Climatic Change

An Interdisciplinary, International Journal
Devoted to the Description, Causes and Implications of Climatic Change

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SPECIAL ISSUE

THE SENSITIVITY OF NATURAL ECOSYSTEMS AND AGRICULTURE TO CLIMATIC CHANGE

Guest Editor

MARTIN L. PARRY

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ESTIMATING THE SENSITIVITY OF NATURAL ECOSYSTEMS AND AGRICULTURE TO CLIMATIC CHANGE – GUEST EDITORIAL

Two obvious and fundamental weaknesses generally accompany any assessment of the impact of possible future climatic changes on ecosystems and society. Firstly, we have inaccurate information on their present-day sensitivity to climatic variability. Secondly, we are uncertain what changes of climate will occur in the future. This is particularly true when we try to estimate the possible effects of increased atmospheric CO_2, because both the general circulation models and most impact models (e.g. crop–weather models) treat the CO_2 perturbation as a 'step-like' event rather than as a transient process. Thus, in the GCM, the increase in CO_2 concentration is modeled as an abrupt change from one concentration to another, not as a gradual change through time; and most impact models treat the predicted climatic anomalies as sudden changes in the mean climate rather than as a gradual change in the mean over perhaps several decades. Yet the biological or economic responses to such an immediate (and enduring) shock to the system may be very different to responses to slower change over the longer term.

As a result, some of the crucial questions concerning CO_2 impacts are not appropriately addressed: for example, how intrinsically *adaptable* are ecosystems and farming systems to different *rates* of climatic change? Where system adaptability is inadequate to absorb the climate impact, what can we do to mitigate the resulting shocks to the system?

With this caveat, then, we should acknowledge that the papers in this issue report the results of preliminary experiments. Their emphasis is less on what the sensitivities or impacts are than on how we can evaluate them more accurately. In performing this task they help elicit a number of general issues in impact analysis, in addition to their more specific conclusions:

1. Climatic change as a change in the level of risk

One of the obstacles to active government interest in impact from possible future climatic change as opposed to present-day climatic variability is its overriding concern with the short rather than the long term. In general, the concern is with impacts from short-term anomalies such as floods, droughts, and cold spells. This suggests that a useful form in which long-term climatic change can be expressed for the policy maker is as a change in the *frequency* of such anomalies. One advantage of this approach is that the change can be expressed as a change in the *risk of impact*. Government programs could then be devised to accommodate specified tolerable levels of risk, by adjusting activities as necessary to match the change of risk.

This change in risk can be measured as a change in the *probability* of an adverse or beneficial event, such as shortfall from some critical level of output or excess above the expected yield. In agriculture, for example, we might thus assume that both farmers and, in a sense, individual plants are entrepreneurs whose activities are based upon the expected return from gambling on 'good' years (which allow substantial profits, or substantial seedsetting and seed establishment) and 'bad' years (substantial losses, or poor seedsetting and seed

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establishment). However, spatial changes in temperature or precipitation, which are often broadly linear (e.g. the rate of change of temperature with elevation and latitude), have strongly nonlinear aspects when redefined as the probability of occurrence of a certain anomaly. There may thus be very marked differences over space in the probability of profit or loss, of viability or nonviability.

If a change in risk is an important consequence of climatic change, we need to measure the frequencies of selected anomalies under normal climatic conditions and to use these frequencies as a base upon which to superimpose effects such as CO_2-induced warming, volcanic-dust-induced cooling, etc. to obtain modified frequencies reflecting such events (see Williams, this issue).

2. *Climatic change as a change in the frequency of extreme events*

The notion of risk as an important measure of climate impact derives in part from the view that economic and social systems adjust to climatic change by responding to changes in the frequency of extreme events rather than to long-term change of the average conditions. If this is correct, then it is not likely that they would naturally and gradually adapt in pace with slow changes in climate. Rather, the problem would be how to perceive and adjust to shifts in the frequency distributions of disruptive climatic events. Thus any policy of matching technological development to climatic change should focus not only on the rate of change in mean climatic conditions but also on the change in the frequency of climatic extremes.

3. *Climatic change as a change in the range of options*

Since, in agriculture at least, climate can reasonably be construed as a resource, climatic change can produce benefits or disadvantages that may require an adjustment to match altered resource levels. One important path of these impacts is through the range of choice: changes in climate can alter the range of options that may compete for investment of time, money, and other resources. Moreover, the *perception* of these changed options is often important because the timing of investment in relation to weather can significantly influence the return on that investment. For example, the timing of farming operations (ploughing, sowing, harvesting, etc.) frequently explains much of the variation in yields from farm to farm at the local level. Changes in climate might tend to enhance the mismatch between weather and farming operations because of a lag in management response to changes in, most importantly, the 'time windows' for planting and harvesting. For this reason, crop selection is probably one of the most effective means of response to an adverse climatic change, for the development of new strains or the introduction of new crops can serve to keep open these time windows sufficiently to allow adequate yields to be maintained.

4. *Matching the scales of explanation, process, and pattern*

The short-term anomalies emphasized above are merely a part of a large range of scales over which the Earth's climate interacts with its ecosystems and farming systems. Clark points out in this issue that these scales span more than seven orders of magnitude in both the spatial and temporal domains. The challenge is 'to match scales of explanations, processes, and patterns in a realistic and effective way.' Given the mismatch of scales in earlier studies, particularly by some historians in the 1960s, it is not surprising that the relationships between climatic change and economic change have been extraordinarily difficult to clarify.

5. *The spatial shift of isopleths or boundaries*

An additional theme that is threaded through these papers is the need to be just as specific about place as about time. To be useful, impact analyses should be particular about the ecosystems and farming systems and their locations. A method that enables us to specify areas that can be altered by climatic change or variability is one that focuses on the shift of limits or margins representing boundaries between arbitrarily defined classes. The classifications adopted in this issue include those relating to ecosystem complexes, biomass potential, agroclimatic resources, levels of agricultural risk, and levels of agricultural production. In each case, the authors have considered the spatial shift of these boundaries for a given change of climate, thus defining areas of possible climate impact.

These approaches and themes were explored by the authors of this issue in a workshop at an International Study Conference on The Sensitivity of Ecosystems and Society to Climatic Change,* cosponsored by, amongst others, UNEP and IIASA. The purpose of that meeting was to evaluate the impact of climatic fluctuations on the sensitive margins of agriculture and of natural terrestrial ecosystems. The emphasis was on climatic changes that might result from increases in the amount of carbon dioxide in the atmosphere, but consideration was also given to past climatic fluctuations, both short- and long-term. Following a plenary session, the meeting divided into two parallel workshops, which considered climate impacts in cold and dry regions, respectively. The following papers have emerged from the preliminary discussions in the Workshop on Cold Margins. Deliberations by participants in the workshop, the observations that emerged, and subsequent recommendations made have been summarized elsewhere (Parry and Carter, 1984).

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Reference

Parry, M.L. and Carter, T.R. (eds.): 1984, 'Assessing the Impact of Climatic Change in Cold Regions', Summary Report SR-84-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.

* Villach, Austria, September 1983.

SCALES OF CLIMATE IMPACTS*

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Abstract. Climates, ecosystems, and societies interact over a tremendous range of temporal and spatial scales. Scholarly work on climate impacts has tended to emphasize different questions, variables, and modes of explanation depending on the primary scale of interest. Much of the current debate on cause and effect, vulnerability, marginality, and the like stems from uncritical or unconscious efforts to transfer experience, conclusions, and insights across scales. This paper sketches a perspective from which the relative temporal and spatial dimensions of climatic, ecological, and social processes can be more clearly perceived, and their potential interactions more critically evaluated. Quantitative estimates of a variety of characteristic scales are derived and compared, leading to specific recommendations for the design of climate impact studies.

1. Introduction

The interactions of climates, ecosystems, and societies have received increasing attention from both natural and social scientists in recent years. The coupling of the Earth's climate, its geochemistry, and its large-scale biological processes appears ever more intimate, and is the focus of some of the most exciting natural science research under way today (e.g. Lovelock, 1979; Bolin and Cook, 1983). Historians are providing increasingly sophisticated assessments of the past influence of climate on human societies (e.g. Wigley *et al.*, 1981; Rotberg and Rabb, 1981; Lamb, 1982). Social scientists have begun to address contemporary problems of human response to climatic variation, to refine their research methods, and to produce a number of case studies (e.g. Hewitt, 1983; Kates *et al.*, 1984). Natural scientists, social scientists, and policy analysts are increasing their collaboration to analyze how societies' present and future activities may significantly alter the basic functions of the biosphere (e.g. World Conservation Strategy, 1980; Holdgate *et al.*, 1982; National Research Council, 1983). The World Climate Programme recently hosted an unusually successful conference on the interactions of climates, ecosystems, and societies, and is supporting an active research program (Parry and Carter, 1984). Other national and international institutions have mounted their own studies.

The lively debate on interactions among climates, ecosystems, and societies engendered by all this research is most welcome and necessary. At a minimum, it provides a middle ground between the past excesses of the climatic determinists on the one hand, and those who would entirely ignore the interactions of climates and societies on the other. Perhaps not surprisingly, however,

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*A longer version of this paper (Clark, 1985), with complete documentation of data sources, was presented at the Social Science Research Council's Conference on Forecasting in the Social and Natural Sciences (Boulder, Colorado, June 10–13, 1984).

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the liveliness of the debate has occasionally been more evident than its effectiveness. Shrill exchanges on whether climatic fluctuation or social organization is 'responsible' for the suffering of peoples and landscapes in drought zones have obscured the complicated interrelations that characterize such situations. Case study chronologies and consequences have been transferred indiscriminately around the globe, with little regard for the special circumstances of place or the stage of historical development. Studies of long-term climate impacts have swung between approaches assuming that no adaptation is too great for societies or ecosystems to make, and equally unrealistic analyses that simply impose possible future climates on today's animal, crop, and human distributions and tally the resulting disruptions.

In most of these cases the disagreements stem not so much from ignorance or inadequate scholarship, but rather from the difficulty of establishing useful perspectives from which to view and order the accumulating range of studies, methods, data, and theories. The problem is bad enough within the individual natural and social science disciplines studying interactions among climates, ecosystems, or societies. It is worse when, as is increasingly the case, the nature of the investigations requires that disciplines be bridged and that results, methods, and explanations be exchanged among them. To complement these individual investigations a parallel effort is needed to develop synoptic perspectives that can help to show (a) how the individual studies relate to each other; (b) what the case studies of the past can and cannot tell us about the implications of climate in the future; and (c) which collections of human activities, ecological processes, and climatic variations need to be considered together if we are to achieve balanced, realistic assessments of future prospects. My goal in this paper is to sketch the foundations of one such perspective.*

2. The Significance of Relative Scale

One perspective that has proven useful in related fields is suggested by Figure 1, drawn from Professor M. Chisholm's 1980 Presidential Address to the Institute of British Geographers.** Chisholm advanced this framework of spatial and temporal scales in the context of continuing debates on the problems of economic development, particularly the causes and implications of different rates and patterns of development exhibited by different societies at different times. He quoted Fernand Braudel, a leading figure in the French *Annales* school, to note that scholars taking an historical approach to social analysis had predictably been sensitive to the time dimension: 'Distinctions will have to be made between long-term movements and sudden growths, the latter being related to their immediate sources, the former to a long-term span' (Braudel, 1972, p. 21). Spatial distinctions, on the other hand, were seen by Chisholm to have been more rigorously attended to in the ahistorical analyses of economists and geographers. He cited a classic paper of Haggett (1964) to illustrate 'a theme long

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*An excellent complementary perspective for the analysis of climate sensitivity is provided by Maunder (1984).

**Neither I nor Chisholm is the first to apply space or time perspectives to the sorts of issues addressed here. My purpose is not to reinvent basic concepts, but to explore what can be learned from comparison of consistently defined and quantified characteristic scales across traditionally separate disciplines.

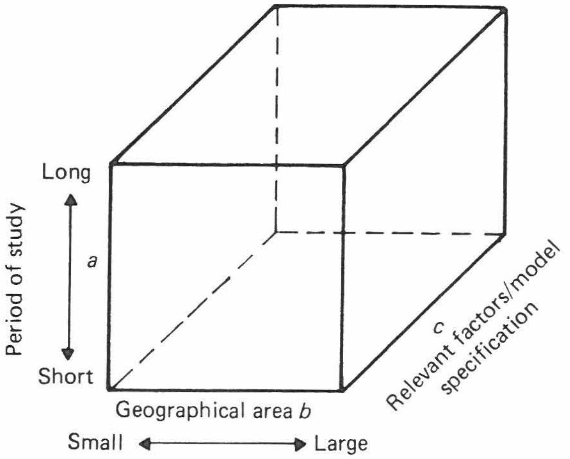

Fig. 1. The relationship of time, space, and explanatory system (redrawn from Chisholm, 1980).

familiar to geographers, namely that as the geographical scale of study varies so does the spectrum of causal factors deemed relevant and also the specification of the explanatory model' (Chisholm, 1980, p. 256). Chisholm presented Figure 1 as a juxtaposition of these historical and geographical styles of analysis. He went on to argue a position vis-à-vis economic development that is relevant to current debates over the interactions of climates, ecosystems, and societies:

> Much of the apparent conflict of testimony arises from the fact that scholars have been working in different parts of the three-dimensional space and, without realizing the problems of transference, have often attempted to compare unlike situations. Furthermore, there have been some remarkable oscillations of fashion regarding both the time-horizon envisaged in the study...and the nature of the geographical area of concern... (Chisholm, 1980, pp. 256–257).

Chisholm's scale perspective parallels a long tradition of similar thinking in the natural sciences, where explicit attention to scale has shed useful light on subjects ranging from ocean physics to the adaptation and evolution of organisms in changing environments.

In ecology, for example, Hutchinson (1953) has argued that the relative importance of environmental factors in shaping patterns of population distribution and abundance should depend on the relation of spatial and temporal scales of environmental variation to the generation time and 'ambit' (typical lifetime range of movement) of the relevant organisms. This perspective has since been explored in some depth, both theoretically and empirically (e.g. MacArthur and Levins, 1967; May, 1976; Southwood, 1976). In general, such studies have shown that where generation times are short relative to the time scale of environmental variations, populations tend to track environmental processes. Environmentally 'bad' times reduce the population, but the return of favorable conditions is effectively exploited through rapid population growth. In such situations, the patterns of population distribution and abundance tend to be shaped more by environmental and reproductive processes and less by interactive processes among species.

Conversely, where generation times are long relative to the time scale of environmental variations, populations tend to experience those fluctuations as 'noise'. Population patterns thus reflect average environmental conditions. Relative stability and its various benefits are obtained, though at the cost of slow population recovery should drastic disruptions occur. Population interactions or social processes thus assume a more important role than environmental or reproductive ones in determining ecological patterns. When generation times and the time scales of environmental variations are comparable, these simple generalizations break down. Complicated relations among environmental, interactive, social, and other processes then jointly determine observed ecological patterns.

Analogous arguments have been made regarding the significance of relative spatial scales. A wide range of relevant analyses involving concepts of environmental 'grain', 'patchiness', and heterogeneity have been advanced by Levins (1968), May (1976), Steele (1978a), and others over the last twenty years. Summaries of the work may be found in Emlin (1973) and Clark *et al.* (1978).

The potential of the scale perspective for helping our understanding of the patterns emerging from interactions of organisms with their environments is brilliantly illustrated in the review by Haury *et al.* (1978) of space–time patterns in marine plankton. Haury *et al.* use the so-called 'Stommel Diagram' to characterize the most significant scales of environmental variability affecting plankton patterns. Their approach was developed by oceanographer Henry Stommel in the early 1960s to illustrate the spectral distribution in space and time of environmental variations exhibited by current velocity, sea level, kinetic energy, and the like in the open ocean (Stommel, 1963). Many technical problems arise in a literal 'spectral' interpretation of the Stommel Diagram.* Nonetheless, the general framework has proven extremely useful for the design of efficient sampling programs and the differentiation of feasible from infeasible research goals (Stommel, 1965). It has also provided a powerful link between physical oceanographers' studies of pattern in marine 'climatology' and biological oceanographers' studies of marine ecosystems. This link is illustrated in Figure 2, taken from the paper by Haury *et al.* The space and time axes are the same as those introduced by Stommel. The vertical axis, however, plots the amount of variation in biological activity, rather than physical energy, associated with the relevant scales. Haury and his co-authors analyze how the physical variation injected at specific spatial and temporal scales by the ocean's 'climatology' (i.e. the patterns of Stommel's original diagram) affects the patterns of variation arising in the biological activities of the ocean's ecosystems. Studies launched from a similar perspective, emphasizing the scales of interaction between physical and biological processes, have become one of the most active and exciting areas of contemporary oceanography (e.g. Steele, 1978a, 1984; Barnett and Patzert, 1980). Moreover, this perspective is implicit in the most illuminating recent analyses of the effects of overall climatic change on the oceans' fisheries (e.g. Cushing, 1982).

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*These problems include limitations of data, ambiguity regarding the proper units for the vertical axis, and what Stommel (1965) called the 'desperate thing' of assuming statistical stationarity in physical and biological processes that most certainly do depend on absolute locations in space and time. The situation is even worse in terrestrial contexts (see Curry and Bannister, 1974; Cliff and Ord, 1975; Granger, 1975; Haggett, 1976).

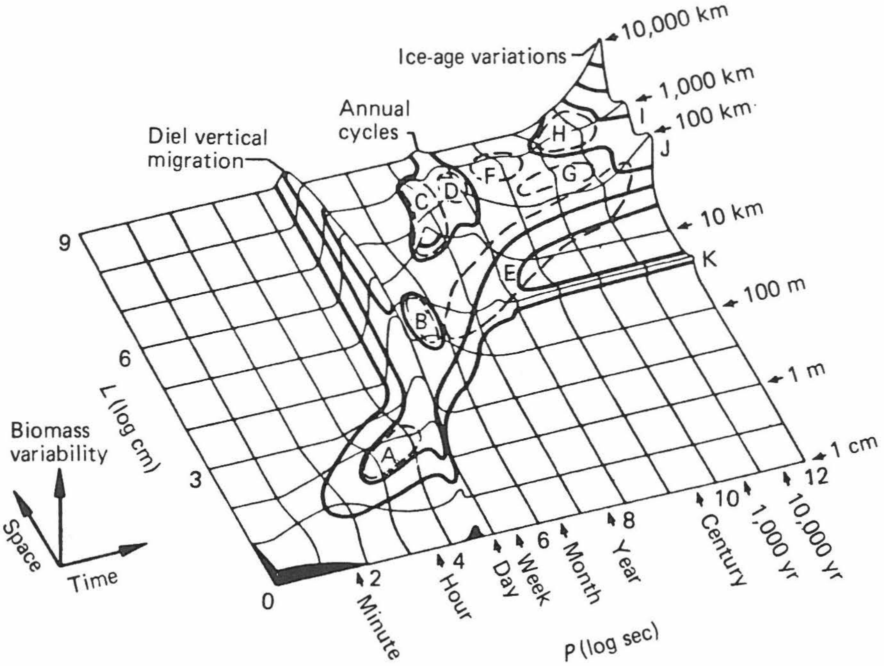

Fig: 2. Stommel Diagram of the time and space scales of variability in zooplankton biomass and contributing physical factors (from Haury *et al.*, 1978). A, 'micro' patches; B, swarms; C, upwelling; D, eddies and rings; E, island effects; F, 'El Niño-type' events; G, small ocean basins; H, biogeographical provinces; I, currents and oceanic fronts (length); J, currents (width); K, oceanic fronts (width).

In the next section, I apply the scale perspective suggested by oceanographers' use of the Stommel Diagram to the more general problems involving interactions among terrestrial ecosystems, societies, and climates.

3. Characteristic Scales of Climatic, Ecological, and Social Phenomena

What are the characteristic scales at which climates, ecosystems, and societies undergo their most significant variations? A tremendous literature has been assembled on specific aspects of this question – a literature that I have neither the wit nor the space to do justice to here. What I have found useful, however, is to analyze, using consistent quantitative definitions, a sample of empirical scale data for some of the processes and patterns most frequently addressed in climate impact studies (e.g. Schelling, 1983; Maunder, 1984). In this exploratory effort, I have cast my net more broadly than discriminately. I am well aware that the resulting catch is of variable quality and far from complete. I hope only that it will provide a stimulus for more systematic efforts to apply a scale perspective in quantitative terms across traditional disciplinary boundaries. A fuller discussion of data sources and interpretations is given in Clark (1985).

3.1. Scales of Climatic Experience

Researchers have devoted a great deal of attention over the past couple of decades to patterns of variation in climate (e.g. National Research Council, 1975; Webb *et al.*, 1985). Nonetheless, a comprehensive characterization of the scale structure of climatic variations is still a long way off. I will argue below that such a characterization is badly needed to improve research on climate impacts. Despite the shortcomings of present data, however, it is possible to ask how a Stommel Diagram of the Earth's climate might look, should we ever get around to computing one. Even an approximate answer to this question might be useful for guiding and interpreting current studies of interactions among climates, ecosystems, and societies.

For temporal scales of a year or less, the space–time structure of atmospheric phenomena has been reasonably well studied. The results summarized in Figure 3 are taken from a Stommel-like plot published by Smagorinsky (1974), supplemented with data from Holton (1972) and Jäger (1983). I have added data from a variety of sources to suggest characteristic scales of several kinds of longer-term climatic variability that may be involved in significant interactions with societies and ecosystems. The resulting scale relationships are plotted in Figures 4 and 5 for subsequent comparison with analogous scales of ecological and social phenomena.

In each case the characteristic spatial scale is reported as a length L, in kilometers. L is defined, as appropriate, in terms of the square root of the area covered by the phenomenon, or its wavelength, or as the shorter dimension of long, narrow phenomena such as fronts and many drought zones.

The characteristic time scale is reported as T_e, in years. This scale can be defined arbitrarily as long as it is defined consistently. Here, I define T_e as an 'e-folding time', the time required for the state of the system to change by a factor equal to the base of the natural logarithms, e (i.e. about 2.7-fold). However, some care is necessary to apply this or any other definition consistently across the wide range of climatic, ecological, and social phenomena compared in this paper. The methods and conventions used are described in Appendix 1.

In Figure 3, the broad band of atmospheric phenomena running from tornadoes to long waves is meant to be characteristic of the free atmosphere, away from the boundary layer. Most of the energy contained in these phenomena (the vertical dimension of the Stommel Diagram) lies at the upper end, associated with the baroclinic instability and its resulting extratropical cyclones (Smagorinsky, 1974, p. 649).

Data on the phenomena having longer time scales are, as already noted, much less systematic. Patterns of sea surface temperature anomalies, here based on Pacific Ocean data, are closely coupled with atmospheric phenomena, but with time scales an order of magnitude or so longer (Namias and Cayan, 1981). One particularly important phenomenon that shows up in sea surface temperature anomalies as well as in atmospheric pressure data is the El Niño Southern Oscillation (ENSO). Characteristic scales for a typical ENSO event, drawn from Philander's (1983) review, are plotted in Figure 3.

Patterns in rainfall variability are characterized by the North American Great Plains drought of the 1930s (Warrick, 1980), the Sahel–Sudan drought of the 1910s (Nicholson, 1982), and a typical regional 'dry summer' phenomenon,

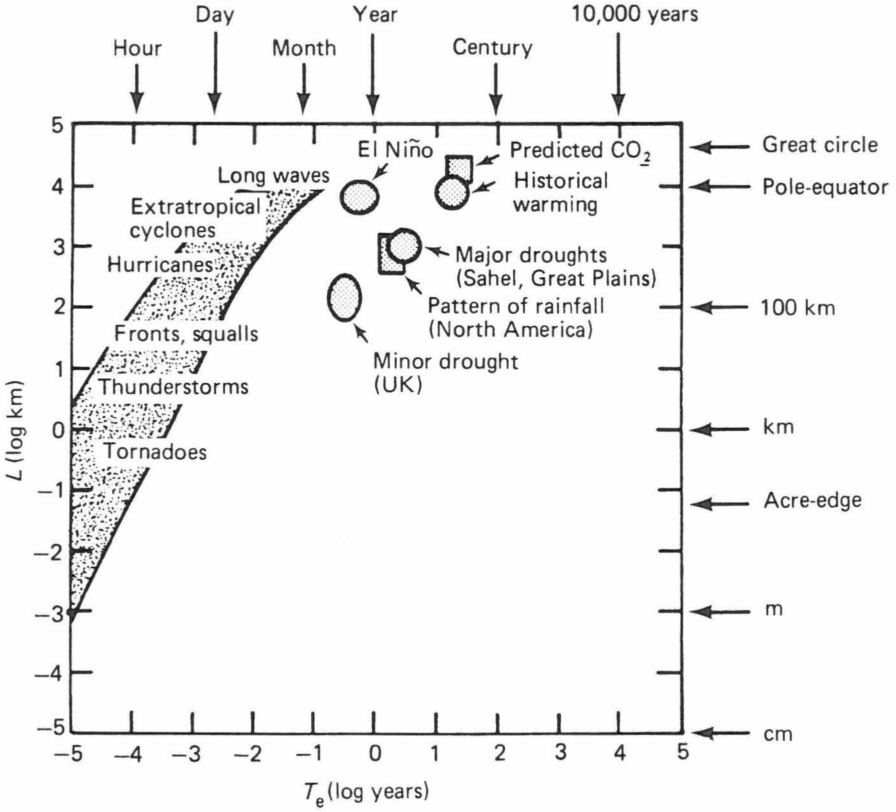

Fig. 3. Scales of climatic phenomena: characteristic time scales and length scales for selected events (sources documented in Clark, 1985).

in this case for the United Kingdom in 1976 (Parry and Carter, 1984). I suspect that other examples could be found to fill the gap that appears in Figure 3 between these extreme forms of drought. Interestingly, however, the gap is not filled by recent studies (Vines, 1984) of spatial and temporal cohesion in long-term rainfall records for North America. (An anomaly pattern would be needed that had a period of 6–8 years and was cohesive over scales of the order of a couple of hundred kilometers.)

The remaining entries in Figure 3 characterize long-term hemispherical to global-scale warming trends. As an historical example, I have used the long-term warming of the Northern Hemisphere that occurred from the mid-nineteenth to the mid-twentieth century (Jones and Wigley, 1980). A case of particular concern to students of climate impact is the predicted warming due to anthropogenic emissions of 'greenhouse' gases like carbon dioxide to the atmosphere. The greenhouse case reported here reflects forecast temperature increases for the next hundred years based on a recent study by the U.S. National Research Council (1983) plus calculations of the time-dependent climate response performed by Schneider and Thompson (1981) and by Cook (1984). Note that the characteristic scales of the historical and the predicted warming are comparable.

3.2. Scales of Ecological and Social Experience

Values of T_e characterizing a wide range of ecological and social processes are summarized in Figure 4. For ecological processes, I omit physiological and behavioral events and begin with the 'intrinsic rate of natural increase' for several insects and mammals. These data reflect physiologically maximal rates of reproduction in an optimal and unlimited environment. Longer time scales characterize rates of animal population increase under natural conditions, rates of biomass accumulation in vegetation, rates of soil accumulation through primary and secondary succession, and the rates at which various tree species expanded their ranges to current positions following the most recent deglaciation of eastern North America. The characteristic times of these ecological processes span five orders of magnitude, from weeks to millennia.

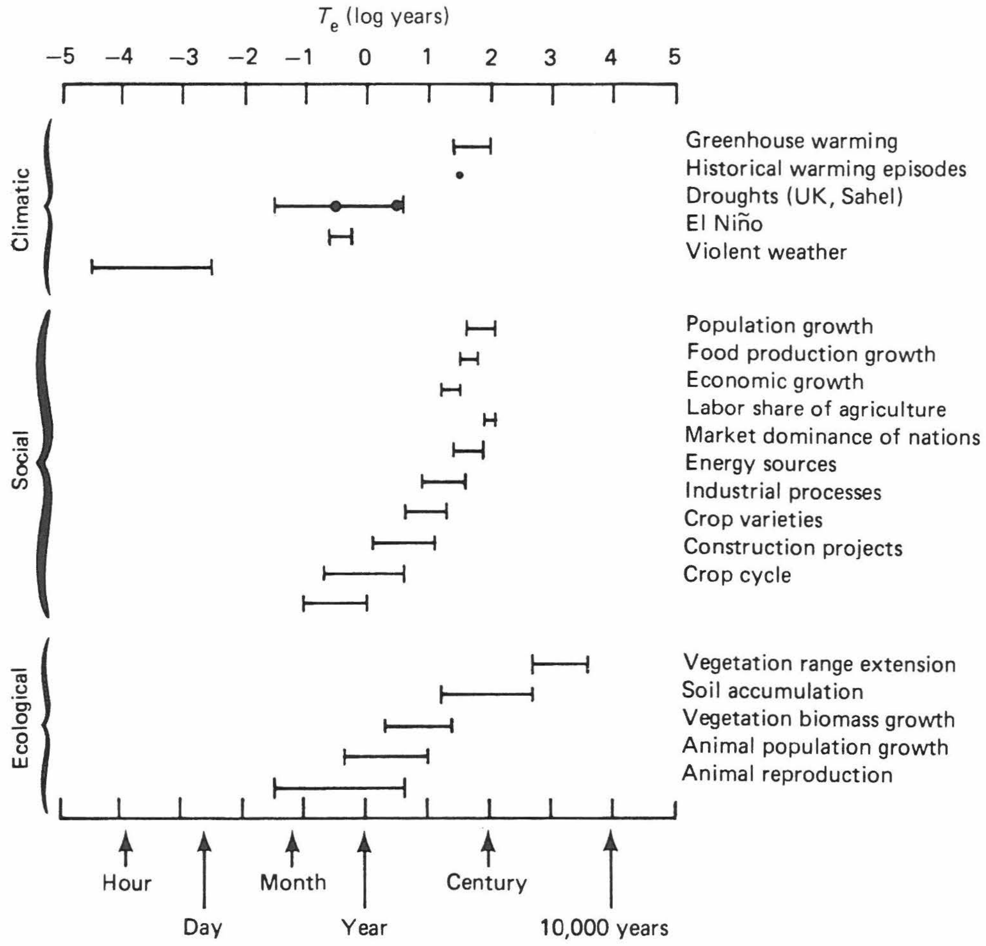

Fig. 4. Characteristic time scales for climatic, social, and ecological processes (sources documented in Clark, 1985).

An analogous treatment is possible for social processes potentially relevant to the interactions of climates, peoples, and ecosystems. A general conceptual framework for thinking about the time scales of various human adjustments to natural hazards has been developed by Burton *et al.* (1978), who give particular attention to the short-term behavioral responses of people faced with disruptive environmental events. In the data summarized in Figure 4, I have tried to complement their work by focusing on some of the longer-time-scale processes that may be particularly important in the responses of societies to slowly changing climates.

The fastest social processes plotted reflect the rates at which single-crop cycles (planting to harvest) and industrial construction projects (plan to operation) are completed. Five substitution processes are shown next, reflecting the rates at which societies change from one set of activities to another. These are based on a series of remarkable papers by Marchetti (Marchetti and Nakicenovic, 1979; Marchetti, 1981, 1983). The figure shows data for substitutions of crop varieties (e.g. the adoption of high-yield grains in mid-century America and contemporary developing countries); of manufacturing processes within industries (e.g. replacement of open-hearth by electric steel-making); of basic energy sources (e.g. oil for coal); and of work force structure (e.g. decline of the share of agriculture in the total work force). Many indices reflecting combinations of these basic rates are also possible. Illustrated are the results of a particularly interesting study by Doran and Parsons (1980) in which the rise and fall of various nations' shares of total world political power is given objective quantitative expression. Figure 4 also shows a more conventional expression of social time scales: the aggregate annual growth rates of national economies, food production, and population (World Bank, 1982).

In summary, substitutions of new agricultural crops or industrial processes have historically occurred on time scales one to two orders of magnitude shorter than comparable demographic changes in population or labor force. Processes dealing with fundamental elements of social structure (e.g. market shares held by various primary energy sources or by various countries in basic industrial products) change at intermediate time scales. Marchetti (1981) has pointed out a tendency of time scales to become shorter, the more recent the initiation of the process being described.

Characteristic spatial scales are summarized in Figure 5. The world's continents, oceans, seas, and major river basins are assigned a 'characteristic length' equal to the square root of their area. Analogous data are presented for some typical lake drainage basins of the previously glaciated parts of the United States.

Ecologists traditionally speak in terms of spatial hierarchies, ranging from the global extent of the biosphere down through biomes, life zones, communities, associations, and so on. The problem with most of these terms for present purposes is that they are highly arbitrary. One objective index of spatial scale in ecology is provided by so-called 'species–area' curves, which plot the cumulative number of species (usually within some taxon) encountered as the spatial scale of sampling is increased. Changing slopes of species–area curves for the world's vegetation (C.B. Williams, 1964) and birds (Preston, 1960) show three distinct spatial scales: 'within associations' (1–300 m), characterized by (ecologically) homogeneous environments; 'between associations' (300 m to continental

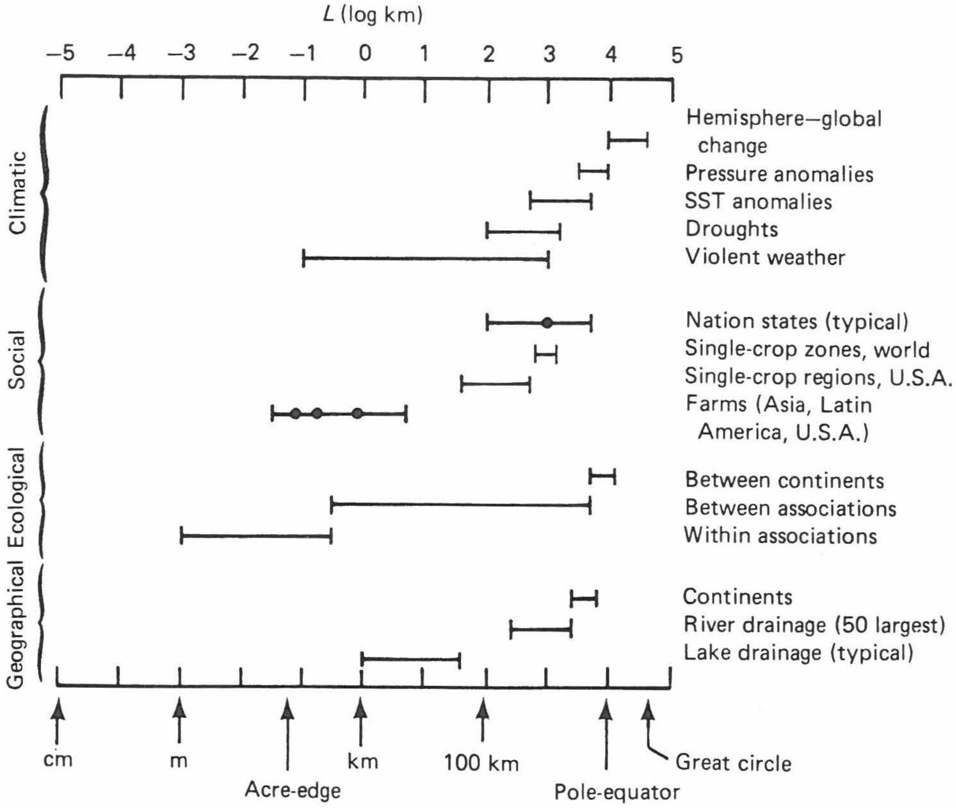

Fig. 5. Characteristic space scales for climatic, social, ecological, and geographical patterns (sources documented in Clark, 1985).

scale), characterized by a continuous gradient of new environments; and 'between continents', characterized by major environmental discontinuities leading to species isolation. The species–area data exhibit no objective scalar manifestations of the common ecological categories of community, biome, ecosystem, and the like.

Consider next the characteristic spatial scales of social phenomena. Figure 5 shows the wide range of spatial scales characterizing individual farms throughout the world, with median values for Asia, Latin America, and the U.S.A. Individual farms are grouped into crop regions and larger crop zones. These zones, as commonly defined by the World Bank and the Food and Agriculture Organization, reflect major agricultural 'styles' and 'cultures' at least as much as they indicate the predominance of a particular crop with particular environmental requirements. Figure 5 also presents sizes of the world's present nation states. These range in area over three orders of magnitude, though most are of the order of one million square kilometers. Together with the continental data already discussed, the nation-state data indicate the characteristic scales for much of the world's political and economic activity.

4. Scales of Interaction

Even the incomplete data presented here indicate some rough relationships between characteristic scales of various ecological and social phenomena, and the central concerns of scholars studying those phenomena. These relationships can be visualized in terms of Chisholm's framework of time, space, and explanatory system as already suggested in Figure 1. To help illustrate the relationships, I have rearranged some of the data from Figures 4 and 5 in the common space-by-time format of Figure 6.

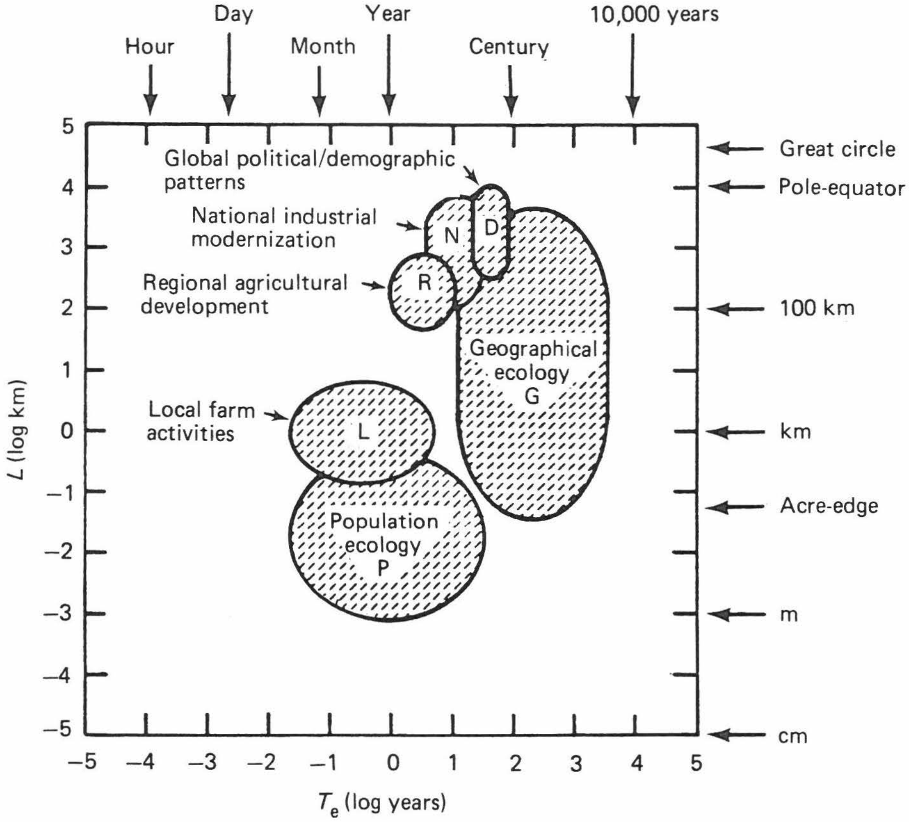

Fig. 6. Scales of social and ecological phenomena: characteristic time scales and space scales for selected clusters (sources: Figures 4 and 5).

4.1. *Clusters of Attention*

Turning first to ecological concerns, Figure 6 reflects two distinct space–time clusters. I have labeled these 'population ecology' and 'geographical ecology'. The labels are conveniences only and should not be taken too literally. Moreover, additional subdivisions of ecological concerns would doubtless emerge from a more complete analysis of relevant data. The important point is that in terrestrial ecology – as in Chisholm's social framework and Stommel's oceanographic framework — scholars working in different parts of the space-by-time field focus on very different questions and modes of explanation. In particular, ecologists at the large-scale end of the regions shown in Figure 6 have emphasized environmental influences on global patterns of productivity and speciation when discussing climate. Those at the small-scale end have tended to focus on dynamic models of animal mortality or plant yield reduction, and on factors triggering pest outbreaks.

The several social structures shown in Figure 6 reflect the more detailed attention I have given to human pattern and process in this analysis of characteristic scales. Again, the labels are less important than the general indication of a range of distinctive interests and concerns.

At the center of the space-by-time field is a cluster of 'local farm activities'. This is defined by the 'crop cycle' and 'farm size' data of Figures 4 and 5. Concerns here focus on basic farm-level decisions about planting and harvesting, on perception of risks, and on individual decisions to adopt innovations. (Note from Figure 4 the substantial overlap with the characteristic time scales of a variety of construction projects.)

At the extreme large-scale end of the social spectrum is a cluster of 'global political/demographic patterns'. This reflects the long time scales that have characterized shifting international distribution of political and economic power. At an even more basic level, these patterns are dominated by the slow tempo of population growth and agricultural labor force transition that characterizes Braudel's 'long duration' social transformations.

Merging with the global patterns just discussed, but characterized by generally smaller and faster scales, is a cluster of 'national industrial modernization'. This is defined by the rates at which nations substitute new basic industrial and energy-producing processes for ones that have become inefficient or unproductive. Such substitutions can also be observed at both sub- and supranational scales. But national characteristics, cultures, and policies often seem to play the key role in their phasing. Much of the last couple of decades' work on technological forecasting and energy policy analysis has focused here.

'Regional agricultural development' is characterized by scales that are an order of magnitude smaller and faster than those of the global political/demographic patterns. I have defined this last cluster of Figure 6 in terms of the size of crop regions and zones around the world, and the characteristic rates at which new, higher-yield or higher-profit crop varieties replace their predecessors in such regions. Concerns at these scales seem heavily influenced by the writings of development-oriented economists of both market and Marxist persuasion.*

We are now in a position to compare the scales of social and ecological phenomena with scales of climatic variation. The overall thrust in the following section is to apply the concepts of relative scale discussed in Section 2 to the data developed in Section 3, in order to help identify key relationships that require attention in the study of interactions among climates, ecosystems, and

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*The gap in Figure 6 between the clusters of farm activities and regional agricultural development is almost certainly an artifact of my opportunistic data set. I suspect that a variety of cooperative or market-related patterns and processes would fill it were the relevant data available. Community-level sociological and microeconomic concerns and, particularly, the work of spatial geographers would probably characterize the relevant scholarship.

societies. Figure 7 overlays the scale characterization of climate first presented in Figure 3 with the scale characterization of social and ecological phenomena from Figure 6. Certain aspects of the relationships suggested in Figure 7 can be seen more clearly and at higher resolution by scanning vertically the plots of time scales presented in Figure 4 and of space scales presented in Figure 5.

