITUDE 30° N. THE ABSCISSA IS DEPARTURE FROM A MEAN GLOBAL CONCENTRATION OF 320 ppm (AFTER BOLIN, 1970).

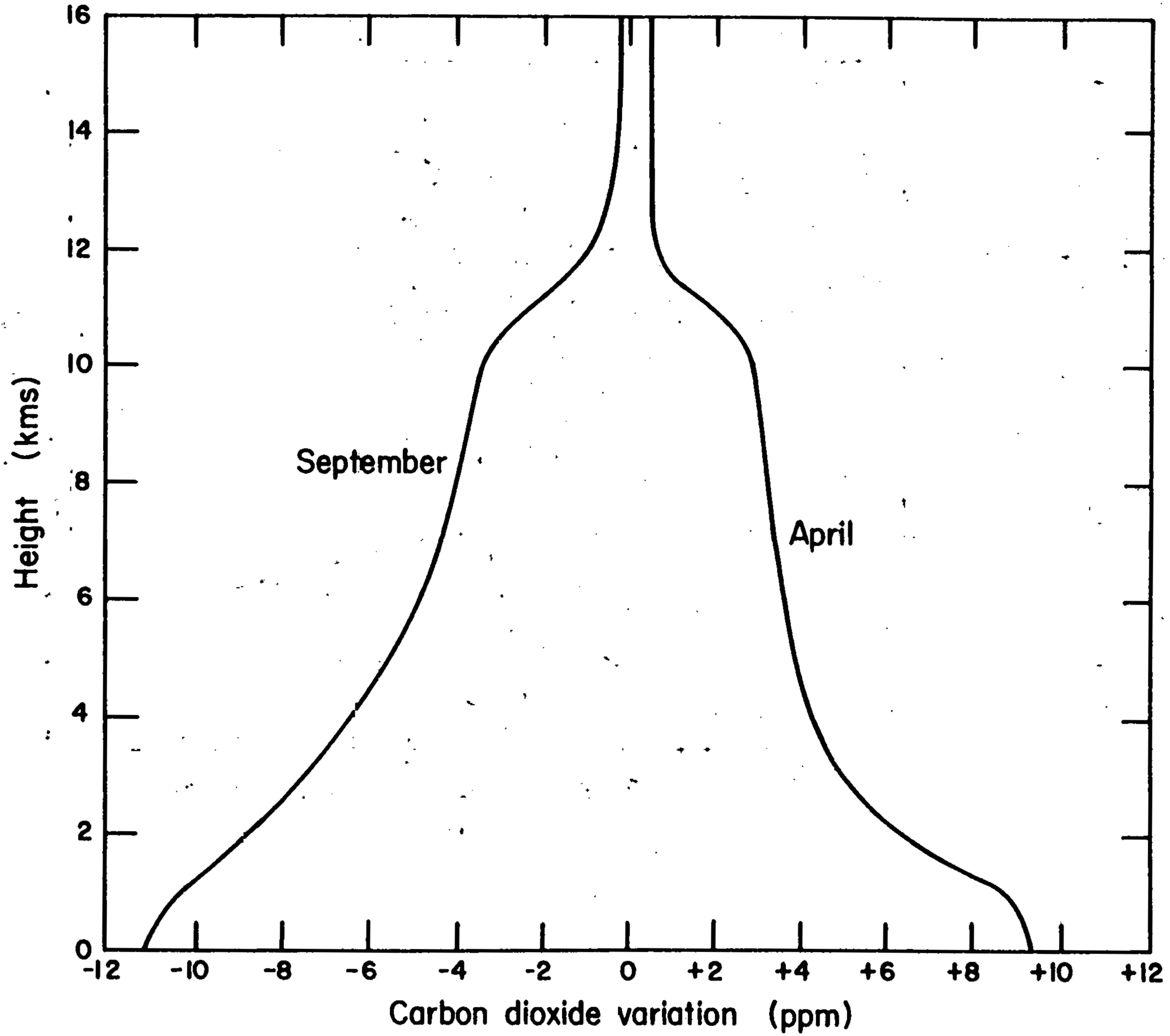
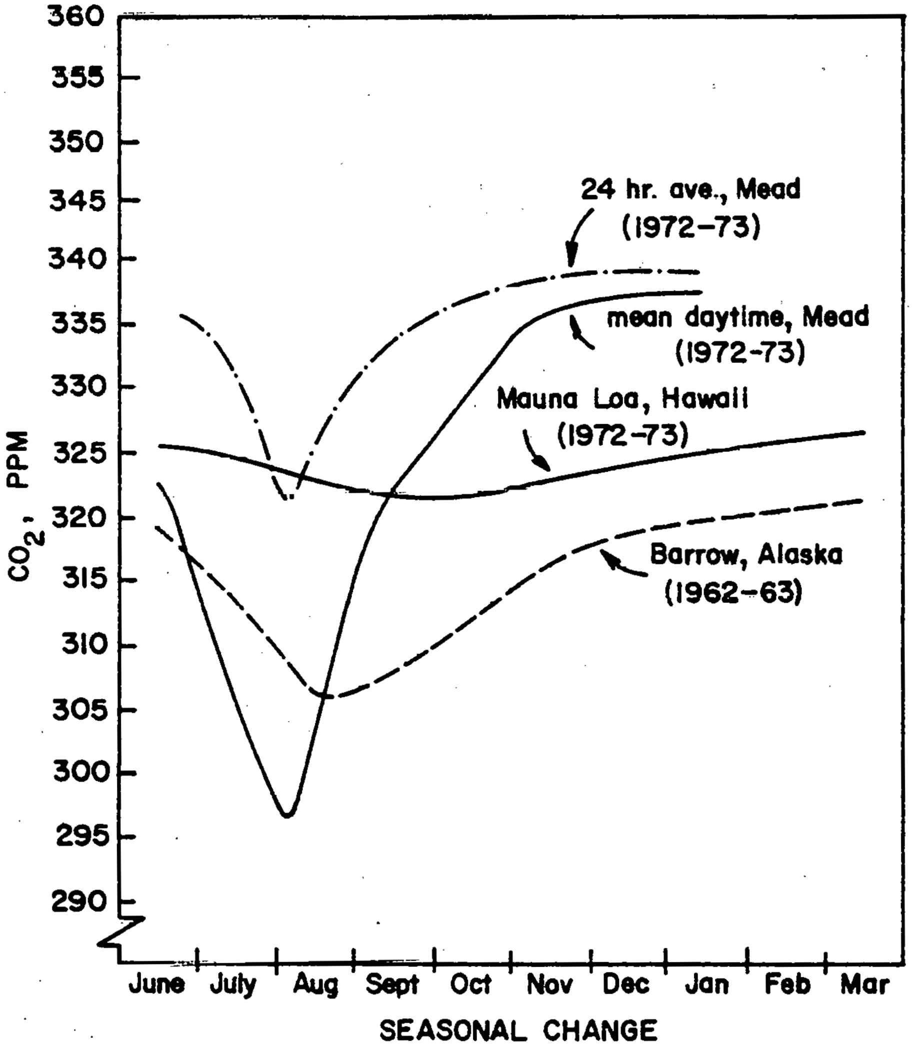