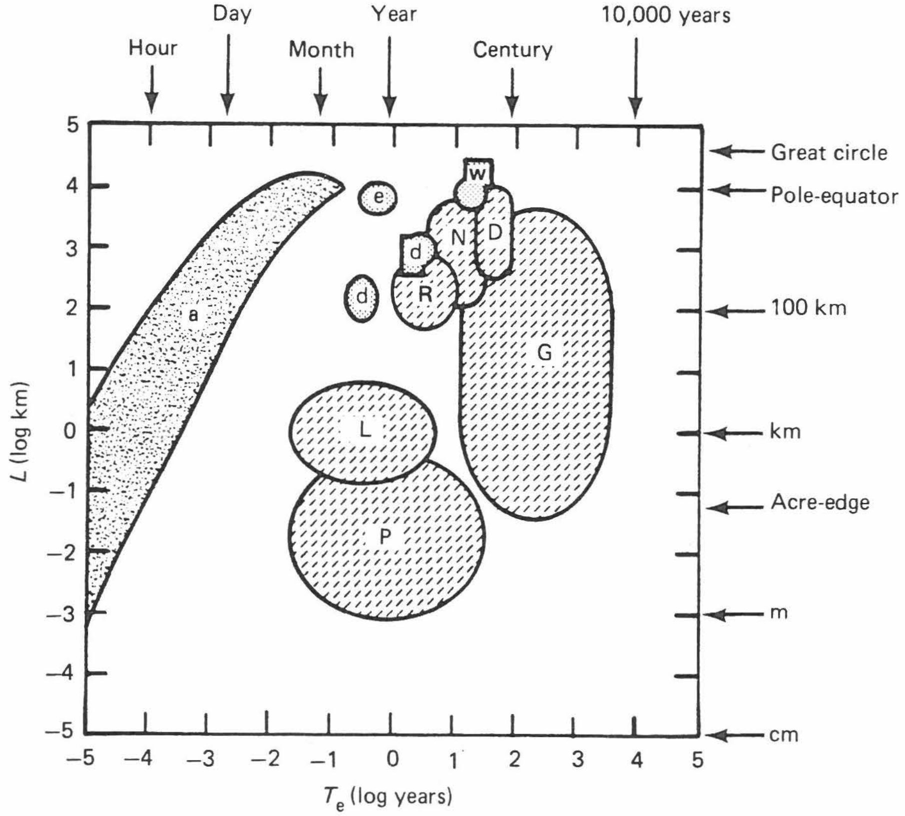

Fig. 7. Scales of interactions among climates, ecosystems, and societies. Stippled areas and lowercase letters represent climatic phenomena from Figure 3: (a) atmospheric phenomena, (e) El Niño, (d) drought, (w) warming. Diagonally shaded areas and uppercase letters represent social and ecological phenomena from Figure 6: (P) population ecology, (G) geographical ecology, (L) local farm activities, (R) regional agricultural development, (N) national industrial modernization, (D) global political/demographic patterns.

4.2. Interactions from a Temporal Perspective

If we study first the temporal domain, several relationships stand out. To begin with, the 'violent weather' that has been the focus of so many studies of environmental hazard clearly comes and goes on much shorter time scales than most of the processes reviewed here. Recall that this is intentional. I purposely omitted from this study fast social and ecological adjustments of the sort discussed by Burton *et al.* (1978) and Ford (1982) on the grounds that these have been relatively well explored. My work only confirms that, to a first approximation, scholars interested in the social or ecological impacts of violent weather events can consider processes such as those listed in Figure 4 as sufficiently slow to be effectively constant over the time scale of the weather event.

A much different and less obvious relationship holds for the very slow climatic changes represented in the figures by the historical global warming of the late nineteenth and early twentieth centuries, and by the future global warming predicted to result from anthropogenic production of various 'greenhouse' gases. Relative to such climatic variations, the characteristic time scales for animal and vegetation biomass accumulation, for the crop growth cycle, and even for the regional substitution of high-yield crops for traditional ones are very short. To a first approximation, such ecological and social processes may thus be expected to keep pace with or track climatic warmings. At any given time in the warming, other things being equal, biomass and crop production are therefore likely to be well adapted to prevailing conditions.

This perspective sheds some interesting light on the many recent studies attempting to analyze agricultural impacts resulting from predicted CO_2-induced climatic changes. Most such studies proceed by imposing an instantaneous climatic change on present crops, and then using within-year statistical or simulation models of crop–weather relations to assess the resultant change in yields (e.g. Santer, 1985, this issue). But the perspective developed here suggests that this approach, however valuable for assessing the impact of short-term climatic fluctuation, is largely inappropriate for the analysis of long-term climatic change. The actual climatic change is likely to occur very slowly relative to normal rates of crop improvement and replacement. It is therefore not the crops represented by present yield models that will in fact be responding to the changed climate, but rather new crops that have been bred and selected under conditions very close to those they will experience in the field.

This point was made explicitly by Waggoner (1983) in his contribution to the recent U.S. National Research Council study on *Changing Climate*. Waggoner first assessed the likely yield decreases of U.S. crops that would result from the instantaneous imposition of CO_2-induced climatic changes expected by the end of this century. He then showed that such decreases would be small relative to improvements in yields expected to arise from genetic, husbandry, and technological changes over comparable time scales. A similar case has been argued by Rosenberg (1982). As Cooper (1982) pointed out, it is important to look carefully at the particular time scales involved in any given case – some large-scale irrigation projects, for example, may have characteristic times comparable to even long-term climatic changes. In general, however, the time scale relationships presented here suggest that studies of agricultural responses to long-term climatic changes should almost certainly concentrate less on yield impacts for specific crops, and more on basic processes of biological/technological change, changes of income levels and distribution, and population growth and migration. The work reported elsewhere in this issue by G.D.V. Williams (1985) on indices of agricultural potential, and by Oram (1985) on the FAO Agroecological Zones Project, shows the kinds of practical and informative steps that can be taken.

Figure 7 also shows clearly that certain ecological processes are significantly slower than the climatic warming predicted to result from increased CO_2. Large-scale range extensions of trees such as those following the last Pleistocene deglaciation operated on a time scale of thousands of years, compared with the hundred years or less characterizing the predicted warming. Some processes of soil formation are almost as slow. This means that vegetational range responses would almost certainly fail to keep up with climatic changes of the sort likely to be associated with a CO_2 warming. The tree species – and in some cases the individual trees – present today are by and large the same ones that will be present during an interval of significant climatic change. In this case (unlike the case of crop yields) the expected climatic change *would* appear as essentially instantaneous relative to the rates of range extension. Forest productivity models of the sort discussed later in this issue by Kauppi and Posch (1985) therefore should be able to shed useful light on the impacts of a CO_2-induced climatic change. Moreover, efforts to analyze large-scale range responses of vegetation to a CO_2-like warming are justified in treating the warmed climate in equilibrium terms (e.g. in terms of model predictions of equilibrium climate under a doubled CO_2 concentration). To a first approximation, the dynamic interactions of climate with the extending vegetational ranges can be ignored. This is essentially the approach adopted by Emanuel *et al.* (1985, this issue) in their extremely illuminating application of the Holdridge ecological classification to analysis of the global ecosystem impacts of a long-term climatic warming.

An additional insight can be gained from Figures 4 and 7 by focusing on social processes that operate on time scales comparable to that of a CO_2-like global climatic change. Of the processes studied here, the characteristic time scale of the forecast CO_2 warming is shared by demographic transformations of agricultural societies, the market shares of various nations' principal industrial commodities, and the relative shares of total energy demand met by particular fuels. This means that over the same time interval as significant CO_2-linked climatic change seems likely to occur, we can expect significant urbanization and market integration of today's less developed countries, significant geographical shifts in the focus of the world's economic and political power, and significant changes in the form and source of the world's energy base. Any convincing assessment of the impacts of a CO_2 warming seems obliged to address such social changes. This is necessary both to evaluate possible responses to or modifications of the climatic change itself and to establish the pattern of social changes that will occur independently of climatic warming and thus set the background against which climatic change will be experienced. Schelling (1983) has emphasized the importance of such attention to 'background' changes in climate impact studies, and argued that CO_2 assessments assuming constant social structures like those of today over the period of forecast climatic warming are likely to be extremely misleading.

The same approach used above to provide a context for CO_2 impact studies can be used to examine the relations among social phenomena, ecological processes, and shorter-term climatic variations in rainfall like the droughts represented in Figure 4. Rather than going through the analysis here, I will leave it to the interested reader. The figures suggest, however, that the social and ecological time scales relevant to even the longest drought episodes lie well below those characterizing the forecast CO_2-related climatic changes. This means that even the best climate impact studies of droughts in the North American Great Plains or in the Sahel have had little reason to become concerned with very long-term processes of political/demographic or national industrial change.* Such drought studies therefore provide very incomplete guidance for the analysis of interactions between societies and a CO_2-induced climatic warming. Perhaps even more significant, scholars drawn to the study of climate–society relationships through case work on droughts and shorter-term climatic variations or anomalies are most likely to think in terms of relatively short-term perspectives of microeconomics, policy analysis, and sociology. The long-term perspectives of economic and political history necessary for analysis of the CO_2 question have simply not been in the mainstream of recent thinking on how to study climate–society interactions.

4.3. Interactions from a Spatial Perspective

Several additional, if not particularly surprising, relationships among climates, ecosystems, and societies are suggested from a comparison across spatial scales (Figures 5 and 7). In terms of the ecological concepts noted in Section 2, global-scale, long-term warmings like those discussed earlier are 'coarse-grain' climatic fluctuations for all of the social and ecological patterns discussed here. The warming defines a single global environmental 'patch' for all farms, nations, and continents alike.

At the other extreme, tornadoes can be taken as representative of small-scale (and fast) episodes of 'violent weather'. They represent 'fine-grain' environmental variation for most of the social and ecological patterns examined here, namely, continents, nations, crop zones, major river basins, and ecological groupings above the association level. Generally speaking, a single tornado will affect only a small portion of such units and not significantly alter their average properties. Conversely, for a typical ecological association of the sort described by C.B. Williams or Preston, tornadoes represent 'coarse-grain' environmental fluctuations. In other words, the typical association will be either entirely encompassed by a tornado or entirely missed by it.

These spatial relationships are more obviously relevant for the design and interpretation of climate impact studies when larger-scale environmental fluctuations are examined. Average-size (say $10^5 km^2$) droughts, for example, pose only fine-grain environmental fluctuations for the world as a whole, for continental masses, or for the largest nations. Global ecological or economic patterns and even truly national properties (e.g. gross domestic economic production) of large nations will be relatively little affected by such droughts. Conversely, however, individual vegetational associations and farms, all but the largest drainage basins, and small nations experience droughts as coarse-grain, all-consuming environmental fluctuations. Important ecological and social properties at these scales may be greatly perturbed by the occurrence of a drought.

Flohn (1980) has emphasized this importance of a nation's size in determining its general sensitivity to climatic variations. The same hurricane,

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***Many climate studies, of course, have concerned themselves with *consequences* of such processes, such as the 'marginalization' of developing societies (Garcia, 1981; Hewitt, 1983).**

drought, or heat wave that causes only acute local difficulties for a country the size of China can affect every person, farm, or forest for a country the size of Bangladesh. Intranational transfers of people, food, or financial aid may be all that is necessary to cope with the climatic fluctuations in the large-country case. In small countries, however, international aid and the obligations it entails may often be the only recourse. The scale analysis presented here suggests that nations larger than one million square kilometers or so should be significantly less vulnerable to a variety of climatic fluctuations than their smaller neighbors. This expectation, as well as the general tendency of vulnerability to decline with increasing size, is borne out by the data on variability in staple food production presented by Oram (1985, Table IV) on p. 144 of this issue.* More explicit attention to the size component of vulnerability would almost certainly help to clarify the current debate on climate sensitivity and impact.

5. Concluding Remarks

The analysis presented here has illustrated the vast range of scales over which the Earth's climate interacts with its ecosystems and societies. These scales span more than seven orders of magnitude in both the spatial and temporal dimensions. Climatically, they include such diverse phenomena as the virtually instantaneous local impacts of tornadoes and century-long trends in globally averaged temperature. From an ecological perspective, everything from the behavioral responses of individual organisms to the biogeographical patterns of speciation is involved. The relevant social phenomena range from the individual farmer's planting decisions to global patterns in the development and wealth of nations.

Each of these scale-defined regimes represents a legitimate focus of inquiry. But it is probably unrealistic to believe that a single 'field' of climate impact studies will ever evolve that can do full justice to the range of diverse concerns and perspectives they encompass. This need not be a problem, so long as participants in debates about the interactions of climates, ecosystems, and societies concede that causal explanations, variables, and generalizations relevant to one scale regime are unlikely to be appropriate at others. The challenge is not to establish the preeminence of any particular scale, but rather to match scales of explanations, processes, and patterns in a realistic and effective way.

The most obvious implication of the perspective developed here is that the choice of which ecological or social processes to include and which to exclude in climate impact studies should be made with much more explicit attention to the time and space scales at which the climatic change is expressed. No simple rule can automatically select the 'proper' scale for attention. The elementary distinctions between fast and slow, big and small that I have employed here have a certain rough-and-ready utility, but they can also be enormously misleading. A variety of ecological, climatological, and marine systems are known in which

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*The major exceptions in Oram's data to this general inverse relation between a nation's size and its variability of food production are the anomalously high variabilities for Algeria and Libya. These two large nations, however, have their agriculture confined to relatively small regions along their coasts.

small and rapid fluctuations 'cascade' up-scale through nonlinear processes to alter long-term, large patterns of system behavior. For the same systems, slow trends in other variables can change conditions in ways that radically alter the impact and propagation of acute local perturbations (Steele, 1978b; Lorenz, 1984; Holling, 1985). The continuing debate in historical research over the role of exceptional individuals or events versus the role of long-term, large-scale trends has much the same character of possible 'cross-scale' influences.

These observations reflect the potential dangers of a simplistic scale-dependent perspective on climate impacts. But potential dangers do not always materialize. Unless and until some general theory can be developed and tested, the greatest need is for careful case studies that distinguish which possible cross-scale influences are important in a given instance and which can be safely ignored. Barring indications to the contrary, I believe that a useful first approximation in the conduct of such studies would be to focus attention on social or ecological processes characterized by approximately the same scales as the climatic change of immediate interest. Other things being equal, processes occurring on much smaller and faster, or much larger and slower scales than the climatic change itself are unlikely to interact with it as strongly as those of comparable scale. Thus, for example, when long-term, large-scale climatic changes like those associated with greenhouse gases are considered, useful impact studies must seriously address the possible significance of long-term, large-scale social changes like those associated with demographic transitions, shifts in the centers of world production of major commodities, and turnovers in the technologies of basic energy production. Whether such processes would turn out to dominate the effects of climatic changes resulting from greenhouse gases can only be determined through careful analysis of particular cases and circumstances. But a beginning must be made to break away from the current habit of analyzing the same social and ecological processes, regardless of whether one is investigating the impact of highland cold-snaps, regional droughts, or global warming.

One way to encourage progress might be through historical studies of how selected long-term, large-scale social or ecological processes have altered the vulnerability of systems to various forms of climatic variability and change. As one example, we should encourage careful, critical studies of the popular hypothesis that increasing integration of a country into the world economy leads to greater vulnerability to climatic change. A related and perhaps contradictory hypothesis posed earlier in this paper, that the size of a nation or free-trade area bears an inverse relation to its vulnerability to climatic change, should also be more systematically investigated.

Much greater attention should be paid to the characterization and analysis of long-term, large-scale social processes that might bear on the human significance of long-term climatic change. The widely held view that the impacts of such changes will be felt primarily through changes in the timing and spacing of extreme climatic events remains largely an assertion backed by little hard evidence or critical analysis. An equally plausible competing hypothesis, that the most important determinants of the social impacts of long-term, large-scale climatic change would be found in the analysis of long-term, large-scale social processes, has simply not been examined. Especially important candidates for early consideration would seem to be those processes dealing with biotechnology in agriculture, the demographic transition in the less developed countries, and world-wide migration of population and production centers. The beginnings of a general framework for addressing such questions have been sketched by Schelling (1983), and deserve further elaboration.

The new kinds of research suggested by a scale perspective on interactions among climates, ecosystems, and societies are a logical extension to and complement of the work now occupying the climate impacts field. Progress is feasible even at the present state of knowledge, and new possibilities are almost certain to open up as initial studies proceed. Infusion of the needed long-term, large-scale thinking will require that economic historians, demographers, and some of the more wild-eyed technological optimists be lured into the present community of climate impact researchers. The resulting cross-fertilization should add new impetus to what is already one of the most exciting fields of interdisciplinary scholarship.

Appendix 1 Relation of T_e to Other Characteristic Times

The phrase 'characteristic time' has been used in different disciplines to cover a variety of properties relating to exponential decay rates, frequencies, residence times, doubling times, and the like. All of these characteristic times are related, and all are useful. They are not, however, the same. For the purpose of comparison in this paper, I have arbitrarily expressed all temporal scales in terms of an 'e-folding' time T_e. This is the 'natural' time scale for expressions of exponential growth or decay such as $N_t = N_0 e^{\alpha t}$, since the time T_e required for an e-fold increase (i.e. $N_t / N_0 = e$) in such a system is a constant, $1/\alpha$. For periodic, logistic, or other forms of system behavior, the e-folding time varies with system state. To permit meaningful comparisons, I therefore define T_e in such cases to be the e-folding time for a change centered on a point halfway between the system's maximum and minimum values. T_e thus equals the time to go from $N_1 = 1/(e + 1)$ to $N_2 = e/(e + 1)$, where the total range of system variation is scaled between 0 and 1. Conventional definitions of residence times, frequencies, and such can be expressed as simple multiples of T_e as shown below.

(1) *Exponential growth*

$$y_t = y_0 e^{\alpha t}$$

$$t = \ln(y_t / y_0) \cdot 1/\alpha \, ;$$

evaluate for $y_t / y_0 = e$:

$$T_e = 1/\alpha \, .$$

(2) *Linear growth*

$$y_t = mt + b$$

Scale to (y) range of 0 to 1 for relevant period:

$$t = (y_t - b) \cdot 1/m \, ;$$

evaluate for $y_2 = e/(e+1)$, $y_1 = 1/(e+1)$:

$$T_e = (t_2 - t_1) = [(e-1)/(e+1)] \cdot 1/m \text{ , or}$$

$$T_e \approx 0.46 \cdot 1/m \, .$$

(3) *Periodic cycles*

$y_t = A_0 + A \sin[2\pi t(1/\tau) + b]$

Scale to (y) range of 0 to 1 for each cycle:

$t = (1/2\pi)[\sin^{-1}(2y - 1) - b]\tau$;

evaluate for $y_2 = e/(e+1)$, $y_1 = 1/(e+1)$:

$T_e = (t_2 - t_1) = (1/2\pi) \cdot 2 \sin^{-1}[(e-1)/(e+1)]\tau$, or

$T_e \approx 0.15\, \tau$.

(4) *Logistic growth*

$y_t = K/(1+e^{c-rt})$

Scale to (F) range of 0 to 1, where $F = (y_t/K)$:

$t = \{\ln[F/(1-F)] + c\} \cdot 1/r$;

(a) evaluate for $F_2 = e/(e+1)$, $F_1 = 1/(e+1)$:

$T_e = (t_2 - t_1) = 2 \cdot 1/r$.

(b) evaluate for $F_2 = 0.9$, $F_1 = 0.1$ (this evaluation was used by Marchetti (1983) to calculate his ΔT):

$\Delta T = (t_2 - t_1) = 4.40 \cdot 1/r$;

$T_e = 0.45\Delta T$.

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CLIMATIC CHANGE AND THE BROAD-SCALE DISTRIBUTION OF TERRESTRIAL ECOSYSTEM COMPLEXES*

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Abstract. The broad-scale distribution of terrestrial ecosystem complexes is determined in large part by climate and can be altered by climatic change due to natural causes or due to human activities such as those leading to increasing atmospheric CO_2 concentration. Classifications that recognize the dependence of natural vegetation on climate provide one means of constructing maps to display the impact of climatic change on the geography of major vegetation zones. A world map of the Holdridge Life-Zone Classification, developed from approximately 8,000 meteorological records, is compared with a Holdridge Map with average temperature increments simulated by a model of climate under elevated atmospheric CO_2 concentration. The largest changes are indicated at high latitudes, where the simulated temperature increase is largest and the temperature intervals defining life zones are smallest. Boreal Forest Zones are replaced by either Cool Temperate Forest or Cool Temperate Steppe, depending on average precipitation. Changes in the tropics are smaller; however, in some regions, Subtropical Moist Forest is replaced by Tropical Dry Forest.

1. Introduction

Relationships between climate and the distribution of terrestrial ecosystem complexes are important unifying principles in ecology (Eyre, 1963; Walter, 1979). On world maps, the boundaries of the natural vegetation zones, soil types, and climatic regions roughly coincide (Trewartha, 1968). Plant productivity is also related to climate, and several investigators have either proposed or empirically calibrated such relationships (Rosenzweig, 1968). Mapping net primary productivity at the world scale is a main goal in making these derivations (e.g. Lieth, 1972; Box, 1981). Climate is an important soil-forming factor (Jenny, 1941, 1980), and Post *et al.* (1982) show a climatic pattern in the organic matter content of soils. The implication of strong relationships among climate, soils, and biota, in evidence both locally and globally, is a basis for anticipating substantial changes in natural terrestrial biomes in response to climatic change.

Almost all systems for classifying climate incorporate relationships between vegetation distribution and climate. In many instances, the name applied to a climatic zone is indicative of the natural vegetation associations expected in regions with that climate. This approach to naming climatic zones gives insight into natural vegetation distribution. To the extent that the overall impact of climatic change can be characterized by shifts in the boundaries of

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major vegetation zones, biomes, or life zones, climate-based classifications can be used to test the sensitivity of vegetation to climatic change at the global scale.

Holdridge (1947, 1964) proposes a Life-Zone Classification to predict the vegetation of a region from values of climate indices. In this paper, the Holdridge Life-Zone Classification is used to test the sensitivity of the distribution of terrestrial ecosystem complexes to a simulated climatic change. Two world maps of the Holdridge Classification, one derived from meteorological data and the other with a change in temperature simulated by a general circulation model of climate under elevated atmospheric CO_2 concentration, are compared. From the standpoint of temperature change alone, the substantial differences between these maps indicate a potentially major impact of increasing atmospheric CO_2 levels.

2. Life-Zone Maps

In this section, the development of world maps of the Holdridge Life-Zone Classification from meteorological data and for climate simulated under elevated atmospheric CO_2 concentration is described.

2.1. The Holdridge Life-Zone Classification

The Holdridge Life-Zone Classification System is a scheme for relating the character of natural vegetation associations to climate indices. The features of the Holdridge Classification are summarized in Figure 1, in which life zones are depicted by a series of hexagons formed by intersecting intervals of climate variables on logarithmic axes in a triangular coordinate system. Two variables, average biotemperature and average annual precipitation, uniquely determine a classification. Average biotemperature is the average temperature over a year, with the unit temperature values (i.e. daily, weekly, or monthly temperatures) that are used in computing the average set to 0 °C if they are less than or equal to 0 °C.

In the Holdridge Diagram (Figure 1), identical axes for average annual precipitation form two sides of an equilateral triangle. A logarithmic axis for the potential evapotranspiration (*PET*) ratio (effective humidity) forms the third side, and an axis for mean annual biotemperature is oriented perpendicular to its base. By striking equal intervals on these logarithmic axes, hexagons are formed that designate the Holdridge Life Zones. Each life zone is named to indicate a vegetation association.

The potential evapotranspiration is the amount of water that would be released to the atmosphere under natural conditions with sufficient but not excessive water available throughout the growing season. The potential evapotranspiration ratio is the quotient of *PET* and average annual precipitation. Holdridge (1964) assumes, on the basis of studies of several ecosystems, that *PET* is proportional to biotemperature (constant of proportionality, 58.93). The *PET* ratio in the Holdridge Diagram is therefore dependent on the two primary variables, annual precipitation and biotemperature.

One additional division in the Holdridge System is based on the occurrence of killing frost. This division is along a critical temperature line that divides

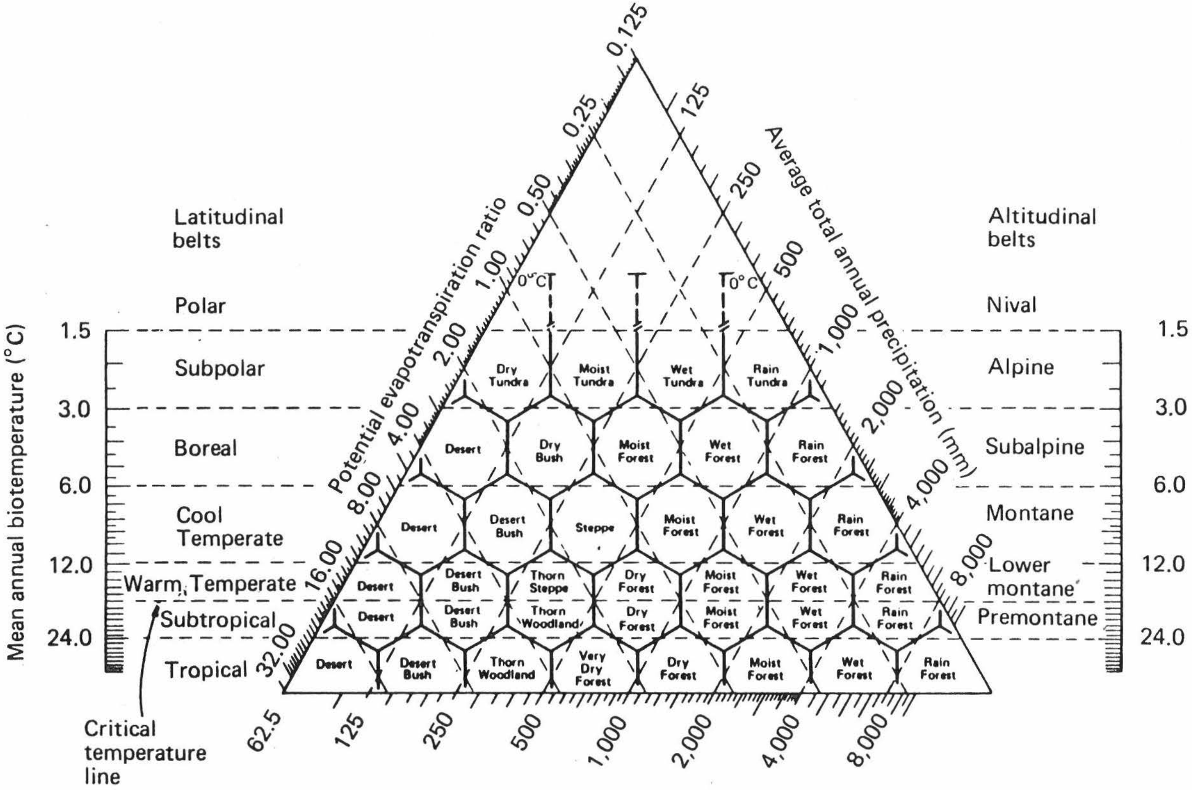

Fig. 1. The Holdridge Life-Zone Classification System.

hexagons between 12 and 24 °C into Warm Temperate and Subtropical Zones. This line is adjusted to reflect regional conditions. The complete Holdridge Classification at this level includes 37 life zones.

Changes in vegetation associations with climate along altitudinal gradients were an important basis for developing the Holdridge Classification (Holdridge, 1964). Subsequently, Holdridge Life-Zone Maps have been developed for a number of regions (e.g. eastern and central U.S.A.: Sawyer and Lindsey, 1963; the Mediterranean borderland: Steila, 1966; Puerto Rico: Ewel and Whitmore, 1973; Utah, U.S.A.: MacMahon and Wieboldt, 1978; Brazil: Tosi, 1983). Holdridge and co-workers have tested the classification extensively in the tropics. Although an entirely satisfactory scheme for relating vegetation and climate is yet to be developed (Spurr and Barnes, 1973), tests of the Holdridge System indicate that many aspects of the natural distribution of vegetation can be mapped using this classification.

Based on the method of derivation, there are three general categories of maps that display information about the relationships between natural vegetation and climate:

(1) maps of climatic zones named to indicate the general character of their vegetation;
(2) maps derived from classifications designed to predict natural vegetation insofar as it is determined by climate;
(3) maps that display natural or potential vegetation with both climatic factors and other influential factors taken into account.

The Köppen (1931) System is the most widely used climate classification (e.g. Trewartha, 1968, appendix). There are substantial differences in the definitions of Holdridge Life Zones and similar Köppen Zones. In large part, these differences arise because the Köppen Classification differentiates among climatic zones in cases where associated distinctions in vegetation may not be clear.

For example, the Köppen Classification indicates a division of the Holdridge Cool Temperate Forest Zone in North America into climatic subregions based on average summer temperature. Although this distinction may be appropriate in describing climate, it does not reflect a particularly obvious subdivision from the standpoint of vegetation. Perhaps for similar reasons, the east–west transition from forests to grassland or steppe in North America is not recognized under the Köppen Classification (e.g. Daubenmire, 1978, figure 55 for comparison).

The 'bioclimatic regions' proposed by Bazilevich *et al.* (1970) are similar to the Holdridge Life Zones (Walter, 1979, figure 123), both systems being based on average temperature and precipitation. However, Bazilevich and co-workers recognize broader and substantially fewer zones than Holdridge.

Walter (1979) divides the biosphere into nine 'zonobiomes' largely based on climate. Soil characteristics and vegetation associations typical of each zonobiome are tabulated. Walter uses a standardized climate diagram (Walter and Lieth, 1960) that graphs monthly average temperature and precipitation on coincident axes and provides an indication of the duration and intensity of relatively arid seasons. The duration and severity of a cold winter and the possibility of late or early frosts are also recorded. In Walter's system, zonobiomes are not specified by distinct intervals of climate variables as much as by a typical climate diagram or diagrams.

Several investigators (e.g. Eyre, 1963; Odum, 1971; Schmithüsen, 1976; Küchler, 1978) have developed maps of natural or potential vegetation that incorporate the influence not only of climate but of other factors as well. Of these, Küchler's maps are perhaps the most widely applied. Many of the criteria used in the nomenclatures that divide vegetation associations on these maps, such as the density of trees in a forest category, cannot be realized at all in a climate-based system.

2.2. World Maps of the Holdridge Classification

A World Holdridge Life-Zone Map based on data from approximately 8,000 meteorological stations worldwide is shown in Figure 2. Meteorological data were assembled from the World Weather Records (e.g. Weather Bureau, 1959) and the climate atlas by Walter and Lieth (1960). With one exception, the data were taken with only cursory inspection for outliers. Stations at high elevations in regions with terrain of generally lower elevation were eliminated.

The instrumental record of climate varies in quality from region to region. The instrumental data contain numerous inaccuracies and are inconsistent in terms of the period of record. There are large geographical gaps in the data set. One aspect of the study reported here is to test the capability of a classification such as Holdridge's to map broad vegetation zones, given these difficulties with meteorological data.

Values of average annual biotemperature and precipitation at each station were calculated from monthly average data. These values were interpolated to a uniform 0.5° latitude × 0.5° longitude grid between 80° N and 60° S using a triangle-based interpolation scheme designed for application on the surface of the unit sphere (Renka, 1982). Since it is largely covered by ice and few meteorological records are available, Greenland was not included in the mapping. The Holdridge Classification (Figure 1) was applied to the interpolated values of biotemperature and annual precipitation to generate Figure 2. The critical temperature line in the Holdridge Classification was adjusted to 21 °C, a value that brings the boundaries of Subtropical Life Zones into agreement with actual boundaries in several test regions. For mapping at the world scale, the 37 life zones depicted in the Holdridge Classification were combined as indicated in the key to Figure 2.

The sensitivity of the Holdridge Classification to climatic change is tested by remapping the Holdridge Life Zones for an alternate climate. Temperature change was adopted from a simulation experiment reported by Manabe and Stouffer (1980). These investigators used a general circulation model to test the sensitivity of climate to a fourfold increase in atmospheric CO_2 concentration. Their contour map (Figure 3) showing the world pattern of increase in average annual temperature was interpolated to the 0.5° grid to be consistent with Figure 2. Manabe and Stouffer map simulation results for a quadrupling of CO_2 concentration and indicate that the change in temperature is logarithmically dependent on the increase in CO_2 concentration. The simulated temperature increases for a quadrupling of CO_2 concentration therefore were divided by two

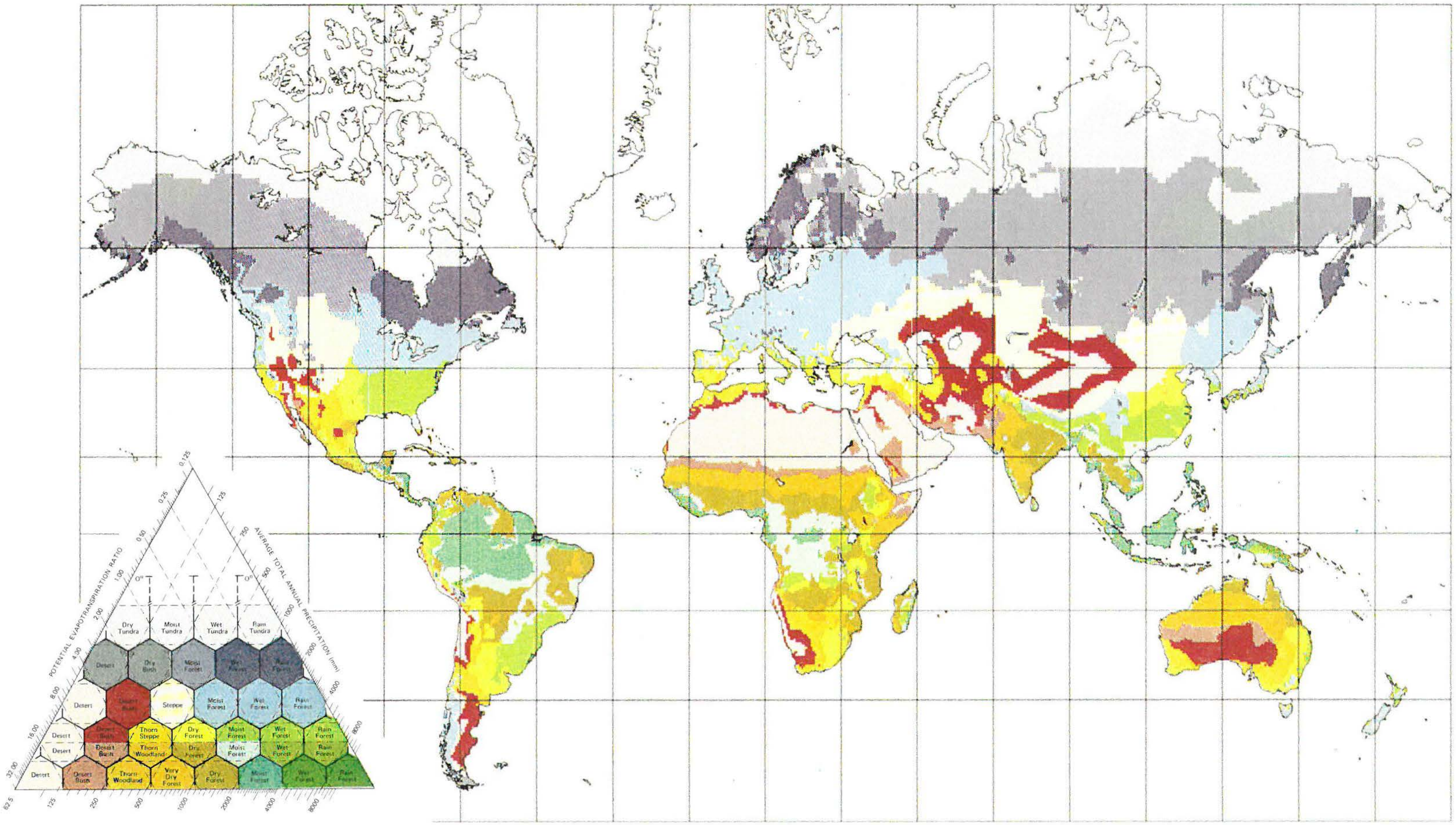

Fig. 2. World map of the Holdridge Classification (base case). The resolution is 0.5° latitude × 0.5° longitude and the extent is from 80° N to 60° S – Greenland is not classified (Aitof's Equal Area Projection). The key is explained in Figure 1.

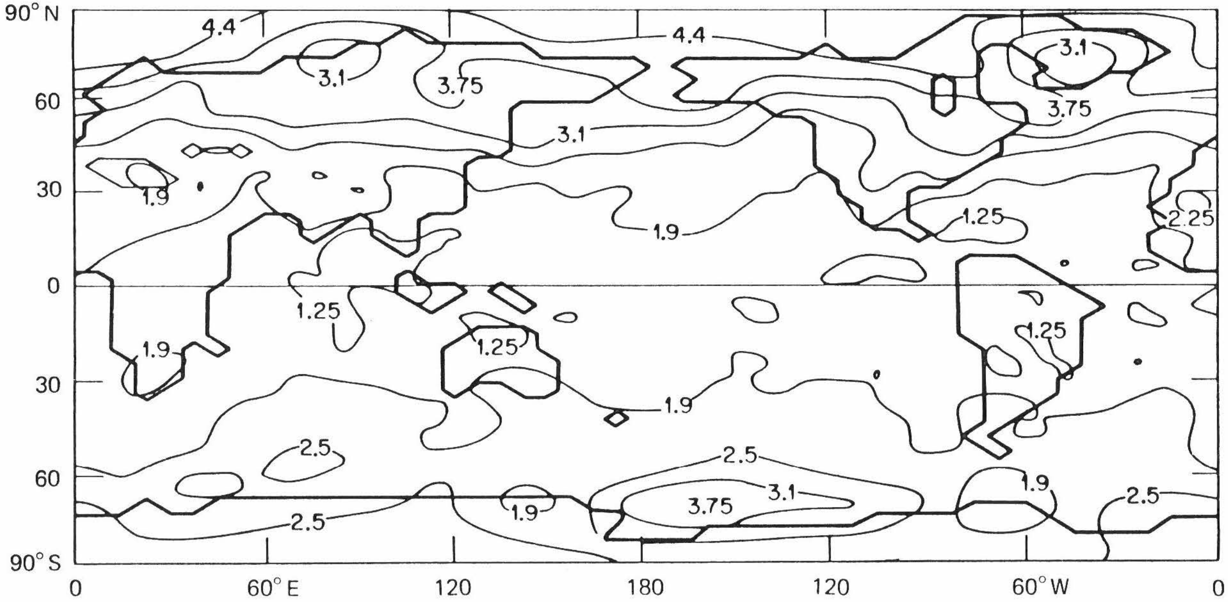

Fig. 3. Simulated difference in average annual temperature for atmospheric CO_2 concentration at twice base-case conditions. Contours of constant temperature increase are indicated. Results were generated with a general circulation model as reported by Manabe and Stouffer (1980).

to correspond to a doubling in CO_2 concentration. The resulting pattern of temperature increase shown in Figure 3 was added to the values of biotemperature derived from meteorological records, and the Holdridge Classification was remapped under this simulated climatic change (Figure 4). The organization of Holdridge Life Zones in the map of Figure 4 is identical to that of Figure 2 and the critical temperature line is the same.

3. Results

Comparison of Figures 2 and 4 shows that large-scale patterns in natural vegetation appear to be quite sensitive to changes in average temperature that may result from increasing atmospheric CO_2 concentration. Table I and the diagrams in Figure 5 clarify the changes in the relative extent of major forest types and biomes indicated in Figures 2 and 4. The extent of the Boreal Forest Zone is almost zero under elevated CO_2 climate. In general, Cool Temperate Forest replaces Wet Boreal Forest, and Cool Temperate Steppe replaces Moist Boreal Forest. Tundra is replaced by Boreal Desert or, in warmer areas, Temperate Desert Bush. The character of these shifts at higher latitudes is essentially uniform in both hemispheres, and the changes in life-zone classifications are at most to neighboring life zones in the Holdridge Diagram (Figure 1).

The Cool Temperate Forest Zone becomes interspersed by Warm Temperate Dry Forest. In Western Europe, the pattern of Cool Temperate and Warm Temperate Forest becomes more complex (Figure 4), with a spatial pattern that is perhaps finer than the density of meteorological data can support. The simulated increase in average temperature in the equatorial zone is about half that at higher latitudes (Figure 3), the logarithmic intervals of biotemperature that define Tropical and Subtropical Holdridge Life Zones are broader than for the Temperate and Boreal Zones, and thus changes in Tropical Zones are substantially less pronounced than those in colder life zones.

Subtropical Zones extend further into regions previously designated Warm Temperate. The distinction between these life zones is based on the occurrence of a killing frost (Figure 1), and changes in this aspect of climate are not summarized in the simulation results as used here (i.e. Figure 3). In South America and Africa, Subtropical Moist Forest is in many instances replaced by Tropical Dry Forest. Savanna or drier tropical forest types are in many instances maintained by fire (e.g. Richards, 1957), the frequency and intensity of which depend on precipitation among other factors (e.g. fuel loads, topography) so that the actual shifts in these life zones may be more complicated.

4. Discussion

Inconsistencies between the climate simulated by general circulation models and that derived from meteorological data limit the interpretation of the sensitivity test provided by Figures 2 and 4. The spatial resolution of climate models is substantially coarser than the 0.5° resolution of the world maps in Figures 2 and 4. When summarized as in Figure 3, the large-scale pattern of warming simulated by Manabe and Stouffer (1980) can be consistently imposed on the grid of biotemperature values interpolated from meteorological data. It is the finer-scale pattern in vegetation, smoothed by the Holdridge Classification when

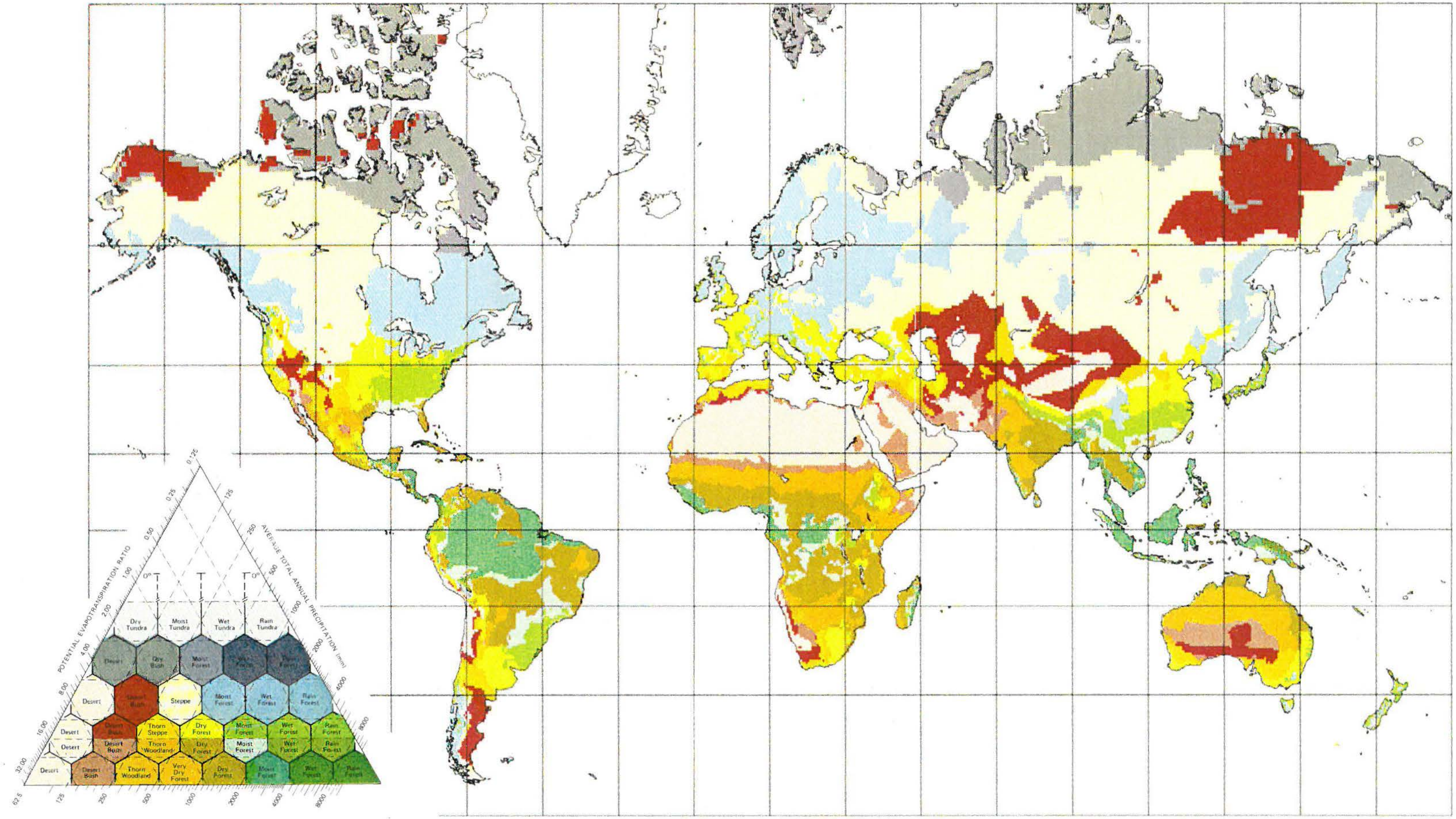

Fig. 4. World map of the Holdridge Classification with biotemperature increased to reflect climate simulated under elevated atmospheric CO_2 concentration (Figure 3). The key is explained in Figure 1.

TABLE I: Summary of Changes in Life-Zone Extents (10^6 km^2).

Life Zone	Area	
	Base case	Elevated CO_2
Forests		
Tropical:		
Rain	0.003	0.003
Wet	0.378	0.402
Moist	8.605	9.971
Dry	10.018	14.589
	19.004	24.965
Subtropical:		
Rain	0.014	0.02
Wet	0.499	0.261
Moist	7.985	5.221
Dry	3.5	3.187
	11.998	8.689
Warm Temperate:		
Rain	0.029	0.021
Wet	0.57	0.509
Moist	7.809	6.12
Dry	7.543	8.89
	15.951	15.540
Cool Temperate:		
Rain	0.256	0.174
Wet	1.626	1.141
Moist	9.344	10.915
	11.226	12.230
Boreal:		
Rain	0.303	0
Wet	4.35	0.009
Moist	12.722	0.826
	17.375	0.835
	75.554	62.259
Grasslands		
Tropical:		
Very Dry Forest	4.712	6.275
Thorn Woodland	2.351	3.276
	7.063	9.551
Subtropical:		
Thorn Woodland	1.651	2.126
Warm Temperate Thorn Steppe	5.171	5.893
Cool Temperate Steppe	9.045	20.335
	15.867	28.354
	22.930	37.905

Table I (continued).

Life Zone	Area	
	Base case	Elevated CO_2
Deserts		
Tropical:		
Desert Bush	2.321	3.02
Desert	8.42	9.457
Subtropical:		
Desert Bush	1.535	2.485
Desert	1.385	1.137
Warm Temperate:		
Desert Bush	4.894	4.738
Desert	1.911	1.448
Cool Temperate:		
Desert Bush	3.571	5.048
Desert	1.241	0.669
Boreal:		
Dry Bush	1.282	2.477
Desert	0.022	0.721
	26.582	31.200
Tundra		
Rain	0.03	0
Wet	1.497	0
Moist	2.701	0
Dry	0	0
	4.228	0
Ice	2.071	0
Total	131.365	131.364

applied to meteorological data, that cannot be analyzed with the coarse-resolution climate simulation results. A second inconsistency is that, except with regard to general features, the climate simulated by general circulation models for CO_2 concentration corresponding to conditions prior to significant releases by fossil fuel use and other sources does not match climate indicated by the instrumental record. Many aspects of climate that give rise to important features in the Life-Zone Maps (Figures 2 and 4) are not accurately simulated by climate models.

Changes in precipitation patterns were not considered in developing the Holdridge Life-Zone Map for elevated CO_2 climate (Figure 4); the sensitivity test is against temperature alone. With warming, more humidity would be expected (Manabe and Stouffer, 1980; Manabe, 1983), and in some instances this additional moisture might compensate for the impacts of warming. When only temperature change is considered, changes in life-zone designations of regions are along intervals of constant precipitation. For example, with warming, Cool Temperate Moist Forest replaces Boreal Wet Forest, but if an associated increase in average annual precipitation also occurs, the change would be to Cool Temperate Wet Forest. The character of ecosystems typical of this wetter life zone may be substantially nearer those of the original life zone. Changes in the seasonality of

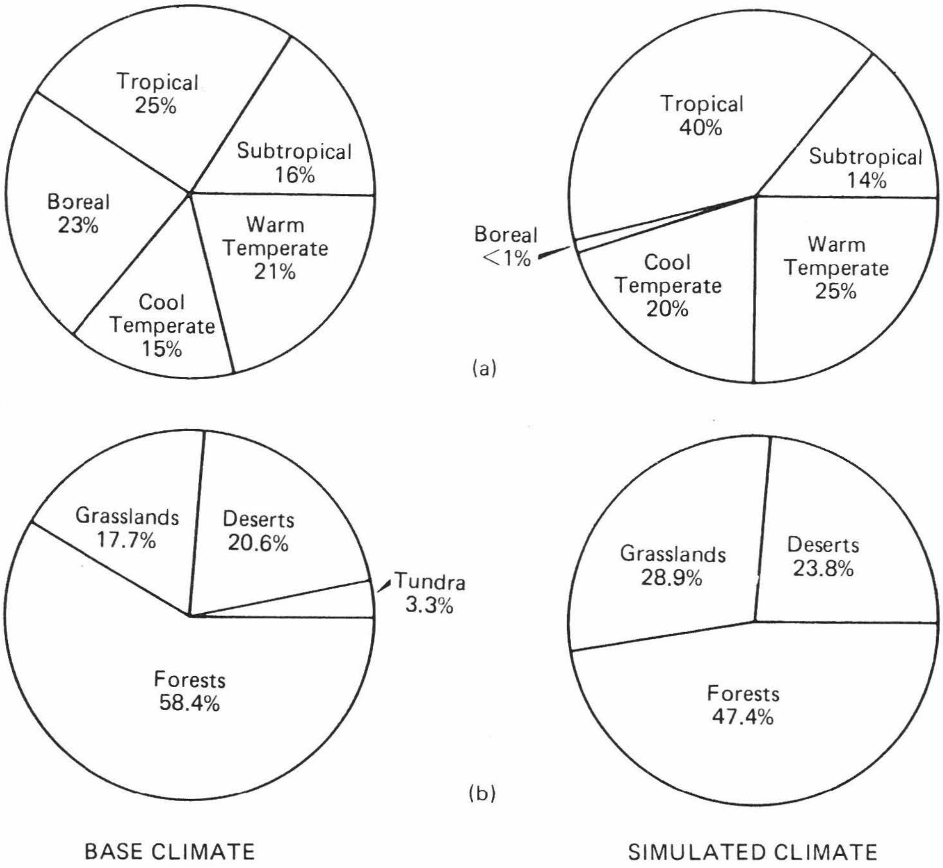

Fig. 5. Changes in areal extent of (a) major forest types and (b) biomes under elevated CO_2 levels.

climate variables may have a marked impact on vegetation, particularly in regions where climate is characterized by an extreme in some variable.

The first perceptible changes in global vegetation patterns due to climatic change may be at the transitions between the major life zones mapped in Figures 2 and 4. There is potential for change in these transition zones where little or no impact on the extent of major life zones is implied. For example, in the experiment described here, there is limited replacement of Subtropical Moist Forest by Tropical Dry Forest. At the boundary between these life zones, a complex mosaic of forest stands, pure grassland, and single trees or scattered shrubs characterizes the landscape (e.g. Richards, 1957; Walter, 1979), and small changes in climate may cause substantial changes in the relative mixture of these vegetation types.

The influence of elevation is recorded in Figures 2 and 4 only insofar as weather stations are positioned to reflect the dependence of average temperature and precipitation on topography and to the extent that these variables alone are adequate to predict the pattern of vegetation in zones where changes in elevation are an important factor. Some aspects of vegetation patterns associated with elevation can be traced in this manner. Referring to Figure 1, Moist Boreal Forest is indicated in regions along the highest elevations in the Rocky Mountains, and in the Eastern Hemisphere Cool Temperate Forest is assigned to the highest regions of the Himalayas. Many features of global vegetation patterns resulting from elevation are not adequately captured by the climate data used to derive the life-zone maps, and like other transition zones, regions of substantial elevation gradients are characterized by complex vegetation patterns.

Soil characteristics are another nonclimatic factor of importance in determining the vegetation of a region. Although many properties of soils are closely correlated with climate (e.g. Jenny, 1941; Post *et al.*, 1982), and are therefore reflected by the Holdridge Classification in terms of their influence on vegetation, physical and geological factors such as parent material are also important soil-forming factors that are not treated in a purely climatic scheme such as the Holdridge Classification. Even in instances where the characteristics of soils are such that vegetation associations are accurately mapped, soils developed under climate, vegetation, and parent material reflected by the Life-Zone Map of Figure 2 for base climate may substantially constrain the rearrangement of life zones due to climatic change. For example, the replacement of Boreal Forest by Cool Temperate Forest may be slowed by the properties of the podzols typical of the Boreal Zone. Over sufficiently long periods, soil characteristics will also change, but this transient may prove to be the longest in the response of the biosphere to climatic change, and in some instances parent material and geomorphology may limit changes in soil properties.

The actual contemporary land cover has been drastically modified by human activities. There are few remaining places where the natural vegetation associations, approximated by the Life-Zone Map in Figure 2, have not been modified. Clearly, the impacts of climatic change on regions composed of highly managed ecosystems will depend on societal response in terms of altered management practices. In cases of less intensive management or where areas once under human control have been essentially abandoned and are reverting to more natural conditions, the impact of climatic change may still depend on the degree to which natural vegetation and soils have been disturbed by human activities. Land-use change that drastically alters the vegetation of a region from natural conditions, for example forest clearing and conversion to grassland for grazing, may enhance the frequency of occurrences such as fire and may prevent recovery of vegetation to that implied by climate – either the present climate or an alternate climate such as that simulated for elevated CO_2 levels.

5. Conclusions

Comparison of the Holdridge Life-Zone Maps in Figures 2 and 4 provides an initial test of the sensitivity of the distribution of major vegetation associations to temperature changes such as may result from increases in atmospheric CO_2 concentration. The indicated changes in global vegetation distribution are quite substantial and more complex shifts can be expected when additional factors are considered.

Even though one might predict a large shift in vegetation in response to a change in climate, inspection of a smaller-scale subregion could demonstrate the presence of a wide range of vegetation at particular sites. One finds grassland in fire-prone regions within forested landscapes or riverine forests even in deserts. Such heterogeneity characterizes the present landscape, and we should expect it in landscapes that might develop in response to altered global climate. With these considerations and an impression of the reliability of the Holdridge Classification and Maps in mind, it is appropriate to discuss the theoretical changes in global vegetation that might result from climatic warming (Figure 4).

The changes in carbon storage that might result from these changes in vegetation distribution are sufficiently large to suggest that the feedback of climatic change on the carbon cycle through this mechanism may be important in understanding how atmospheric CO_2 concentration will increase as further fossil fuel use occurs. Furthermore, the changes in land cover implied by Figures 2 and 4 indicate significant changes in the Earth's albedo that should be considered in simulating the sensitivity of climate to changes in CO_2 concentration.

The most important factor limiting the realism of the exercise reported here is the absence of precipitation change in the analysis. The discussion above implies that the impacts of climatic change on natural vegetation distribution may be considerably different when moisture changes are also studied. Climate models now simulate changes in precipitation, although not as realistically as temperature, and the required analysis should be completed in the near future.

Inconsistencies between the resolution of simulated climatic change and life-zone maps derived from meteorological data require refinements to climate models that may not be practical for some time. The applicability of simulation results from climate models to analysis of vegetation patterns associated with seasonality, topography, and transition zones is also restricted by the coarse resolution of climate models. Simulation of climate at the continental or regional scale with greater spatial resolution may provide the first simulation results for studying the sensitivity of these more complex vegetation patterns to climatic change. However, available methods for relating vegetation distribution and climate, such as the Holdridge Classification, also require refinement in this regard.

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SENSITIVITY OF BOREAL FORESTS TO POSSIBLE CLIMATIC WARMING

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Abstract. General circulation models indicate substantial CO_2 warming in high latitudes. In these regions, which include the boreal coniferous forests, the activity of ecosystems is largely controlled by temperature. The effective temperature sum (degree-days) is used in this study for describing the regional variability in the productivity of boreal ecosystems. Although the concept is simple, it takes into account two basic factors: the length of the growing season and the day-to-day level of activity of the ecosystem. This study examines which areas in the boreal coniferous forests would be most sensitive to a possible climatic warming. The data used in the study are for Finland.

A regression is estimated between regional forest growth rate and effective temperature sum. A climatic warming is assumed and the corresponding growth response is calculated, using the regression, for northern and southern areas, and for maritime and continental areas. The response is expressed in terms of (i) absolute increase in growth (grams per m^2 per year) and (ii) relative increase in growth. The results indicate that a given climatic warming would yield the greatest absolute increase in growth in warm (i.e. southern) and maritime parts of the biome. In terms of the relative growth response the sensitivity would increase northward and toward maritime areas.

1. Boreal Coniferous Forests

A large fraction of the Northern Hemisphere at high latitudes is dominated by the boreal biome – a band with a width of more than 1,000 km north–south across the Eurasian and North American continents (Hämet-Ahti, 1981). The area, about 6.7 million km^2 depending on the classification criteria, contains roughly 14% of the world forest biomass (*The Global 2000 Report to the President*, 1980). The biome is dominated by coniferous forests and has a sparse human population.

The significance of a possible change in the primary productivity of ecosystems as a result of climatic warming can be assessed using alternative indicator variables. The absolute change in productivity can be expressed, for example, in grams of biomass per square meter per year. This can be related to the volume of ecological activities, for example to the annual turnover of the herbivore biomass. However, all ecosystems are adapted to the existing patterns of productivity. Therefore, it is useful to calculate the ratio of the estimated future productivity to the productivity level observed from the historical records, i.e. the relative change in productivity. This variable is expressed as a percentage and describes how dramatic the change would be relative to the historical

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reference level. Both variables are useful for assessing the impact of a possible climatic warming on human societies. The absolute change in productivity would affect the volume of the forest industry, for example. The relative change in productivity could be linked with regional economic activities, and would be an especially useful variable for areas where indigenous forest resources play an important role in the regional economy.

Temperature is a very important ecological factor in the boreal region, both in natural forest ecosystems (Mikola, 1950) and in agroecosystems (Mukula *et al.*, 1978). The productivity of ecosystems is limited over large areas by temperature rather than moisture. A climatic warming should *a priori* increase the productivity of these ecosystems in both absolute and relative terms.

The response of ecosystems to a climatic change depends on both the character of the change itself – the *action* – and the character of the ecosystem that produces the *reaction*. The greatest productivity response would occur in areas where a substantial climatic change – a strong action – coincides with a sensitive ecosystem – a prone reaction. Many uncertainties still exist regarding the action: general circulation models do not yet describe sufficiently accurately the magnitude and geographical distribution of the effects of a possible CO_2 warming, and more research is needed. It is nevertheless necessary to focus research simultaneously on the possible reaction.

This study examines the sensitivity of the boreal coniferous forests to a climatic warming that may occur, for example, as a result of CO_2 enrichment of the atmosphere. The objective is to find which areas in these forests would be most sensitive – northern or southern parts, forests in continental regions or those in maritime areas.

2. Effective Temperature Sum

Even within one biome, the boreal zone, there is large variability in the climate and in the ecosystems. Finland, for example, is entirely classified as a boreal area, and yet the annual average temperature in northern Finland is 5.5 °C lower than that in the southernmost part of the country. Moreover, a gradient exists with an increasingly continental climate toward the north. Such differences in climate cause substantial variability in ecosystem productivity. A model is needed for relating climate variables to productivity variables. This study focuses on a very large region, and the model must be kept simple. A regression model is introduced that describes the magnitude of the productivity response (absolute or relative) as a function of the effective temperature sum.

The effective temperature sum (*ETS*) is defined as the cumulative total of the daily average temperature values that exceed a threshold temperature T_0. Below that threshold the temperature is not considered 'effective'. The threshold has frequently been fixed at +5 °C (Arnold, 1959):

$$ETS = \sum_{i=1}^{n} (T_i - 5) , \qquad (1)$$

where T_i is the daily mean temperature and n is the number of days with $T_i \geq 5\,°C$.

The effective temperature sum has been used since de Réaumur (1735) for describing the potential productivity of ecosystems (cited by Sarvas, 1972). The variable aggregates information about two important factors: (i) the length of the growing season, and (ii) the day-to-day 'level of activity' of the ecosystem within the growing season. The length of the growing season is described by means of the threshold temperature: days colder than +5 °C are omitted. The level of activity within the growing period, i.e. above the threshold, is described as a linear function of temperature.

3. Relating *ETS* to Forest Growth

Regional variability of forest productivity cannot be fully ascribed to climatic variability, because soil conditions and, especially, management practices significantly affect productivity. The data used in this study are from Finland, a country extending 1,000 kilometers north–south through the boreal biome. The country is fairly uniform with respect to soil conditions, topography, and land management practices.

A regression is formed between effective temperature sum and tree growth rate, which is closely related to the primary productivity of forest ecosystems. The *ETS* data are from Kolkki (1969) and the tree growth data are from the National Forest Inventory provided regionally for 19 Forestry Board Districts, which vary in size from 4,000 to 51,000 km^2. The inventory data are measured and compiled in about eight-year intervals, the most recent published data being for 1971–76. Earlier data from 1951–53 are used here, because these coincide with the period of the *ETS* data of Kolkki (1969). (No essential change in forest productivity pattern has been observed between the 1950s and the 1970s (*Yearbook of Forest Statistics*, 1983); see, however, Arovaara *et al.* (1984).) The tree growth data are based on statistically representative sampling over the whole of Finland. The data are ideal in the sense that they describe regional forest growth, not just the growth of individual forest stands in different parts of the country.

Although it is a simple static model, the regression fits rather well to the observations of regional forest growth (Figure 1). The purpose of constructing the regression model is to generate scenarios of growth in the anticipated warmer climate. A plateau is introduced into the regression, implying that in conditions warmer than those in southernmost Finland today, growth would essentially depend on factors other than temperature. We thus assumed constant growth in high-*ETS* conditions. On this basis the following relationship is formed between *ETS* (in degree-days) and tree growth G (in m^3 ha^{-1} yr^{-1}):

$$G = a \cdot ETS - b \tag{2}$$

with

$$a = 0.0066135, \quad b = 3.61157.$$

G is set equal to zero if Equation (2) gives a negative value, and $G = 6$ if Equation (2) yields a value greater than 6. This equation is used in the following sections for estimating the sensitivity of forests to a possible climatic warming in different parts of the boreal zone: in maritime and continental parts, and in southern and northern parts.

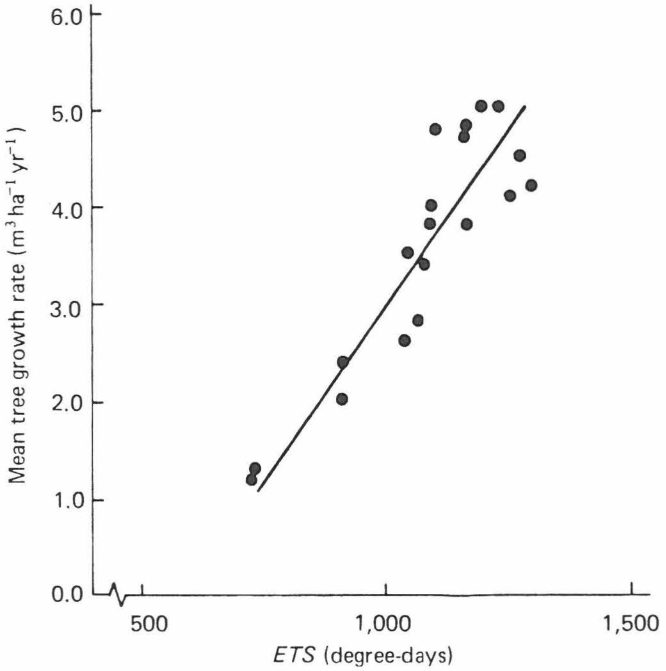

Fig. 1. Regression between the effective temperature sum and the annual mean tree growth rate.

4. Impacts of Thermal and Maritime–Continental Gradients on *ETS*

The annual value of *ETS* is best calculated by summing the daily values of the effective temperature from the time series data, i.e. by integration of *ETS* over time. An identical result is obtained by using another method, which can be called integration over temperature distribution. This method is based on the distribution that describes the relative duration of any given temperature within the course of the year (Figure 2a). The frequency of each temperature class is weighted by the selected response function and *ETS* is obtained by adding these weighted frequencies. Both methods for calculating *ETS* are equally demanding in their data requirements. Daily mean temperatures form the data base also for the second method. However, if an additional simplifying assumption is made, integrating over the temperature distribution provides a basis for expressing *ETS* as a function of two variables: annual mean temperature and 'degree of continentality'.

A measure for the degree of continentality can be obtained from the temperature frequency distribution. The broader the distribution, the greater the difference between summer and winter temperatures and the more continental the climate. We assume that a normal distribution is suitable for describing the distribution in Figure 2a. This allows us to define the degree of continentality σ as the standard deviation of the temperature frequency distribution. Then the

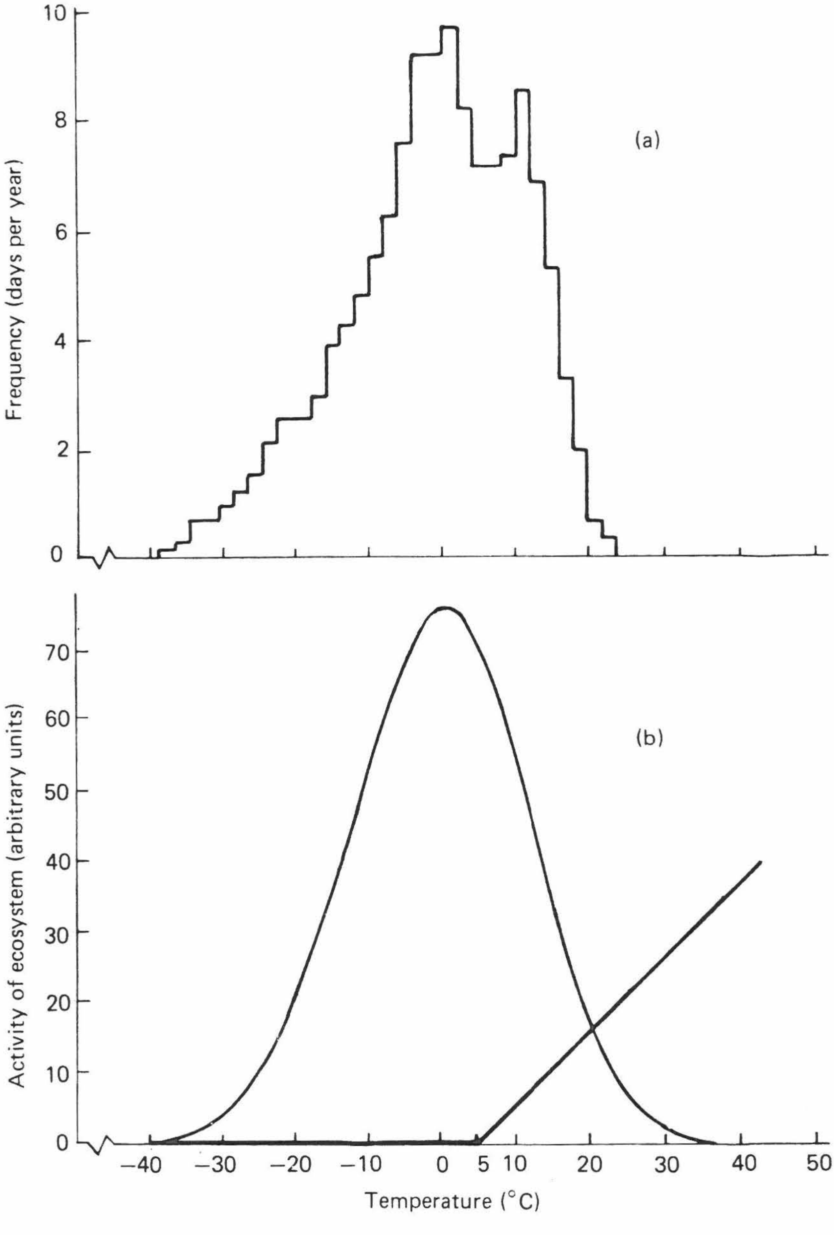

Fig. 2. (a) Temperature frequency distribution over the years 1961–80 in Sodankylä, Finland, longitude 26.5° E, latitude 67.4° N (Heino and Hellsten, 1983). (b) Idealized temperature frequency distribution (of the Sodankylä data), and the response function with +5 °C threshold temperature.

effective temperature sum can be expressed as a function of the number of days N (365), the threshold temperature T_0, the mean temperature $\bar{T}$, and the degree of continentality σ in the following way:

$$
\begin{aligned}
ETS(T_0,\bar{T},\sigma) &= \int_{T_0}^{\infty}(T-T_0)\,\frac{N}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(T-\bar{T})^2}{2\sigma^2}\right]\mathrm{d}T \\
&= \frac{N\sigma}{\sqrt{2\pi}}\exp\left[-\frac{(\bar{T}-T_0)^2}{2\sigma^2}\right]+\frac{N}{2}(\bar{T}-T_0)\left[1+\operatorname{erf}\left(\frac{\bar{T}-T_0}{\sqrt{2}\sigma}\right)\right], \qquad (3)
\end{aligned}
$$

where

$$
\operatorname{erf}(x) := \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\mathrm{d}t \;.
$$

T_0 was fixed in this study at +5 °C. Equation (3) weights the idealized temperature frequency with the response function and integrates it over temperature. The idealization implies the assumption of a normal distribution (Figure 2b). The significance of this assumption was tested with empirical data from 22 sites in different parts of Finland (data from Heino and Hellsten, 1983). The calculated values of *ETS* were compared with the corresponding observed values. The fit is sufficient although at the northernmost site Equation (3) overestimates the effective temperature sum by about 15% (Figure 3). The fit suggests that, under Finnish conditions, the assumption regarding the normality of the distribution can be accepted.

Equation (3) describes the impact of mean temperature, or the north–south gradient, and the impact of the standard deviation of the distribution, or the maritime–continental gradient, on the formation of the effective temperature sum. This feature is useful when analyzing the sensitivity of forests to climatic warming along such gradients.

5. Results

A uniform 2 °C increase from baseline levels was selected as an example of climatic warming. The temperature pattern was assumed to remain unchanged. That is, both the winter and summer temperatures were assumed to rise by 2 °C. The growth response to the possible climatic warming was calculated in the following way.

The baseline growth rate G_b was determined for any combination of $\bar{T}$ and σ, first by computing *ETS* from Equation (3) and then by using Equation (2) to convert the obtained *ETS* value to an approximation of the growth rate. The new growth rate after the climatic warming, G_n, was computed in the same way after adding 2 °C to the baseline temperatures. Absolute increase in growth was computed as $G_n - G_b$, and the relative increase in growth as $100\,(G_n - G_b)/\,G_b$.

Growth increase, absolute and relative, was expressed as a function of the annual mean temperature $\bar{T}$ and the degree of continentality σ. Within Finland, $\bar{T} = +4.5$ °C represents a southern area of the boreal zone and $\bar{T} = -1.0$ °C a northern area. Similarly, $\sigma = 8.0$ °C represents a maritime site and $\sigma = 13.0$ °C a continental site (Heino and Hellsten, 1983). The maritime extreme is located in

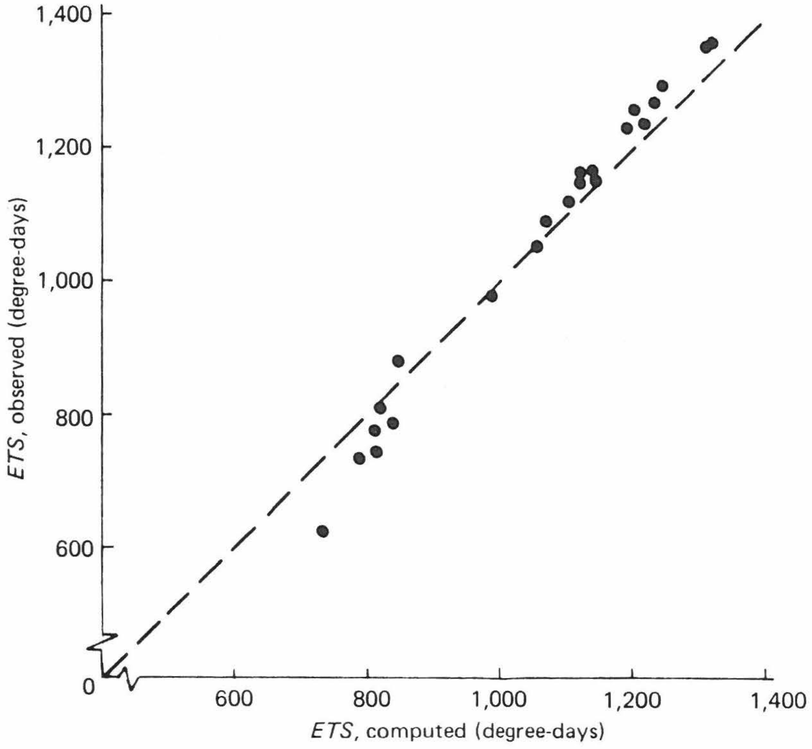

Fig. 3. Calculated and observed values of the effective temperature sum.

southern Finland and the continental extreme in northwestern Finland. Within these ranges the maximum increase of growth, in absolute terms, would occur in southern-central and maritime ecosystems (Figure 4). The relative increase of growth would not have a specific maximum because the baseline growth rate G_b is zero in northern areas. However, given a constant σ, the relative increase of growth would be the largest in northern (cold) regions (Figure 5). In the same way, given a constant annual mean temperature $\bar{T}$, the relative response would be largest in maritime regions. These qualitative results were tested and found valid in the range of temperature increases from 0.1 to 5 °C.

6. Discussion

The response of an ecosystem is jointly determined by the *action* and by the *reaction*. The results of Figures 4 and 5 essentially describe the reaction, i.e. the sensitivity of areas to a possible climatic warming. General circulation models indicate that a CO_2 warming would not be evenly distributed over the whole land surface (e.g. Manabe and Stouffer, 1980). Therefore a highly sensitive region may not give a high response without an associated large warming. This can be demonstrated with an example. Figures 4 and 5 indicate that coastal

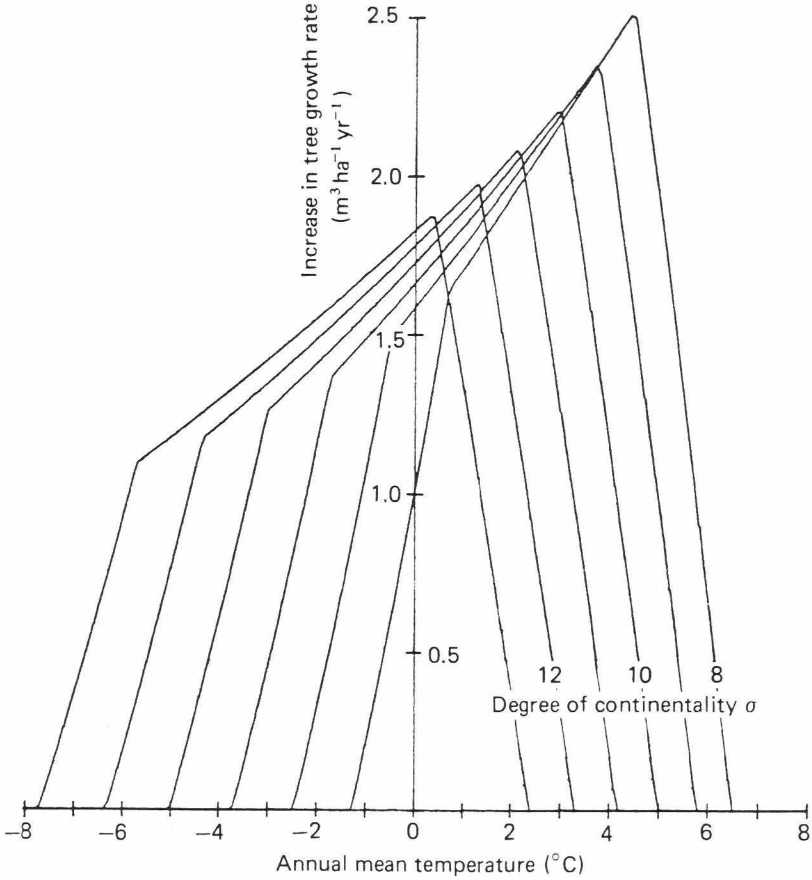

Fig. 4. Calculated growth response to the given +2 °C climatic warming as a function of the annual mean temperature $\bar{T}$ and the degree of continentality σ.

ecosystems would be especially sensitive to climatic warming. However, the possible warming in these areas may well be small compared with that in continental areas, and might therefore induce only a moderate response in these highly sensitive ecosystems.

The analysis in this study includes several sources of uncertainty. The selected productivity variables describe only some aspects of the real life of the boreal biome. They do not take into account, for example, the species composition of the ecosystems. Climatic warming might force many species of the boreal zone into extinction. Even the gaining species might not respond in the manner extrapolated from Figure 1 in the case of a rapid change to a warmer climate. The calculated growth responses, both absolute and relative, are likely to be overestimated because adaptation to a new climate takes time.

All data used in the analysis are from Finland, and we are certain of their accuracy. However, although Finland clearly belongs to the boreal zone, it covers only about 5% of the entire zone, so that not all conditions in the zone are

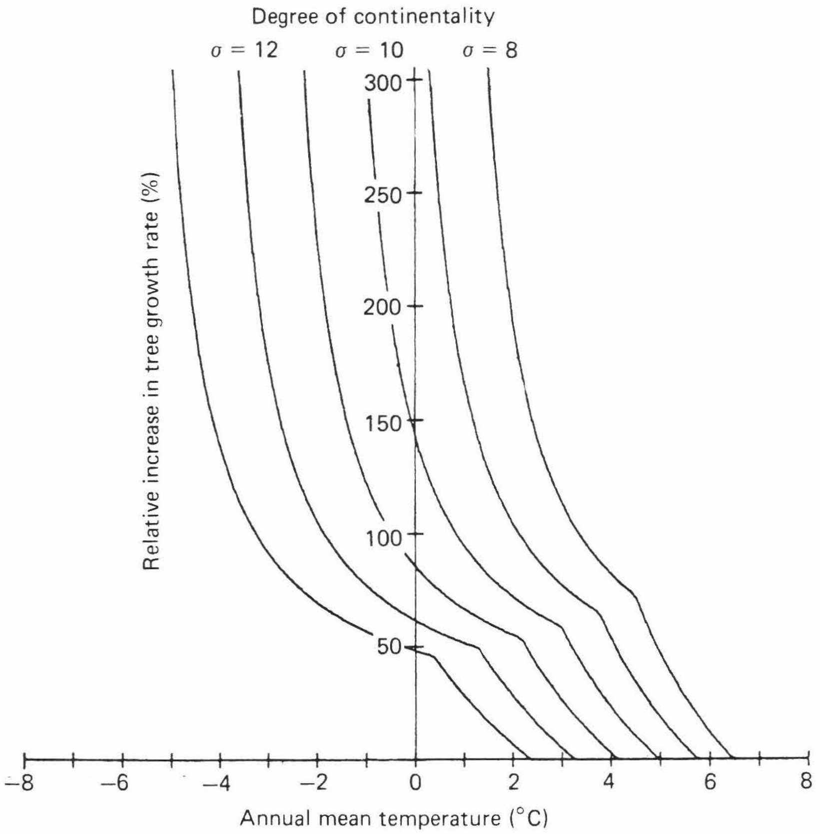

Fig. 5. As in Figure 4, but with the increase in growth rate expressed in relative terms.

adequately represented by the data. In particular, the continental extremes are not represented.

The method relies heavily on the relationship of Equation (2), which converts *ETS* values into approximate growth rates. Different regressions might be needed for other areas with different plant species, soils, and land management practices. The assumption of constant growth with high-*ETS* conditions may need reexamination. However, the qualitative findings of this study should remain the same for a range of similar growth functions.

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ESTIMATED BIORESOURCE SENSITIVITY TO CLIMATIC CHANGE IN ALBERTA, CANADA

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Abstract. An index of dry-matter productivity is used to assess the sensitivity of bioresources in Alberta, western Canada, to changes in the thermal and precipitation regimes, particularly to climatic warming. Results suggest that warming would improve productivity in northern Alberta, but reduce it, because of the associated increased moisture stress, in the relatively warm, dry southeastern part of the province. Estimated productivity generally increased with precipitation regardless of location or temperature. Warming induced by CO_2 quadrupling would apparently give a net increase of about 18% in bioresource productivity for the province, and CO_2 doubling would lead to a 16% increase. However, the bioclimate would be changed much more than this might suggest. For CO_2 quadrupling, Alberta would acquire a thermal regime similar to that of present-day Nebraska, some 2,000 km to the southeast. Also, the increase in productivity of plants due to the effects of CO_2 on photosynthesis might be much larger than the climate-related effects. Climate impact assessment in Canada is made especially challenging by the shortness of the period of instrumental record, the relatively high degree of sensitivity to climatic change, and the sparseness of the station network, particularly in the most sensitive areas.

1. Introduction

Canadian agriculture as a whole is quite sensitive to climatic variability, particularly in northern marginal areas. In the prairie region, which includes a major part of Canada's agricultural land, both temperature and moisture inadequacy are important, and in the drier areas wind erosion can also be a serious problem, compounding the effects of dry periods. It is estimated that droughts in the period 1929–38 caused losses in Canadian prairie wheat production totaling over $2 billion in terms of today's technology and prices, and that droughts during 1957–68 caused similar losses (Williams, 1983a).

Major nonclimatic constraints to Canadian agriculture include land-use conflicts in the most favored agroclimatic areas, such as urban expansion on to agricultural land, and soil constraints in the north, largely a result of soil removal by glaciation in prehistoric times.

To some extent, climatic and soil constraints can be expected to result in a 'no-win' situation for Canada in the case of climatic change. For instance, cooling of, say, 1 °C might reduce the area where wheat can be grown by one-third (Williams and Oakes, 1978). However, because of the soil constraints, climatic warming could not be expected to extend the limits of agriculture northwards significantly in Canada. Furthermore, productivity farther south could be reduced by increased moisture stress due to warming, unless warming were accompanied by significant increases in precipitation, and the literature does

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not give much hope for this, at least for CO_2-induced warming (Manabe *et al.*, 1981). Nevertheless, warming would probably permit northward extension of crops like winter wheat (in place of the lower-yielding spring wheat) and corn, which might balance the adverse effects of warming. In the northernmost agricultural areas it certainly appears that warming would benefit agriculture, but these areas would include only a small portion of Canada's agricultural land.

It would be desirable to have long periods of climatic record to provide the basis for analyzing the frequency of various climatic occurrences or conditions. This may be particularly so in the case of temperature, for which more severe conditions probably occurred between one and four centuries ago than in the past century. Unfortunately, the period of instrumental record goes back less than 100 years for most Canadian locations. Another problem in Canada is that, with population spread so thinly over such a large area, it has not been possible to develop climatological networks that give adequate spatial representation for mapping agricultural potential, especially in northern marginal areas.

Previous estimations of the likely effects of various climatic scenarios in Canada (Williams, 1975; Baier *et al.*, 1976) generally made use of either large-area weather-based crop yield equations (Williams, 1969, 1970; Williams *et al.*, 1975), which tended to reflect mainly moisture-related effects, or temperature-related agroclimatic resource mapping techniques (Williams and Oakes, 1978; Williams *et al.*, 1980). However, instead of approaches that permit the assessment of only one component at a time, it is preferable to employ methods that reflect both moisture and temperature effects, particularly in an area like the Canadian prairies, where both the moisture and temperature limitations are pronounced.

In a recent research study on assessing climate for ecological land classification, methods were employed that reflected both the heliothermic and the precipitation effects (Williams and Masterton, 1983). One of the sets of procedures used in that study involved calculations for the climatic index of agricultural potential (*CA*) described by Turc and Lecerf (1972), who mapped *CA* for France. *CA* has also been mapped for Mozambique (Barreto and Soares, 1974). This index was intended to reflect total harvestable dry-matter production, and was found to have a good correlation at a global scale with indices developed by other authors for forest production and for natural vegetation (Turc and Lecerf, 1972). *CA* was also found by its authors to relate well to dry-matter productivity of forages, maize, and other agricultural crops.

In Canada, *CA* was computed and applied (Williams and Masterton, 1983) with climate data that had been derived, assuming 1931–60 normals, for the 110 intersections of whole-degree latitudes and longitudes in the province of Alberta (which lies between 49° and 60° N and 110° and 120° W). The climatic estimates for these points had been computed using spatial climatic modeling techniques. *CA* is composed of a heliothermic and a dryness factor, and it was found in the Alberta study that these components could be quite useful for differentiating ecoregions. Analyses of variance of *CA* and of annual sums of the heliothermic and dryness factors (Williams and Masterton, 1983) indicated that each of these differed significantly from one class to another among a dozen ecological land classes (e.g. short grass, fescue, dry boreal mixed wood, boreal uplands, etc.). Pending more detailed quantitative studies, these results provide at least an initial indication of the applicability of *CA* in Alberta.

For the present study the derived climate data were modified and *CA* and its components were recalculated to simulate the effects of various climatic scenarios on the bioresources of Alberta.

2. Methods

2.1. The Climatic Index of Agricultural Potential (CA)

For each month, calculations are made with the monthly climatic normals as follows (Turc and Lecerf, 1972):

(1) Calculate how much irrigation water would be needed (*Bi*) if the soil moisture deficit (*SMD*) were to be overcome (*Bi* = 'besoin en eau d'irrigation'):

(a) calculate *SMD1* (after the first month *SMD1* is the value of *SMD2* from the previous month); in any given month *SMD1* and *SMD2* are the initial and final values;

(b) calculate $Y = SMD1 + ETP - P$, where *ETP* is evapotranspiration, determined as explained by Turc and Lecerf, and *P* is normal total precipitation for the month. (For the present purpose it was decided to use Turc and Lecerf's own methods for calculating *ETP*, rather than an alternative formula that had been used by Williams and Masterton (1983).)

(c) compare with $SMD_{\max}$, the assumed maximum soil moisture deficit, i.e. the soil moisture-holding capacity. A value of 70 mm was used, corresponding to 100 mm capacity in work where actual monthly values for each of a number of years were being used rather than climatic normals as was the case here (Turc and Lecerf, 1972).

If $Y > SMD_{\max}$, then $Bi = Y - SMD_{\max}$ and $SMD2 = SMD_{\max}$.
If $Y < SMD_{\max}$ and $Y > 0$, then $Bi = 0$ and $SMD2 = Y$.
If $Y < SMD_{\max}$ and $Y < 0$, then $Bi = 0$ and $SMD2 = 0$.

(2) Calculate the dryness factor *Fs* ('facteur sécheresse'):

(a) calculate the carryover *Ca* ($-1 \leq Ca \leq 0$; *Ca* is nonzero only in very dry conditions);

(b) calculate *X*, where *X* is *ETP* or $(0.3ETP + 50)$, whichever is smaller;

(c) let *Xbc* represent $(X - Bi)/X + Ca$.