FIGURE 4. A PART OF THE ANNUAL CYCLE OF CO_2 CONCENTRATION AT MEAD, NEBRASKA. THE LINES ARE DRAWN THROUGH MONTHLY MEANS OF THE DAYTIME AND 24 HR CONCENTRATIONS. COMPARATIVE DATA FOR BARROW, ALASKA AND MAUNA LOA, HAWAII ARE ALSO SHOWN. (VERMA AND ROSENBERG, 1976).



Physiologically the C_3 species are considered less efficient during the active photosynthetic process than the C_4 species (Lemon 1977). This is particularly true with respect to the net balance of CO_2 fixation. The advantage of the C_4 over the C_3 species can be explained largely on the basis of differences in photorespiration. The C_3 species have a greater respiratory loss of CO_2 during the daylight hours under active photochemical reduction conditions. As a result, this photorespiratory loss of CO_2 apparently contributes to the C_3 species positive responsiveness to higher levels of atmospheric CO_2.

Turning to the question of climatic responses, the C_4 species are generally adapted best in high temperature - high sunlight intensity which occur naturally in the tropical and subtropical areas. The primary crop examples are those of tropical grass origin -- maize, sorghum, and cane sugar. In contrast, the C_3 plants are more adapted to cooler temperatures and lower sunlight intensities. The primary examples are the cool season grass crops represented by wheat, barley, rye and oats. In addition, most species of vegetables, tree fruits, and commercial forest species are classified in the C_3 group of plants.

The ten major food crops of the world are listed in Table 1 in order of total worldwide production. Among this list three are C_4 type crops and seven are C_3 type crops. These ten crops represent approximately 65% of the world food production. If the list was extended to represent the twenty-five most productive crops used in worldwide agriculture, over 90% of the world's land based food energy would be represented. Approximately 80% of these twenty-five crop species are C_3 type species while the remaining 20% are C_4 type species. Further, crop production in the cold temperature and subarctic regions is almost completely dependent on C_3 type crop species.

Table 1. Ten Major World Food Crops.[3]

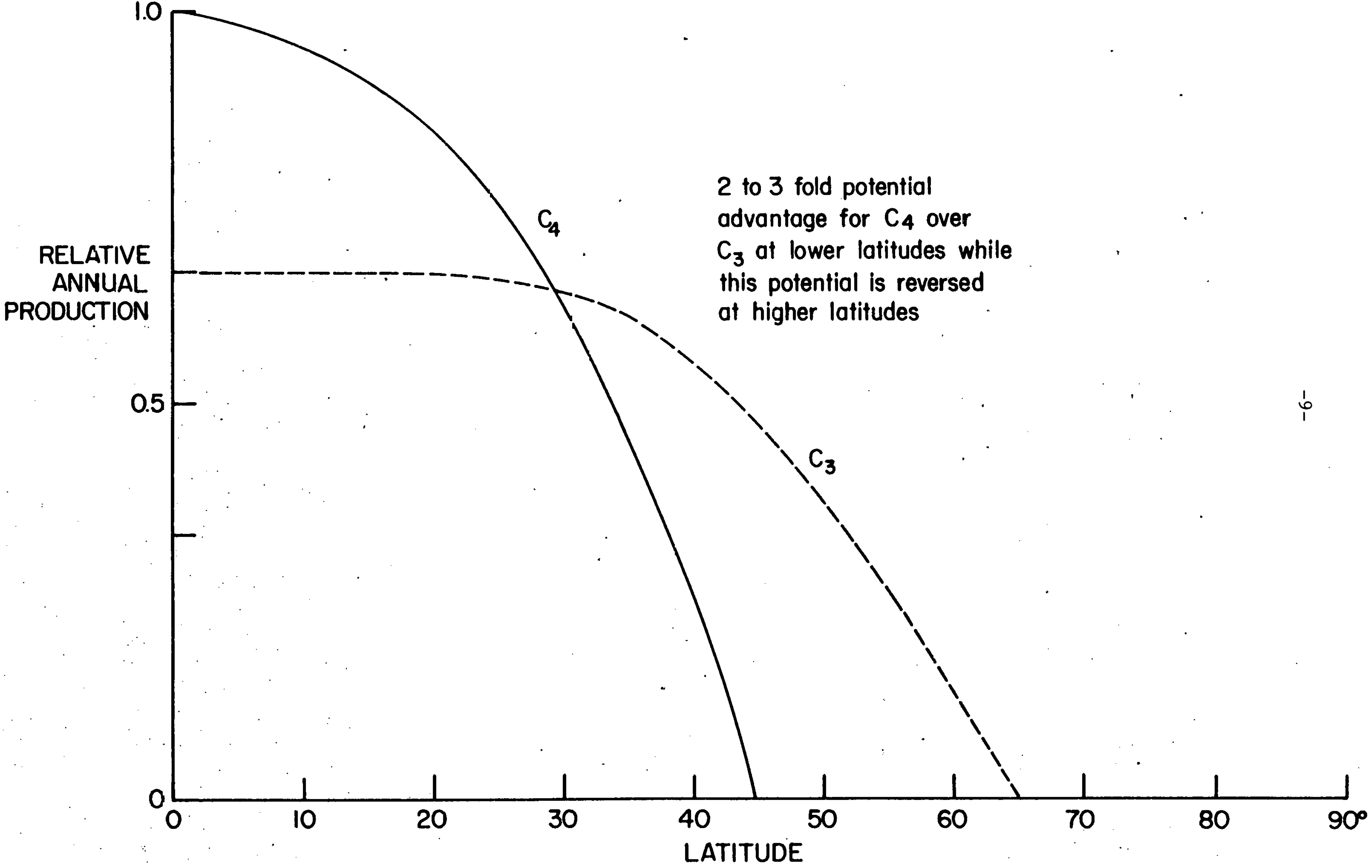
Crop	C_3 or C_4	Latitudinal range
Wheat	C_3	25 to 55
Rice	C_3	0 to 45
Maize	C_4	0 to 45
Potato	C_3	30 to 60
Barley	C_3	45 to 65
Sweet Potato	C_3	25 to 40
Cassava	C_3	0 to 30
Soybeans	C_3	25 to 45
Sorghum	C_4	0 to 40
Cane Sugar	C_4	0 to 30