If $Xbc \geq 0$, then $Fs = Xbc$
(and the carryover to the next month is then zero).

If $Xbc < 0$, then $Fs = 0$, and the carryover to the next month is *Xbc* if *Xbc* is between 0 and -1; otherwise, the carryover to the next month is -1.

(Note: If there are no irrigation needs then Bi and Ca are both zero, and $Xbc = 1$ (no dryness). The product of the moisture and heliothermic factors, $HT \cdot Fs$, in this case would be $HT \cdot 1 = HT$.)

(3) Calculate the solar (helio-) factor Fh:

Fh is the smaller of : $H - 5 - (La/40)^2$ and $0.03Ig - 3$, where

H = length of day (hours per day)
La = latitude (degrees)
Ig = global radiation (langleys per day).

(4) Calculate the thermal factor Ft:

Given

t = normal mean temperature (°C) and
m = normal mean daily minimum (°C),

then when m is between 1 and 5,

$Ft = [t(60-t)/1000](m-1)/4$,

while

if $m > 5$, m is arbitrarily set to 5, and
if $m < 1$, m is arbitrarily set to 1, making $Ft = 0$, in which case the product $HT \cdot Fs$ will become zero also.

(5) Calculate HT, the heliothermic factor for the month:

$HT = Ft \cdot Fh$.

(6) Calculate the monthly product $HT \cdot Fs$.

(7) Obtain this product for each of the 12 months and sum the products to obtain the overall annual value, CA. In practice it is convenient to go through the computations using the climatic normals from January to December and then to go through a second time, so that an $SMD1$ term and Ca, if appropriate, can be obtained for January from the December data from the first set of calculations.

2.2. Applying CA to Assessing Climatic Change Impacts for Alberta

Estimated impacts for various climatic scenario values of the index CA, and also 12-month sums of HT and of Fs, were computed for each of the 110 points of intersection of whole-degree latitudes and longitudes in Alberta. Normals for 1931–60 that had been generated by spatial–climatic estimation procedures (Williams and Masterton, 1983) were employed for these calculations. These climatic normals were then modified by adding a positive or negative adjustment to temperatures to simulate warmer or cooler climatic conditions, and by taking a percentage to simulate more (>100%) or less (<100%) precipitation. The CA, HT, and Fs values were recomputed and the results compared with the results based on normals to estimate the impacts. To estimate impacts for the province as a whole, values of *CA* for all 110 points were averaged.

A graph depicting latitude–time distributions of the difference in continental zonal mean surface air temperature between 4 × and 1 × CO_2 scenarios was consulted (Manabe and Stouffer, 1979, figure 2; 1980, figure 16c). The Manabe and Stouffer results were used in order to be consistent with several other studies undertaken in preparation for the meeting in Villach, Austria, in September 1983, on climate impacts in cold marginal areas. For the purposes of the present investigation, it appeared that this scenario would be as good as any of the others available at the time.

To represent Alberta for this study, the latitude 55° N was selected, and a temperature scenario was abstracted from the latitude–time graph. The use of a single latitude simplifed the calculations, and it was considered that the spatial precision of the climatic model would probably not be such that the extra effort in using more latitudinal detail within the province would be justified. The latitude–time graph for the continents was used rather than the geographical distributions (Manabe and Stouffer, 1980, figure 23), because the latter maps showed only the annual differences and those for the winter and summer seasons, the data were not provided for spring and autumn or for individual months, and the maps were highly generalized. In future studies the grid data might be obtained from the modelers.

Use of this temperature scenario for 4 × CO_2 involved adding the abstracted amounts to the monthly temperature normals. It should be kept in mind that these increments are differences between 'statistical equilibrium states' obtained from the climatic model after repeated iterations for 1 × CO_2 and 4 × CO_2 (Manabe and Stouffer, 1980), and that the 1 × CO_2 values might differ significantly from the normals. The monthly increments (in °C) were:

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
7.7	7.0	8.3	8.5	6.8	5.2	4.2	4.2	4.9	6.0	6.1	7.3

For the 2 × CO_2 scenario, these temperature increments were halved, e.g. 3.5 was added to February temperature normals. This procedure is somewhat controversial, but is in keeping with the contention by Manabe *et al.* (1981) that 'the change of atmospheric temperature due to a CO_2-doubling is about half as large as the corresponding change due to a CO_2-quadrupling and the distributions of these changes are very similar to one another.'

Although a considerable amount has been written on the likely soil moisture impacts of increasing atmospheric carbon dioxide (Manabe and Stouffer, 1980; Manabe *et al.*, 1981), there seems to be little guidance on the likely changes to be expected in month-to-month precipitation *per se*. Manabe and Stouffer (1980) do indicate an increase in precipitation at the latitude of Alberta, and they suggest a global increase of 6.7% in the 'intensity of the hydrologic cycle', but there is no distinction between continents and oceans, or between different months. Increasing the precipitation by 10% would generally seem to cover the likely increases based on their global estimates and on their graphed distribution of precipitation increases according to latitude; and reducing precipitation by 10% would provide an idea of the possible effects if precipitation were decreased to the east of the Rocky Mountains in conjunction with a CO_2-induced climatic change. For the present study it was therefore decided to employ the derived temperature scenarios in combination with each of three assumed precipitation regimes: 90, 100, and 110% of normal.

3. Results and Discussion

3.1. Sensitivity to Climatic Changes in General

The results (Table I) indicate that increasing the temperature by the same specified amount for every month without changing the precipitation would increase productivity substantially in the coldest locations and reduce it somewhat in warm, dry locations, particularly at the higher-temperature increments. The overall effect for the province would be a modest increase in productivity. A lowering of the temperature would reduce productivity by a large proportion at the coldest locations but by fairly small amounts elsewhere.

Temperature decreases shorten the growing season, thus reducing productivity in all parts of the province. Temperature increases lengthen the growing season but also increase the moisture stress, resulting in a tendency to reduce productivity in the warmer, drier areas. One can say that a change to either a

TABLE I: Sensitivity of Biomass Productivity to Various Climatic Scenarios.[a]

			1931–60 Precipitation, × :				
			0.7	0.8	0.9	1.0	1.1
1931–60 Temp. (°C), +:	Point A 59°N, 116°W	−1	28	–	–	56	63
		0	61	74	85	100	120
		1	118	139	160	182	203
		2	154	185	216	246	277
		3	181	–	–	–	–
		4	115	–	–	344	389
	Point B 55°N, 119°W	−1	55	–	–	96	110
		0	59	72	85	100	115
		1	62	77	91	106	120
		2	59	74	90	105	120
		3	53	–	–	–	–
		4	50	–	–	99	115
	Point C 50°N, 110°W	−1	42	–	–	94	115
		0	44	65	82	100	122
		1	40	60	79	103	118
		2	31	50	70	89	109
		3	26	–	–	–	–
		4	24	–	–	90	111
	Alberta as a whole	−1	52	–	–	92	104
		0	56	71	85	100	114
		1	60	76	92	108	123
		2	63	80	97	114	131
		3	63	–	–	–	–
		4	61	–	–	117	136

[a] Productivity as percentage of that for no change.

cooler or a considerably warmer climate would adversely affect biomass productivity in the latter areas.

The estimated effects of changing precipitation (Table I) emphasize that this is clearly a region of limited moisture. For the province as a whole and for each of the sample points and temperature combinations (Table I), estimated productivity increased with each precipitation increment throughout the range considered here (70 to 110% of normal).

The tabulated results can be used to examine the effects of various combinations of change of temperature and precipitation. For example, a 2 °C warming of the climate for every month, coupled with precipitation reduced to 80% of normal, resulted in an estimated 20% reduction of biomass productivity (from 100% to 80%, Table I) for Alberta as a whole. At an unusually cold point in the province (point A, Figure 1) this scenario *increased* estimated productivity by 85%, while at a warm, dry location (C) it *reduced* estimated productivity by 50%.

3.2. Sensitivity to CO_2-Induced Climatic Warming

At the very cold location (point A), the 4 × CO_2 scenario (Table II) resulted in a three- or fourfold increase in estimated biomass productivity: 335% for 0.9 of normal precipitation and over 400% for the 1.1 × normal precipitation scenario. This reflects the overriding effect of the temperature constraint there. Moving to warmer, drier parts of the province, the effect of the increased moisture stress associated with warming becomes quite significant. At point C, the warming scenario if accompanied by a one-tenth reduction in precipitation could be expected to cause a 35% decrease in biomass production, and the warming would need to be accompanied by a precipitation increase if productivity levels were to be maintained. For the province as a whole, the warming scenario would be expected to increase biomass productivity by 18% if precipitation were unchanged. Estimated productivity was reduced slightly when precipitation was decreased by one-tenth.

Doubling CO_2 generally resulted in smaller impacts at any particular point, with the increase in biomass less in the north than with 4 × CO_2, and the decrease less in the south, but for the province overall the impacts were only slightly smaller for 2 × CO_2 than for 4 × CO_2.

An indication of the likely movement of boundaries that would be computed on the basis of the CO_2-induced warming scenarios was given by examining the *HT* summations. Before warming, the annual *HT* sums in Alberta ranged from zero in alpine areas to nearly 29 in the short-grass zone (Figure 2). For comparison with a tropical country, in Mozambique the annual *HT* varies from 88 to 135 (Barreto and Soares, 1974). The *HT* = 28 line initially encompassed only a small portion of southeastern Alberta, but with 4 × CO_2 warming it was estimated that most of the province would have *HT* sums higher than 28 (Figure 3). Even with 2 × CO_2 warming, a very large proportion of the province would have *HT* sums above 28. Before warming, only three of the 110 points had *HT* sums above 28, while after 4 × CO_2 warming, only seven of the points had heliothermic sums below 28. This would appear comparable to changing the thermal climate of Alberta to one more like that of Nebraska, some 2,000 km to the southeast in the midwestern United States. With 2 × CO_2 warming, just over one-third of the points had *HT* sums below 28.

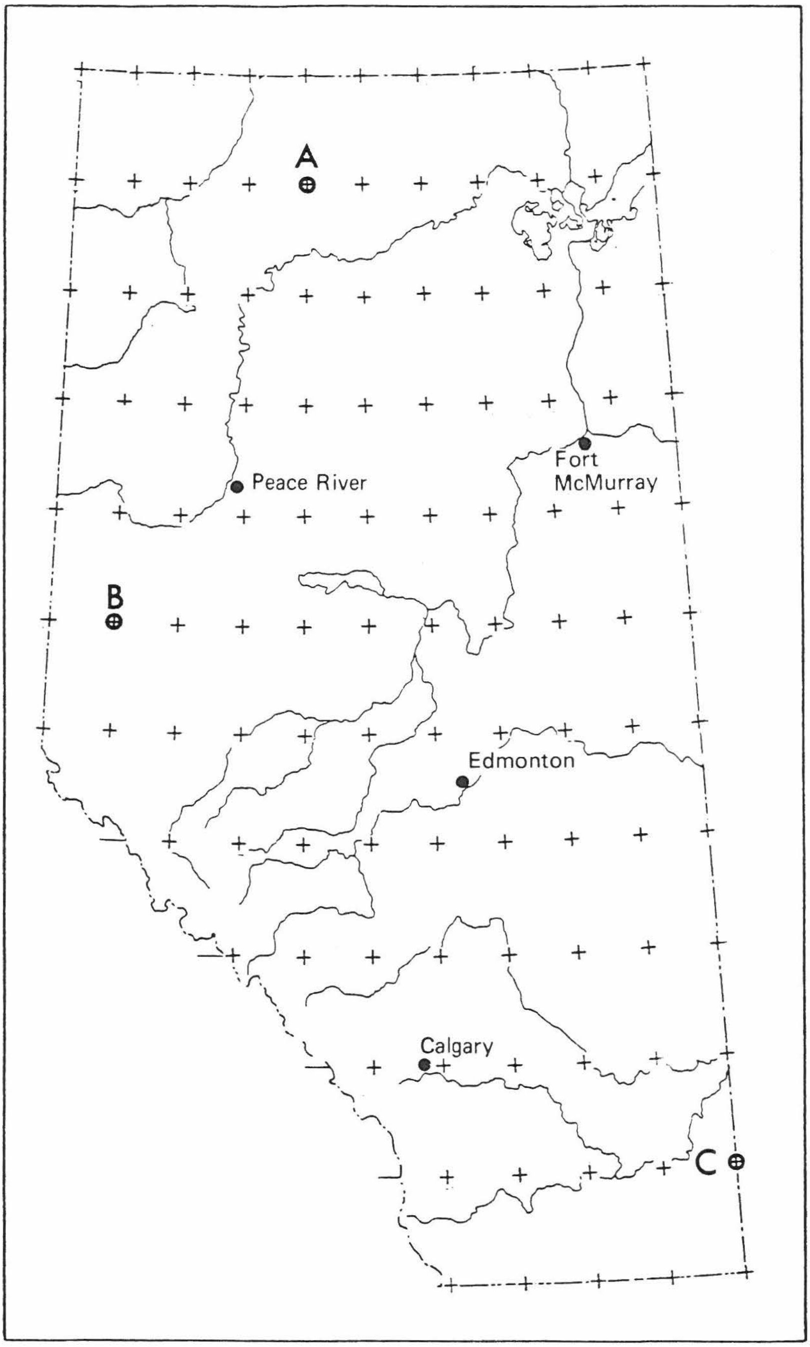

Fig. 1. Map of Alberta, showing grid system and example points.

TABLE II: Sensitivity of Biomass Productivity to CO_2-Induced Climatic Warming.[a]

Temperature scenario:[b]			$2 \times CO_2$			$4 \times CO_2$		
Precipitation, x :			0.9	1.0	1.1	0.9	1.0	1.1
Location								
A	59° N	116° W	247	280	314	335	384	434
B	55° N	119° W	86	102	117	94	112	130
C	50° N	110° W	77	98	120	65	92	120
Alberta as a whole			99	116	133	98	118	138
Alberta as a whole, including direct CO_2 effects			132	154	178			

[a] Productivity as a percentage of that for $1 \times CO_2$, computed using Turc's index.

[b] For $4 \times CO_2$, temperatures increased for each month as follows (Jan.–Dec.):

7.7 7.0 8.3 8.5 6.8 5.2 4.2 4.2 4.9 6.0 6.1 7.3

For $2 \times CO_2$, these increments were halved.

Climatic changes such as those computed here for the CO_2 warming scenarios would have major implications for provincial agriculture and forestry. However, given the present degree of uncertainty concerning the various climatic change possibilities, the more important result of this analysis is probably the very fact that it has demonstrated a method for estimating impacts. It has shown how output from a climate model in a very simple form can be taken and used to derive estimates of the effects on biomass productivity and agriculture of the scenario represented by the climate model output. As other scenarios become available, similar methods can be used to estimate the likely impacts on agriculture of such changed climates.

In practice the impact would probably be felt as a change in the frequency of adverse events (e.g. crop failures). At the cold margins, warming would probably decrease this frequency. However, because of the paucity of climatological stations, particularly in northern marginal areas, spatial climatic modeling is needed to generate the required climate data. Spatial climatic modeling refers to procedures for estimating climatic patterns over a region where the climatological network is sparse and does not adequately represent the region's climate. These procedures may employ equations for estimating temperature normals at any point in a region from latitude, longitude, and altitude, as was the case in the Alberta ecoclimatic study (Williams and Masterton, 1983). As is typical in such applications, these equations had been derived using existing climatological normals and were applied in estimating normals as required, in this case for each of the 110 points in Alberta. It would have been far beyond the scope of the present study, and the previous one (Williams and Masterton, 1983), to have attempted to derive equations for estimating frequencies of climatic events.

Canada lacks a history of significant length of how the system adapts, but it seems likely that farmers will gradually change their practices in response to environmental changes. For example, if the climate warms in the Peace River region of Canada, which is at the northwestern margin of Canadian agriculture, the number of hectares of wheat there could be expected to increase. If it

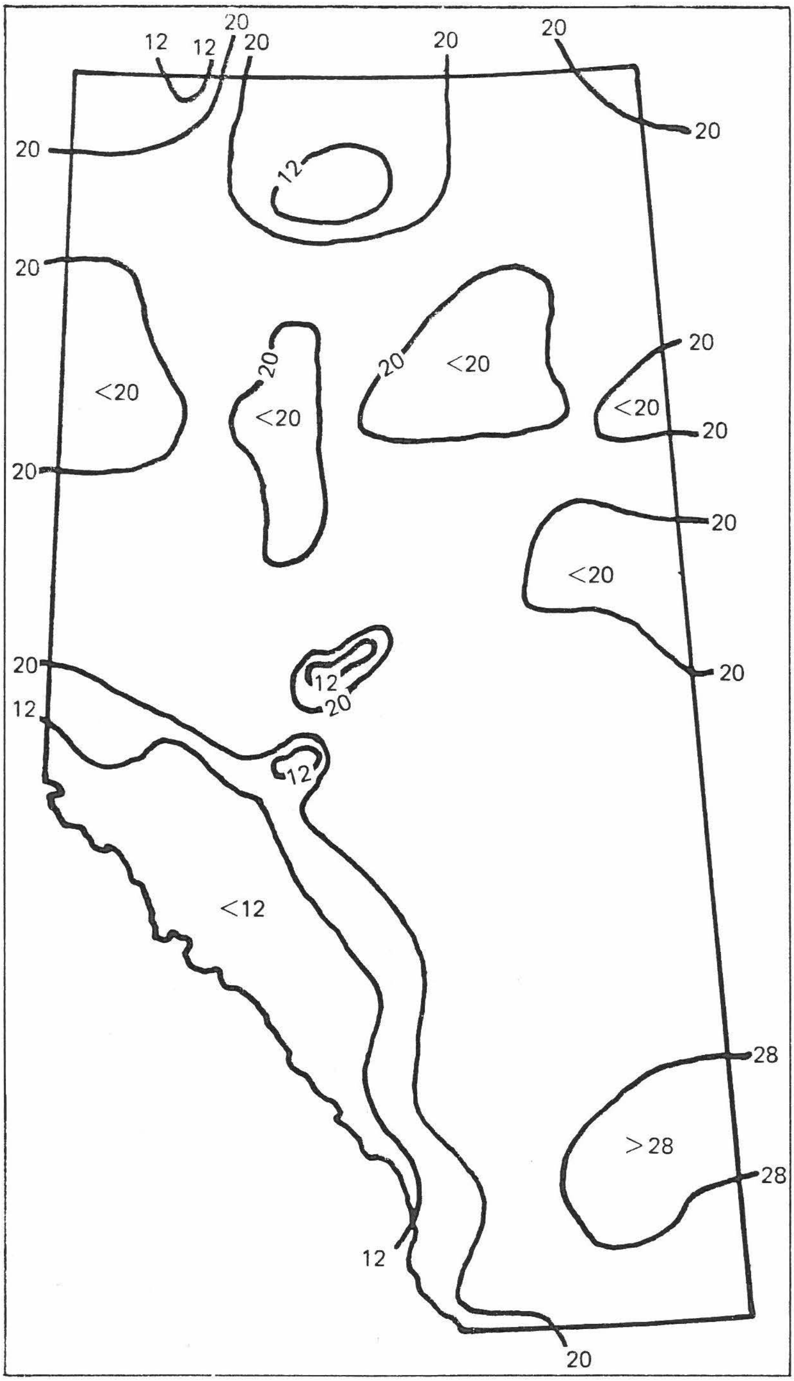

Fig. 2. Heliothermic factor (ΣHT) for Alberta for a 1 × CO_2 scenario.

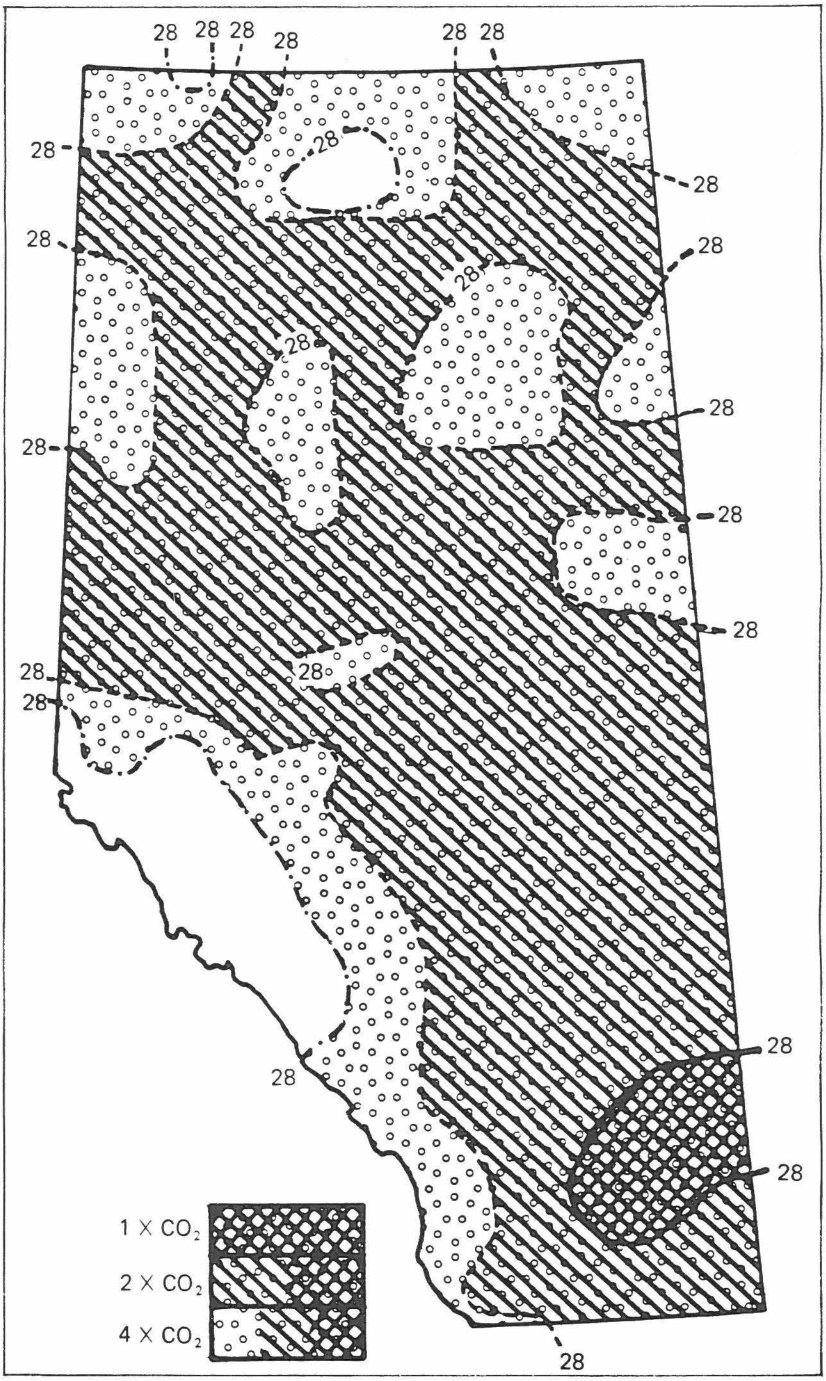

Fig. 3. Areas of Alberta with $\Sigma\ HT > 28$ for three CO_2 scenarios.

became cooler, there would probably be shifts to hardier or faster-maturing crops like barley, and forage seed crops. In Canada's case it should be kept in mind that the northern margin is often a soils limit, as much of our northern land had most of its soil removed by glaciation. Alberta is somewhat of an exception to this but, in general, climatic warming might not expand Canada's agricultural land area significantly, whereas cooling could significantly reduce the area.

In any practical application of results computed in regard to what the agroclimatic impact of, say, CO_2 doubling would be, attention would also need to be given to the direct, nonclimatic effects. It has been suggested that the direct effect of CO_2 doubling might be expected to increase agricultural productivity by 33% (Kimball, 1983). As a first approximation one could assume that the combined effect of a 16% increase due to warming and 33% due to the direct effect would be the same as if the warming increase came first and then the 33% was applied to the new, warm-climate productivity, or vice versa. In either case one multiplies $1.16 \cdot 1.33 \cdot 100$ to obtain 154% (Table II), i.e. a 54% increase in biomass productivity for Alberta with CO_2 doubling and no change in precipitation. The 33% direct-effect increase is a general figure, not specific to Alberta, so it can be expected to apply equally as well to the warmer conditions indicated by the CO_2 doubling scenario as to the present climatic conditions in Alberta.

4. Suggestions for Further Research

It should be possible to compute actual shifts in boundaries fairly readily. It was found elsewhere that a graph with the heliothermic factor plotted against the dryness factor could be quite useful in helping to define ecoregions (Williams and Masterton, 1983). One could produce such a plot based on a 'normal' climate, and then repeat it with a specified climatic change scenario, and examine the 'before' and 'after' positions of each geographical location on this plot. This would enable one to determine the shift in ecoregion boundaries with a fair degree of objectivity. Subjective judgment would be required in cases where the identification of the ecoregion from climate data could be ambiguous.

It would probably be worth while to try to integrate climatic and economic scenarios in assessing likely changes in geographical distributions of crops. The economic aspects might be dealt with using methods such as those of Lozano (1968), who used income–population potential for the economic side of his analysis and determined how margins for various crops in 48 states of the U.S.A. depended on either economics or climate or both. Income–population potential is described by a functional relationship, and increases with population, income, and proximity to that population. For a given geographical location, the potential is high if there is a center with a large population and high average income near that location.

For each of a number of different important crops, models need to be adapted or developed to enable one to estimate likely impacts on the crops, given the climatic conditions. In the case of Alberta, models for wheat, barley, and oilseed crops would be of particular interest. For example, results from models indicating the suitability of the climate for bringing the crop to maturity have been mapped for Canada for wheat and for barley (Williams and Oakes, 1978). Such models relate to specific crops, and often to particular aspects, in this case to the ability to reach maturity, rather than to biological productivity in general. Maps and tabulations should then be prepared that show the likely impacts in agroclimatically sensitive areas for each of the crops. Examples of models for several crops that could be used in such climate impact studies include those that Dumanski and Stewart (1981) employed in mapping crop production potentials for five important crops in Canada.

To give some general guidance in the meantime, analyses for agriculture as a whole should be carried out using techniques such as Turc's index of agricultural potential, or the agroclimatic resource index mapped elsewhere for Canada (Williams, 1983b). It is important that these methods permit the investigation of moisture and heliothermic effects both in combination (as with *CA*) and separately (as with *Fs* and *HT*).

Even if one believes that CO_2-induced warming of W degrees is most likely, one still would like to have a range of possibilities to consider (something like that in the Crop Yields and Climate Change study by the U.S. National Defense University, 1980). For example, if warming were considered most likely, there might still be a 10% chance of cooling, and society should be prepared to insure itself against the risks associated with such cooling, as well as with warming. Scientists in relevant disciplines should be prepared to try to estimate the various probabilities and the associated impacts. A comment by the late E.F. Schumacher (McRobie, 1981) about the development of 'appropriate technology' could equally well apply to the question of coping with climatic change. He said:

> Look, even the most wonderfully designed ocean steamer carries lifeboats, not because some statistician has predicted that the steamer will run into an iceberg, but because icebergs have occasionally been seen. Isn't it time that the modern world provided some lifeboats?

For some parts of the world one can analyze long series of records and develop frequencies on the basis of station data. This approach is not very practical in Canada, because the records are not long, and because techniques for overcoming the lack of station representativeness are more applicable to deriving normals than frequencies. In the long run, perhaps on the basis of proxy data, we need to develop frequencies for natural climatic conditions and then use these as a base on which to superimpose effects such as CO_2-induced warming, volcanic-dust-induced cooling, etc., to obtain modified frequencies reflecting such events. These climatic frequencies then need to be translated, by impact models, into likely effects on Canada's bioresources, including estimated crop limits and agricultural and forest productivity. The climate and impact studies need to be integrated, with continuing dialogue between researchers in the two fields, so that the impact analyses are based on scenarios that are as realistic as possible and the climatic scenarios provide information that is as relevant as possible to bioresource productivity.

Comprehensive further research on climatic change impacts on agriculture should be pursued from a perspective that considers that there is a whole spectrum of possible agricultural intensities, from oil palm and paddy rice at one end, through to the polar margins for cereals and beyond. For example, moderate climatic cooling in Canada's Peace River region (represented by point B in Figure 1) might not eliminate agriculture; it might simply result in a shift completely out of wheat, and perhaps out of barley and oilseeds as well, and into more concentration on forage and forage seed production. Where the crop intensity becomes so low that it is not worth the human effort of harvesting it, it may still be harvested by grazing animals. Warming might be expected to result in expanded wheat production in the Peace River region, the movement of winter wheat and maize production northwards from the U.S.A. into the more southerly parts of Alberta, and expansion of the cattle-ranching, short-grass area in the southeastern part of the province.

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THE USE OF GENERAL CIRCULATION MODELS IN CLIMATE IMPACT ANALYSIS – A PRELIMINARY STUDY OF THE IMPACTS OF A CO_2- INDUCED CLIMATIC CHANGE ON WEST EUROPEAN AGRICULTURE

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Abstract. An investigation is made of the possible impacts of a climatic change (induced by a doubling of atmospheric carbon dioxide concentration) on the European agricultural sector. Two general circulation models have been used to develop climatic change scenarios for the European study area. From the scenarios, information was obtained concerning the possible behavior of temperature, precipitation, solar radiation, and relative humidity in the altered climatic state. This meteorological information was then employed in two separate crop–weather models – an empirical/statistical model (for winter wheat) and a simple simulation model (for biomass potential). This type of approach represents a considerable departure from that employed by previous large-scale climate impact studies. Both the seasonal and regional components of a possible climatic change are incorporated directly in the two crop–weather models. The results of this investigation demonstrate that a simple crop–weather simulation model may be more suitable for the purposes of agricultural impact analysis than the linear regression models frequently used in such studies. In order for such an impact analysis to be accepted as a valid scientific experiment, a full presentation of the underlying assumptions and uncertainties is essential.

1. Introduction

During the last ten years, several major studies have attempted to assess the possible effects of a defined climatic change on managed agricultural systems. Certain of these investigations have considered specific forcing factors, such as increasing atmospheric carbon dioxide (National Academy of Sciences, 1983) or stratospheric transport systems (the CIAP study: U.S. Department of Transportation, 1975). Other studies have not looked at specific forcing factors, and have treated climatic change within such general terms as a 'large global cooling' or 'large global warming' (National Defense University, 1980).

The starting point for all of the above-mentioned impact analyses is provided by a climatic change scenario. This may be defined as a description of the spatial patterns and seasonal behavior of temperature, precipitation, and other important meteorological variables in an altered climatic state. It is important to add the qualification that a scenario offers an educated guess as to the physical nature of a future climatic state, and not a prediction of what will occur.

This somewhat subjective definition implies that previous impact studies have not really dealt with climate scenarios, since they have neglected the regional and seasonal aspects of a potential climatic change. Thus, the climatic change has often been treated as uniform over a large geographical area, and as though it acts by means of increases or decreases in annual average values of

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temperature and precipitation. However, it is just such regional and seasonal details that are of particular interest to the impact analyst operating in the agricultural sector. This particular investigation represents a first attempt to incorporate the regional and seasonal components of a climatic change in the impact analysis. This is achieved by coupling two climatic change scenarios, derived from general circulation models, with two separate crop–weather models.

The historical background to this project requires a brief description. The results discussed here comprise only one section in a larger investigation, entitled The Socio-Economic Impacts of Climatic Changes due to a Doubling of Atmospheric CO_2 Content, which commenced in 1981. Its first aim was to assess the possible effects of a doubling of atmospheric CO_2 levels on the climate of Western Europe, and to define one or more climatic change scenarios. The second major objective involved the use of such scenarios in an evaluation of the potential impacts on the European sectors of agriculture, water resources, and energy (in terms of both energy demand and the supply of energy from renewable resources). The project was completed in January 1984, and for a more comprehensive description of objectives, methodology, and results, reference should be made to Meinl *et al.*(1984).

The first of the following sections deals with the selection of the climatic change scenarios. Section 3 is concerned with the selection of the crop–weather models, a brief consideration of their structure, and a description of the methods employed in coupling the models with the scenario climate data. The final section presents and analyzes the climate scenarios and the results produced by the crop–weather models.

2. Selecting Climatic Change Scenarios

Three major techniques are available for the development of climatic change scenarios; each makes use of a different source of information.

In the first technique, instrumental data (i.e. data that have been measured in the past for selected climate variables) are used to describe extreme warm or cold years or periods that have occurred during the time span for which instrumental records are available. Such extreme historical situations may be treated as analogs for a future altered climatic state. This type of approach has been adopted by Lough *et al.* (1983) and Palutikof *et al.* (1984) in a recent analysis of the possible impacts of a climatic change (induced by increasing atmospheric CO_2) on West European agriculture and energy demand.

A second method for the construction of climate scenarios involves the use of paleoclimate data. This may be defined as indirect or proxy information, which predates the period of direct instrumental measurement of temperature, precipitation, atmospheric pressure, and other meteorological variables. Such data can be obtained from tree rings, ice cores, pollen analysis, archeological data, and a variety of additional sources (Wigley *et al.*, 1981). Flohn (1980) and Kellogg (1983; Kellogg and Schware, 1981) have analyzed paleoclimate data for preinstrumental warm periods, searching for clues to the possible behavior of climate in a future warm state.

Numerical models form the basis of the third technique employed in the development of climatic change scenarios. The models used in scenario construction are generally two- or three-dimensional in their representation of the radiative and dynamic processes in the atmosphere; the most complex are the three-dimensional atmospheric general circulation models. Many atmospheric GCMs have been coupled with ocean models of varying complexity. The coupled ocean model/atmospheric GCM has then been referred to as a 'climate model'. Strictly, the use of the term 'climate model' should be reserved for models in which the atmosphere is capable of at least limited interaction with the ocean (i.e. AGCMs with climatological sea surface temperatures are not climate models). Climate models generally limit their treatment of the climate system to the atmosphere and ocean, and most are not coupled with either the land cryosphere or the biosphere.

Schlesinger (1983, 1984b) provides thorough reviews of the structure and capabilities of all the model types mentioned above, and of the results obtained with them during perturbation experiments (i.e. a doubling or quadrupling of atmospheric CO_2). These reviews are extremely useful for the scientist approaching the CO_2 problem from the perspective of the impact analyst.

For the specific purpose of developing climatic change scenarios, the use of each type of information – instrumental or paleoclimate data, and numerical model results – entails certain advantages and disadvantages. It is not the intention here to provide an assessment of the relative merits of each technique. This issue has been treated in more detail elsewhere (e.g. Pittock and Salinger, 1982). However, it must be pointed out that the specific advantages and disadvantages of these methods are very strongly linked to the nature of the questions posed in the initial stages of the investigation. In this instance, the problem under consideration was to assess the possible climatic response to a *doubling* of atmospheric CO_2 levels, and the likely impacts of such changes in a West European study area. The use of results from GCM experiments seemed most relevant for answering this particular question. This decision can be criticized on many grounds, given the justifiable concern about:

- GCM performance in representing present-day climate;
- uncertainties regarding the modeling of very basic atmospheric feedback processes (e.g. Hunt, 1981);
- the spatial and temporal resolution of GCM results;
- weaknesses in the modeling of the ocean, and the neglect of some cryospheric and biospheric components of the climate system.

However, criticism of the suitability of GCMs for use in impact studies often occurs on an almost intuitive level, and remains undifferentiated rather than focusing on specific points. One major objective of this investigation was to provide just that specificity – that is, to make an objective assessment of the performance and limitations of two GCMs when used for the purposes of impact analysis. This was viewed as the primary aim, and the generation of yield change forecasts assumed secondary importance. It is hoped that a study of the difficulties involved in coupling GCM results with crop–weather models will provide the basis for a more productive dialogue between general circulation modelers and climate impact analysts (Gates, 1984).

For the purposes of this project, results were obtained from perturbation experiments that had been performed with different GCMs. Research institutes that have provided model results include the British Meteorological Office (Bracknell), the Geophysical Fluid Dynamics Laboratory (Princeton), the Goddard Institute for Space Studies (New York), the National Center for Atmospheric Research (Boulder), and Oregon State University (Corvallis). Bach *et al.* (1984) then compared the temperature and precipitation results produced by individual models.

Further analyses conducted by Bach and co-workers involved statistical significance testing of the GCM results, and the examination of model performance in simulating the features of present-day climate. All comparisons, significance testing, and verification studies were performed for the West European study area (20°W to 20° E and 30 to 70° N), using a 4° latitude by 5° longitude reference grid. By transferring simulated data to such a reference grid, it was possible to compare results produced by models with different spatial resolutions. The choice of the grid spacing was influenced by the fact that the observed climate data (Schutz and Gates, 1971, 1972) were expressed on a 4° latitude × 5° longitude reference grid.

On the basis of this preliminary investigation, two GCMs were selected for use in the impact analysis – a model developed at the British Meteorological Office (hereinafter referred to as the BMO model) and one developed at the Goddard Institute for Space Studies (the GISS model). The BMO model has a 5-layer atmospheric GCM, and a climatological ocean with prescribed sea surface temperatures, upon which a latitudinally unvarying +2 K increment is superimposed in the CO_2 doubling experiment. The model structure and experiments performed with it have been described by Mitchell (1983) and Corby *et al.* (1977). It is not a climate model (in the sense of the definition given earlier), since the ocean does not interact with the atmospheric GCM. The GISS model consists of a 9-layer atmospheric GCM (referred to as Model II in Hansen *et al.*, 1983) coupled with an interactive, mixed-layer ocean (maximum depth 65 m), and hence qualifies as a climate model. The physics of the model are described in Hansen *et al.* (1983, 1984).

Other GCMs could have been selected for the subsequent impact analysis, but it is important to stress that the BMO and GISS models fulfilled two prerequisites that were specified during the statement of the initial problem:

- the model should have been used in a CO_2 doubling experiment; and
- it should be capable of simulating seasonal changes in climatic variables, which are more important for agricultural impact analysis than changes in annual means (and the variables considered should include temperature, precipitation, solar radiation, and relative humidity).

3. The Crop–Weather Models

The selection of the two crop–weather models used in the impact analysis was to some extent dictated by the spatial resolution of the GISS and BMO climate models. The BMO model has a grid length of approximately 330 km, whereas the GISS model uses a grid spacing of 8° latitude by 10° longitude. Given this resolution, there would have been little justification for conducting an impact analysis at the level of an individual European country. In order to make maximum use of the meteorological information available in the two climatic change scenarios (i.e. to accentuate the differences in the climatic change projected for different European areas), it was decided that the impact analysis should focus on the whole of the European Community.

This decision imposed some constraints on the selection of crop–weather models, as did model availability. The two models that eventually were chosen typified two fundamentally different approaches – empirical/statistical and simple simulation modeling. Almost all previous impact studies with comparable objectives have concentrated exclusively on the empirical/statistical approach (using linear regression models), often devoting little attention to the statistical problems associated with the use of such models (Haigh, 1977; Katz, 1979).

In this study we sought to analyze possible statistical problems inherent in the linear regression approach, and to make a critical examination of the performance of a simple simulation model. Again (as for the case of the GCM selection and scenario development), it must be stressed that the aim was the evaluation of basic methodological problems associated with the use of such crop–weather models, and not simply the generation of yield change statistics.

The empirical/statistical model chosen was developed by Hanus for predicting yields of winter wheat, and is described in detail in an investigation conducted by Hanus (1978) for the European Community. It consists of a series of linear regression equations, for each of 42 European meteorological stations, using data for the seven months from January to July only. Each equation expresses an empirical relationship (derived using 20–30 years of yield and meteorological data) between nationally averaged winter wheat yield and the following predictor variables:

- mean monthly temperature
- mean monthly maximum temperature
- mean monthly minimum temperature
- total monthly precipitation
- time (the year is incorporated in each regression equation as a variable in order to describe the yield trend).

For the Federal Republic of Germany, the Hanus model has been validated with independent yield data over the period 1968–83, and produced an average error of the estimate over this period of less than 5% (Hanus, private communication). The model has not been validated with independent yield data for other European countries.

The simulation model employed in the impact analysis was developed by Briggs (1983) during the course of the European Ecological Mapping Project. The model was designed with the objective of evaluating the 'biomass potential' of the European Community – that is, the potential for producing energy from plant biomass. Since the concept of 'biomass potential plays an important role in the subsequent discussion of results, it is useful to present the definition of this term given by Briggs (1983):

> The potential annual above-ground biomass production (as expressed, for example, in kg/ha/yr) by a standard crop under constant management conditions. This definition is adopted to avoid the short-term effects of differences in soil management procedures (e.g. in fertilizer practice, irrigation, pesticide usage) and cropping practice, and the

longer-term effects of differences in age, successional status, or environmental stability of the existing vegetation cover.

Thus 'biomass potential' is an abstract concept, expressing the theoretically achievable biomass production of a uniform reference crop (in this case, a mixed-species grass sward) under the specific climatic and edaphic conditions prevailing in a given area (Figure 1).

It should be emphasized that the Briggs model was not developed for the particular purposes of impact analysis. The use of the model in such a specific context has certain disadvantages. Briefly, these can be summarized as:

- validation difficulties, due to the somewhat abstract nature of biomass potential, and the use of a grass reference crop;
- simplifications and empiricisms incorporated in the actual structure of the model.

These issues are considered in detail elsewhere (Meinl *et al.*, 1984), but are important enough to deserve some mention here.

One problem encountered in the validation of the Briggs model relates to the difference between theoretically achievable 'biomass potential' and the biomass production actually attained. Such discrepancies are due to the neglect of specific factors in the model – i.e. inputs of fertilizers, the effect of irrigation, and the influence of pests and diseases. The use of grass as a reference crop provides another explanation for possible discrepancies between actual biomass production and 'biomass potential'. Europe is not covered uniformly by a grass reference crop, thus making model validation difficult in areas where a mixed-species sward does not occur. Briggs (1983) has attempted to validate the model in England and Wales, using data on grass yields at experimental sites. However, a rigorous validation of the model in other areas of the European Community has not been performed.

The major structural simplifications in the model relate to the calculation of actual and potential evapotranspiration, the estimation of available soil water capacity, the neglect of Hortonian overland flow and rainfall interception by the vegetation cover, and the assumption of a 5°C threshold for the initiation of grass growth. The major model empiricism involves the use of a Lieth–Box net primary productivity equation to convert 'effective evapotranspiration' to biomass potential.

This picture must be balanced by mentioning two of the advantages that the Briggs model offers the impact analyst. Firstly, it considers differences in the edaphic environment (in terms of available soil water capacity) throughout the European study area. In other words, the capacity of a given area of land to produce plant biomass is an explicit function of both soil and climatic characteristics. In contrast, areal differences in soil characteristics are only implicitly considered in the Hanus model.