A generalized summary is illustrated in Figure 5 for C_3 and C_4 type crop species. It relates hypothetical advantages in annual growing season biomass production to latitude (Loomis and Gerakis 1975). Under the present atmospheric CO_2 concentrations the biochemical reaction rate of the C_3 photosynthesis pathway would theoretically produce a net advantage at higher latitudes under lower sunlight and cooler growing season temperatures. The reverse would likely be true at lower latitudes where the C_4 type photosynthesis pathway could produce net advantages under high sunlight intensities and higher growing season temperatures. How the latitudual distribution of these hypothetical advantages or disadvantages among C_3 and C_4 crop species will shift during the future world climate change is another paramount research question to be addressed.

Current literature reporting increased water use efficiencies in crop species due to increased concentrations of atmospheric CO_2 is limited. However, some scientists have reported preliminary results showing considerable advantage for some C_3 crop plants over C_4 crop plants. A sample of these findings has been reported by Ho 1977; Enoch and Sach 1978; and Cowan 1978, plus several other investigations not yet published or unavailable in foreign literature.

Growing crops under CO_2 enriched atmospheric conditions has fascinated the agricultural scientist for at least the last 50 years. Therefore, increased plant growth and crop production has been an accepted fact in greenhouse enriched CO_2 environments. But, crop biochemical and morphological differences relating photochemical reactions to environmental CO_2 concentrations among the major food crops were not generally appreciated until the early 1960's, (Sinclair 1975). It was during this period that numerous authors found that most C_3 type plants responded better to higher increases in CO_2 enrichments than did the C_4 type. This find-

FIGURE 5. SUMMARY HYPOTHESIS OF PRODUCTION BETWEEN C_3 AND C_4 CROP SPECIES IN RELATION TO LATITUDE. (ADAPTED FROM LOOMIS AND GERAKIS 1975)



2 to 3 fold potential advantage for C_4 over C_3 at lower latitudes while this potential is reversed at higher latitudes

ing was followed in the late 1960's and early 1970's by a number of investigators reporting on differences in stomatal closure between C_3 and C_4 type plants to increased CO_2 environments, (Akita and Moss 1972). This difference is an important matter in crop water use efficiency changes under global atmospheric CO_2 increases. The confirmation of these findings has been covered in recent reviews by Lemon 1977 and Allen 1979.

The impact of elevated atmospheric CO_2 concentrations on crop transpiration has become a subject of some recent investigations by a number of researchers in several countries around the world. These early investigations have reported increased water use efficiencies at higher atmospheric CO_2 concentrations for almost all species so far. In general, plant transpiration rates decrease when atmospheric CO_2 concentrations are increased, (Carlson 1980).

A postulated summary of these early findings is presented in Figures 6A, 6B as reported in a recent paper, (Enoch and Hurd 1979). Based on a summary of current information these authors predict a 10% reduction in relative crop transpiration rates under a doubling of atmospheric CO_2 concentrations, suggesting a 10% increase in crop water use efficiencies.

Agricultural Growing Seasons

Traditionally, agricultural growing seasons have been determined by the annual length of the frost-free period in days, (Brown 1976). This concept has been applied historically across latitudes where freezing temperatures occur regularly on an annual basis. In general, this includes all agricultural production areas between the sub-tropics and the sub-arctic in the world. But, the frost-free period approach of determining agricultural growing seasons is both crude and very incomplete from a climatic requirement viewpoint, because it does not include other climatic requirements of an annual crop growing season, (Brown et al. 1977).

Freezing temperatures do not occur at lower elevations in the low latitude tropical climates. In these regions agricultural growing seasons are limited to annual periods of water availability. In tropical rainforest climates annual crop growing seasons are continuous or nearly so. But, at higher tropical latitudes in either hemisphere, under dry land farming practices, crop growing seasons are determined almost entirely by the annual length of the rainy season[4]. Therefore, annual agricultural growing seasons are determined almost entirely by soil moisture availability in these tropical regions. Figure 7 addresses this point.

In the higher latitudes of the sub-tropics and warm temperature regions, adequate water availability in the form of seasonal soil moisture is often more limiting in annual crop production than thermal energy or frost-free period requirements. Seasonal frost-free periods and thermal energy requirements usually become the primary limiting factor only in the high

FIG. 6A. ESTIMATES OF GLOBAL ATMOSPHERIC CO_2 CONCENTRATIONS BETWEEN THE YEARS 1890 AND 2030.

FIG. 6B. CALCULATED RELATIVE TRANSPIRATION RATE. THE TRANSPIRATION RATE IN THE YEAR 1890 IS TAKEN AT 100%.

(AFTER H. Z. ENOCH AND R. G. HURD)