Secondly, it would have been beyond the time and financial constraints of this project to attempt to use simulation models for a whole range of vegetation types and/or crops (even if such models had been available). As Briggs (1983) points out, the use of a reference crop is defensible on the grounds that:

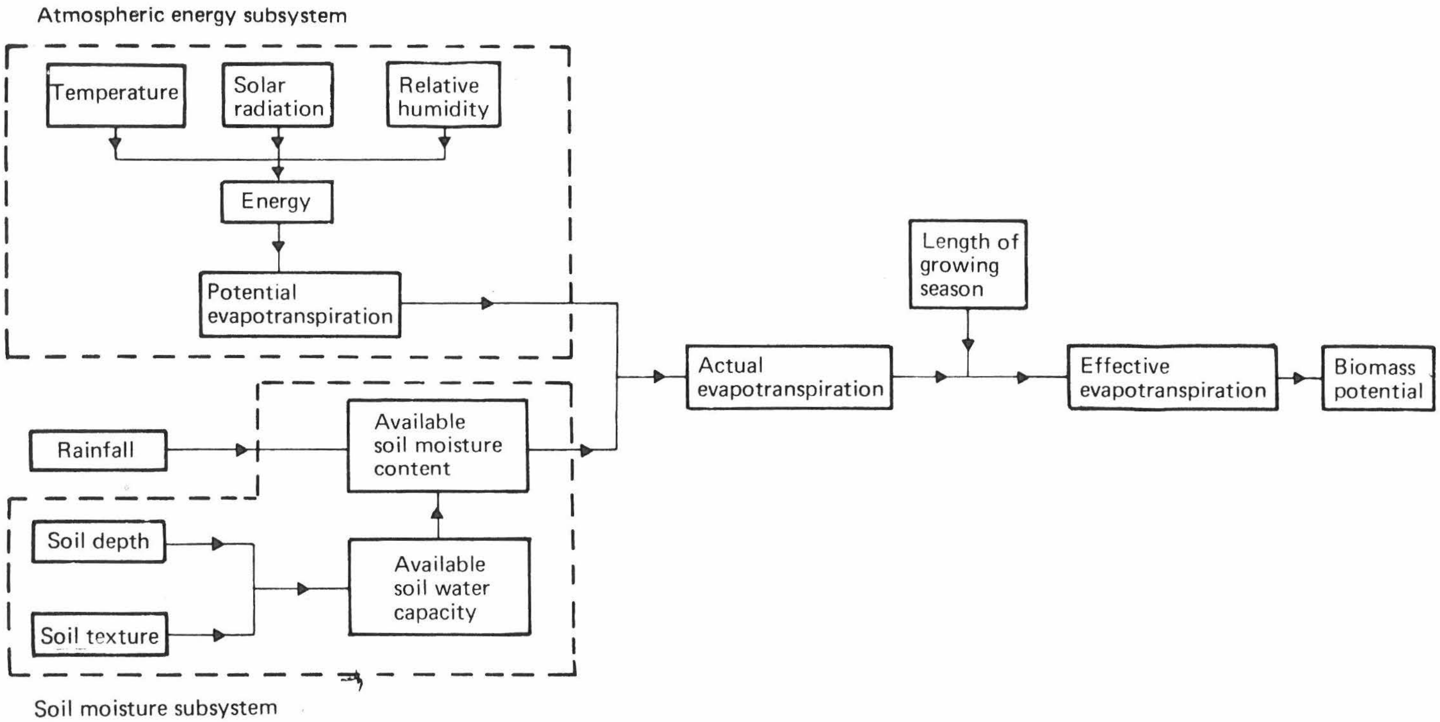

Fig. 1. Chief components of the Briggs model (after Briggs, 1983).

> Grass has a relatively long growing season, and thus its overall demands on water and energy supplies are high compared to other shallow-rooting crops with shorter growing seasons; this means that its growth potential provides a good general index of the capacity for biomass production – a reasonable correlation might be expected in most cases between the potential for grass growth and that for other crops.

Both the Briggs and Hanus models had data requirements that could be fulfilled by the two GCM-derived climatic change scenarios, with the exception of the net solar radiation information required by the Briggs model. To overcome this problem, net solar radiation was calculated with a model employing mean monthly data for temperature, relative humidity, and cloud coverage (Bach *et al.*, 1984). The degree of cloud coverage was taken from the model results of the GISS experiment and the climatological data of the BMO experiment.

In the case of the Briggs model, monthly mean data relating to temperature, precipitation, relative humidity, and net solar radiation were then interpolated from the GISS and BMO grid points to the 233 meteorological stations used by Briggs. The interpolation process made no attempt to take into account station elevation and situation relative to mountain ranges (e.g. windward or leeward). This seemed justifiable, given that both GCMs (and indeed all GCMs) introduce simplifications in their treatment of the orographic characteristics of the Earth's surface. These simplifications include the averaging of fine-scale topographical information (such as the 1° Scripps topography or 1° Berkofsky and Bertoni topography) over the area of model grid-boxes (Rowntree, 1978; Hansen *et al.*, 1983). Obviously, the averaging of topography may obscure climatic details that are important for impact considerations (and also complicates the comparison of observed climate data with data from model runs).

In a similar procedure, and with similar simplifications, monthly mean temperature and precipitation data (for January–July, the seven months used in the Hanus model) were interpolated from the GISS and BMO grid points to the 42 meteorological stations in the Hanus model. The Hanus model, as has been stated above, makes use of mean monthly maximum and minimum temperature. Since neither GCM was capable of providing this type of information, it was assumed that the relationship between maximum, minimum, and mean monthly temperature, as expressed in the observed climate data used by Hanus, remained unchanged in the altered climatic state.

The impact analyses with the two crop–weather models were carried out by Briggs and Coleman and by Hanus (Meinl *et al.*, 1984). Both were provided with the above-described interpolated meteorological information from the two control runs and two perturbed runs of the GISS and BMO GCMs (i.e. GISS 1 × CO_2, BMO 1 × CO_2; GISS 2 × CO_2, BMO 2 × CO_2). In the Hanus model, relative changes in temperature and precipitation (2 × CO_2 minus 1 × CO_2) were used directly in the regression equations in order to calculate changes in winter wheat yields. The Briggs model operated with absolute values of temperature, precipitation, relative humidity, and solar radiation – that is, the relative changes in these variables (2 × CO_2 minus 1 × CO_2) at each of the 233 stations were added to a set of observed climate data for these stations ('BIODATA'). These composite meteorological data sets were then used to calculate new absolute values of biomass potential.

In the assessment of the possible impacts of a CO_2-induced climatic change on European winter wheat yields and biomass potential, it was assumed that climate was the only factor changed; all other factors with the potential to influence wheat yields and biomass production were left unaltered. No attempt was made to incorporate the effects of future technological developments, possible changes in climatic variability, or the direct physiological effect of increasing CO_2 levels on plants. A further assumption was that atmospheric CO_2 levels doubled in a 'step-like' perturbation; i.e. the transient response of the climate system to a gradual CO_2 increase was not considered. These assumptions are treated in more detail in the final section; they are crucial to any assessment of the scientific value of the results of the impact analysis.

4. The General Circulation Models: The Results

In this section we examine the performance of the two GCMs used in the impact analysis – in terms of their ability to model the regional and seasonal features of present-day climate (in the European study area), and in terms of the results they produce in CO_2 perturbation experiments. *The GCMs under investigation were not developed for the specific purpose of being used in this type of impact analysis;* this also applies to other existing GCMs. GCMs are global, and not regional models. It is as unfair to focus on their simulation performance at the detailed regional level as it is to enlarge a photograph a thousand times and criticize the quality of the resulting print. However, such 'microscopic' analysis of model control-run performance and experimental results is essential if the impact analyst is to

- gain a better understanding of model limitations (in terms of data quality, temporal/spatial resolution, and the climate variables that can be treated); and
- make a precise specification of his or her data requirements to the climate modeler.

4.1. Model Verification: Annual Means and Seasonal Cycles

The first questions that the impact analyst must address are: How well does a model that is used to develop a climatic change scenario actually represent the existing climatic situation? Is the model capable of reflecting the regional patterns and seasonal cycles of temperature, precipitation, and other meteorological variables in the area of interest?

A model that cannot provide an accurate representation of even the large-scale features of the present climatic state may have definite limitations when it is used for impact analysis. An awareness of these limitations is essential if the results of the impact analysis are to be placed in the correct perspective.

Bach *et al.* (1984) have performed a verification of the annual mean temperature and precipitation rate distributions in the BMO and GISS control experiments, and give a full description of the procedures employed in verification and the verification results. Only the most important points pertaining to the verification procedure and results are discussed here. In the case of the BMO temperature data, the verification was performed for temperature at the 0.9σ layer (ca. 900 mbar) and not for surface temperature. Such an approach can be justified because the BMO model uses only one sample from the diurnal cycle of each simulated day (at 0.00 GMT). By comparing observed temperature (interpolated from the surface to the model's 0.9σ layer) with simulated temperature at the 0.9σ layer, the effect of the diurnal cycle was minimized. All other temperature and precipitation rate verifications were for surface values.

In the BMO control run, the model was integrated for 1,192 days, and the simulated temperature and precipitation results were obtained by averaging over the final three years of the integration (Mitchell, 1983). The corresponding results of the GISS model's 35-year control run were averaged over years 26–35 of the integration (Hansen *et al.*, 1984). The observed temperature data were taken from Schutz and Gates (1971, 1972); observed precipitation data were supplied by Jäger (1976).

From the perspective of the impact analyst, the most important results of the verification of simulated annual means can be summarized as follows. In terms of annual mean temperature, the differences between the present-day temperature distribution in the study area and the temperature distributions predicted by the BMO and GISS models are sometimes in the same range as the temperature changes predicted by most GCMs for a doubling of CO_2. Maximum observed/simulated differences range from +2 K to −2 K for the GISS model, and from 0 K to −4 K for the BMO model (Bach *et al.*, 1984; Santer, 1984).

Secondly (for both models, and for both temperature and precipitation), the sign of the difference between modeled and observed data varies throughout the study area – the differences do not simply represent an overall bias. Finally, it should be noted that both models show 'precipitation rate anomalies' (i.e. differences between measured and modeled data) of greater than 1 mm/day, which are by no means insignificant. For example, an examination of long-term observed climate data for stations in southern France (Müller, 1982) indicates that a precipitation rate anomaly of 1 mm/day represents an error of over 50% in the total annual average precipitation.

Additional verification studies of model seasonal cycles were performed specifically for this paper. Figures 2a and 2b show a comparison of observed and simulated seasonal cycles of temperature and precipitation, which has been carried out for two of the meteorological stations of the F.R.G. used in the Briggs model. Mean monthly data from the GISS and BMO control runs were filtered and interpolated to station coordinates (Bach *et al.*, 1984), and then compared with long-term monthly means for the period 1931–60 (Schirmer, 1977). Such comparisons were made for a number of stations throughout the study area, and the two stations chosen for use in Figures 2a and 2b show typical results.

Figures 2a and 2b illustrate that for Jever and Kahler Asten, the qualitative 'sense' of the temperature cycle is described reasonably well by the BMO and GISS simulations. One exception is the March temperature simulation by the BMO model, which shows temperature decreases from February to March, as opposed to the increase shown by observed data. This may be due to an increase in the easterly flow (at the 0.9σ layer) across large areas of Europe, which is simulated during each of the three winters in the control integration (Reed, 1984).

In absolute terms, there are substantial differences between observed and modeled temperatures (often greater than 5°C). In the case of the GISS model, one important factor in the explanation of such observed/simulated temperature discrepancies relates to the difference between actual station elevation and

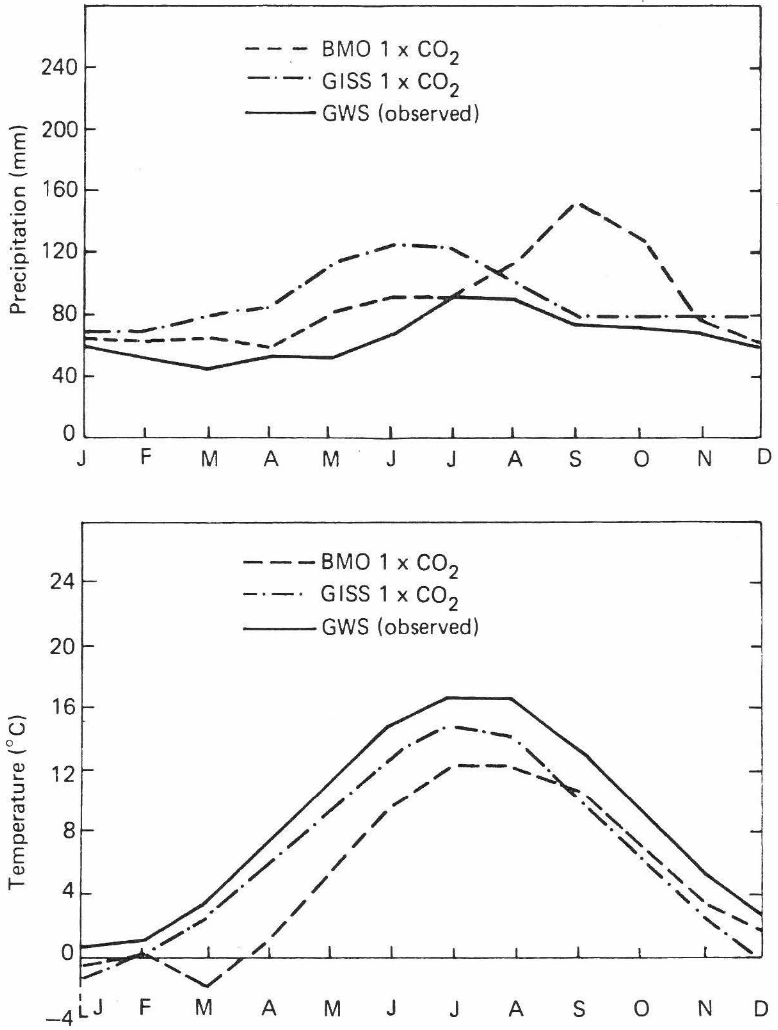

Fig. 2a. Jever, Federal Republic of Germany: temperature and precipitation differences between three meteorological data sets – BMO 1 × CO_2, GISS 1 × CO_2, and German Weather Service (measured data, 1931–60). Actual station elevation, 7 m.

the 'average' elevation of the model grid-box in which the station occurs. In the case of the BMO model, these discrepancies are largely dependent on the relationship between actual station height and the elevation of the model's 0.9σ layer (and, to a lesser extent, on the model's use of only one sample from the diurnal cycle).

In terms of simulating the annual precipitation cycle, neither model performs well – this applies both to the absolute values of precipitation, and to the qualitative 'sense' of the precipitation cycle. In some cases, the model data show

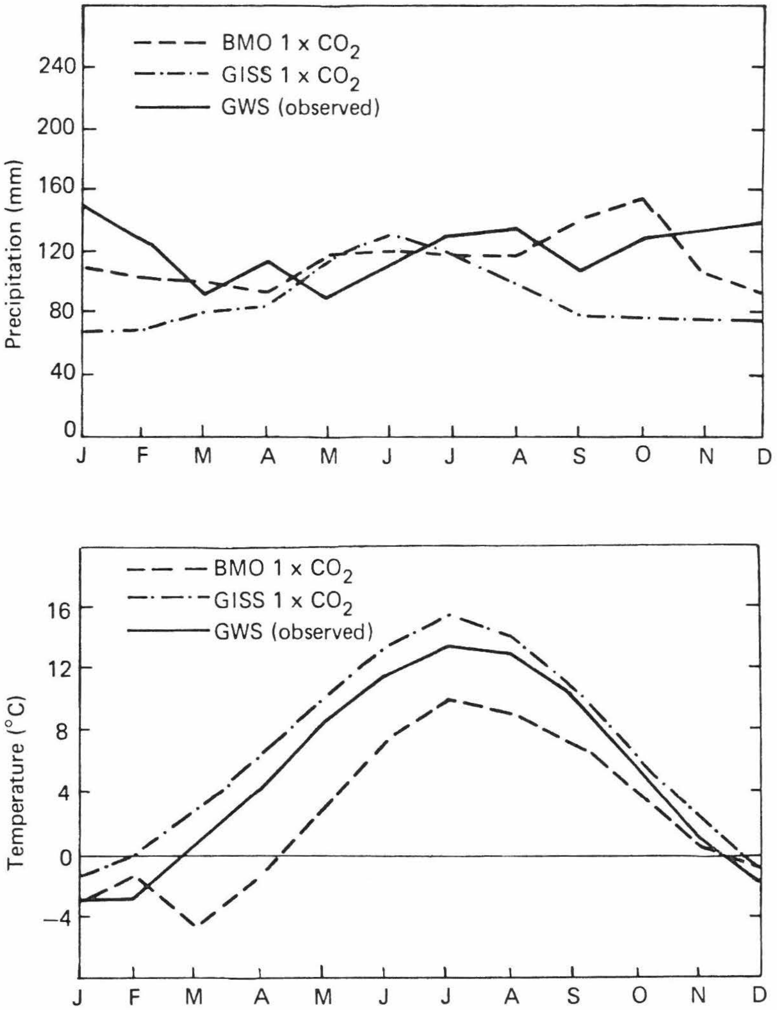

Fig. 2b. Kahler Asten, Federal Republic of Germany: temperature and precipitation differences between three meteorological data sets – BMO 1 × CO_2, GISS 1 × CO_2, and German Weather Service (measured data, 1931–60). Actual station elevation, 836m.

no similarity with the observed data, and some monthly values are in error by up to 100%.

Examination of the performance of the GISS and BMO models in simulating present-day annual means and seasonal cycles (of temperature and precipitation) raises a basic question. Can a comparison of the control runs of two (or more) GCMs be used to determine which of the models is more likely to produce 'believable' temperature and precipitation changes when the models are perturbed?

Clearly, an analysis of control-run performance alone does not supply sufficient information to answer the question of overall model reliability. In order to make any statement about the plausibility of model-predicted climatic changes, it is necessary to examine the structural differences between GCMs (i.e. how different models treat the ocean, clouds, sea ice, surface albedo, etc., and how they parameterize sub-grid-scale processes). However, it does seem that a good case can be made for closer examination of control-run performance, and for studies in which the control runs of different models are compared (e.g. Schlesinger, 1984a). Detailed intercomparisons of control runs against one or more standard sets of 'present-day' climate data may provide useful information – both from the modeler's viewpoint (diagnosing the climatic effect of structural differences between models) and from the impact analyst's perspective (evaluating the plausibility of climatic changes predicted by different models in perturbation experiments). The value of such a control-run intercomparison would be increased still further if the models also employed the same observed climate data sets for the specification of boundary conditions.

4.2. Model Scenarios: Relative Changes in Temperature and Precipitation for a Doubling of Atmospheric CO_2

The relative changes in temperature and precipitation ($2 \times CO_2$ minus $1 \times CO_2$) were determined for all four seasons, as well as for annual mean values, for both the BMO and GISS models (Bach *et al.*, 1984). The resulting scenarios differ markedly, and a full discussion of these differences is given in Bach *et al.* (1984) and Santer (1984). Only a few illustrative aspects are considered here.

From the perspective of the impact analyst, the most important difference between the two GCM-derived scenarios relates to the behavior of precipitation rate south of ca. 50° N. For major parts of this area, the BMO model shows a substantial decrease in the annual average precipitation rate. The decrease in precipitation rate is exhibited during all four seasons, and reaches its greatest magnitude in winter and summer (−1.2mm/day). The area experiencing a precipitation rate decrease reaches its greatest extent in winter.

A comparable decline in precipitation rate is not indicated by the GISS model; only small portions of the study area experience a slight decrease in precipitation rate (−0.2 mm/day) in winter and in summer. In terms of annual means, the GISS model predicts an increase in precipitation rate throughout the study area.

When the predicted temperature change is examined, the two scenarios are only broadly comparable. If the annual means are considered, the temperature response of the GISS model to a CO_2 doubling is approximately 1 K greater than that of the BMO model. On a seasonal basis, the temperature difference between the two models often exceeds this figure.

For the purposes of impact analysis, all of the above-described differences between the two scenarios are significant. Therefore, it might be expected that the agricultural impact analysis would produce two substantially different sets of answers when the two crop–weather models are coupled with meteorological information from the two GCM-derived scenarios. Whether this is the case is examined in the next section.

5. The Crop–Weather Models: The Results

5.1. The Hanus Model

The major results of the Hanus model are presented in Tables I and II. In Table I, the predicted increases or decreases in winter wheat yield (made using the BMO and GISS meteorological information) are expressed in terms of decitonnes/hectare; in Table II, these changes are converted to percentage changes in yield, relative to 1975–79 national averages. The results for each individual country represent an average of the results for all stations within that country. Before these results can be interpreted, it is necessary to provide some clarification of the meaning of these changes.

The 0.7 dt/ha increase in winter wheat yields that the Hanus model predicts for Ireland (Table I, BMO data) using the 'January' regression equations can be defined in the following way. If January temperature and precipitation (at the six Irish stations used in the Hanus model) changed by the amounts specified in the BMO scenario, the final yield of Irish winter wheat would increase by 0.7 dt/ha. The 'mean monthly yield change' for Ireland, as defined by Hanus (−0.6 dt/ha, BMO data) is simply the average of the yield change contributions over the period from January to July.

Thus the 'mean monthly yield changes' defined by Hanus incorporate three significant weaknesses:

- The calculation of each of the monthly yield change contributions (in Table I) is completely independent of temperature and precipitation changes in previous months. Thus, each monthly estimate of yield change has no 'memory' of how temperature and precipitation have affected the wheat crop in previous months.
- The yield change contributions are averaged over the growing season. In this averaging procedure, the effect of individual months with large positive or negative contributions is minimized drastically.
- Spatial patterns of climate are related to nationally averaged yields, rather than spatial patterns of yield. In such a spatial average, large positive and/or negative yield change contributions made by individual stations either are minimized or tend to cancel each other out.

For these reasons, it is suggested that the mean monthly yield change results presented in Tables I and II should be viewed as substantial underestimates of the yield changes (for winter wheat) likely to be produced in Western Europe by temperature and precipitation changes of the orders of magnitude expressed in the BMO and GISS scenarios.

Slightly less unrealistic estimates may be obtained by using a cumulative approach, and adding rather than averaging the individual yield change contributions. The 'cumulative yield changes' listed in Tables I and II still suffer from the first and third of the above-listed weaknesses (independence of monthly yield change estimates, and consideration of nationally averaged yields), but do give a greater weighting to large positive or negative yield change contributions than a simple averaging procedure.

TABLE I: Hanus Country Model: Calculation of 'Mean Monthly Yield Changes' and 'Cumulative Yield Changes' for Yields of Winter Wheat in Eight Countries of the European Community. (All Figures are in dt/ha.)

Country	Model	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Mean monthly yield change[a]	Cumulative yield change[b]
Ireland	BMO	0.7	−0.5	1.8	−1.7	−2.2	−0.9	−1.4	−0.6	−4.2
	GISS	1.0	−0.7	2.8	−3.5	−3.8	−1.7	−2.5	−1.2	−8.4
Denmark	BMO	5.6	4.0	4.9	5.1	−2.8	−4.3	−2.7	1.4	+9.8
	GISS	3.2	3.3	2.4	3.8	−4.8	−4.5	−2.8	0.1	+0.6
Netherlands	BMO	2.8	2.0	0.6	0.5	−1.8	0.3	−3.7	0.1	+0.7
	GISS	3.8	3.7	0.5	0.6	−3.0	0.4	−5.8	0.0	+0.2
Belgium	BMO	2.3	0.4	−1.5	−3.4	0.8	−4.9	1.8	−0.7	−4.5
	GISS	2.5	0.6	−1.3	−2.9	1.1	−6.2	3.0	−0.5	−3.2
Luxemburg	BMO	0.0	−0.2	2.4	0.7	−0.4	−1.8	1.7	0.3	+2.4
	GISS	0.0	−0.9	1.8	0.7	−0.5	−2.1	2.9	0.3	+1.9
France	BMO	0.8	−0.4	1.9	−1.9	−1.9	−4.0	1.3	−0.6	−4.2
	GISS	1.7	−1.5	1.3	−1.6	−2.6	−4.9	2.2	−0.8	−5.4
F.R.G.	BMO	1.8	−0.3	3.5	−1.5	−0.6	−2.8	−0.6	−0.1	−0.5
	GISS	1.9	−0.9	2.4	−1.2	−1.1	−3.7	−1.0	−0.5	−4.0
Italy	BMO	0.8	0.0	−1.0	−0.4	0.5	−1.0	0.9	0.0	−0.2
	GISS	1.5	0.0	−1.5	−0.6	0.7	−1.6	1.1	−0.1	−0.4

[a] Mean monthly yield change is defined as the average of the yield changes for each of the seven months.

[b] Cumulative yield change is defined as the sum of the yield changes in each of the seven months.

TABLE II: Hanus Country Model: 'Mean Monthly Yield Changes' and 'Cumulative Yield Changes' for Eight EC Countries, Expressed as Percentages of 1975–79 Average Yields.

Country	Average yield, wheat and spelt, 1975–79[a] (dt/ha)	BMO mean monthly yield changes (%)	GISS mean monthly yield changes (%)	BMO cumulative yield changes (%)	GISS cumulative yield changes (%)
Ireland	47.9	−1.25	−2.5	−8.8	−17.5
Denmark	52.5	+2.7	+0.2	+18.7	+1.1
Netherlands	58.2	+0.2	0.0	+1.2	+0.3
Belgium	47.2	−1.5	−1.1	−9.5	−6.8
Luxemburg	30.9	+1.0	+1.0	+7.8	+6.1
France	43.8	−1.4	−1.8	−9.6	−12.3
F.R.G.	46.6	−0.2	−1.1	−1.1	−8.6
Italy	25.8	0.0	−0.4	−0.8	−1.2

[a] All average yields are for winter wheat and spelt, except for Ireland, for which only wheat and spelt data were available.

Even using such 'cumulative yield change' estimates, the impact analyst faces problems in interpreting the results. When the temperature and precipitation coefficients employed in the regression equations are examined, they are often difficult to explain in terms of physical or biological climate–yield relationships. This is particularly evident in the case of the results for Italy and Ireland (Tables I and II).

In the case of the Italian cumulative yield changes, the results do not reflect the substantial precipitation rate differences that exist between the GISS and BMO scenarios. This lack of sensitivity is apparently a function of the small size of the precipitation coefficients in the Hanus regression equations. Multicollinearity (i.e. correlations between the observed series of temperature and precipitation data used by Hanus) may explain why the precipitation coefficients are often several orders of magnitude smaller than the temperature coefficients. The implication of this is that the effect of the predicted temperature change on winter wheat yields becomes exaggerated.

Similarly, the large predicted yield decreases in Ireland (which are primarily a result of the large negative temperature coefficients in the April–July regression equations) are difficult to understand. New absolute April–July temperatures in Ireland (i.e. values that take into account the temperature changes specified in the BMO and GISS scenarios) are not in a range likely to cause direct physiological damage to the winter wheat crop. There seems to be little physical basis for the predicted yield decreases.

A further problem is caused by the assumption of the nonlinearity of relationships between temperature, precipitation, and yield. It is unlikely that the Hanus model performs well in areas where the new absolute values of temperature and precipitation (i.e. the values after the specified climatic change) are close to 'thresholds of linearity'. The most important nonlinear effect in the present investigation probably involves relationships between high temperature (greater than 30 °C during the pre-harvest stage) and winter wheat yield in Italy and southern France.

These few examples illustrate why a simple linear regression approach may be fundamentally unsuitable for making any credible assessment of the impacts of climatic change on crop yield.

5.2. The Briggs Model

Figure 3 presents the most important results from the application of the Briggs model – the percentage changes in 'biomass potential'. These were determined using 'composite' meteorological information (BIO.GISS and BIO.BMO; see Section 2) to calculate biomass potential in the altered climatic state, and observed climate data (BIODATA; see Briggs, 1983) to calculate present-day biomass potential. The percentage changes at individual stations have been averaged in order to present percentage biomass potential changes per country. For simplicity, the discussion is confined to results obtained for the 50 mm available water capacity class; comparable results have been obtained for the other available water capacity classes employed in the Briggs model (infinity, and 250, 200, 150, 100, and 75 mm).

One result is immediately apparent. The BIO.GISS scenario projects that the average change in biomass potential – after a climatic change induced by a doubling of CO_2 – will be positive for all ten EC countries. In contrast, the BIO.BMO scenario projects that Italy and Greece will experience decreases in biomass production, and that France in particular will show a far smaller biomass increase than in the BIO.GISS scenario. These results appear to reflect the BMO

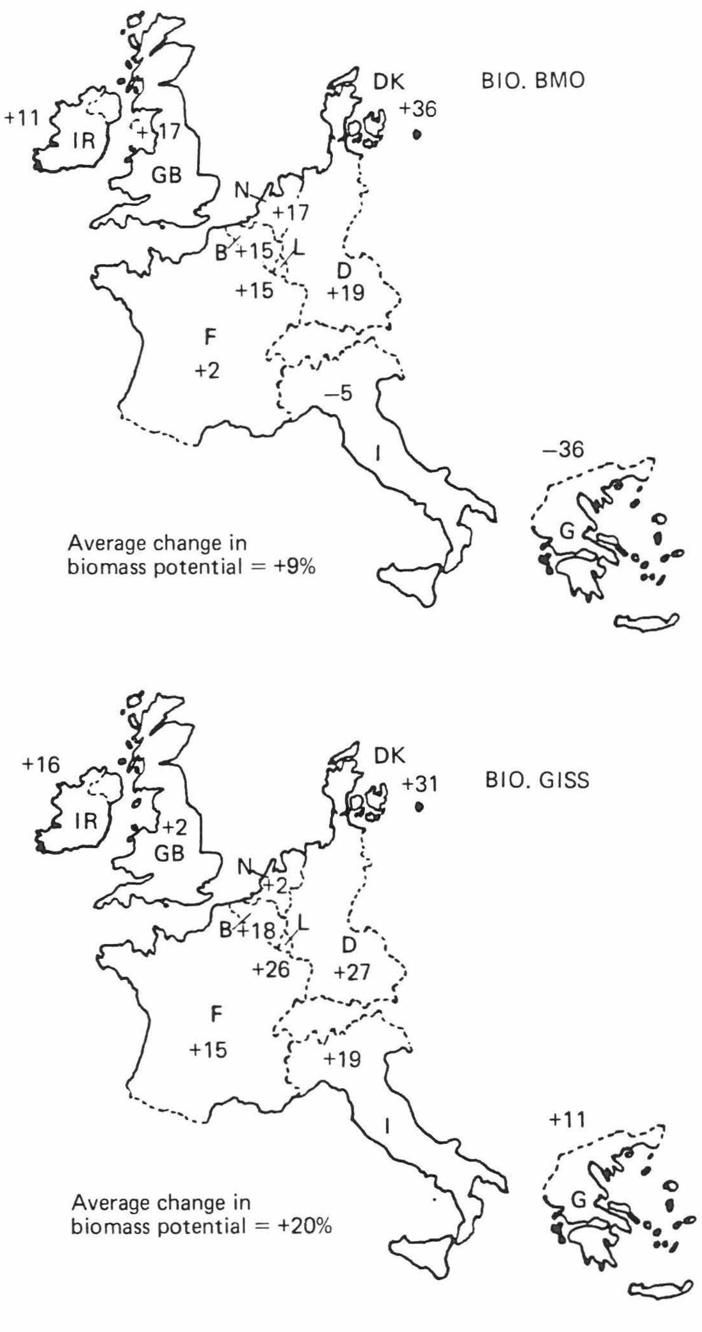

Fig. 3. The Briggs model: calculation of percentage changes in the average biomass potential of ten European countries, using meteorological information from the BIO.BMO and BIO.GISS scenarios.

model's predicted decrease in precipitation rate over Southern Europe.

Precipitation is not the only factor of importance in the explanation of percentage changes in biomass potential. This becomes evident in Figure 4, where the percentage changes in biomass potential are examined at the level of individual stations.

Figure 4 indicates that even in the BIO.BMO scenario (with its substantial decrease in precipitation rate over Italy), not all Italian stations exhibit a percentage decrease in biomass potential. Those stations located within the boundary of the 1000 m contour sometimes show percentage increases in biomass potential (or, in some cases, small decreases). Similarly, in the BIO.GISS scenario, the stations with the largest percentage increases in biomass potential are found above 1000 m. When the strength of the correlation between station elevation and percentage change in biomass potential is examined (for all Italian stations), the respective R_2 values for the BIO.BMO and BIO.GISS scenarios are 0.39 and 0.55.

One possible explanation of these results is that temperature acts as a more effective limit to biomass production than moisture stress at stations above 1000 m. This limit is imposed by direct low-temperature stress, and by a restriction in the length of the growing season. The large temperature increases in the BIO.GISS and BIO.BMO scenarios, particularly in the winter months, ameliorate low-temperature stress and increase the length of the growing season at high-elevation stations. This explains the high percentage increases in biomass potential predicted for stations above 1000 m.

The correlation between percentage increase in biomass potential and station elevation may be stronger for BIO.GISS data (0.55) than for BIO.BMO data (0.39) because the precipitation decrease in the BIO.BMO scenario also exerts an important effect on the magnitude of the change in biomass potential. In other words, the final change in biomass potential is a function of how both temperature and precipitation change at any individual station. Therefore, in the BIO.BMO scenario, the positive influence of a temperature increase (at stations above 1000 m) is counteracted by the decline in precipitation rate. Since the BIO.GISS scenario has no comparable precipitation decrease, the relationship between elevation and percentage change in biomass potential is more marked.

For a more detailed analysis of the Briggs results, reference should be made to Meinl *et al.* (1984). However, even from the brief discussion given above, it is evident that:

- In order to understand the estimated changes in biomass potential, it is necessary to examine how current biomass production is limited by either temperature or moisture stress (or by a combination of these factors).
- A simple simulation model, may provide the impact analyst with results that have more basis in physical reality than the results of linear regression models.

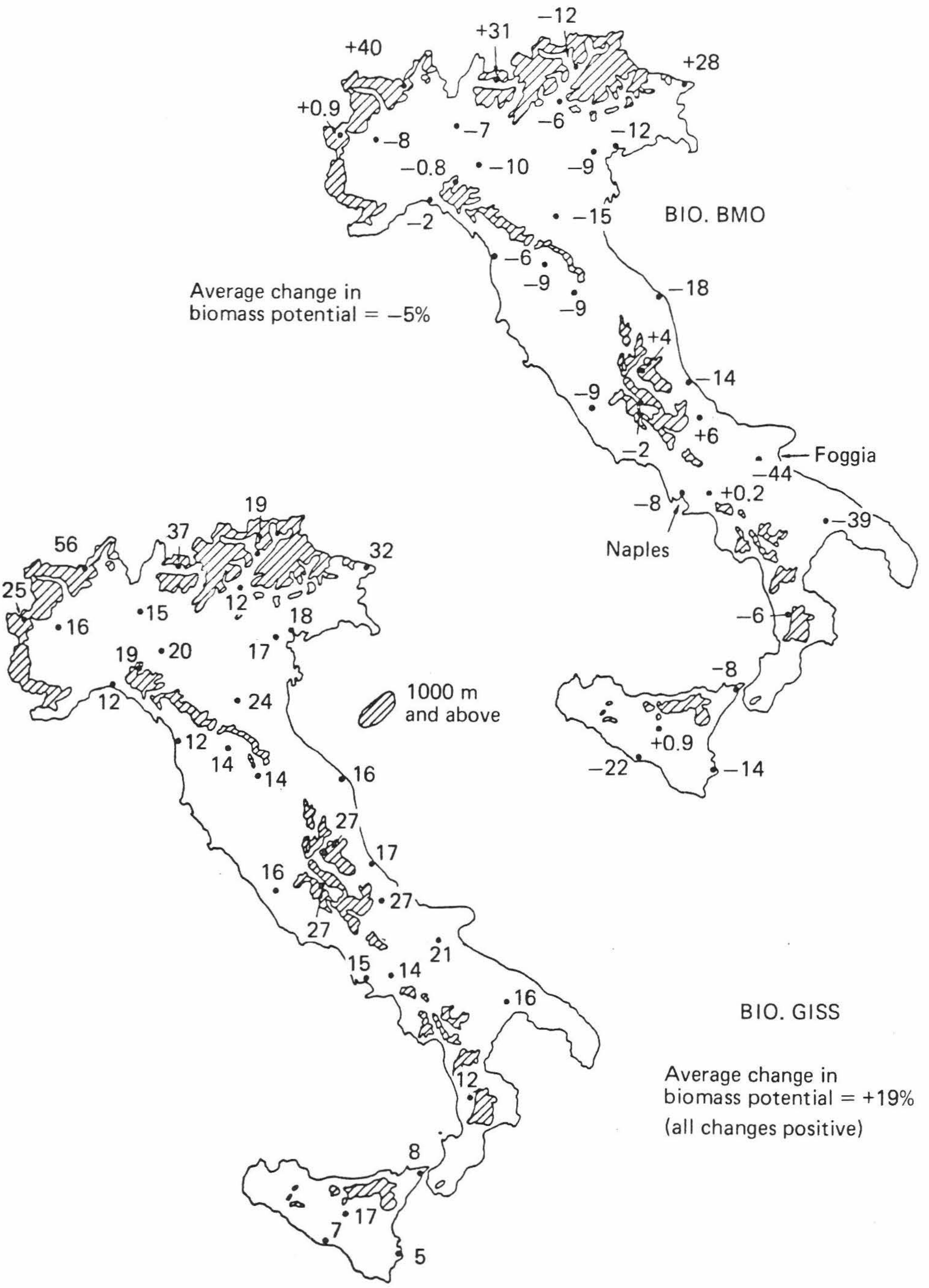

Fig. 4. The Briggs model: calculation of percentage changes in the average biomass potential of 32 Italian stations, using meteorological information from the BIO.BMO and BIO.GISS scenarios.

6. Conclusions

In this project, a first attempt has been made to use the results of GCMs in climate impact analysis. The methods employed, when applied to the verification of GCM control runs, and to the interpolation of 'perturbed run' climate data to stations used in crop–weather models, have raised more problems than they have solved. These problems must be addressed before the results of general circulation models can be used in impact analysis in a realistic way. They include:

- Development of a methodology for validating the results of different GCM control runs, in terms of the parameters used in impact analysis, and on appropriate temporal and spatial scales. This would involve the compilation of a standard set (or sets) of measured data, and the selective modification of such data in order to ensure that inconsistent comparisons of measured and modeled data are avoided.
- Development of a methodology for transferring the 'perturbed run' results of GCMs to the coordinates of stations used in specific crop–weather models. As in the case of model validation, interpolation procedures need to be developed, and methods need to be devised to derive sub-grid-scale detail that is compatible with local climate-determining factors (such as topography; see Kim *et al.* (1984) for further discussion of the 'climate inversion' problem).

It is not the GCMs alone that require improvement, nor the procedures used in transferring climate information from GCMs to crop–weather models. It has also been demonstrated that there is a need for improvement and more critical verification of the impact analyst's crop–weather models. Simple linear regression models may well be unsuitable for assessing the possible agricultural impacts of a substantial climatic change.

The development and improvement of GCMs is a dynamic process. As their numerical representation of the climate system becomes more realistic, there may be some grounds for believing that their results can be used as predictions rather than simply as scenarios. At such a time, the climate impact analyst will need to have experience in using the temperature and precipitation output from GCMs (and output related to other relevant meteorological parameters) intelligently and to the best effect. This experience can and must be gained now, rather than waiting for the 'ideal GCM' to arrive.

The scientific value of this study's impact results must be seen in the context of the assumptions underlying the entire investigation and in the perspective of the uncertainties associated with GCM predictions. A doubling of atmospheric CO_2 levels will not occur as a step-like event. Results from transient response experiments were not available for this investigation; it is both necessary and desirable for subsequent impact studies to attempt the coupling of transient response results with appropriate crop–weather models. Transient response is, however, still poorly understood. Although some investigations have looked at the climate system's transient response to a step-function increase in CO_2 (Bryan *et al.*, 1982; Hansen *et al.*, 1984), few groups have considered the response to a time-dependent increase in CO_2 (Thompson and Schneider, 1982). It may well be some time before the results of transient response experiments are reliable enough to use in impact analysis.

Another area of uncertainty relates to the role of technological advances. It is evident that advances in agricultural technology will exert a significant influence on future crop yields, although the exact nature and magnitude of such effects are almost impossible to predict. If technological developments over the next 70–100 years are anything like those over the past century, their impacts on agriculture and on all forms of human activity will be enormous.

Increasing atmospheric CO_2 levels will almost certainly exert a direct physiological effect on plant growth and biomass production. But again, it is difficult to forecast how elevated CO_2 levels will affect yields of C_3 and C_4 crops under 'uncontrolled' conditions in the natural environment (Lemon, 1983).

Finally, it is indisputable that future changes in the frequency of extreme climatic events (which may result from changes in the mean and/or changes in variability) will be more important in determining the nature and magnitude of agricultural impacts than changes in mean values alone. But the question of how variability might change in a world with increased CO_2 levels has not received detailed attention in GCM experiments.

It is possible to argue that the present study would have been more realistic if it had attempted to incorporate all of the above-mentioned factors – transient response, technological changes, the direct effects of CO_2, and changes in climatic variability. However, the consideration of all these factors would have necessitated the inclusion of an *entire range of new assumptions*. As was stated initially, the aim of this investigation was to examine the uncertainties in one particular area – the coupling of GCM-derived climatic change scenarios with crop–weather models. Even this relatively limited study has shown that there are sufficient problems deserving serious attention in that one area. Future impact analyses must address the questions that were neglected in this study. But they should also show an awareness that increased 'realism' (when attempting to forecast the impacts of a CO_2 doubling) can only be gained by making an increased number of assumptions.

Acknowledgments

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THE EFFECT OF CLIMATIC VARIATIONS ON AGRICULTURAL RISK

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Abstract. The thesis of this paper is that impacts from climatic change can be evaluated effectively as changes in the frequency of short-term, anomalous climatic events. These can then be expressed as changes in the level of risk of impact from climatic extremes. To evaluate this approach, the risk of crop failure resulting from low levels of accumulated temperature is assessed for oats farming in southern Scotland. Annual accumulated temperatures are calculated for the 323-year-long temperature record compiled by Manley for Central England. These are bridged across to southern Scotland and, by calculating mean levels of risk for different elevations, an average 'risk surface' is constructed. One-in-10 and 1-in-50 frequencies of crop failure are assumed to delineate a high-risk zone, which is mapped for the 323-year period by constructing isopleths of these risk levels. By redrawing the risk isopleths for warm and cool 50-year periods, the geographical shift of the high-risk zone is delineated. The conclusion is that relatively recent and apparently minor climatic variations in the United Kingdom have in fact induced substantial spatial changes in levels of agricultural risk. An advantage of expressing climatic change as a change in agricultural risk is that support programs for agriculture can be retuned to accommodate acceptable frequencies of impact by adjusting support levels to match new risk levels.

1. Introduction

In the field of climate impact assessment there has been a tendency to distinguish between the role of short-term climatic variability and the role of long-term climatic change. One affects the range and frequency of shocks that society absorbs or to which it adjusts. The other alters the resource base, for example the agroclimatic resources that can affect farming options and the patterns of comparative advantage, which themselves help to determine why some crops are grown in one place and different crops in another. Following this line of thought, some studies have attended specifically to those shifts of cropping zones that might occur as a result of long-term changes in mean climate (Williams and Oakes, 1978; Newman, 1980).

Yet this distinction between short-term and long-term reflects more statistical convenience than an understanding of human behavior. Few societies or individuals look far ahead or behind. Farmers, for example, may plan over one or two years but rarely more than five. Any *future* impact from long-term changes in mean climate can thus be seen as being embedded in *present-day* impacts from short-term climatic variability; and it is likely that these short-term impacts will remain the medium through which any long-term change is felt. The thesis of this paper is, therefore, that impacts from climatic change should be expressed as *changes in risk* of impact from the short-term anomalous event. One advantage of considering possible impacts from climatic changes in this form is that they can be expressed in a language understood by

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the policy maker. Using present-day frequencies of climatic events as a reference, we can superimpose effects such as CO_2-induced warming to obtain a new set of frequencies showing the possible impacts of costly, extreme events (such as droughts, floods, cold spells, etc.). Government programs could then be constructed to allow for specified tolerable risk levels by adjusting activities according to the change in risk.

In this paper we explore the extent to which levels of climate-related risk have varied in the past, as indicated by the instrumental record. The analytical methods would be similar if we were to consider future variations, but the great advantage of the historical approach lies in our ability to determine the statistical characteristics of the data set, such as the mean, variance, and autocorrelation, by direct calculation. In a future scenario approach, these characteristics must be prescribed. Our choice of data and study area was governed by two requirements: firstly, for a long instrumental record (to detect impacts from short-term changes in patterns of climatic variability); and secondly, to examine a region where climatic risk is high, and where changes in climatic risk would have a readily detectable effect on the economic system. Subsequently, with a deeper understanding of the issue, we can extend an investigation of this kind to regions where climatic risk is less pronounced but nonetheless still important.

The longest instrumental record available is that for temperature in Central England compiled by Manley (1953, 1974). This is representative of inland locations in the English Midlands at about 150 feet (46 m) above sea level. At this elevation, however, levels of climate-related risk for agriculture are not high. We thus need to look at upland areas with higher levels of risk. An appropriate area is the Southern Uplands of Scotland, which previous work has indicated as being characterized by highly marginal forms of arable agriculture (Parry, 1975). We shall focus specifically on the cultivation of oats, which, at elevations of about 340 m in southern Scotland, is near its physiological limit.

However, the instrumental record for this region extends back only to 1856. Only at Edinburgh is it extant for the eighteenth century (from 1764). For the period before 1764 we must look to the data for Central England available from 1659. By bridging between the data sets for Central England and Edinburgh, and between those for Edinburgh and our upland region, it is possible to derive a 323-year run of temperature data for southern Scotland. We shall analyze these data for long-term changes in climatic risk, first in Central England and subsequently in southern Scotland, and assess the impact of these changes on marginal agriculture in the upland region.

2. Long-Term Variations in Growth Potential

2.1. Selection of the Parameter

In maritime upland areas relatively small increases in altitude generally result in marked foreshortening of the growing season and a great reduction in the intensity of accumulated warmth (Manley, 1945). Moreover, the variability of accumulated warmth relative to the mean increases with altitude, and further contributes to the rapid altitudinal fall in potential for crop growth (Manley, 1951).

For oats, which is more tolerant of high rainfall, frequent soil waterlogging, and greater soil acidity than are wheat and barley, the intensity of growing season temperatures is the single most limiting climatic factor. The most effective measure of this is one of accumulated temperature (or the number of growing degree-days, GDD). Growing degree-days are calculated as the excess of mean monthly temperature $\bar{t}_i$ over the base temperature t_{b}, multiplied by the number of days in the month, m_i, and cumulated over one year to give an annual total A:

$$A = \sum_{i=1}^{12} m_i(\bar{t}_i - t_{\mathrm{b}}) \qquad \text{for } \bar{t}_i \geq t_{\mathrm{b}} . \tag{1}$$

We have used a base of 4.4°C, established from phenological studies as being appropriate for oats in northern Europe (Nuttonson, 1955), to calculate annual accumulated temperatures for Central England from 1659 to 1981.

2.2. Central England Accumulated Temperatures, 1659–1981

Central England temperatures were assembled by Manley from several discontinuous series into a table of monthly means. This was derived from the average of data recorded in Oxford and at a number of stations in Lancashire from 1815. Data for the period from 1771 to 1815 were obtained by averaging the departures for each month at a number of inland stations whose records are sufficiently long to be 'bridged' into the later run of data. For the period before 1771, data were bridged into the record from a variety of scattered observation points.

From these monthly data accumulated temperatures in month-degrees were calculated by Manley (1951) for the period 1751–1949 for sites at a height of 183m in the English Pennines. However, using the full run of data, we have calculated growing degree-days at 46m (the height represented by the Central England temperature data) for a 323-year period (Figure 1).

2.3. The Chronology of Accumulated Warmth

The history of these accumulated temperatures is, in one sense, a barometer of the buoyancy of the local farming economy, particularly in the cold, marginal uplands of northern Europe where agriculture is constrained by a growing season that is both short and lacking in intensity. The most important events in this chronology (bearing in mind that it represents lowland conditions) were probably the cooler than average years, particularly those with less than 90% of mean accumulated warmth (about 1,660 GDD). We can classify these extreme occurrences into: (1) those that are single, isolated extremes (e.g. 1740, 1782, 1860, 1879, 1922); (2) those that represent clustered events of two, three, or even more extremes in successive years (e.g. 1673–75, 1688–98, 1838–40, 1887–88, 1891–92); and (3) those that represent periods characterized by a high frequency of scattered, not successive, negative extremes (e.g. 1812–17, 1879–92). Though not necessarily mutually exclusive, these could have recognizably different effects: the isolated event having a sudden but short-lived impact, while successive extremes bring about increasingly greater economic hardship.

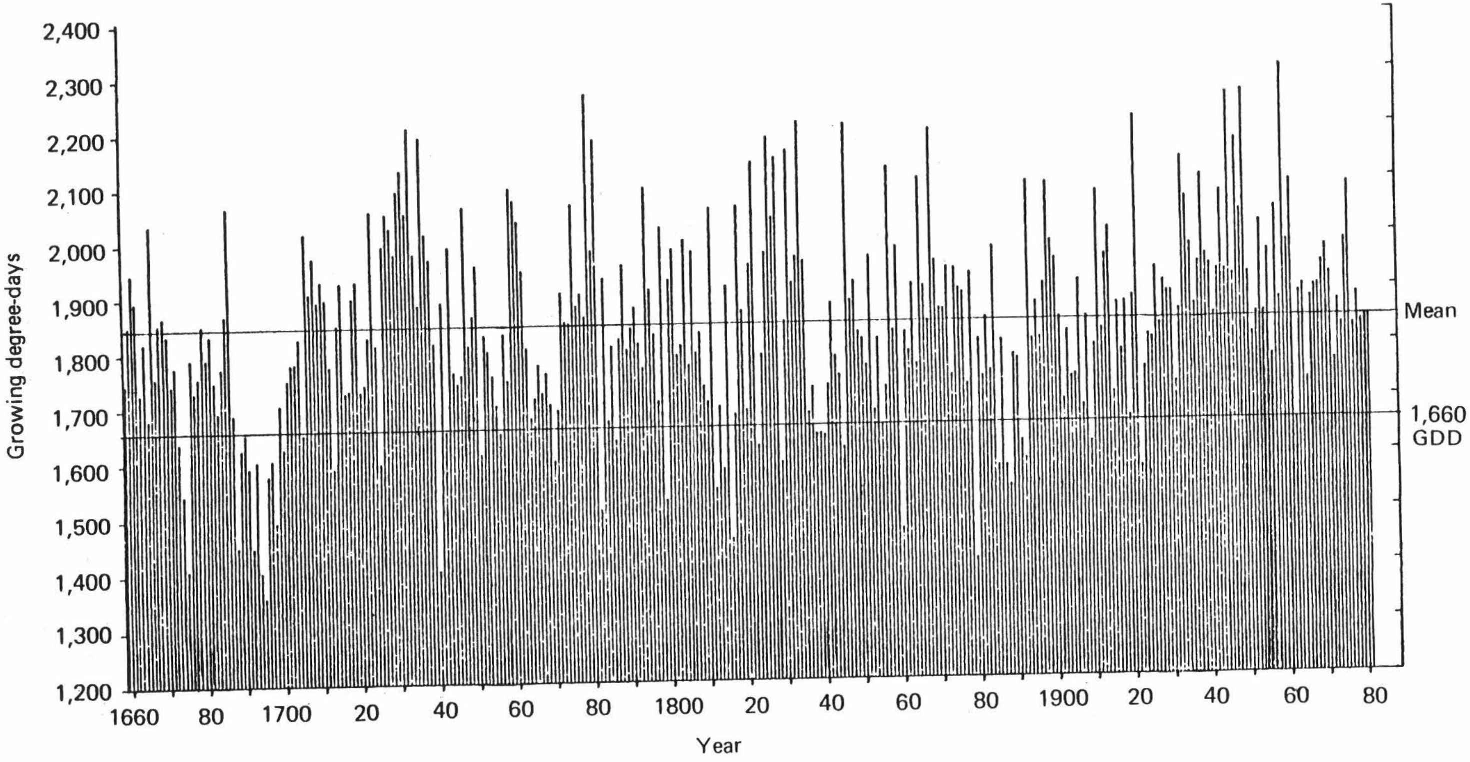

Fig. 1. Annual growing degree-days at 46 m above sea level in Central England, 1659–1981. Base temperature is 4.4 °C.

For example, 1740 saw a spectacularly poor harvest in Scotland, yet food shortages were made good the following summer (Parry, 1978). Similarly, the cool summer of 1782 delayed the upland oats harvest until December. In Aberdeenshire, farmers had to shake the snow off the crop before cutting (Pearson, 1973). Yet there was little lasting hardship.

The limited impact of such isolated events can be contrasted with the effects of a run of extreme years, which, by forcing farmers to consume their seed stocks or spend their cash reserves, could seriously prejudice their harvests in subsequent years. In this respect, the effect of the so-called 'Seven Ill Years' of the 1690s on the rural population in northern Europe was catastrophic. In Finland, at least one-quarter, and possibly one-third, of the people died in the Great Famine of 1696–97 largely as a result of epidemic diseases spreading through an ill-fed and weak population (Jutikkala, 1955).

Finally, we can detect the cumulative, erosive effect of the periods characterized by frequent, but scattered extremes. In these instances, the process of recovery was halted and reversed by a series of recurrent shocks that, over several years, the farm economy had insufficient stamina or resilience to absorb. In the U.K., the scattered extremes over 1879–92 slowly brought more and more farmers to a state of bankruptcy, particularly because grain prices, held back by cheap imports since the repeal of tariffs on North American grain, failed to respond to depressed yields (Royal Commission, 1883; Perry, 1974).

Such historical, ideographic descriptions of the effects of single, successive, and clustered extremes are, however, not a sufficient basis for generalizations concerning the impact on agriculture of climatic variability and of changes in that variability. Such a basis can only be provided by study of specific responses in particular farming systems. We shall focus specifically on the probability of crop failure because we believe that this is a most effective measure of impact from climatic variations. There are two reasons for this. Firstly, marginal farmers, by definition, operate near the limits of profitability and are more concerned with survival (i.e. the probability of their avoiding failure) than with accumulating wealth (i.e. their increment above a minimum average condition). Secondly, the nonmarginal, profit-maximizing farmer knows well that net returns are a function not simply of average yield, but also of the balance struck between gambling on 'good' years and insuring against 'bad' ones (Edwards, 1978).

We shall focus on those changes in probability of crop failure that can occur as a result of changes of climate. To do this historically, however, requires a long run of climate data. This is obtained by bridging across to our upland study region from the Central England temperature record.

2.4. Derivation of Proxy Accumulated Temperatures for Southern Scotland

A 323-year proxy record of accumulated temperatures for southern Scotland was constructed by bridging from Central England to Edinburgh, and from Edinburgh to a network of 27 stations covering the study area.

2.4.1. Bridging from Central England to Edinburgh

Data for the period of overlap between the two records (1764–1896) were analyzed to establish linear regression equations, for each month, of Edinburgh temperatures on Central England temperatures. Correlation coefficients were also recorded, and all indicate a close relationship between the two sets of monthly temperatures (r^2 ranging between 0.601 and 0.807 for June and January, respectively). A plausible means of extrapolating the Edinburgh record is, therefore, to use the regression coefficients as predictors of temperatures at Edinburgh for the full period, 1659–1981.

2.4.2. Bridging from Edinburgh to Southern Scotland

Twelve regression equations relating mean monthly temperature to elevation were calculated, one for each month, from the 40-year record (1856–95) for the 27 stations (excluding Edinburgh) in southern Scotland. These equations were used to estimate monthly means (1856–95) for a site representative of the whole region at the same altitude as the Edinburgh station (76 m). The differences between these estimates and the actual monthly means for Edinburgh were then used as correction factors to adjust the proxy Edinburgh data to obtain longer-term temperatures for the study area. We can thus derive a 323-year set of accumulated temperatures for southern Scotland, within which to examine the frequency of crop failure.

3. The Frequency of Crop Failure

3.1. Method

For many crops the point of 'failure' is an arbitrary one because, however small the return of grain, the residue material (straw, etc.) is often valuable as fodder. There is a point, however, where the grain yield falls so short of the expected yield or the yield required to cover costs of inputs such as seed, labor, and fertilizers that, in economic terms, the year's venture may be considered a failure. Clearly crop failure can thus be defined in many different ways, each appropriate for different farming systems and crop types.

Our definitions and data for crop failure refer to Red and Blaislie varieties of oats, which were commonly grown in the study region in the nineteenth century. By examining diaries and farm journals for that period, we can identify the years of crop failure and, by referring to the meteorological record, the weather of those dismal summers. Empirically, it had been concluded from earlier work that where accumulated temperatures failed to exceed 970 degree-days, oats harvests were extremely late and reduced (Parry, 1978).

Knowing the regionally averaged lapse rate of temperature with elevation in the region (0.68 °C/100 m; Parry, 1976), we can calculate, for each year, the height at which the minimum accumulated temperature is achieved. Above this height, which shifts upwards and downwards substantially from year to year according to variations in accumulated warmth, the oats crop would have been long delayed (Figure 2). We thus have a picture, for the period 1659–1981, of the year-to-year shifts in the hypothetical upper limit of the oats crop caused by annual variations in temperature. In this way, climatic variations can be expressed as the spatial variation of a boundary, which shifts across an economic surface: thus a farmer who in one year lies on the 'right' side of the boundary and, *ceteris paribus*, has an oats crop to harvest, may in another year lie on the 'wrong' side and recoup very little. It is but a simple step to express the farmer's position in terms of risk of crop failure due to inadequate accumulated warmth and, furthermore, to express climatic changes as changes in that level of risk. Before doing so, however, it is useful to explore the value of Figure 2 as a predictive tool in historical research and thus to provide some verification of the model.

3.2. Predicting the Location of Crop Failure

Following the tripartite classification introduced earlier, we can predict the locations at which crop failure occurred either in individual extreme years or in successive extremes, or in periods with particularly frequent extremes. Where adequate historical information is extant, the 'predictions' can be tested against records of actual events.

As an example of the predicted impact from a single, isolated extreme we can predict that in the cool summer of 1782, farms located above 300 m (see Figure 2) would have experienced failed oats harvests. There is some confirmation of this from a contemporary account for the high-lying parish of Lauder, which reports that 'It was the end of December before the harvest was finished, after a great part of the crop was destroyed by frost and snow. None of the farmers could pay their rent; some of them lost two hundred to five hundred pounds sterling' (*The Statistical Account of Scotland*, 1791–99). There were some farm bankruptcies, with the subsequent amalgamation of holdings, but unlike the effect of successive extremes in the 1690s, the parish returns for the Statistical Account reported little sign of lasting hardship in the 1790s resulting from that single poor summer in the preceding decade.

As for the clusters of consecutively cool summers, three would have caused consecutive failure above 300 m: 1674–75, 1694–95, and 1816–17. More substantial runs of failure would have occurred at higher levels. For example, above 340 m failure would theoretically have occurred in 11 successive years from 1688 to 1698 (Figure 2). This elevation approximately matches the actual upper limit of oats cultivation in the seventeenth century, so we can hypothesize that the highest arable farmer in southern Scotland saw failure for 11 continuous years in that time. In fact, a comparison of the manuscript Pont maps dating from about 1596 with those of the Military Survey of Scotland of 1747–55 indicates that few of those high-lying farms survived: of 32 recorded in about 1600, only 10 remained in the next century.

Less immediately marked but probably as enduring in their effects were the periods of more frequent (though scattered) extremes. The late nineteenth century is an appropriate example. For this period our calculations (Figure 2) point to harvest failure at elevations exceeding 310 m for 5 years out of the 16 between 1877 and 1892. At these high levels adverse weather and depressed prices were reflected in the long-term change of arable to permanent grassland and rough pasture. Official annual acreage returns for the region reveal a 5% reduction in the area under crops and grass between 1880 and 1885, and reductions of about 1% every five years from 1885 to 1900.

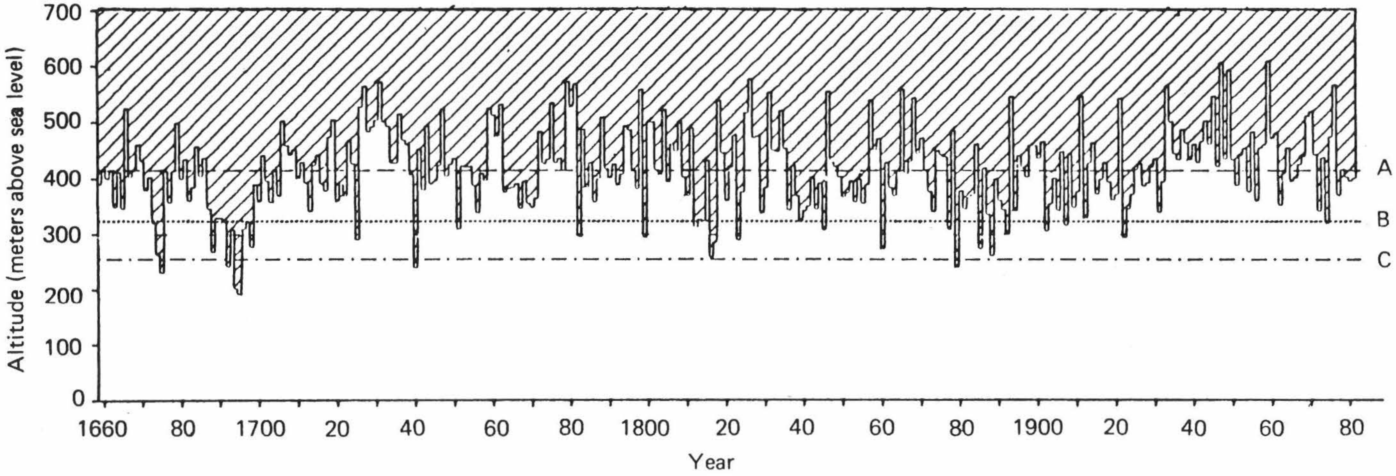

Fig. 2. Hypothetical shift of oats crop failure with altitude in southern Scotland, 1659–1981. A, mean altitude of crop failure; B, 1-in-10 failure frequency; C, 1-in-50 failure frequency.

It is not the aim of this paper to describe these historical impacts in any detail. The complicated task of disentangling the relative roles of climatic, economic, and social factors is a matter for more lengthy treatment elsewhere. Yet it is apparent from the preceding discussion that, by reference to a long run of instrumental weather data that have been reformulated as altitudes of crop failure, it is possible to identify for any particular year or period the areas most seriously affected by variations in accumulated temperature.

4. A Risk Surface of Crop Failure

With increasing elevation, the decrease in temperature clearly imposes a greater restraint on cultivation, increasing the probability of inadequate accumulated warmth and crop failure. In an earlier paper (Parry, 1976) we had assumed annual totals of accumulated warmth to be normally distributed, and found a strongly nonlinear relationship between altitude and risk of crop failure, the probabilities increasing almost exponentially at certain heights (Figure 3). Subsequently we referred to this as an assumed 'risk surface' and emphasized that one important effect of changes in climate could be to change the location and inclination of this risk surface (Carter and Parry, 1984). We can now discard the assumption of normality and, by considering the observed surface of risk over the 323-year period for which we now have data, can estimate the *changes* in the probability of crop failure that have occurred during this long period.

Actual occurrences of crop failure (i.e. years with less than 970 GDD) for the period 1659–1981 in southern Scotland were calculated for 10 m intervals. These are plotted as frequencies of single and two consecutive failures in Figure 3. The curves indicate the corresponding theoretical frequencies assumed for a normal distribution of accumulated temperatures. The theoretical frequencies of two consecutive failures are computed assuming year-to-year accumulated temperature totals to be statistically independent. A comparison of actual and theoretical frequencies indicates a risk surface for single failures that is approximately normal, but a distinct clustering of cool years results in a steeper-than-normal risk surface for consecutive failures. At 340 m (which is approximately the limit of cultivation in the region) the observed frequency of consecutive failures is more than double that of the assumed frequency. In some respects, then, the real risk surface is steeper than expected.

5. Delimiting High-Risk Areas

It is also possible to delineate, on the basis of this long run of data, a high-risk zone in which oats is near its physiological limit and where probabilities of failure are very high. Isopleths of crop failure frequency reveal the distribution of these areas (Figure 4). For the present we shall adopt the frequencies of 1-in-10 and 1-in-50 as delineating the upper and lower edges of the high-risk zone. Ideally the choice of frequencies would be based empirically upon behavioral surveys at the farm level. But, whatever the critical frequencies for certain farming decisions, the effect of altitude on levels of risk is much the same. For example, on the gentle slopes of the southern part of the study area the probability of crop failure doubles over a distance of only about 5 km (Figure 4).

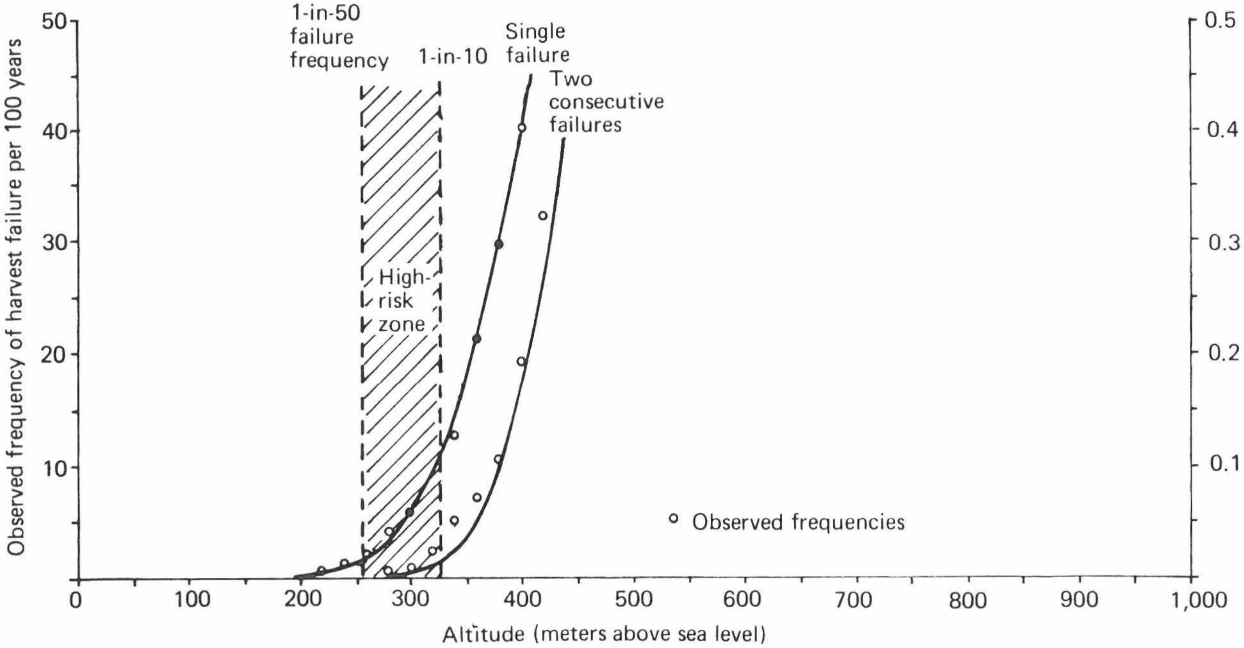

Fig. 3. Actual and assumed frequencies of harvest failure (annual growing degree-days below 970) in southern Scotland, 1659–1981.

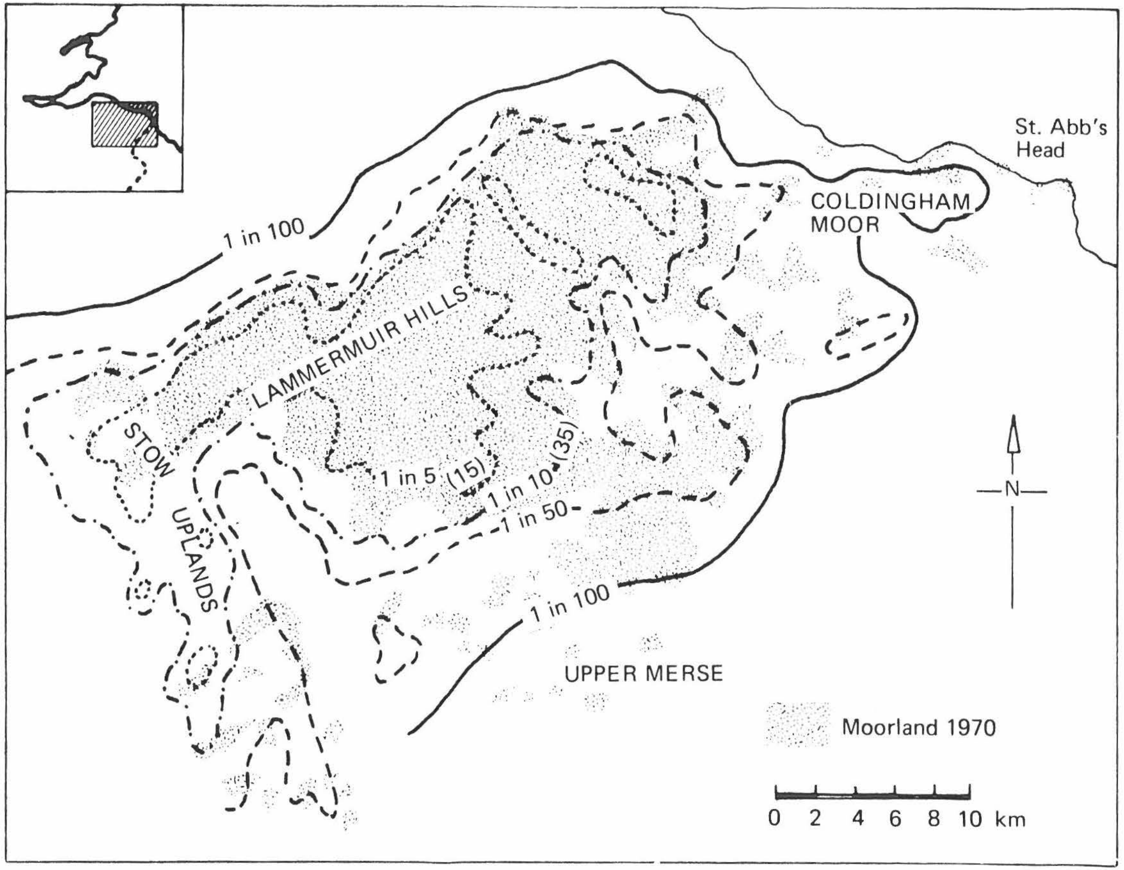

Fig. 4. Isopleths of actual frequency of crop failure in southern Scotland, as defined by years with less than 970 GDD. The actual frequency of two consecutive failures is given in parentheses.

6. Changes in the Frequency of Crop Failure

The risk isopleths of 1-in-10 and 1-in-50 are average frequencies derived from the 323-year record. However, it is clear from Figure 1 that accumulated temperatures have varied greatly from one period to another, and Figure 3 indicates that these would have produced significant spatial shifts of the limit of crop failure. It follows that the high-risk zone is not static but, depending on the time scale of study, apparently shifts from year to year, decade to decade, and century to century. A perturbation in the climate, expressed as a change in the mean or variability or both, can thus be reinterpreted as the shift of such a risk zone.

To evaluate the effect of temperature variations that have occurred over the past 300 years, we have determined the risk surface and high-risk zone for cool and warm 50-year periods in the record (1661–1710 and 1931–80, respectively), and have analyzed their shifts between these periods.

The shift of the assumed risk surface is considerable, as illustrated by the curves in Figure 5. Furthermore, the shift of observed frequencies (plotted as points) is greater still, owing to the higher-than-expected failure frequency in the cool period concurrent with fewer failures than expected in the warm period.

The altitudinal movement of the high-risk zone exceeds 85 m, such that the line of 1-in-50 frequency for the recent warm period lies above even that of the 1-in-10 frequency for the cool period, at the nadir of the 'Little Ice Age'. In geographical terms, the location of this zone has been radically altered (Figure 6). While in the late seventeenth century a substantial proportion of the foothills (above about 280 m) was submarginal with respect to the cultivation of oats, the climatic limit to cultivation for the modern period stands on average at 365 m, representing an additional 150 km^2 of potentially cultivable land.

7. Conclusions

We have considered elsewhere the possible connections between changes of climate and changes in the use of marginal land (Parry, 1978). Those connections were analyzed on the basis of *estimated* 50-year averages of temperature, the argument being that long-term changes in climate were the changes that had an enduring economic effect, if any did. However, the present analysis of yearly data based on mean monthly temperatures has revealed the importance of the short-term event, particularly of extreme years. It has emphasized that an important path of impact from change in average climatic conditions is a change in the frequency of extreme events. Changes in this frequency can be expressed in terms of a shift of the risk surface or of critical boundaries of risk.

We have not sought to establish these critical levels empirically. That remains to be done, but there are grounds for accepting the 1-in-50 frequency of crop failure as an approximation of the limit to viable cereal farming in the study region. For example, its isopleth for 1931–80 coincides with the present limit of cultivation, or 'moorland edge', a fairly stable boundary that reflects an adjustment of agriculture to prevailing economic and environmental conditions, and an adjustment that operates on a decadal rather than an annual or secular scale.

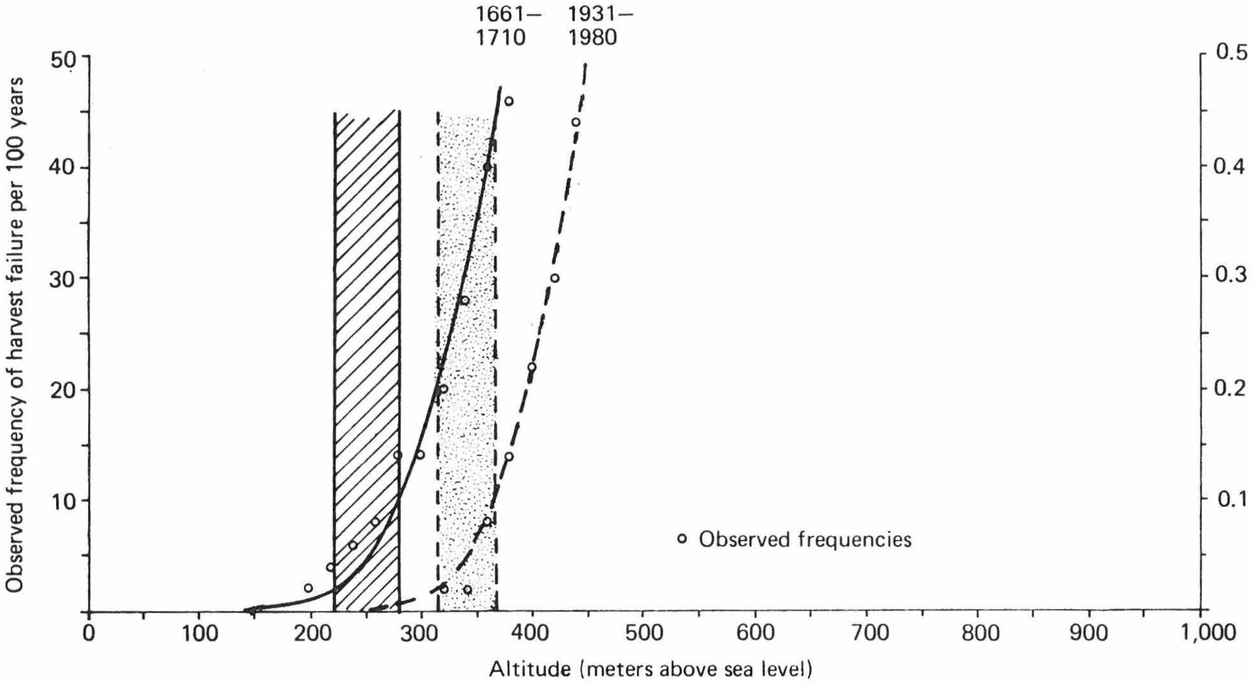

Fig. 5. Differences in the risk surface of crop failure for the cool (1661–1710) and warm (1931–80) 50-year periods in southern Scotland. Shaded and stippled areas denote 'high-risk' zones.

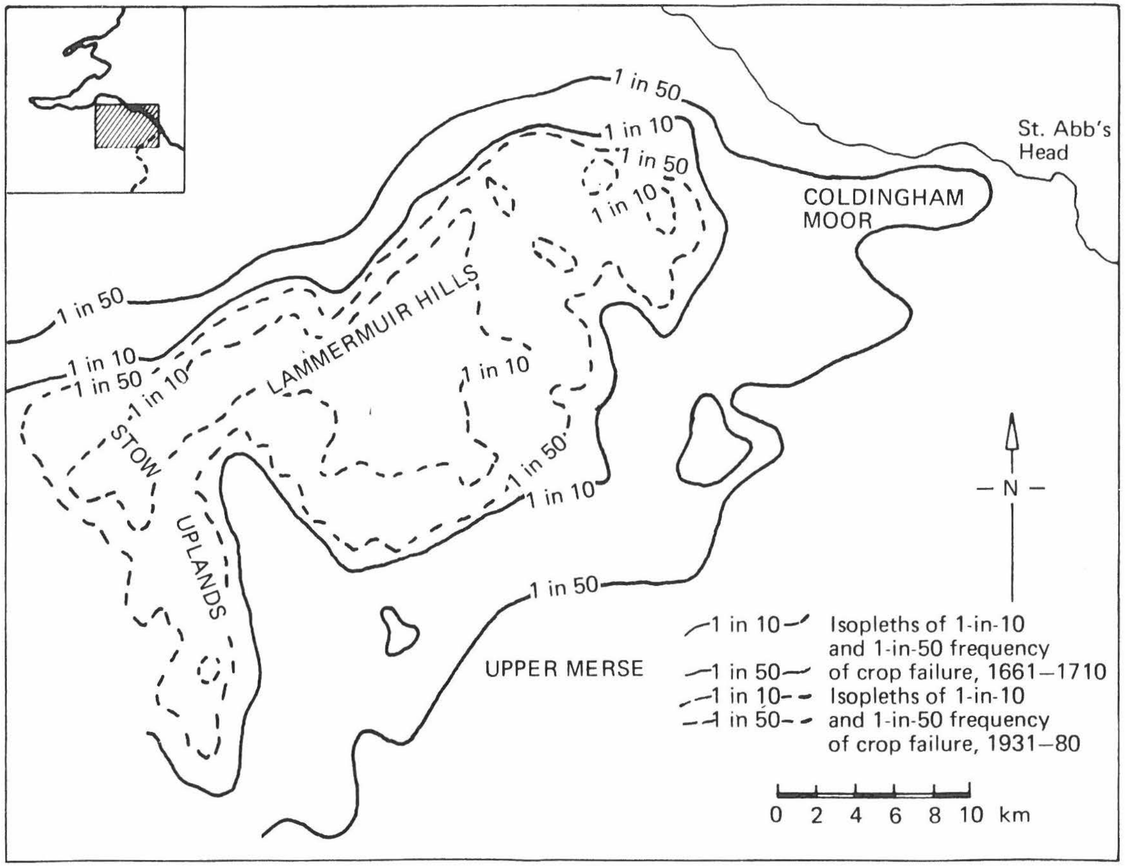

Fig. 6. Locational shift of a high-risk zone between the cool (1661–1710) and warm (1931–80) periods. Risk is expressed as frequency of oats crop failure.

If there were a simple causal relationship between climatic risk and the cultivation limit, then, *ceteris paribus*, we would expect both to have shifted in sympathy. Not surprisingly the actual relationship is far from simple and there are many intervening factors. Nevertheless, the shifts of risk level and growth potential (or of other derived parameters that have not been considered here) can be taken as a prediction of impact on agriculture, a prediction that can be tested against historical records and then, if necessary, reformulated. If we can specify the likely statistical characteristics of a future climate, it should be feasible to improve our predictions of impacts from possible future changes of climate by expressing them as changes in the frequency of extreme events and, thus, as changes in the level of risk. One advantage of this approach is that, as an adaptive measure, agricultural support programs could be retuned to accommodate acceptable levels of risk by adjusting support levels to match the change in risk. More generally, we may conclude that if changes of risk are an important possible consequence of climatic change, then we need to measure the frequencies of occurrence of extreme events under present (normal) climatic conditions and to treat these frequencies as a reference upon which to overlay the effects of a possible future climatic change, thereby obtaining new frequencies of occurrence of such anomalies.

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SENSITIVITY OF ICELANDIC AGRICULTURE TO CLIMATIC VARIATIONS

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Abstract. Haymaking and grazing in summer and winter are fundamental to Icelandic agriculture. This paper shows that the growth of grass depends very much on the climate, particularly the temperature, and that winter temperatures are especially important. The climate of Iceland is highly variable, and the long-term variations are great in comparison with most other European weather regions. This may be attributed partly to the role of the sea ice, which lags behind the variations in atmospheric temperature. From observations in this century it is possible to compute the potential livestock in the country as a function of temperature, and this computation is tested with historical data. A possible response to climatic variations, by varying the use of fertilizer to counteract the impact of cold preceding winters, is discussed. The paper also discusses the growth of barley and forests, which is barely possible in the cold climate and reacts strongly to climatic variations and changes.

1. Climate and Agriculture in Iceland

Farming in Iceland is highly vulnerable to climatic (long-term) changes and (short-term) variations. Temperature variability is great, particularly over the long term. This may be explained partly by the proximity of the east Greenland polar ice and its secular variations. The impact of temperature on grass growth will be analyzed in this paper, as well as its effect on winter fodder for livestock. This gives an estimate of the potential livestock in the country for a given area of improved grassland. The estimate will then be tested historically. The weight of lambs in the autumn will be shown to depend on the temperature. The possibilities of barley ripening will be discussed, as well as the growth of birch and Norwegian spruce. Sea ice will be shown to be a good indicator of Icelandic climate, and its correlation with mortality due to starvation in past centuries will be analyzed. Hay yields in the spring can be forecast by correlation of yield with winter temperature, and it will be shown how the forecasts can be used to recommend variable application of fertilizers by farmers as a safeguard against low yields.

1.1. *Agricultural Products*

Cattle and sheep products represented about 80% of the value of agricultural production in Iceland in 1974. This proportion was probably more than 90% before 1900. The number of sheep was about 750,000 during the winter of 1981–82; cattle numbered 65,000 and horses 54,000 in the same period. Icelandic agriculture is therefore heavily dependent on grazing and haymaking. The growth of grass is sensitive to winter and summer temperatures. Moreover, supplies of hay in the autumn need to be greater for colder winters because grazing in winter and spring can be seriously affected by snow and low

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temperature. This was particularly the case until recently, but even in recent decades many farmers have relied considerably on winter grazing for their horses. In some regions summer grazing is a limiting factor for the number of livestock, particularly in unfavorable years.

Potatoes are the main garden products. The harvest is quite variable, but in the best years it is sufficient to meet home demand. Some attempts have been made to cultivate fast-growing strains of barley and they have been fairly successful in the regions having the mildest climate. With respect to forestry, the Icelandic birch is thought to have survived the last Ice Age, but its growth is quite slow. Trials with some coniferous trees are promising in certain areas.

Although the growing of garden products, barley, and forests is not very important economically in Iceland, their particular sensitivity to climate suggests that they are a suitable subject for studies of climate impact.

1.2. The Climate

Iceland is located at the shifting frontier between the *taiga* and *tundra*. When the climate is cold the taiga region in the lowland contracts. In warmer periods the taiga gains territory, northwards in the lowland and upwards in the mountains. The agricultural frontier is, as we shall see, equally sensitive to climatic variations.

Figure 1 shows the annual mean temperature from 1846 to 1982 at the Stykkisholmur climatological station on the west coast of Iceland. There is a strong interannual variation, together with pronounced long-term changes, e.g. shortly after 1920. For comparison, Table I shows some characteristics of temperature climate at three stations: Stykkisholmur (65° N), Edinburgh (56° N), and Berlin (52° N).

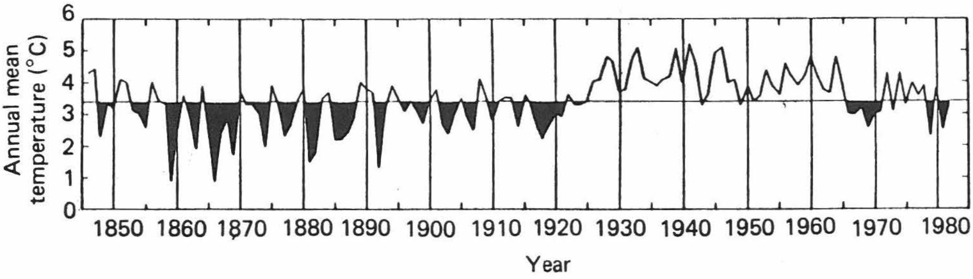

Fig. 1. Annual mean temperature at Stykkisholmur, 1846–1982. Values below the average are shaded.

TABLE I: Thermal Characteristics at Contrasting Climatological Stations in Europe.

	Stykkisholmur	Edinburgh	Berlin
Mean annual temperature, 1851–1950 (°C)	3.3	8.5	9.2
Standard deviation of *annual* temperature	0.88	0.54	0.76
Standard deviation of *decadal* temperature	0.54	0.17	0.24
Temperature difference between 1901–50 and 1851–1900	0.74	0.21	0.14

As examples of a cold and of a mild climatic period in Iceland, we can take the years 1873–1922 and 1931–60, respectively. For the earlier 50-year period, temperature normals have been computed for many Icelandic stations, while 1931–60 is the normal period now in use. The figures for Stykkisholmur are presented in Table II.

TABLE II: Stykkisholmur: Monthly and Annual Mean Temperatures (°C) for the Cool Period (1873–1922) and the Mild Period (1931–60).

Month:	1	2	3	4	5	6	7	8	9	10	11	12	Year
1873–1922	−2.0	−2.5	−2.1	0.5	4.3	8.1	9.9	9.2	7.2	3.7	0.6	−1.5	3.0
1931–60	−0.8	−0.9	0.2	1.8	5.7	8.7	10.4	10.0	7.9	4.5	2.3	0.5	4.2

1.3. The Role of the Sea Ice

The sea ice off the east coast of Greenland is an important clue to climate and its variations in Iceland. Figure 2 illustrates the extent of this ice at the end of May over the period 1966–75. When the ice is at its maximum extent, the North Atlantic can be frozen half the way from Greenland to Norway, with Iceland resembling an icy peninsula extending from the Greenland ice cap. There is a marked feedback effect between the ice and the climate. Cooling will extend the ice but, once formed, the ice will also cool the air, particularly when winds blow from the north. The northern part of Iceland is more affected by these variations, both because of the proximity of the ice and because the föhn will modify the cooling effect of northerly winds in south Iceland. This may be seen in Figure 3, which is based on available lowland observations. Furthermore, the ice has a high persistence compared with atmospheric temperature, thus increasing the probability of two or more severe years in succession. This tendency may be noted in the Stykkisholmur graph, Figure 1. For the same reason, cold winters (when livestock requires more fodder than usual) tend to follow cool summers, with limited haymaking.