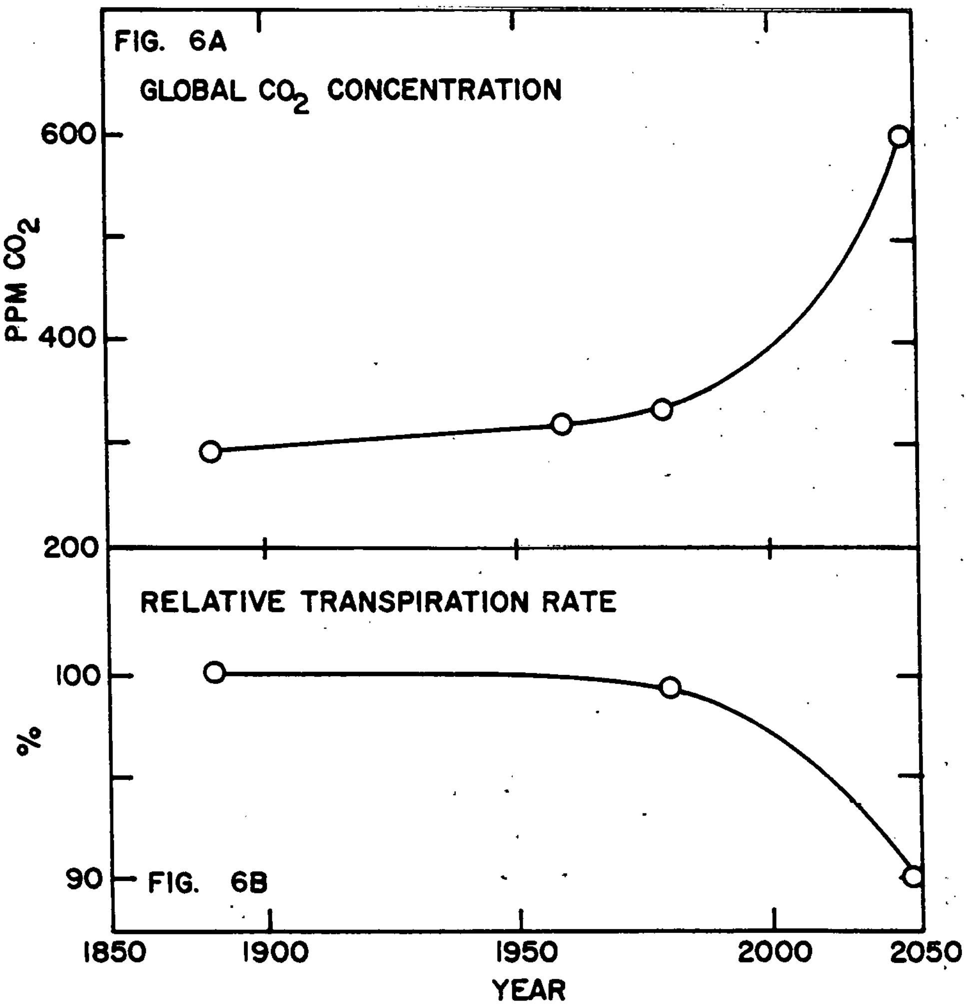
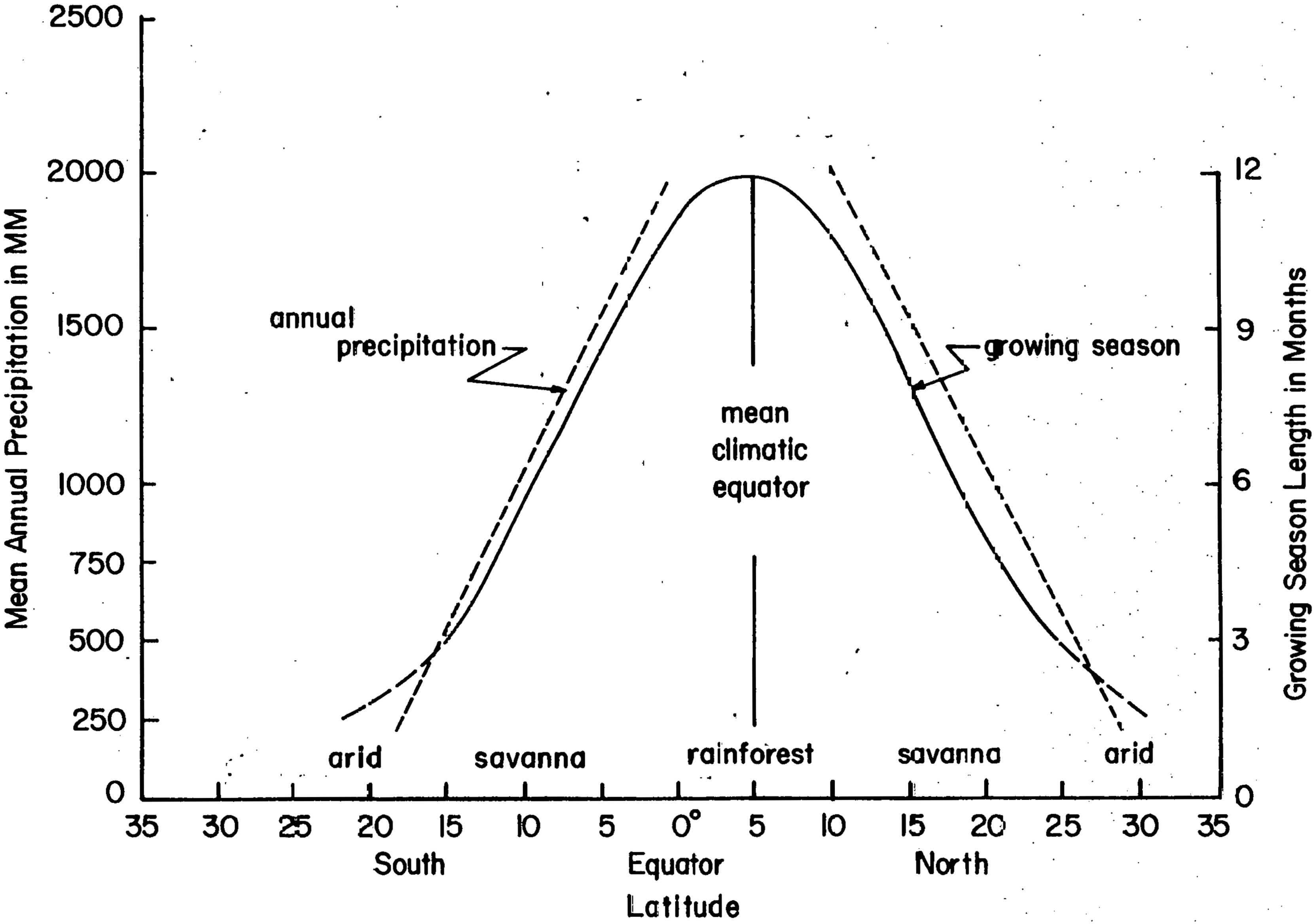


FIGURE 7. THE RELATIONSHIP BETWEEN MEAN ANNUAL PRECIPITATION AND GROWING SEASON LENGTH IN TROPICAL CLIMATES. (NEWMAN, 1977).



latitudes of the cool-temperate and sub-arctic regions. In fact, annual crop growing seasons in the sub-tropical and warm temperate mid-latitudes occur before, as well as after, the normal frost-free periods for many cool-season crops.[5] Winter wheat is perhaps the best example. This matter was addressed by Newman and Wang 1959. They classified agricultural growing seasons in the mid-latitudes by relating crop growth to several temperature ranges during the year.