2. Climate and Grass Growth

Grass for haymaking and grazing is the main crop in Icelandic farming. The author has attempted to assess the impact of climatic variations upon grass cultivation in Iceland for the period 1901–75, using statistics on temperature, fertilizers, and hay yield per hectare of cultivated grassland (Bergthorsson, 1982). Even if availability of soil water may in some cases affect the yield, it is reasonable to assume temperature to be the main limiting factor for grass growth in the country. This assumption will subsequently be tested.

A somewhat surprising conclusion is that cold winters are more effective than cold summers in restricting the growth of grass. Among the possible reasons for this may be the winter killing of grasses, partly as a result of direct killing by severe cold. A less direct effect may be the prolonged snow cover in cold winters, frequently melting during brief thaws and then refreezing. Moreover, severe winters can leave the soil frozen, delaying growth, and sometimes killing the grass because of water lying on impermeable frozen soil in the spring. On the other hand, winter warmth seems to be favorable only to a certain degree,

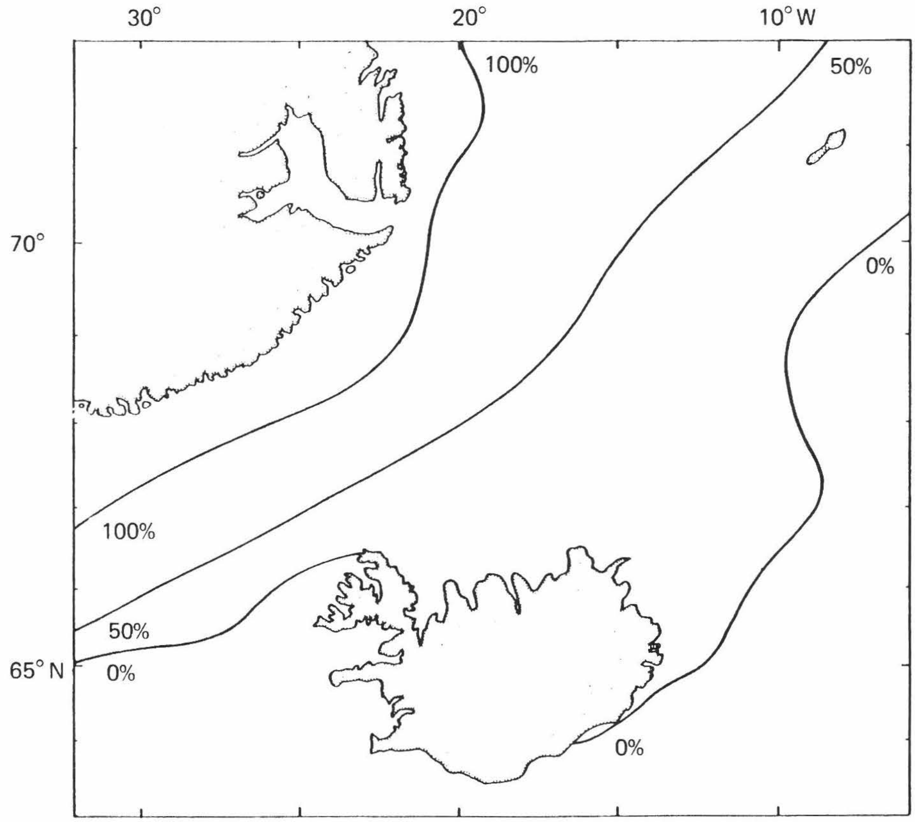

Fig. 2. Percentage frequency of occurrence of all known ice covering at least one-tenth of total sea area at the end of May over the period 1966–75 (based on ice charts from the Icelandic and the British Meteorological Offices).

possibly because very warm winters can induce an untimely start of grass growth.

While winter temperature is important for grass growth, summer temperature also affects the hay yield. It will be shown that the average temperature for the period from October 1 to September 30 is a good indicator of the annual hay yield. However, in the assessment of the impact of temperature on hay yield, the great increase in the use of commercial fertilizers after 1920 is a disturbing factor. Fertilizer will therefore have to be included in the regression equation for hay yield.

2.1. A Model of Grass Growth

To express the annual hay yield the following model has been found useful:

$$Y = (0.169+0.2814S-0.02S^2)(1{,}820+28.06N-0.051N^2)\,. \qquad (1)$$

The yield Y is here given in kilograms per hectare, S is the average temperature for the period from October 1 to September 30, and N is the total amount of

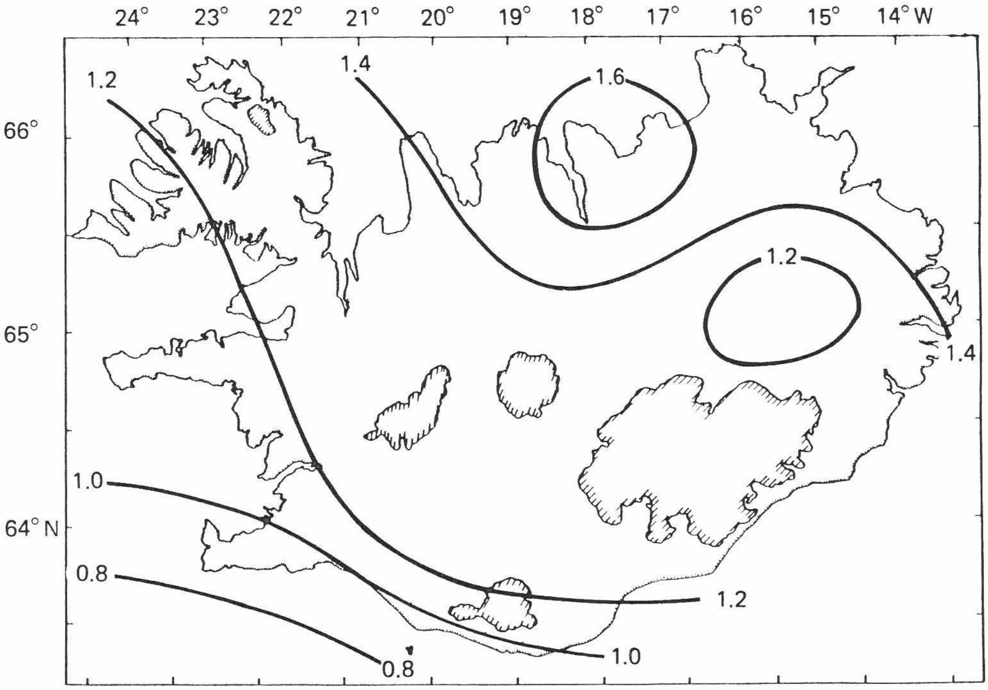

Fig. 3. Isolines of warming (°C) from the period 1873–1922 to 1931–60.

nitrogen fertilizer in kilograms per hectare, including manure. It is assumed that nitrogen is the main limiting nutrient. The temperature data are taken from one station only, Stykkisholmur.

This model enables us to distinguish the impact of fertilizer from that of temperature. Figure 4 depicts the annual hay yield corrected for the effects of fertilizer. The yield, expressed as a percentage of the mean yield in 1931–60, is plotted against Stykkisholmur temperatures. The lowest yield, in 1918, is only half the average for 1931–60, while the greatest yield is about 120% of this average. The curve is fitted to the observations according to the model. In this case we assume applications of fertilizer to be constant. However, before the first use of commercial fertilizer in about 1920, applications of nutrients were not constant, since the available manure was proportional to the hay eaten by the animals during the winter. This tended to amplify the effect of climatic variations and changes. Table III shows estimated temperature impact on the hay yield in relative figures, depending on whether the total amount of fertilizer per hectare is constant or whether only the available manure is used. The yield has been indexed to 100 for an annual temperature of 3.2°C.

3. Climate and Winter Fodder

Not only hay yield is affected by low temperatures: winter and spring grazing will also be more difficult because of snow, ice, and bad weather. In this connection it should be noted that in Iceland there is an unusual autocorrelation in

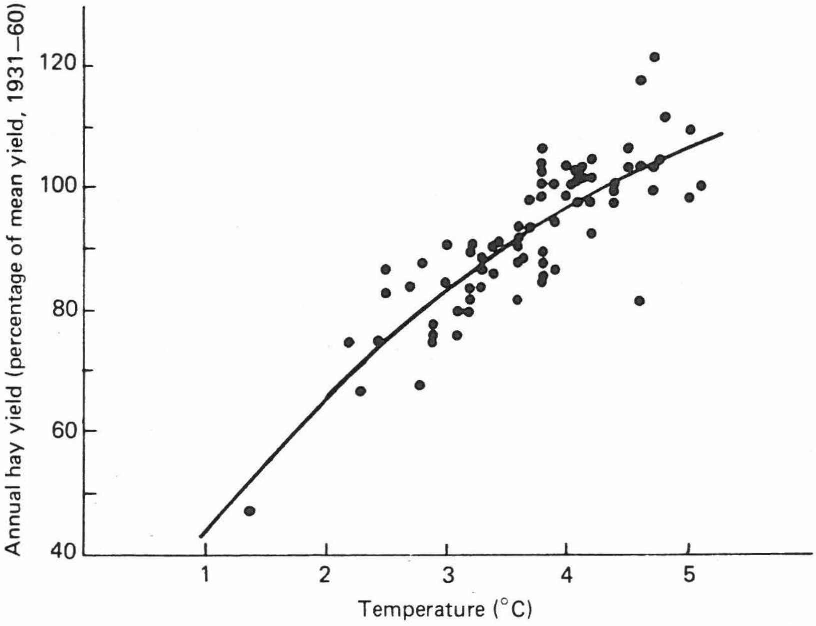

Fig. 4. Hay yield in Iceland, 1901–75, as a function of the October–April temperature in Stykkisholmur. The yield is corrected for the variable amount of fertilizer used in the period.

TABLE III: Hay Yield and Temperature.

Annual temperature (°C)	2.2	3.2	4.2
Hay yield using manure only	73	100	124
Hay yield using constant fertilizer	80	100	116

temperature of seasons and years, so that a severe winter is more likely when the preceding seasons have been cold. This may be partly due to the damping effect of the sea, and in particular of sea ice.

Phenological observations of hay consumption and temperature in the period 1941–49 enable us to estimate the required hay consumption as a linear function of winter temperature at Stykkisholmur, as shown in Figure 5. Since winter temperature is correlated with annual temperature in the long run, we can relate variations in fodder supply to annual temperature (Table IV).

Less information on this subject is available for recent years. It is, however, likely that the effect of temperature on the winter fodder for sheep is now less important than it was in 1941–49, because winter grazing of sheep has been reduced considerably.

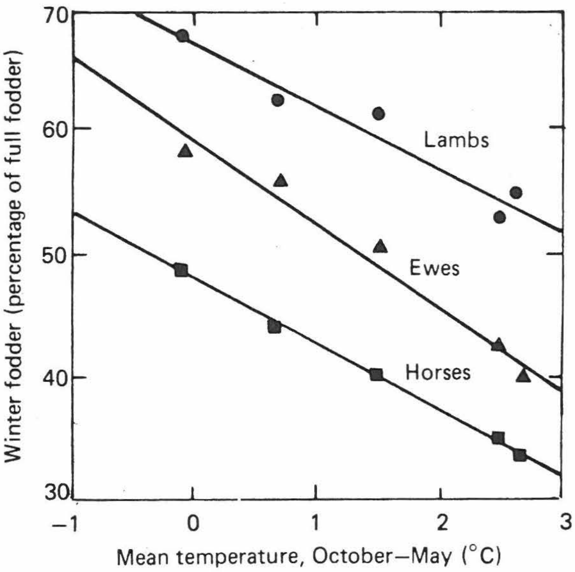

Fig. 5. Winter fodder of lambs, ewes, and horses in the years 1941–42, 1942–43, 1945–46, 1947–48, and 1948–49, as a function of mean temperature in October–May.

TABLE IV: Winter Fodder and Temperature.

Annual temperature (°C)	2.2	3.2	4.2
Winter fodder of sheep	112	100	88
Winter fodder of horses	112	100	88
Winter fodder of cattle	104	100	96

3.1. Winter Fodder and Carrying Capacity

The above considerations indicate that climatic variations affect available winter fodder and its consumption and thus influence the carrying capacity of cultivated grassland. It should be possible to compute from this relationship the potential livestock capacity of the country as a function of the climate.

We assume conditions representative of the nineteenth century in Iceland, that is, that only manure is used as fertilizer. It is assumed that the cultivated grassland area is constant, and that the hay from the cultivated areas is all given to dairy cattle. Haymaking on uncultivated, unfertilized land was extensive at that time, and hay was used for sheep and horses, as well as for non-dairy cattle. The consumption of hay is assumed to vary with the climate, as shown in Table IV.

The result of this computation is shown in Table V, which gives the livestock numbers in relative figures. The results are almost identical for sheep, horses, and cattle: *A temperature deviation of 1°C from the 1901–30 normal (3.2°C) will change the potential livestock carried by cultivated grassland in Iceland by some 30%.*

TABLE V: Potential Livestock on Cultivated (Improved) Grassland and Temperature.

Annual temperature (°C)	2.2	3.2	4.2
Sheep	71	100	132
Horses	71	100	132
Cattle	71	100	131

4. Climate and Actual Number of Livestock

As a test of the computation above we have investigated the actual relationship between climate and the amount of livestock in the period 1846–1900. To account for the cumulative climatic effect over consecutive years, a weighted mean of the preceding annual temperatures was used. The weighting functions found to be suitable were 1.0 for the immediately preceding year and $(5/7)$, $(5/7)^2$, $(5/7)^3$, etc. for the progressively earlier years. The amount of livestock is given in 'ewe-values', based on relative hay consumption by sheep, cattle, and horses (1:20:2.5). The outcome of this regression is shown in Figure 6. It is practically the same as the estimate: A temperature deviation of 1 °C from the 1901–30 normal (3.2 °C) would change the livestock number by 29%.

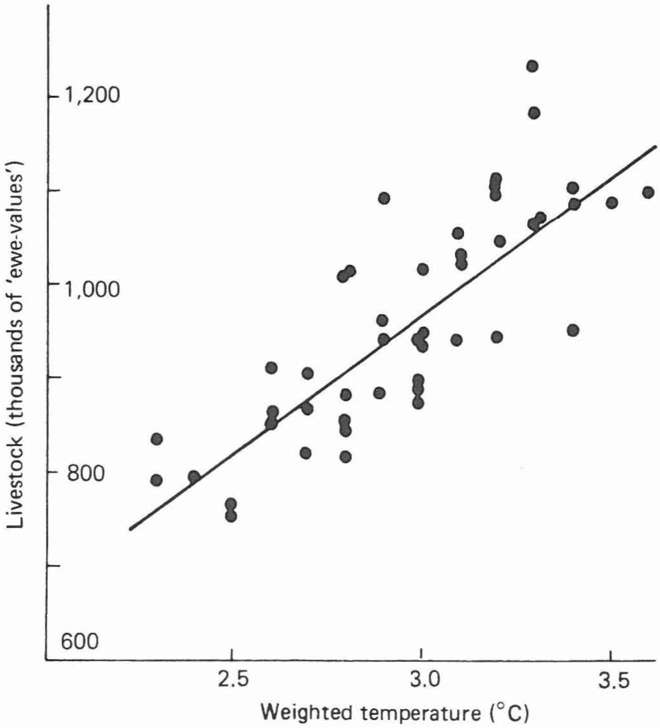

Fig. 6. Livestock in Iceland as a function of weighted temperature of the preceding years, for the period 1846–1900.

A corresponding investigation for the period 1962–82 indicates only a slightly reduced dependence of stock number on climate: 27% per degree Celsius deviating from 3.2 °C.

5. Climate and Grazing Capacity for Sheep

Apart from the cultivated grasslands, the extensive rangelands are important for summer grazing, particularly for sheep (Dyrmundsson, 1979). We shall now attempt to correlate the average carcass weight of the lambs in autumn with the following variables:

(1) density of sheep in the range lands;
(2) computed grass growth index according to the temperature at Stykkisholmur, as discussed above, assuming that no fertilizer is used;
(3) farming practices.

Since 1940 the total number of sheep has been quite variable, ranging from 400,000 to 900,000. Because of a certain lung disease that arrived from abroad before 1940, all the sheep in many regions were replaced by a new stock from unaffected areas, mainly in the years around 1950. This led to a marked short-term decrease in stock numbers and at the same time a significant increase in carcass weight.

The annual temperature in Stykkisholmur (October 1 to September 30) has been shown to be a good indicator of grass growth, and consequently it is reasonable to expect that it will affect the carrying capacity of the rangelands. However, sheep-farming practices have changed greatly, though gradually, resulting in increasing carcass weight, ***ceteris paribus***. In the last term of the following regression equation we have attempted to express this increase by a linear function of time since 1940:

$$W = 9.35-0.003F+0.032G+0.066A \, , \qquad (2)$$

where W is the national average annual carcass weight (kg), F is the number of winter-fed sheep in the country (in thousands), G is the computed grass growth index as given by Y in Equation (1), and A is the year after 1900 (A = 75 denotes 1975).

According to Equation (2), a lowering of the grass growth index by 0.1 will have the same impact on carcass weight as an increase in the number of sheep in the country by some 105,000, which is equivalent to approximately 15% of the stock. This implies that when it is cold the carrying capacity of the rangelands will be decreased in the summer, even if sufficient winter fodder could be supplied.

5.1. *Grazing Experiments*

The carrying capacity of the rangelands can be tested experimentally as well. Table VI shows the average carcass weight for the years 1977–79 in Audkuluheidi in north Iceland as a function of the stocking rate of the sheep (Gudmundsson and Arnalds, 1980). A moderate stocking rate is here given the index 100. This result is in good agreement with the sheep numbers given in the regression Equation (2).

TABLE VI: Carcass Weight and Grazing Capacity.

Stocking rate of sheep	Light	Moderate	Heavy
Stocking rate index	42	100	162
Carcass weight, deviation (kg)	1.09	0	−1.65

6. Climate and Growth of Barley

Barley, one of the hardiest cereals, is very close to its growing limits in Iceland so that a relatively slight warming or cooling significantly affects its viability. Observations in Samsstadir in south Iceland indicate that a precondition for the ripening of a fast-growing variety of barley (Dönner) is that the growing degree-days from sowing to harvest, with the base 3 °C, should be at least 850 (Bergthorsson, 1969). Anomalous precipitation during the vegetative period will raise this required temperature sum by 30 for every 100 mm exceeding 200 mm in the vegetative period. According to Norwegian experience (K. Vik, private communication) this required temperature sum may be lowered by 30 for every degree of latitude further north, for barley requiring long hours of daylight. This enables us to compute the probability of barley ripening at different stations, knowing the temperature, precipitation, and latitude. According to this assessment, at only one station in Iceland (Reykjavik) would barley have ripened in 60% of the years during the cold period, 1873–1922. In the mild period, 1931–60, 21 of 48 stations should have had ripened barley in 60% of the summers.

7. Climate and Forests

To assess the climatic conditions of forest cultivation in Iceland it is possible to make use of the studies of the Norwegian forester Elias Mork (1968). Mork investigated the relationship between the daily afternoon temperature and the daily height increment of Norwegian spruce. Using this relationship as a basis, he was able to define 'growth units'. One unit corresponds to 1% of the annual height increment of the Norwegian spruce. The relationship is not a linear one, as may be seen from Table VII.

TABLE VII: Mork's Growth Units as a Function of Temperature.

Temperature of the warmest 6 hours	8.1	13.5	17.0	19.4	21.2	22.8
Growth units	1.0	2.0	3.0	4.0	5.0	6.0

Since the temperature of the warmest 6 hours of the day is not readily available from published records, the author suggests the use of the average of (1) the daily maximum temperature, and (2) the daily mean temperature. Calling this average temperature t, we can express the daily growth units empirically using the following relation in the interval 2–20 °C (see Appendix 1):

$$G = (t - 1.6)/(7.4 - 0.215t)\ . \tag{3}$$

If we use the monthly mean of the temperature t, we have only to multiply the resulting growth units by the days of the month to obtain the monthly sum of growth units. This relation is based on observations published by Mork for a mountain region north of Oslo, near the tree line.

The annual impact of temperature can then be obtained as the sum of the monthly growth units during the summer. Mork found that a minimum annual sum of growth units is required in the long run for species like birch or Norwegian spruce to establish forests in the Norwegian mountains. The minima for the period 1931–60 are, according to Equation (3) for the period 1931–60:

for birch	267 growth units
for Norwegian spruce	300 growth units

They are 45 units higher than Mork's figures, since all months in spring, summer, and autumn are used in the computation, not only the vegetative period. By applying these criteria to 28 Icelandic weather stations, it is possible to identify which stations will permit culture of birch or Norwegian spruce in our two different (cold and mild) periods (Table VIII). All the 28 stations are situated within the inhabited area of the country.

TABLE VIII: Stations Permitting Cultivation of Birch and Norwegian Spruce.

Period	Number of stations	
	Birch	Norwegian spruce
1873–1922	10	4
1931–60	21	13

This variability in growth potential bears comparison with the pollen record, which indicates that the coverage of birch in Iceland has fluctuated markedly during the 10,000 years after the Ice Age, even before human settlement 1,100 years ago.

Comparison with conditions in Iceland gives on the whole a good confirmation of the Norwegian experience. For example, at Hallormsstadur in the eastern part of Iceland, where Norwegian spruce forest should reach a limit of 140 m above sea level and the birch line should be at 225 m, there is good agreement with the actual limit of tree growth.

8. Sea Ice and Living Conditions in Historical Times

Figure 7 shows the relationship between decadal sea ice prevalence and temperature in Iceland for the period 1851–1980, prevalence being measured in months per decade. The ice data of this period may be divided into two distinct classes, before and after 1920. There is little doubt that much more thorough observations are the reason for the recording of relatively heavier ice after 1920. In that year the Icelandic Meteorological Office started compiling the ice data, while before 1920 there were no regular ice observations organized by any Icelandic institution. The main source concerning ice before 1920 is Thoroddsen's ice annals (Thoroddsen, 1916–17), based on historical information available to him. Historical ice data compiled by Thoroddsen also exist for the period before 1850, but he only attempted to represent them graphically after 1780, because before that time the information was less complete. This lack of data must, however, not be interpreted as a sign of mild climate.

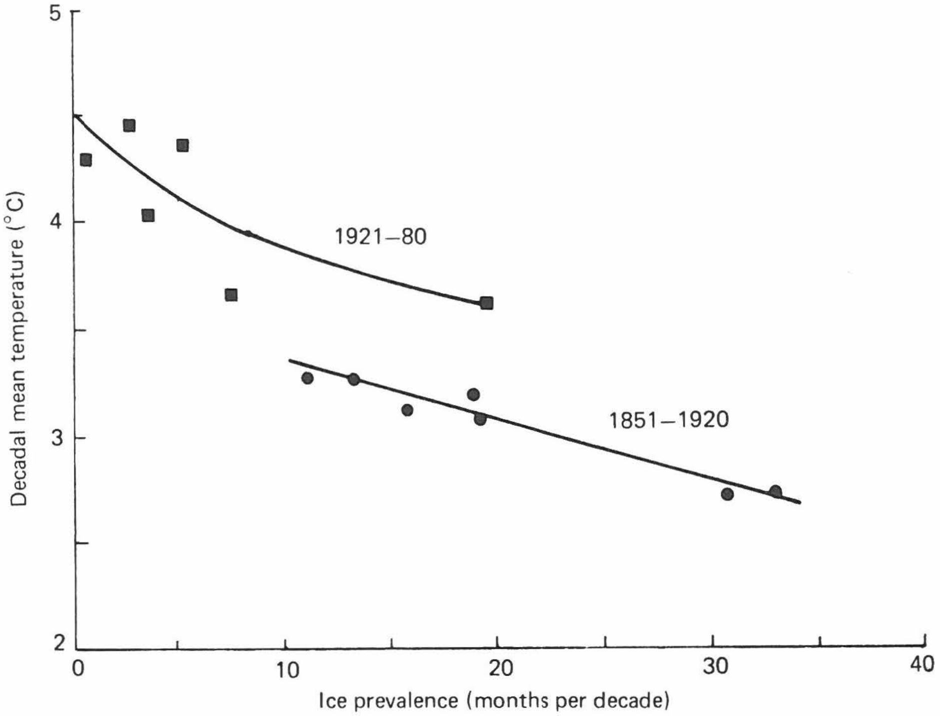

Fig. 7. Decadal mean temperature in Iceland as a function of sea ice prevalence. The relative increase of ice after 1920 is here considered to reflect more thorough observations.

To reconstruct the decadal temperature before 1846, Bergthorsson (1969) used indirect information on mild and severe years to fill in the Thoroddsen ice data for the period 1591–1780. More recently, Ogilvie (1981) unearthed a considerable number of historical sources, mainly for the eighteenth century. She computed two historical indices for the period 1601–1780. One is an index of ice prevalence, using direct ice data only, while the thermal index is based on the general weather information. There is some correlation between the two indices, but the ice index in the seventeenth century is lower than would be expected from the contemporary thermal index.

Bergthorsson's ice index of the seventeenth century compares well with Ogilvie's thermal index for the same century, suggesting that Bergthorsson's interpolation of the ice data is reasonable. That conclusion is furthermore supported by Koch's (1945) estimate of the ice in the seventeenth and eighteenth centuries, showing approximately the same relation with Ogilvie's thermal index in both centuries. Therefore, it is the present author's conclusion that in spite of some material being missing in his index of the ice since 1590, it can still serve as a reasonable estimate.

9. Sea Ice and Starvation in Iceland

We have a fairly reliable record on years of mortality from starvation in Iceland for the last centuries (Thoroddsen, 1916–17). Judging from the strong relationship between ice and temperature and the relationship between temperature and amount of livestock, it is reasonable that starvation will be connected with the weighted means of sea ice prevalence in the years *preceding* famine. The weighting of the previous ice prevalence is: in the preceding year 1.0, the second to last year 5/7, the year before that $(5/7)^2$, and so on. Table IX compares the frequency of starvation with the weighted mean of ice prevalence. This seems to confirm rather strongly the impact of climatic variations on living conditions in Iceland in former times.

TABLE IX: Starvation as a Function of Previous Ice Prevalence in the Period 1591–1846.

Class	Weighted mean of ice prevalence (months)	Number of years	Years of starvation	
			Number in the class	Percentage of all years in the class
1	0–1	26	0	0
2	1–2	87	4	5
3	2–4	131	25	19
4	more than 4	11	6	55

10. Practical Application: Forecasts of Hay Yields

One of the aims of assessing the impact of climate on agriculture is to attempt improvements in farm management. One example will be discussed briefly here: the variable application of fertilizer to counteract the winter effect upon hay yield. The fertilizing of grassland in Iceland usually occurs in May. By then we are able to estimate the effect that winter temperatures will have on hay yield, as already discussed. For a winter temperature lower than 1 °C this impact can be expressed by

$$Y = (0.883+0.117W)(1{,}820+28.06N-0.051N^2), \qquad (4)$$

where Y is the hay yield (kg/ha), W is the mean temperature from October 1 to April 30 in Stykkisholmur, and N is the amount of nitrogen fertilizer (kg/ha).

Figure 8 gives the annual hay yield for 1901–75 as a function of the yield predicted by this regression equation. In spite of some scattering it is evident that by considering a period of several years it is possible to obtain a fairly constant yield, even in a long period of unfavorable years as experienced in the nineteenth century (Figure 1). This can be accomplished by using a variable amount of fertilizer according to the climate. To test this hypothesis, an experiment has been conducted for seven years at Hvanneyri in west Iceland. Keeping the amount of fertilizer constant at 100 kg N/ha, the resulting hay yield can be expressed as a function of the winter temperature, the yield being denoted in kg/ha (dry matter):

$$Y = 5{,}680+690W. \qquad (5)$$

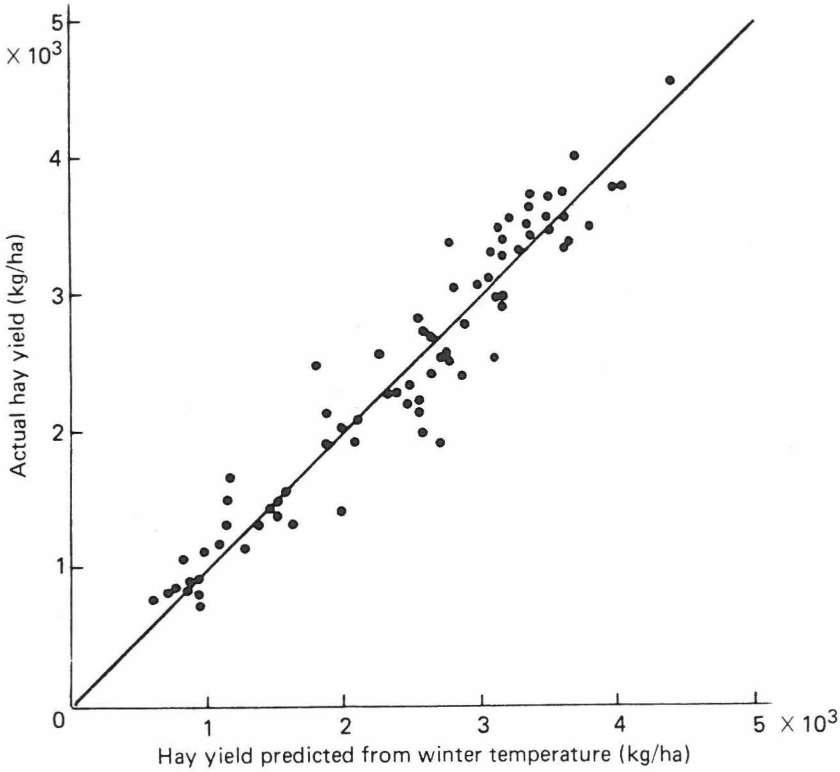

Fig. 8. Hay yield in Iceland compared with the yield computed from the amount of fertilizer and the October–April temperature in Stykkisholmur in the preceding winter and spring, during the period 1901–75.

As is usual in trials of this kind, the yield is considerably higher than that obtained on ordinary hay fields, but the relative impact of the winter temperature is in good agreement with Equation (4). When the amount of fertilizer was varied to obtain constant yield, the following regression equation was obtained:

$$Y = 5{,}440 + 30W. \qquad (6)$$

In this way the impact of the winter temperature could be practically eliminated, as intended, using an average application of 99kg N/ha.

Finally, we give a test of Equation (4), for the period 1976–83, as shown in Figure 9. Graph A gives the Stykkisholmur winter temperature, and B represents the total hay yield in the country, in millions of cubic meters. In these years the grassland area and the amount of fertilizer used were fairly constant.

It is important that in favorable years the fertilizer should be not so excessive that an additional amount in colder years cannot give the desired increase in yield. This limited use of fertilizer in good years is relatively easy in Iceland, because most of the farmers are able to expand their cultivated grassland by improving the rangelands. This method should enable the farmers to keep their livestock without reduction during single or consecutive severe years.

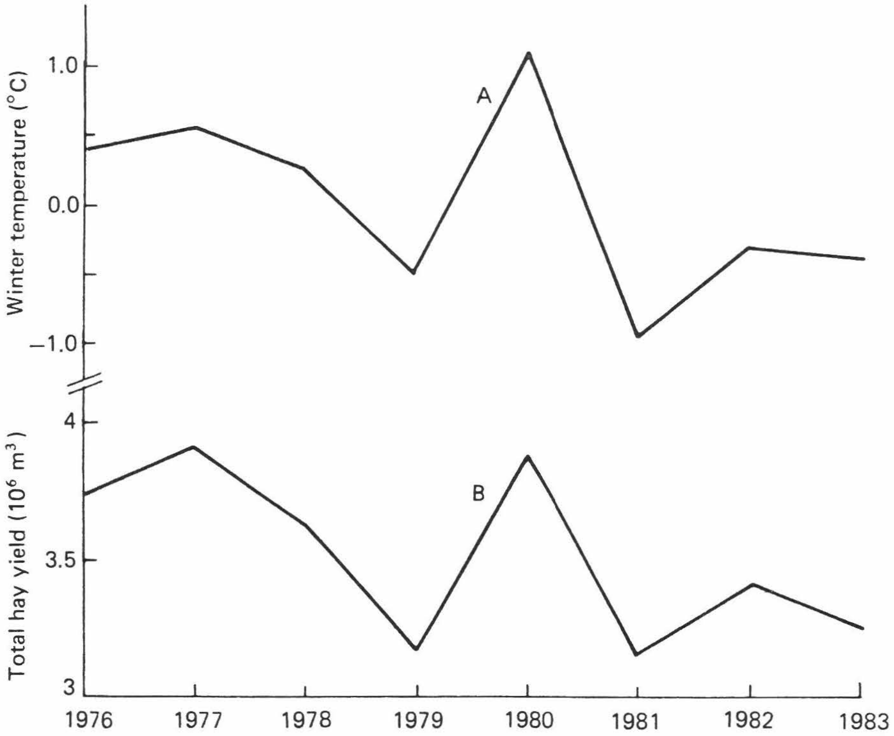

Fig. 9. A test of the relationship between winter temperature and hay yield depicted in Figure 8, for a different period. A, October–April temperature in Stykkisholmur; B, hay yield in Iceland.

11. Conclusions

Farming in Iceland is highly sensitive to climatic variations. Long-term changes in temperature are great, partly because of the variable extent of the polar ice off east Greenland. Winter temperature is especially important for the livestock, affecting both hay consumption in the winter and grass growth in the following summer. A model has been derived that relates grass growth to the annual temperature for the period from October 1 to September 30. In addition, phenological observations have been used to relate consumption of winter fodder to temperature. From these relationships it is possible to compute the potential livestock in the country as a function of the long-term temperature. Furthermore, it has been shown that the annual temperature affects the carcass weight of lambs in autumn, and experiments with barley show that relatively slight temperature variations significantly affect its viability. Finally, this study of the effect of temperature variations suggests a method of mitigating climate impacts by a variable application of annual fertilizer.

Appendix 1 Air Temperature and the Growth of Grass and Cereals

Temperature sums have been frequently used as an indicator of growth. Originally, the freezing point was used as a threshold or base temperature, but in most cases it has turned out that a higher threshold temperature is more appropriate, depending on climate and the type of vegetation involved (Table X). We can conclude that the higher the average temperature of the vegetative period, the higher is the appropriate threshold temperature.

TABLE X: Average Temperature and Threshold Temperature for the Vegetative Period of Common Cereals and Grass.[a]

	Average temp. (°C)	Threshold temp. (°C)
European part of the U.S.S.R. (Budyko, 1974)	(15–20)	10
British Isles (Smith, 1975)	(12–15)	5.6–6.1
Iceland (Bergthorsson, 1965)	(10)	3
Northern Ireland, grass in winter (Keatinge *et al.*, 1979)	>0	0

[a] Figures in brackets are the estimates of the author.

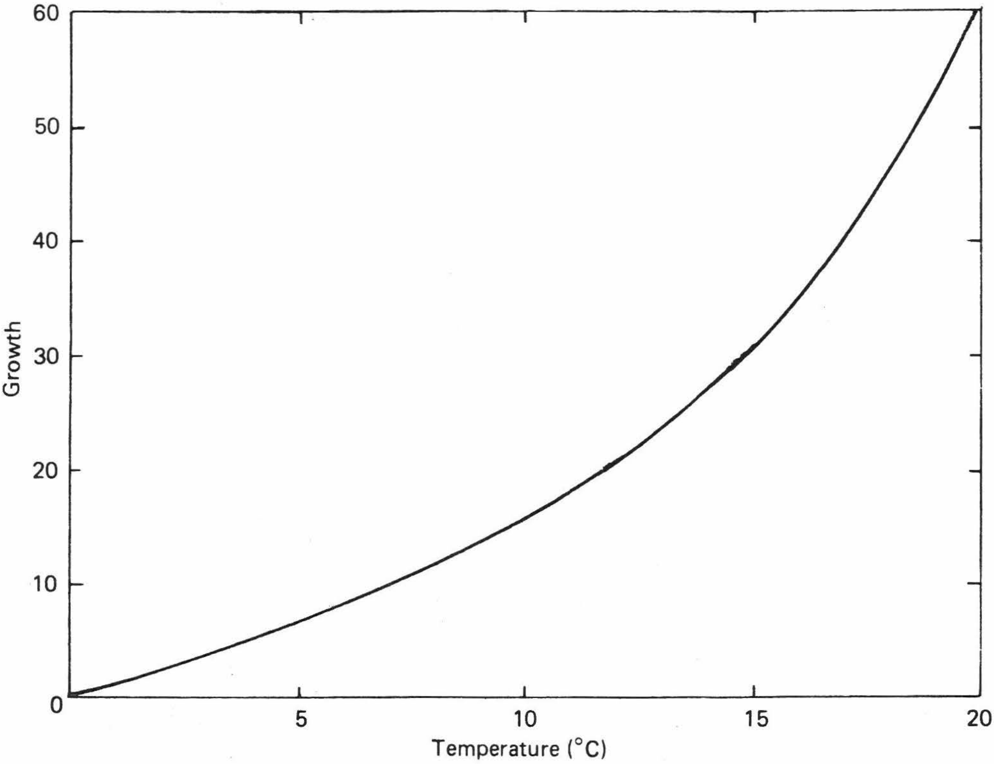

Fig. 10. A graph of growth index G as a function of the mean daily temperature T: $G=T/(1-T/30)$. This function is intended for the computation of temperature sums, avoiding the use of the variable regional threshold temperatures.

Calling the average temperature T and the threshold temperature T_g, we can put for the interval 0–20 °C:

$$T_g = T^2/30\,. \tag{7}$$

Assuming that there exists a common growth function for all four regions in Table X, depending on temperature, it follows from the idea of temperature sums that its *derivative* will at any point be, for the interval defined,

$$\mathrm{d}G/\mathrm{d}T = G/(T - T^2/30)\,. \tag{8}$$

Integrating this differential equation, we find:

$$G = T/(1-T/30)\,. \tag{9}$$

This is a kind of daily temperature, approaching the temperature itself when it is close to 0 °C. In all the four climatic regions in Table X, the sums of this function are approximately proportional to the regional temperature sums. This growth function may have to be modified if, instead of the mean daily air temperature, we use another measure of temperature, such as the temperature of the growing points of vegetation, the average of the daily maximum and mean temperatures, etc. The growth function (9) is shown graphically in Figure 10. As Table X indicates, it should not be used for temperatures higher than 20 °C or lower than 0 °C.

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SENSITIVITY OF AGRICULTURAL PRODUCTION TO CLIMATIC CHANGE

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Abstract. Although the range of cultivated species is relatively restricted, domestic plants and animals exhibit considerable resilience to stochastic shocks, and the study of their ecological adaptability and critical physiological and phenological requirements is a valuable first step in determining their possible response to climatic change. Methods of assessing agroclimatic suitability and their limitations are discussed, and suggestions are made for simulating the probable impact of shifts in the main climatic parameters on the productivity and spatial distribution of key crops and livestock. Some regions and crops are climatically more vulnerable than others; some regions (in particular North America) are strategically more critical to the stability of world food supplies, while in others resources for agricultural production are under more severe pressure.

As well as attempts to forecast long-term climatic trends and their effects on agriculture, combating climatic variability merits high priority. This is an ever-present source of instability in production and could be enhanced in association with changing climate. Its magnitude differs widely among crops and geographical regions, but its impact from year to year is often greater than that predicted from climatic change even in extreme scenarios. The paper indicates a number of potentially desirable areas for action and suggests that several of these would be beneficial both as a buffer against short-term effects of variability and as a means of combating climatic change.

1. The Inherent Vulnerability of Production Systems

While undisturbed ecosystems are the climax response of vegetation to soil and climatic influences, agricultural systems represent induced changes in the natural balance imposed by man and domestic animals. They comprise a much narrower range of species than would normally be found in the natural environment; moreover, because the microclimate may be modified by human manipulation (drainage, soil amendment, irrigation, etc.), production systems may contain species that would not be found naturally in that area at all.

It is arguable that the artificiality of agricultural production systems makes them less flexible, and therefore more vulnerable to climatic change than the naturally occurring species of the ecosystem within which they fit, and that the more unstable the climate the greater this vulnerability is likely to be. This is a reflection partly of the time-bound seasonality of agricultural production, particularly where annual crops predominate; and partly of the fact that agriculture is undertaken for economic and social reasons. In an undisturbed state there is no pressure on an ecosystem to deliver a product within a given period; in farming it may literally be 'produce or perish'.

Time factors in combination with climate largely determine what crops and livestock can be supported within a given ecological situation; social and economic factors interacting with technological change have a major influence

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on determining which will be preferred by producers among the range of commodities that is feasible within those climatic parameters.

Social and economic factors also play a decisive role in determining whether attempts will be made to modify the natural environment, so as to mitigate unfavorable constraints imposed by soil and climate and thus either to introduce new crops, livestock, or trees into traditional systems or to reduce risk and increase productivity of those already forming part of these systems. Modifications introduced into the natural environment may be long-term in nature (irrigation, reclamation, terracing, land clearance, reafforestation); or quite short-term (mechanization, fertilizer and other soil amendments, weed and pest control, or other cultural practices).

However, whether they are short- or long-term in their immediate impact on production, attempts to manipulate the environment may have far-reaching effects on the ecosystem within which the production system is contained, on other ecosystems 'downstream' (through flooding, siltation, salinity, erosion, etc.), and on the marine environment. In the case of large-scale removal of tropical forests they may alter CO_2 sinks and modify rainfall patterns. Thus human interference with the environment for agricultural production can have a wide effect that may compound difficulties and risks imposed normally by climate, as well as contributing a further element of unpredictability to climatic change in the long run. While the magnitude of this change may not be as large as those postulated for other human influences (industry, urbanization, etc.), the interactions of management factors in the broadest sense with climate can have a profound impact on the potential for agricultural production. How to take this interaction into account has probably not received sufficient attention and requires interdisciplinary study involving, among others, agriculturalists, climatologists, and social scientists.

This paper indicates the more important interactions between climate and food production, in relation to both possible climatic change and short-term climatic variability. It discusses the need for better agroclimatic assessment, and some recent approaches to this, and briefly reviews possible interactions between agricultural technology and climatic variability.

2. Major Climatic and Soil Factors Influencing Production Systems

Crop responses to the climatic and soil factors that critically determine what can be grown in a given ecosystem vary widely. All plants have certain minimum requirements with respect to light, water, and temperature, but whereas some will tolerate low or high temperatures others will stand no frost and not too much heat. Some flourish best under short-day conditions, some under long days, and some are neutral to day length. Some withstand drought better than others, irrespective of absolute temperature. Nutrient requirements, pH range, and ability to withstand flooding or waterlogging vary greatly. The sowing date is more critical for some species than for others; and some plants have a sharply determinate growth pattern, with little flexibility with respect to date of maturation, while others can be harvested over a long period. This may be an advantage or a disadvantage, depending on the production system and on end use. There are marked differences in adaptability to temperature and day length between crops with a C_4 and those with a C_3 carbon assimilation pathway. As a broad generalization, optimum photosynthetic response is obtained at higher levels of temperature and radiation in C_4 plants than in C_3 species (Table I).