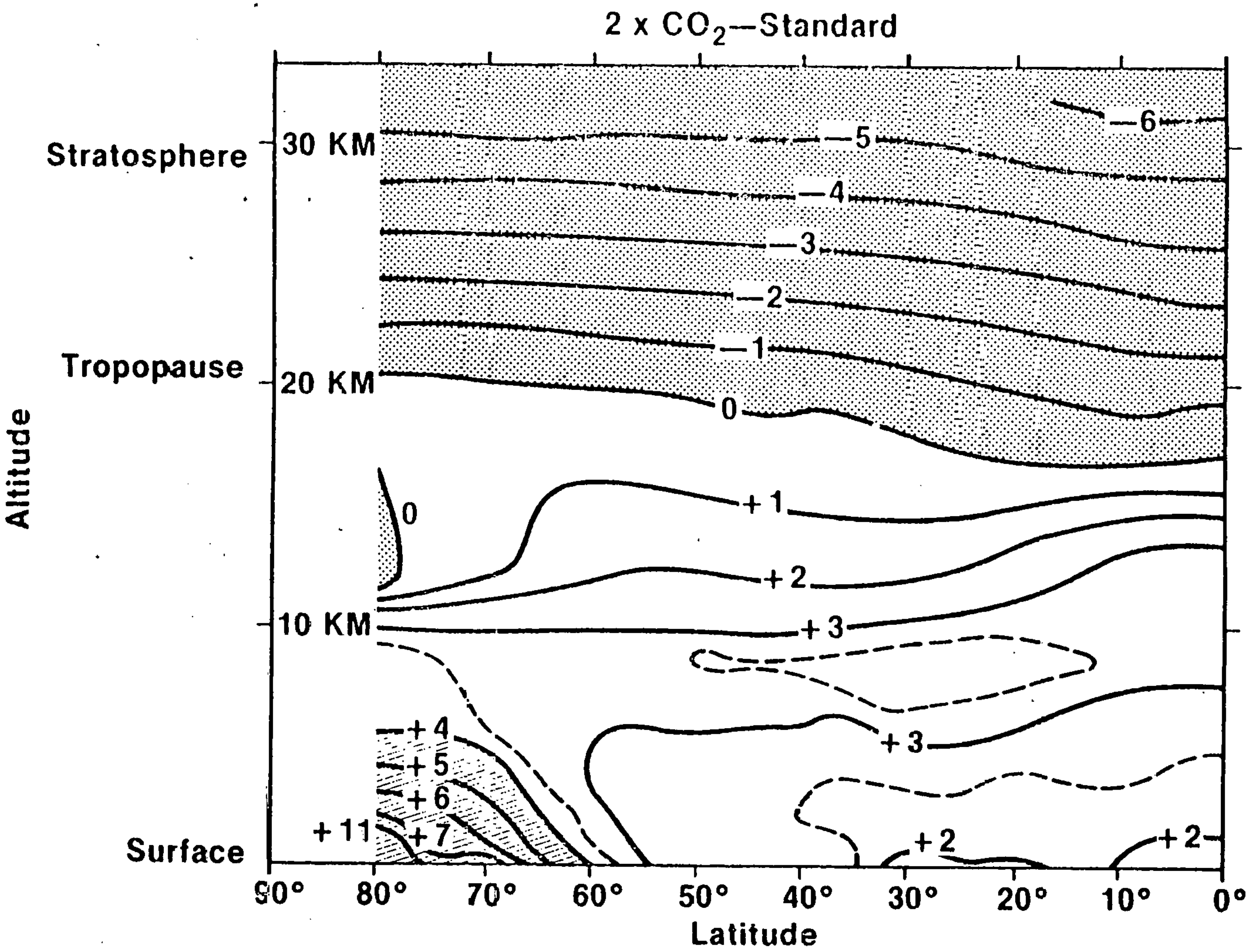
If an adequate assessment of climate change impacts on crop growing seasons is to be accomplished, then these impacts must be evaluated by more responsive criteria than merely changes in annual periods of frost-free days. This would be true for all tropical latitudes and most mid-latitude areas as well. Further, on a worldwide basis, water in the form of seasonal soil moisture availability is the most limiting climatic condition in almost all types of dry land agriculture.

On a global scale, the gradients of climate vary across latitudes in the broadest sense. Any climate shift caused by or related to increases in atmospheric CO_2 is likely to occur on a global scale, (Manabe and Wetherald 1975). Therefore, the assessment of associated climate impacts on annual agricultural growing seasons is likely to be associated with hemispheric scale latitudinal gradients as illustrated in Figure 8.[6]

Annual agricultural growing seasons are determined by a combination of climatic and agronomic conditions, (Papadakis 1966). Climate-wise the growing season is determined by an adequate water supply, plus the necessary solar and thermal energy over a seasonal period long enough to plant, grow, and harvest the crop, (Papadakis 1970). Further, annual crop growing seasons are often determined by the most limiting element or factor of climate.

In the tropical rainforest climates the only limiting climatic factor is flooding; so from a climatic viewpoint the growing season is continuous. However, crop production is usually limited in these climates by the agronomic concerns of pests, diseases and impoverished soils. In the higher tropical latitudes of wet and dry climates the period of annual rainfall determines the crop growing seasons. At the higher sub-tropical and warm temperate latitudes annual crop growing seasons are determined largely by soil moisture availability and thermal energy in the form of adequate temperate levels. The length of the frost-free period is normally not a limiting factor. Thermal energy is often excessive, leaving the occurrence of available water supplies during the growing season as the limiting factor most often. In the temperate to cool temperate latitudes, annual crop growing seasons are determined by a combination of frost-free seasons lengths, thermal energy levels and adequate soil moisture during the frost-free season.

FIGURE 8. SIMULATED NORTHERN HEMISPHERE ANNUAL TEMPERATURE CHANGE (°C) DUE TO DOUBLING ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS (MANABE AND WETHERALD, 1975).



The combination approach to determining possible climate change impacts on agricultural growing seasons was applied to the North American Corn Belt, (Newman 1979). This analysis reveals that the North American Corn Belt shifts in a southwest-northeast direction approximately 175 kilometers per degree celsius change in growing season temperatures (See Figure 9). This analysis includes the influences of growing season temperature change on evapotranspiration and thermal units during the normal frost-free growing season for maize. At the highest latitudes of the cold-temperate and sub-arctic regions, annual crop growing seasons are largely determined by the length of the frost-free period plus the level of thermal energy during the frost-free period.

III. Specific Research Problem

There is a high priority need for reasonable first approximation estimates of possible impacts of global climate change on agricultural growing seasons. In addition, there is an equally important need to estimate the possible impact of increasing atmospheric CO_2 concentrations on the water-use efficiencies for the C_3 and the C_4 type crop species. After acceptable estimates of possible atmospheric CO_2 induced-climate change impacts on growing seasons and plant water use efficiencies have been achieved, the interactions of these two possible impacts must be included in any complete assessment. The highest priority research problem within the mid-latitudes is likely to be the seasonal shifts plus seasonal variability in temperature changes related to any CO_2 induced shifts in global climate.

IV. Research Plan

The general approach to this research plan must begin with impact studies directed toward each specific area to include the following:

(1) Simulate the impact of possible climate change on agricultural growing seasons across and within various latitude belts based on historic climate data from North, Central and South America.

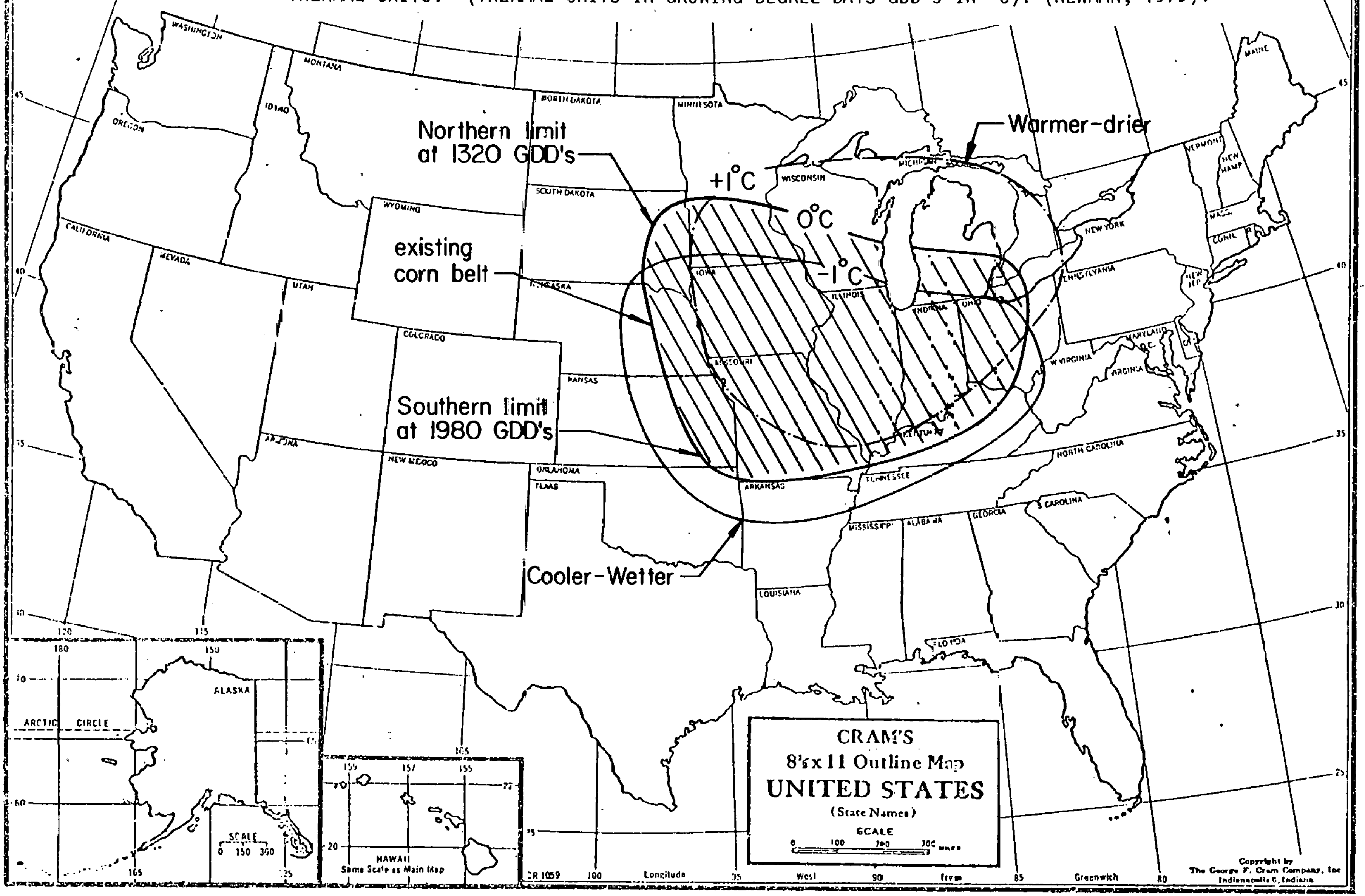
(2) Experimentally determine the impact of rising atmospheric CO_2 on water use efficiencies in selected C_3 and C_4 type plants to include annual and perennial crop species plus forest and range species.[7]

(3) Simulate the impact of interactions between climatic element changes and crop water-use efficiencies within given growing seasons across latitude belts of the Americas.

A. Climate change impact assessments of agricultural growing seasons.

The climate change impact assessment on agricultural growing seasons

FIGURE 9. SIMULATED GEOGRAPHICAL SHIFT IN U.S. CORN BELT BASED ON FROST-FREE GROWING SEASON THERMAL UNITS. (THERMAL UNITS IN GROWING DEGREE DAYS-GDD's IN °C). (NEWMAN, 1979).



would begin with a pilot study project within the continental limits of of the United States. This study would be confined to a well defined grain belt area for specific crops to include major grain or oil seed crops that represent C_3 and C_4 type plants. It would have as its prime objective that of creating the necessary data sets for simulating global climate change impacts on a major food grain region. The approach would be by simulating changes in daily temperature records similar to those reported by Nield, Richman and Seeley 1978. Techniques would be developed to simulate annual and crop growing season temperature changes for the major crop, range and forested regions across the Americas. These simulated annual and growing season temperatures changes would be based on the global simulation of climate change such as reported by Manabe and Wetherald 1975.

From historical climatic data for at least 30 years or longer, the daily maximum and minimum temperatures would be selectively changed to simulate the impact of annual temperature changes in a major grain producing region.[8] These simulated changes in annual temperatures would be analogous to those created by general circulation models. Next, these simulated annual temperature changes will be subjected to simulated crop growing season temperature changes. This would be followed with simulated impacts of annual and crop growing season temperature changes on evapotranspiration-precipitation balances. Such simulating procedures are likely to produce reasonable estimates of global climate change impacts for major agricultural food producing regions across the Americas.

Impact assessment on growing seasons across latitude belts would begin by selecting climate data bases at various latitudinal locations across North, Central and South America. The specific locations of these climatic data must be related to the geographical production areas of food, fiber, range and forestry agriculture. The data base must include at least daily ranges in temperature and daily precipitation over the 30-year period of 1951 through 1980 as a minimum. The station location selection must represent the major grain belts, range lands, forested areas, plus the major specialty crops in the tropical, sub-tropical and temperate regions of the Americas. The following specific areas should receive special attention: (1) The North American Corn and Soybean belt (U.S.), (2) The North American Spring Wheat belt (Canada), (3) The North American Range Lands (U.S.), (4) The South American Winter Wheat belt (Argentina, Paraguay, Uruguay), (5) The South American tropical range lands (Brazil), (6) The Tropical Rain Forest (Brazil), (7) Specialty Crops areas of Central America including Southern Mexico, Central American States, plus Colombia and Venezuela.

From this historical climatic data set, a number of 30-year normals must include --

1. a. annual mean temperature

   - b. daily mean temperatures
   - c. daily maximum temperatures
   - d. daily minimum temperatures
   - e. daily range temperatures

2. At locations where freezing temperatures occur annually:
   - a. Normal frost-free period in days to include normal beginning and ending calendar dates.
   - b. The normals for frost-free growing season thermal units (growing degree day indexes) based on the normal frost-free period. These frost-free thermal unit accumulations will need to be related to one standard base temperature for all areas.

3. Crop water availability during the normal frost-free season is needed in the criteria for determining crop growing seasons where the computed annual ratio of precipitation over potential evapotranspiration is less than unity, i.e., sub-humid to arid conditions.

4. In the tropics where annual freezing temperatures are absent, growing seasons will be determined by crop water availabilty periods during the year. In such areas the annual crop growing seasons could be related to seasonal ratios of precipitation over potential evapotranspiration greater than unity, plus a soil moisture storage factor.

Generated terrestrial surface temperature changes from global climate model output similar to those reported by Manabe and Wetherold 1975, would be introduced to the selected station locations across the Americas. The procedures stated under 1 through 4 can be repeated. These procedures can produce a simulated climate change impact estimates on agricultural growing seasons by latitude across the Americas. Further, these procedures can be repeated in time as global climate modeling results improve in predictive power.

B. Rising atmospheric CO_2 impacts on water-use efficiencies among agricultural crops, commercial forest and managed range land species.

   1. The first phase of research activities must begin with investigations of how increasing concentrations of CO_2 within plant aerial environments impact stomatal control in selected crop, forest and range species. The species selection must be done in a manner that will create the necessary knowledge and predictive interpretation among the major world food crop, range and commercial forest species. Some investigations will need to be performed under carefully controlled environmental growth chambers, using plant seedlings in most cases. The CO_2 concentrations will need to be varied from low levels much less than currently existing in the atmosphereic environment to that of several times the present atmospheric concentrations. Particular attention must be given to CO_2

concentrations between 300 and 600 ppm, since these levels are the projected range possible within crop production environments during forthcoming decades.

These fundamental determinations of stomatal responses to aerial environmental CO_2 concentrations must include the normal observed variation in CO_2 concentrations during annual and diurnal changes in both the free aerial and within the vegetative canopy of the biospheric environments of crop monocultures. Such experimental determination must be included as part of the total possible variability within a given plant environment.

2. A second phase of these investigations needs to be initiated concurrently with the first. This research will need to be directed toward the measurement of plant water-use in relationship to growth in the form of total dry matter production under varying CO_2 concentrations. Both the aerial and canopy environments will need to be monitored for CO_2 levels. The evaporative power of the aerial environment must be controlled or closely monitored during experimental growth periods. The aerial CO_2 concentrations will need to be varied in a similar manner as stated under the first phase. The experimental species selection will need to represent C_3 and C_4 types among the major food crops, range land and commercial forest.

3. The first and second phases of investigations must occur concurrently with the series of greenhouse and field investigations. These investigations would include appropriate crop and forest species monocultures as well as managed range species. The greenhouse environments would be less precisely controlled, but the total volume of experimental mass could be several orders of magnitude greater, which can reduce experimental errors and estimates as well. The aerial CO_2 concentrations should vary over a range of one-half to four times current atmospheric concentrations. Greenhouse crop water use would be measured under a small scale crop monoculture, a vegetative structure similar to open field conditions. Results from production scale greenhouse investigations may give interpretable estimates on crop water-use impacts for increased CO_2 concentrations in the biosphere. In addition, there is a need for field investigations into CO_2 profiles within and above vegetative canopies. This is particularly true for highly productive commercial forests, range vegetation and the major crop monocultures.

Current reports show annual variations in atmospheric CO_2 concentrations to be approximately 20 ppm above latitude 30° N.[9] Reports of diurnal variations in well developed vegetative canopies among crop monocultures vary from 5 ppm to over 50 ppm.[10] These early investigations suggest that annual and diurnal variations can be large enough in highly productive forests and crop monocultures to be worthy of establishing normal expected values in major types of vegetative canopies. Such information will be necessary in modeling the possible impacts of continued increases in atmospheric CO_2 concentrations under managed and unmanaged biospheric conditions.

C. The interactions between climatic element changes and plant-water use efficiencies within a given growing season across latitude belts of the Americas.

Computed temperature change from global climate models, resulting from assumed increases in atmospheric CO_2 concentrations, will be compared with simulated impacts on the agricultural growing seasons. This will consist of computed changes in thermal units and water balances during a given crop or area growing season as related to a computed change in temperature and/or computed changes in evapotranspiration.

These procedures will be followed by comparing the net differences in crop growing season thermal units and/or water balance changes resulting from the climate change simulations and the experimentally determinded crop water use efficiency changes. Determining the net differences in these crop growing season changes is the central issue in assessing the real climate change impact on a given crop or agricultural production system.

V. Resources Needed

A. Facilities

1. Climate change impacts on agricultural growing seasons.

The necessary facilities to carry out pilot study research investigations exist at several institutions within the United States. The facility requirements are largely met by adequate computer equipment and data analysis laboratory space.

Hemispheric or worldwide climate change impact assessment on crop, forest and range growing seasons will require the services and facilities of U.S. government agencies in securing the necessary data sets or data set summaries. It will require the cooperative support of the UN-WMO through the USDC, NOAA-EDIS facilities at Asheville and the UN-FAO through the USDA, SEA-AR, Beltsville, Maryland. The simulation of impacts of the interactions between climate changes and crop water use efficiencies on agricultural growing seasons can be performed at facility arrangements similar to those mentioned under the pilot study.

2. Facilities for carrying out crop water use efficiency studies should receive high priority consideration for much of the research effort on crop water-use investigations proposed in this commission paper. The reason for this priority is that controlled environmental laboratories are both time-consuming and expensive to construct. It would be highly desirable if controlled environmental facilities existed in conjunction with the necessary greenhouse and field laboratory facilities. Field laboratory facilities properly equipped with physical environmental measurements are rather limited in number. This is particularly true in managed forests and range lands.

   In summary, the following facilities are recommended as necessary to carry out the research outlined herein:

   ^{11}1. Controlled environmental laboratories with biophysical monitoring capability.

   ^{11}2. Controlled greenhouses that can monitor CO_2, water vapor, radiation, temperature and air movement.

   ^{11}3. Field laboratory areas for the large scale growth of crop monocultures with supportive micrometeorological monitoring equipment to include

      a. annual crop monocultures over large areas
      b. commercial forestry monocultures
      c. managed rangelands.

B. Scientific Personnel

As a general guideline, lead scientific personnel should consist of persons with experience in statistical estimates of climatic risks, simulation modeling of climate change and climate change impacts, ecological systems modeling, crop production systems modeling, forest production systems modeling, and rangeland management system modeling. Lead scientific personnel are likely to be well qualified from the following scientific disciplines: meteorology-climatology with specific interests in micro, bio, or agrometeorology; biology with specific interests in biophysics, ecology, or environmental biology; and the agricultural sciences with special interests in agronomy, horticulture, soil science, forestry or agro-engineering. Technical back-up personnel are likely to consist of persons with adequate training in statistics, computer science, engineering, biology, agronomy, forestry and meteorology.

VI. Timetable of Accomplishments

A. Agricultural Growing Seasons

A pilot project dealing with potential climate change impacts on agricultural growing seasons must precede the large geographic efforts in this area. The pilot study effort is recommended to begin in fiscal year 1981 extending through 1983.[12]

The extension of the study across North, Central and South America is recommended to begin in 1982 and continue over a 5-year period or through 1986.

B. Water use efficiency investigations

1. Experiments within controlled environments for determining stomatal responses among the C_3 and C_4 commercial crop, forest and range species is recommended to begin in fiscal year 1981. The minimum timetable for project completion is 5 years or through 1985. But, a more efficient use of scientific talent and facilities is likely if these efforts were subdivided into several smaller researchable projects at several institutions covering specific species and extended over 7 to 10 years, from 1981 to 1987.

2. Experimental water use determinations within controlled environments among the important commercial crop, forest, and range species is recommended to begin in 1981 for a minimum of 5 years or through 1985. These experimental determinations should lag stomatal response experimentation by about 1 to 2 years in order to confirm the predictability of stomatal response results.[13]

3. Water use determinations in greenhouse and under field experimentation for commercial crop, forest and range species should lag controlled environmental experimentation by 1 to 2 years. Therefore, it is recommended that greenhouse and field investigation begin in fiscal year 1982 or later. The minimum period of 5 years is recommended or through 1986.

C. Interactions between elements of climate change and crop water use efficiencies.

The simulation of the possible interactions between elements of climate change and experimentally determined changes in crop water use efficiencies is recommended to begin in 1986 and extend through 1988. As results from investigations in crop water use efficiencies and on crop growing season simulated impacts from global climate models become available, the interactions should be simulated as the final step in the climate change impact assessment on the production of renewable resources across the Americas.

Table 2. Timetable of accomplishments

Study Activity Title	Budgetary Fiscal Year									
	1981	82	83	84	85	86	87	88	89	1990
Plant-water use efficiencies										
stomatal control	81		83							
controlled environments	81		83							
greenhouse	81				85					
field		82				86				
Agricultural growing seasons										
pilot study	81		83							
North/South America		82				86				
Interactions studies						86		88		

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Footnotes

[1] To include diurnal and seasonal changes in sensible heat (temperature), latent heat (humidity and evaporation), radiation balances (short and long wave), (precipitation and cloudiness), as well as estimated changes in wind.

[2] The meteorological differences within growth chambers VS open field environments as related to turbulent transport would likely account for the less spectacular results.

[3] In order of importance in world food supply. (Source UN-FAO, 1976).

[4] Plus the amount of water stored in the soil-crop rooting zone.

[5] For some crops, within certain latitudes, the length of the freeze-free period has not significant.

[6] Further, the seasonal distribution of any temperature change is likely to be of greater importance in determining the impact on agriculture, particularly in the middle and higher latitudes.

[7] Reviewer R. H. Shaw seriously questions whether this can be done quantitatively under open field conditions.

[8] Using simulation procedures developed by R. E. Neild, et al. 1978.

[9] See Figure 3.

[10] See Figure 4.

[11] Three reviewers R. H. Shaw, N. J. Rosenberg and R. E. Reifsnyder suggest that field studies receive the same priority as controlled environmental laboratory and greenhouse studies.

[12] Reviewers R. H. Shaw and I. M. Caprio suggest that simulation studies in seasonal patterns of temperature, as related to assumed climate change in annual mean temperature, be a part of the pilot study.

[13] Reviewers R. H. Shaw and N. J. Rosenberg question the value of experimental water-use determinations use controlled environments. They suggest that such determinations must be confirmed under carefully designed and conducted field experiments.

[14] For a more complete list of references on plant responses to carbon dioxide concentrations see -- 1979 -- Report of the Workshop on anticipated plant responses to global carbon dioxide enrichment, Edited by B. R. Strain, Duke Environmental Center, Duke University, Durham, NC. 27706.

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