Within species as well as between genera, there are marked physiological differences that affect when and where crops can be grown. Thus in the case of wheat, non-winter-hardy bread wheats such as the 'Mexican' high-yielding varieties can be sown in the autumn in mild subtropical climates such as the Mediterranean littoral of Turkey or in Australia; but not where winters are cold and there is a lot of frost, as in the Anatolian plateau of Turkey. Under colder conditions, wheats of this type can be sown only in spring after the main frost hazard has passed; often, as spring wheat yields in the U.S.S.R. show, at a yield penalty. In some areas, for example in much of Anatolia, the spring growing period is not long enough before summer drought commences, thus the payoff to spring planting is low. The optimum variety there is a fully winter-hardy wheat sown in the autumn; on the other hand, such wheats will not pass from vegetative to reproductive growth in milder climates because a cold phase is needed as a trigger, so they cannot be sown in the littoral. In most tropical regions temperature is not limiting except at high altitudes, and water availability largely determines crop yields; however, water is much more critical at some phases of growth than at others, an important consideration when designing irrigation systems (Bunting *et al.*, 1982). Thus temperature effects of a secular climatic change are likely to have a greater impact on production systems in colder regions of the Earth, while the effects of a change in total precipitation or its distribution will be most pronounced in lower latitudes.

In general, day length and temperature are strongly correlated with latitude in lowland areas, while temperature tends to decrease linearly with altitude, and the probability of sufficient warmth decreases logarithmically. These factors are more predictable and less variable from year to year than rainfall. Low temperatures and particularly the incidence of frost are a major factor in limiting crop growth (at around 5–6 °C), and in determining the length of the potential growing season and the actual duration of growth of crops in higher latitudes and at higher altitudes (Monteith and Scott, 1982). Grainger (1981–82) plotted yields of four major cereals in the principal producing countries against the average latitude in those countries and found a high correlation, with factors related to latitude accounting for 65% of the variation in barley yield, 42% in potato yield, 40% in rice yield, and 31% in maize yield. While barley and potatoes are not crops of the lowland tropics, maximum yields even for rice were obtained outside the tropics. Grainger attributes the latter to insufficient day length and excessive temperatures, but seems to overlook climate–disease interactions. However, except in relatively primitive production systems there is some danger of attributing too much simply to climatic factors. Climate is a major determinant of what can be grown successfully; but nonclimatic factors related to variety, technology, access to capital, prices and availability of markets and inputs, land tenure, flood control and irrigation, and education levels of farmers are often the key factors determining high yields.

While the range of physiological adaptability of plant species is remarkable, and provides considerable buffering capacity against the variability associated with climatic change and other stochastic shocks, it also means that a fairly profound knowledge of both their potential and their limitations is required

TABLE I: Average Photosynthesis Response of Four Groups of Crops to Radiation and Temperature.

Characteristics	Crop adaptability group			
	I	II	III	IV
Photosynthesis pathway	C_3	C_3	C_4	C_4
Rate of photosynthesis at light saturation at optimum temperature (mg CO_2 $dm^{-2} h^{-1}$)	20–30	40–50	70–100	70–100
Optimum temperature for maximum photosynthesis (°C)	15–20	25–30	30–35	20–30
Radiation intensity at maximum photosynthesis (cal $cm^{-2} min^{-1}$)	0.2–0.6	0.3–0.8	> 1.0	>1.0
Major crops of the study	Wheat Potato Phaseolus bean (temperate and tropical high-altitude cultivars)	Phaseolus bean (tropical cultivars) Soybean Rice Cotton Sweet potato Cassava	Pearl millet Sorghum (tropical cultivars) Maize (tropical cultivars) Sugarcane	Sorghum (temperate and tropical high-altitude cultivars) Maize (temperate and tropical high-altitude cultivars)

Source: Food and Agriculture Organization (1978, Vol. 1).

when modeling production systems and the possible effects of climatic change on those systems. We see this from Carter and Parry (1984), with respect to sowing dates. This applies as much to livestock-dominated or mixed systems (as the Icelandic example for hay illustrates: Bergthorsson, 1985, this issue) as to sole-crop production. The problem becomes particularly difficult where mixed cropping is practised, such as with maize and beans in Latin America, annual oilseeds and cereals in South Asia, or multiple cropping in Southeast Asia. The area of such cropping is not unimportant now, and it may well increase in the future as an insurance against uncertainty if climatic insecurity increases.

3. Assessment of Agroclimatic Suitability

In order to facilitate work on developing crop–climate models it therefore seems desirable to catalogue the main cultivated species in terms of the factors that determine their agroclimatic suitability and degree of flexibility to tolerate climatic shifts. These factors include their carbon assimilation pathways, and their critical requirements with respect to temperature, day length, moisture, sowing date, length of growing season, growth phases, growth habit, radiation during the growing period, potential transpiration, soil type, pH, and moisture storage characteristics, drainage, and erosion hazard. For some years the Food and Agriculture Organization (1978–80) has been forming an assessment of agroclimatic suitability somewhat along these lines, for 13 of the most important crops in the world in terms of the area they occupy, their total production, and its value. These crops are wheat, rice, maize, pearl millet, sorghum, soybean, cotton, phaseolus bean, white potato, groundnut, sweet potato, sugarcane, and cassava.

The basic characteristic for determining crop adaptability in this classification is photosynthesis. This is defined for a much larger number of crops than the major crops listed above; in fact, over 60. These crops are divided into five groups based on their carbon assimilation pathways (C_3, C_4, or CAM), and on the response of photosynthesis to temperature and radiation, because these factors determine productivity when the climatic phenological requirements of a given crop are met, that is, temperature, water availability, and photoperiodism (Table I). The phenological calendar is based on the length of the growing season, determined either by water availability and water balance, including soil moisture storage, or by the combination of water availability and temperature. The spatial distribution of soil units is then vectored in, based on the Soil Map of the World. Net biomass production and yield are then calculated for the major crops mentioned above under an assumption of freedom from agroclimatic and soil constraints within the growing period; and finally, assumptions concerning yield losses due to the four main constraints (moisture stress; excessive wetness; pests, diseases, and weeds; and factors affecting yield formation and quality) are imposed to arrive at an agroclimatic suitability assessment. Yields are calculated at low and high input levels and varied according to altitude/temperature changes at different intervals for different crops.

The main product of this study is a series of generalized regional maps of agroclimatic suitability showing isolines of length of growing season. The agroclimatic suitability for Africa is illustrated in Figure 1. These maps are accompanied by tables, showing the area of land in each major climatic division in

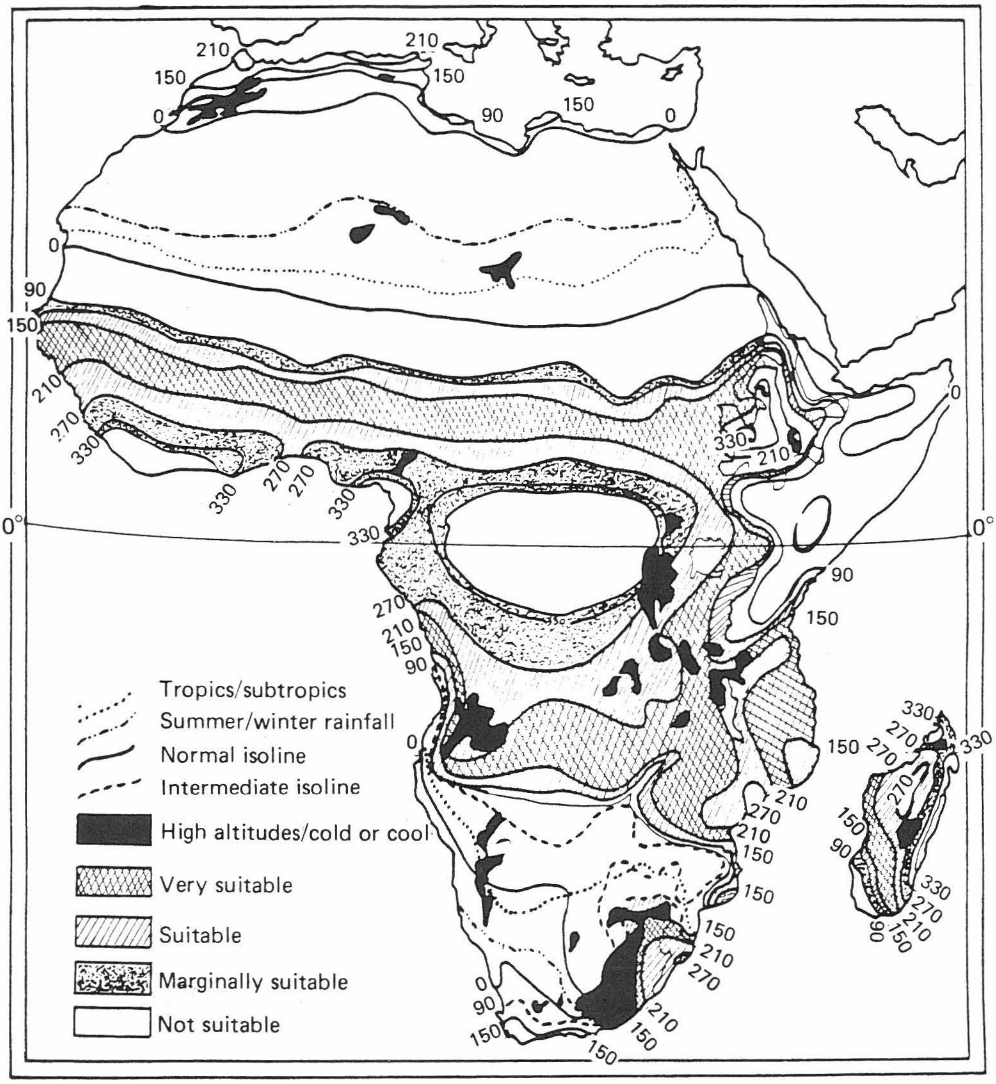

Fig. 1. Generalized agroclimatic suitability assessment for rain-fed production of the phaseolus bean (source: FAO, 1978, Vol. 1). Isolines show length of growing season.

four classes from 'very suitable' to 'not suitable'.

The regional studies have now been aggregated into a report that relates potential production of 14 major crops plus pastures and livestock to actual population in 1975 and projected population in the year 2000, at three input levels, in an attempt to determine the capacity of the developing countries to support a larger population and to identify critical areas where land resources are inadequate to meet food needs (FAO, 1982).

The approach followed by the FAO may provide one basis for agricultural evaluation of climatic change, since the zones of least suitability are also indicative of marginality and high risk for the specific crops described. However, the model would need some refinement for this purpose since it is not, as it stands, a climate sensitivity analysis. It does not allow for climatic change, although it could probably be adapted to simulate this, so that shifts in the climatic suitability of land for a large range of crops within broad geographical regions or even individual countries could be looked at. Nor does it cover all climatic regions, being confined essentially to the developing countries of the subtropics and a few temperate areas at high altitudes within those regions. Thus it omits the main grain-producing and trading countries, including Australia, Canada, the U.S.A., the U.S.S.R., and Western Europe. Another limitation of the model is that it does not map current land use (although the aggregate study makes some effort to show which are the dominant patterns), and therefore does not indicate which crops would actually be affected most by climatic change, and where. Poor validation also reduces the value of certain other studies with somewhat similar objectives, such as the attempt by Buringh *et al.* (1975) to calculate the maximum food production potential of the world. The FAO study also looks only at *food* production potential, and assumes that all land will be used for food production. A 'throwaway' paragraph at the end acknowledges that up to one-third of land area may be required for cash crops, but failure to incorporate this into the analysis seriously weakens its relatively optimistic conclusions as to human carrying capacity.

Nevertheless, this study is of great interest and contains some useful pointers to analysis of the impact of climatic change on agriculture. It shows, for example, the important interaction between climate and soil, and indicates that zones with severe climatic and/or soil constraints generally respond poorly to increased levels of inputs. Soil factors are overriding on climatic potentials in a number of situations, especially at low input levels, and unchecked degradation of soils is estimated to lead to an overall decrease in productivity of rainfed land in the regions studied of 18.5%. The highest potential carrying capacity (0.74 persons per hectare) occurs in the warmer areas of the climatic regions studied (much of the cooler land is at higher altitudes) and (except where irrigation is widespread) in the areas with long growing periods exceeding 269 days. These are mainly in the humid lowland tropics where population density tends to be low at present because of the prevalence of human and animal disease and the debilitating climate. The impact of a global warming trend would probably be smaller at these latitudes than in colder regions; but if it led to reduced precipitation south of the Sahara it could have catastrophic effects on the already deteriorating Sahelian zone, while perhaps benefiting the potentially productive wetter areas further south where tsetse fly is currently a serious impediment to settled crop-livestock farming.

This illustrates the need to look carefully at potential interactions between climate and other factors, some of which (such as soil degradation) may have an impact on agricultural production as large as or larger than that which might result from a moderate global warming or cooling trend. It also emphasizes the importance of trying to assess and balance the likely geographical distribution of gains and losses that could result from any global climatic change, and especially how the economically disadvantaged regions might fare in such a situation.

Because of the critical buffering role in world food production played by a number of the temperate countries not included in the FAO study, it is important to examine how their production capacity might be affected by climatic change in any overall attempt to obtain a long-term view of the prospects for world food supply and food security. Existing reports from industrialized countries do not provide an adequate base for this; they tend to be variable in their methodology and assumptions and, because they are often quite location-specific, present some apparently conflicting conclusions as to the effects of climate on agricultural production. Attempts at a more global view tend to founder on the inability of experts to agree on the direction of change (National Defense University, 1980).

It would certainly seem worth while to attempt to simulate the likely impacts of shifts in temperature and precipitation on the yields and area boundaries of the major temperate crops, and to relate these to risk and payoff to changes in land use. This might be done by modifying the FAO model, or by filling the gap through adapting other models simulating climatic change (Williams and Oakes, 1978; Hough, 1981; or Palutikof *et al.*, 1983). The scenarios in these papers are based, at least in part, on temperature isolines for constraints defining the length of the growing season, and, in Hough's model, on photosynthesis, as in the FAO Agroecological Zones Project described above. Stewart has followed the FAO approach in a study of the agroecological potential in Canada.

Two important points emerge from some recent assessments. First, as another Canadian study shows (Williams and Oakes, 1978), the most easily measurable effect of climatic change may be a shift in area – in this case a very large decrease for wheat. In Scotland there is a similar effect for oats, complicated by the influence of altitude (Parry, 1978). In order to measure the potential impact of such shifts one would first have to assess the new boundaries and patterns of production resulting from climatic change, and then recalculate yield for the predominant soil and climatic variables in the new zone of production. This leads to the second point, the soil factor. In higher latitudes land at the margin of cultivation is often of very low fertility, with low pH and anaerobic conditions due to poor drainage. It is by no means certain that a rise in temperature would enable large new areas of land to be brought into cultivation, even in relatively flat areas; the potential of upland areas may be more limited still. It is interesting to note that in the Canadian example the effect of a lower temperature regime on barley production would be less than that on wheat partly because the area from which barley would retreat would generally be one of poorer soils than that occupied by wheat. It might be possible to substitute another short-maturing crop tolerant of poor geomorphic conditions, such as rye, oats, buckwheat or triticale, for barley, but the likelihood of adequate payoff to such a change is uncertain.

4. Economic Sensitivity of Food Production Systems to Climatic Change

Because of the juxtaposition of natural and socioeconomic influences, food production systems can vary widely even within a single ecological region. Theoretically, this makes analysis of future production possibilities under a situation of climatic change quite complex. However, in practice, there are certain dominant farming patterns associated with given soil and climatic situations, which are dictated primarily by soil/climate/slope factors, and which have led to the establishment of marked dietary preferences for specific crops and livestock products. These originated in an historical context of geographical isolation, subsistence production, and limited human mobility; but, despite the introduction of new crops, the influence of urbanization, and improved storage and transportation facilities, they can still be observed today, not only in the Third World but even in industrialized countries (Oram *et al.*, 1979). This makes it possible to evaluate the probable economic impact of climatic change over large areas without having to deal with an infinity of commodities and microclimates (Figure 2).

Table II shows the distribution of area for 13 of the world's major food crops. *The dominance of cereals in the global production system is immediately obvious.* In no broad geographical region do they occupy less than two-thirds of the land under staple foods, and in North Africa and West Asia, Australia, Canada, Western Europe, and the U.S.S.R./Eastern Europe the proportion is in the neighborhood of 90% or more. On average it is higher in the industrialized than in the Third World countries. There, the food pattern, especially in some humid tropical subregions, is less cereal-oriented: for example, in Equatorial Africa, parts of Latin America, and the South Pacific, tropical roots and tubers, such as taro, yams, and cassava, occupy 40% or more of the land devoted to food production.

The species forming the cereal component of land use in the tropics also differ from those in the temperate countries, with rice and maize dominant in Asia, sorghum and millet in the drier regions of Africa, and maize in the more humid tropics, both in Africa and in Latin America. Only in the subtropics and in some high-altitude areas of the tropics are temperate crops, such as wheat and barley or white potatoes, of major significance.

The distribution of production of the major food crops is reflected in food consumption patterns, but with significant modifications due to socioeconomic factors and the adequacy of transport, refrigeration, and storage facilities. Thus, although cereals are so dominant in the land-use pattern everywhere, their importance for direct human consumption tends to decline with rising incomes, while that of meat, dairy products, fish, fruits, and vegetables increases. Cereals become increasingly crucial, however, for livestock feed. In poorer countries their chief use remains for human nutrition, since demand for expensive protein of animal origin is constrained by low incomes, and livestock of all types are mainly free-ranging in drier regions, with little or no concentrate feeding.

Nevertheless, over time, population growth, urbanization, and to a lesser extent income growth are forcing up demand for cereals and animal products in many Third World countries, with an increasing tendency to prefer wheat or rice as easily prepared foods of convenience for larger urban populations. This latter trend is causing embarrassing import problems for a number of African countries that cannot grow either crop easily (or at all) because of climatic constraints, and whose staple food production has been growing too slowly to match their needs.

Where food-deficit countries are short of foreign exchange, or suffer a climatic emergency, they may require food aid, but this may trigger or accelerate changes in consumption patterns because wheat is the key main surplus food commodity both in world trade and in aid, and has become the

Key

Main commodity grouping	Ecological grouping
▦ Wheat/barley	Temperate/Mediterranean winter rainfall zone (100–200-day growing season modified by altitude).
▨ Millet/sorghum/ groundnuts	Semiarid tropical summer rainfall zone (75–150-day growing season).
▥ Maize	Subhumid tropical summer rainfall zone (150–210-day growing season). Cropping pattern often modified by altitude.
▤ Rice	Lowland humid tropical – mainly Asia (180–365-day growing season). Rainfall may be bimodal with several or no dry months.
▥ Starchy crops/rice	Humid tropical – Africa. Length of growing season increases from north to south in West Africa. Rainfall may also be bimodal.
░ Mixed crops (India)	Range from warm temperate to humid tropical.
▣ Mixed crops (China)	Range from cold temperate to subhumid tropical.

Fig. 2. Developing countries grouped by major commodities and ecological zones (source: Oram *et al.*, 1979). In the temperate or tropical highland regions, both cold and aridity may limit the length of the effective growing season. In the lowland tropics, rainfall and high temperature are the dominant climatic influences. The map must be interpreted with caution as it illustrates very broad crop/country generalizations; for example, areas of desert are not differentiated.

TABLE II: World Areas of Major Food Crops (1981), and Distribution of those Areas within Geographical Regions and Selected Countries.[a]

Commodity	World area (10^3 ha)	%age area	Africa %age area[b]	Latin America %age area	Near East %age area	Asia (DME) %age area	Asian CPE[c] %age area	All developing countries %age area	Australia %age area	Canada %age area	U.S.A. %age area	U.S.S.R. & E. Europe %age area	W. Europe %age area	All industrialized countries %age area	%age of world total for crop
Wheat	239,381	25.9	5.7	12.3	51.7	14.3	22.0	17.3	68.4	55.6	30.6	41.1	36.2	38.7	60.2
Barley/ oats	106,561	11.5	4.1	2.1	17.6	1.1	1.7	3.1	24.8	32.5	7.0	31.2	40.0	24.0	83.9
Rice	144,915	15.7	5.2	1.0	2.8	40.1	31.2	25.4	0.6	–	1.5	0.4	0.6	1.3	3.4
Maize	134,024	14.5	17.3	35.0	4.8	7.1	15.8	14.6	0.3	4.8	28.2	5.5	12.6	14.4	39.8
Millet	43,203	4.7	17.8	0.2	3.9	9.0	3.3	7.3	0.1	2.0	0.2	1.7	–	0.7	6.4
Sorghum	47,762	5.2	13.8	6.5	9.9	7.9	2.3	7.4	4.0	–	5.2	0.1	0.3	1.9	14.4
All cereals	740,148	80.2	65.8	67.2	92.2	79.5	78.9	76.4	98.3	97.8	72.8	88.8	92.4	85.8	41.1
Groundnuts	19,329	2.1	6.1	0.9	2.5	4.2	1.9	3.3	0.1	–	0.6	–	–	0.2	0.5
Soybeans	50,219	5.4	0.3	14.4	0.3	0.8	5.8	3.9	0.3	1.3	25.2	0.8	0.1	7.8	57.5
Beans (phaseolus)[d]	24,805	2.6	2.4	10.7	0.6	4.6	1.4	4.1	–	0.2	0.8	0.4	1.3	0.1	10.0
Pulses	65,693	7.1	13.2	12.0	3.9	13.0	4.5	10.1	1.1	0.4	0.9	4.1	3.2	2.6	14.8
Potatoes	17,861	1.9	0.5	1.3	1.0	0.5	1.3	0.8	0.2	0.5	0.4	6.3	4.3	3.5	73.8
Cassava	14,054	1.5	8.6	3.5	0.1	1.5	0.5	2.5	–	–	–	–	–	0.0	0.0
Sweet potatoes	11,771	1.3	0.9	0.4	–	0.4	7.0	2.1	–	–	–	–	–	0.1	1.0
All roots/ tubers	48,164	5.2	14.6	5.5	1.1	2.5	8.9	6.3	0.2	0.5	0.5	6.3	4.3	3.6	27.7
Total	923,823	100	100	100	100	100	100	100	100	100	100	100	100	100	
%age of world food area			9.3	8.5	4.5	2.8	14.6	59.7	1.9	2.4	11.6	17.6	5.3	40.3	

[a] All main groups include areas of miscellaneous minor crops not shown separately. Therefore they do not add to the total in the last row.

[b] Egypt, Libya, and Sudan are included with the Near East group. South Africa is included in the total of industrialized countries.

[c] CPE stands for centrally planned economies, e.g. China. The 'Asia' column comprises the DME (developing market economy) countries.

[d] Phaseolus is shown separately, as it is the most widely grown pulse species. However, it is included under the total of 'pulses' and the areas should not be counted twice.

Source: *FAO Production Yearbook* (1981).

cornerstone of contingency policies for disaster relief. Thus wheat provides the main fallback for much of the world in terms of reserve stocks. Wheat and barley are also of great importance for food and feed in the industrialized countries, and are vital to the diet of the developing countries of North Africa and the Near East (where they occupy nearly all the arable area), as well as to Pakistan, Northern India, and the People's Republic of China with their huge populations. First priority in climatic modeling should, it is suggested, be given to these cereals and to maize, which is also widely traded and is grown in a great range of ecosystems. Maize is among the staple crops in parts of the semiarid tropics, a zone of high climatic risk where sorghum, millet, pulses, and groundnuts are also of major importance. This region merits high priority for assessment of the impact of climatic change.

By contrast, the crops of the lowland humid tropics (rice, cassava, sweet potatoes, yams, etc.) seem less likely to suffer climatic extremes, even if global temperature rises as a result of increased CO_2, because of the relatively low interannual variability of precipitation in that climatic region and the widely accepted assumption that the impact of climatic change will be more pronounced in high latitudes and/or at higher altitudes.

It seems evident that in attempting to make contingency plans for anticipated climatic change we have to look well beyond the year 2000, the year that most perspective studies have taken as their planning horizon. Assuming that no global holocaust supervenes, these studies show somewhat of a consensus that factors other than a global climatic change will exercise a dominant influence on both supply and demand for food. These are income growth and technological change on the supply side in both developed and developing regions; and income distribution and population growth, particularly in Third World countries, on the demand side.

5. Sensitivity of Production Systems to Climatic Variability

So far this paper has dealt mainly with sensitivity to potential climatic change. This process is likely to be relatively slow, especially if the global level of CO_2 emissions declines, as is apparent from studies that largely discount a detectable effect on climate within the next two decades, and possibly longer at current CO_2 levels (Clark *et al.*, 1982). If it takes a century for atmospheric CO_2 concentration to double, leading to an estimated 2 °C increase, a gradual process of adjustment seems feasible and it may be possible to plan to cope with it on more than an emergency basis.

However, it has been suggested that any secular change in climate may be accompanied by an increase in year-to-year weather variability. Not only might this make it more difficult to distinguish the real direction of long-term change, but it would greatly compound food security problems.

5.1. Present Patterns of Variability of Production

Table III shows coefficients of variation of yield for two recent historical periods, for 12 major crops or groups of crops, and a number of geographical regions. These crops represent the dominant components of food production systems in the world. There are striking differences in the variability of production of major crops among individual countries and regions. These emerge more sharply from Table IV, which shows the high coefficients of variation in the North Africa/Middle East region (with the exception of Egypt, which is entirely irrigated), and the three drier countries in Africa (Senegal, Tanzania, and Upper Volta). This table also illustrates how different countries vary in their dietary dependence both on cereals (Zaire, with its very high rainfall, is heavily dependent on root crops) and on domestic production for their food supply (Egypt, for example, depends heavily on imports of food).

The high variability of wheat, barley, and maize in the Mediterranean climate is striking, and illustrates the commanding influence of unreliable rainfall in a region where low temperature is rarely limiting. The FAO rates the West Asia/North Africa region as most critical among future food-deficit areas for rain-fed crop production. A similar high variability can been seen in production data from Chile, Southern Africa, and Australia, where wheat and barley are also grown largely in a Mediterranean winter rainfall climate; and, in Australia, these cereals have been pushed out to increasingly marginal areas by the development of new varieties and cultural techniques, resulting in lower average yields and greater year-to-year fluctuations in yield, but higher total production.

In its main areas of cultivation (South and Southeast Asia) rice shows relatively low variability: lack of rain is not usually a serious problem in those areas (although too much sometimes is), nor is temperature limiting. Disease, insects, and flooding are probably the main causes of low yields. Where rice is grown under more marginal conditions (upland, swamp, and flood plains), as in much of Sub-Saharan Africa and Brazil, its yields are more variable. This is due to a complex of soil factors, fluctuating water supply, and disease.

Variability among root and tuber crops, which, except for potatoes at high altitudes, tend also to be grown in warmer and more humid regions of Third World countries, is quite low. By contrast, pulses and especially leguminous oilseeds (groundnuts and soybean) tend to exhibit high yield variability, particularly in the Mediterranean climate and the semiarid tropics of Africa and South Asia, where low rainfall and high atmospheric evaporative demand produce water stress at frequent intervals. A relatively minor share of the total areas of these legumes is in the more humid tropics, where disease causes severe losses – for example in cowpea.

Although most industrialized countries have the majority of their cultivated area outside the tropics and subtropics (Australia is an exception), Table III shows that their annual variability of yield is not always lower, but for different reasons. Low autumn and spring temperatures, killing frosts, fluctuating snow cover, and variable rainfall are main causes of loss in Canada, the northern Great Plains, and parts of the U.S.S.R. In Australia and Argentina unreliable rainfall and high summer temperature, as well as frost in some areas, tend to limit yields. The low average variability of yields in the United States compared with other major developed countries shown in Table III is noteworthy.

It is significant that in many countries and for a wide range of crops the current variations in crop yields from year to year are larger than those predicted in the National Defense University (1980) study for a range of scenarios of global climatic change, from large cooling to large warming at some time far in the future. Even in the United States, with its low average annual

TABLE III: Coefficients of Variation of Yield for Two Periods: (1) 1961–69 and (2) 1970–77, for Major Food Crops in Selected Regions and Countries.

	Argentina		North Africa and Middle East		West Africa (Sahel)		East Africa		Southern Africa		South America	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Wheat	26.36	26.69	5.30	7.51	1.73 (14.07)	9.58 7.91	1.56	6.65	14.49	14.08	12.99	8.33
Rice	17.11	13.81	6.43	1.68	5.41 (7.21)	4.09 (12.75)	1.03	7.09	8.47	14.85	3.55	2.79
Barley	–	–	11.96	13.68	– (1.76)	– (2.78)	0.96	13.06	10.58	14.46	8.76	8.10
Maize	14.73	19.09	3.19	3.85	4.55 (11.74)	3.98 (4.90)	4.53	5.25	6.61	12.07	4.78	5.20
Millet	22.09	17.17	2.89	4.49	9.43 (5.04)	5.63 (8.13)	4.85	7.14	5.50	1.32	8.51	10.29
Sorghum	22.35	19.23	2.75	9.82	9.25 (5.89)	5.18 (7.85)	6.04	2.75	6.02	9.87	14.59	8.22
Soybeans	–	–	16.66	13.81	6.84	2.57	15.91	8.81	17.01	30.40	10.68	3.35
Groundnuts	22.20	24.84	8.65	6.97	12.30 (8.62)	12.26 (15.69)	6.61	11.04	6.35	7.22	8.41	11.09
Pulses (total)	19.29	11.91	6.05	7.28	13.75 (7.77)	15.34 (6.30)	2.32	4.47	3.55	2.20	4.28	5.26
Legumes (total)	–	–	6.09	6.75	11.61 (10.03)	12.06 (13.50)	1.89	2.80	5.36	5.06	4.86	1.88
Cereals (total)	–	–	6.02	7.29	4.37 (3.24)	4.39 (7.69)	2.64	2.48	5.03	10.21	3.18	4.28
Roots and tubers (total)	8.94	14.54	3.96	2.53	3.63 (4.42)	0.98 (5.68)	2.50	1.38	3.27	2.20	4.82	3.31

Source: FAO and USDA production data compiled by the International Food Policy Research Institute, Washington, D.C.

Table III (continued).

	Southeast Asia		India		China		Australia		Canada		U.S.A.		U.S.S.R	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Wheat	13.43	14.85	10.78	5.64	7.28	5.56	15.44	16.52	12.96	9.29	3.43	5.55	13.09	12.95
Rice	3.24	1.37	8.64	6.81	1.93	1.22	10.56	8.91	–	–	4.19	3.24	20.39	2.36
Barley	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Maize	3.26	6.05	4.78	12.09	4.32	7.16	11.23	6.26	17.12	8.45	3.78	10.15	24.40	8.43
Millet	16.12	7.07	9.03	15.13	6.42	2.89	19.51	10.76	–	–	–	–	17.80	37.73
Sorghum	34.09	15.03	7.52	6.29	21.06	3.00	19.86	16.45	–	–	6.36	10.09	12.81	22.07
Soybeans	3.39	4.37	–	–	–	–	–	–	–	–	–	–	–	–
Groundnuts	3.70	4.03	11.60	13.27	4.63	5.92	24.51	16.18	–	–	5.79	4.18	81.63	56.50
Pulses (total)	4.32	2.72	10.62	8.18	0.91	3.07	18.82	24.00	9.56	6.24	5.25	4.61	28.34	16.20
Legumes (total)	1.06	1.90	–	–	–	–	–	–	–	–	–	–	–	–
Cereals (total)	3.03	1.72	–	–	–	–	–	–	–	–	–	–	–	–
Roots and tubers (total)	2.56	3.93	9.73	4.04	5.17	3.56	8.03	4.18	4.09	3.58	2.61	1.83	4.98	10.00

TABLE IV: Variability in Staple Food Production, 1961–76.

	Staple food production instability		Probability of actual production falling below 95% of trend (%)	Correlation coefficient between total staple food production and consumption	Correlation coefficient between cereal production and total staple food production
	Standard deviation[a] (10^3 tonnes)	Coefficient of variation[b] (%)			
Asia					
Bangladesh	765	6.4	22	0.90	0.99
India	6,653	6.4	22	0.89	0.99
Indonesia	1,040	5.4	18	0.92	0.94
Korea, Republic of	445	7.1	24	0.20	0.96
Philippines	346	5.7	19	0.03	0.99
Sri Lanka	107	9.3	29	0.56	0.91
North Africa/Middle East					
Algeria	531	28.9	43	0.78	1.00
Egypt	282	4.5	13	0.29	0.96
Jordan	119	65.6	47	0.63	1.00
Libya	56	28.0	43	0.62	1.00
Morocco	1,156	27.2	43	0.98	0.96
Syria	702	38.8	45	0.92	1.00
Sub-Saharan Africa					
Ghana	121	5.8	20	0.98	0.93
Nigeria	958	5.7	19	0.99	0.92
Senegal	325	18.6	39	0.99	0.81
Tanzania	430	12.7	35	0.98	0.09
Upper Volta	128	9.8	30	0.95	0.99
Zaire	190	4.9	15	0.96	−0.21
Latin America					
Brazil	1,631	5.2	17	0.92	0.60
Chile	215	11.1	33	0.54	0.99
Colombia	126	4.4	13	0.51	0.85
Guatemala	56	6.5	22	0.51	0.99
Mexico	1,060	7.7	26	0.53	1.00
Peru	197	9.8	30	0.37	0.97

[a] Defined as the standard deviation of the variable $Q-Q$.

[b] Defined as the standard deviation of the variable $(Q-Q)/Q \times 100$.

Source: Valdes and Konandreas (1981).

variability, the production of basic food and feed crops in the 1983 harvest season was forecast to be reduced by almost half because of exceptional drought, leading to a rise in food prices of around 6.5%. Moreover, as the total volume of world production increases, the amplitude of seasonal fluctuations in production around the mean due to weather variability can also be expected to increase, whether there is any major shift in climate or not. In this connection it is important to note that even where coefficients of variation are relatively low, as in China and India, the size of the standard deviation, measured in tonnes, may be very large simply because of the size of the country and the volume of production.

The NDU study concludes that, at least for the next two decades, technological change is likely to have a much greater impact than climatic change on yields, and therefore on total production. If we accept this conclusion, then the influence of technology on product variability will be extremely crucial to the stability of food supply and thus to food prices.

5.2. *Interactions between Climatic Variability, Technological Change, and Other Sources of Production Instability*

In much of the literature on development there has been an implicit assumption that technological change has a stabilizing influence on crop yields. Recent studies by Barker *et al.* (1981), Mehra (1981), and Hazell (1982) challenge this assumption. Barker *et al.* argue that although some components of technological change, such as breeding for tolerance to adverse environments or irrigation, are yield-stabilizing when taken independently, they tend to raise the marginal productivity of recurrent inputs such as fertilizer or allow the spread of crops to areas previously thought to be submarginal, both of which tend to be destabilizing. In addition to weather variability, insect and disease damage (which may of course be correlated with weather variables as well as with crop variety) is a major source of loss, while uncertainties of water, fertilizer, and electricity supply – especially in developing countries – are important sources of fluctuations in yields. Thus there are complex and somewhat controversial interrelationships between yield-increasing technology, climatic variability, and risk. Further research of an interdisciplinary nature is needed to shed more light on this issue, since it could have crucial implications for agricultural research and the direction of new agricultural technology, which are likely to vary under different agroclimatic situations and probably among individual crops and production systems.

After looking further into this problem in relation to India, Hazell (1982) concludes that instability of total cereal production there has increased, in the ten years from 1967/68 to 1977/78, compared with the previous decade. While changes in the variability of individual crop yields within Indian states have been an important contributory factor to the increase in the coefficient of variation of total cereal production, he attributes the main source of aggregate instability to increases in various intercrop and interstate covariances affecting both crop yields and areas sown (the latter becoming more positively correlated with yields over time). He states, 'The sources of these fundamental shifts in patterns of association are difficult to identify, but they probably have less to do with the improved seed/fertilizer-based technologies . . . than with changes in weather patterns and the more widespread use of irrigation and fertilizers at a time when supplies of these inputs are not reliable.' Hazell (private communication) also suggests that the variance of total cereal production in the United States (due there mainly to yield rather than to area factors, and again largely to interstate correlations) increased between 1950–66 and 1967–80, especially with respect to maize. This could be due to the narrowing of the genetic base that has occurred in the breeding of modern maize hybrids. This reduction of genetic variability is not confined to maize varieties; it also applies to wheat. Lamb (1981) has suggested that the breeders have produced varieties that sharply maximize yield within a quite narrow range of weather conditions, but give lower yields than before under conditions outside that range, implicitly assuming a no-change climatic forecast. This is probably correct; as agriculture has become more sophisticated there has been a trend away from trying to breed for wide adaptability toward tailoring cultivars to local conditions, a fact noted by Dalrymple (1978) in his review of the development and spread of high-yielding varieties of wheat and rice. While geneticists at the International Agricultural Research Centres are now trying to develop materials with increased plasticity and tolerance of climatic adversity, the tendencies identified above must be a cause of future concern in relation to the response of crops to climatic change, increased climatic variability, or other climate-related factors such as pest and disease attack, or reliability of water supplies for irrigation and electricity generation.

The impact of year-to-year weather variation can also be very severe for livestock, especially range animals. Both north and south of the Sahara, losses of 50% in ruminant animal numbers have been reported; and, as has been pointed out by the International Livestock Centre for Africa (1983), the combination of deaths with semi-starvation of growing stock may impair overall production for a decade. In higher latitudes grazing animals are more likely to benefit than lose from a moderate warming trend, since this would probably increase pasture growth and extend the growing season in regions that might remain marginal for cultivation either because of high variability or, more likely, because of unsuitable soils. However, even in industrialized countries with more temperate climates and sophisticated systems of management it has been demonstrated that the incidence of several animal diseases is significantly correlated with weather variables, and that control of these diseases by farmers is not geared to cope with them, despite the availability of forecasts for some diseases (Ollerenshaw, 1981).

Thus despite the need for a long-term view with respect to climatic change, much must also be done to safeguard producers against the more immediate hazards of climatic variability. While the fact and magnitude of change are still uncertain, variability is always present and often high. Fortunately many of the policies that could prepare us better for the first contingency are also those that would provide some insurance against the second.

6. Planning for Future Climatic Contingencies

It is difficult to look far ahead with any confidence both because of the uncertainty attached to forecasting climatic change in itself, and because of the externalities unrelated to climatic change that are involved. There are grounds for optimism and for pessimism. These include the following.

6.1. Population Growth

According to the World Bank (1982), population is expected to rise, at least to around the year 2100, in the low-income and many middle-income developing countries, but may become stationary by the year 2000 in some higher-income industrialized countries. If climate changes only slowly there should be time to adjust to the increased world population, but if climatic shifts are rapid and accompanied by greater variability, a difficult situation can be foreseen early in the next century. In some areas of the humid tropics a tendency to cooler or drier climate might facilitate redistribution of population from overcrowded areas within countries to those now underpopulated because of diseases related to climate, but migration across national boundaries cannot be regarded as a realistic solution, as recent history shows.

Finally, it is evident that population pressure can act as a spur to the intensification of agricultural production and the adoption of new agricultural techniques, as in Western Europe, East Asia, and increasingly in South and Southeast Asia (Oram, 1982). The impact may therefore not be wholly adverse, provided that these new practices do not lead to environmental degradation; the worst examples of misuse of natural resources are in areas where increasing population is *not* accompanied by improved farming methods or by conservation measures.

6.2. The Potential of Agricultural Technology

The proportion of the increase in cereal production in Third World countries attributable to yield increase rose from 42% between 1960 and 1966 to 70% between 1967 and 1975. Although this dependency is likely to rise as new land becomes scarcer, great scope remains for yield improvement in the Third World, as can be seen from comparisons between yields of similar crops in closely analogous growing conditions in developed and developing countries; for example, the higher productivity of wheat in the Pacific Northwest of the U.S.A. compared with Turkish Anatolia; or the wheat/sheep system in Mediterranean Australia, compared with rain-fed systems in the Mediterranean basin itself. The main obstacles to higher productivity are often social (especially farming structure) or economic rather than technological. Should scientists be aiming at maximizing yields with risks of increasing variability, or at yield stability, with possible penalties in lower yield potential? The trade-off in terms of growth of food production clearly merits serious study.

Increased yield and labor productivity have been the main contributors to agricultural growth in developed countries since 1945, but yield shows signs of leveling off there, with increasing costs for each increment at the margin. Can new breakthroughs in research accelerate growth and/or reduce costs? Sundquist *et al.* (1982) suggest that the gains from further increases in nitrogen fertilizer use, the main contributor to yield growth (and variability) in the U.S. corn crop since 1945, are virtually exhausted. The genetic and physiological plasticity of plants referred to earlier gives ground for hope, but a corollary is that a determined effort will have to be made to screen the world's germ-plasm resources, and to conserve them for use in times of future need.

6.3. The Effects of Increasing Urbanization

Agricultural population has declined absolutely in developed and some developing countries and is declining relatively almost everywhere. This suggests, for one thing, that the proportion of total production required for rural subsistence will decline and that the changes noted earlier in the pattern of food consumption may accelerate. Labor shortages on the land may also increase, necessitating substitution of capital (mechanization) for labor, with uncertain repercussions on cost/price relationships and energy requirements.

6.4. Rising Real Incomes and Improved Income Distribution

Rising incomes in industrialized countries have led to increased demand for fruit, vegetable, and animal protein/feed-grain production, with consequent changes in land use and production systems. Similar trends are now evident in middle-income developing countries. Will diversification of the diet increase or reduce vulnerability to climatic change? Improved income distribution in poor countries leads initially to higher consumption of food staples, especially cereals, but eventually also to changes in the composition of the diet. This process could generate increased imports of cereals by low-income countries for both food and feed, whether through trade or aid.

6.5. Location of the Major Midlatitude Grain Producers

Although Argentina, Brazil, and Thailand may be able to increase their grain and oilseed exports, the main future burden (or benefit) of meeting increased demand for food and feed is likely to fall on North America, the principal grain-surplus area today (Table V). The heavy dependence on North America for world grain reserves (almost 80% of the 1975–77 marketable surplus) has increased the sensitivity of world food supply to the weather and climate of that region. This gives cause for concern in an uncertain future – especially if there is a likelihood of poor years occurring simultaneously in the major midlatitude grain-producing regions of North America, the U.S.S.R., and Australia, as Lamb (1981) has suggested.

6.6. Measures to Increase Food Security

In recent years the developed countries have shown greater concern for the food security of the Third World, although the main international aid instrument – the World Food Programme – still receives only a minor proportion of the world grain surplus, and much aid is provided bilaterally and with political strings. It has been hotly debated whether developing countries themselves should attempt to hold large grain reserves, since this is costly and inefficient; however, not to do this could put them at the mercy of unpredictable political and commercial forces in a time of global scarcity. Recently other proposals, such as an insurance against excessive departures of production from the normal trend, backed by the International Monetary Fund, give hope that cost-effective

TABLE V: Estimate of Annual Cereal Surplus and Deficit by Region and Economic Group: Averages (in 10^6 tonnes)[a] for 1969–71 and 1975–77.

Region/economic group	1969–71 average			1975–77 average		
	Gross surplus	Gross deficit	Net surplus/deficit[b]	Gross surplus	Gross deficit	Net surplus/deficit[b]
World total[c]	77.3	81.8	–4.5	153.1	123.3	29.8
Region						
North America	52.0	–	52.0	116.5	–	116.5
Europe	1.1	28.3	–27.2	5.3	38.1	–32.8
U.S.S.R.	–	4.4	–4.4	–	18.1	–18.1
North Africa/Middle East	–	9.3	–9.3	–	13.3	–13.3
Sub-Saharan Africa	3.1	2.0	1.1	2.3	3.3	–1.0
Latin America	8.3	7.3	1.0	12.5	12.2	0.3
Asia and Oceania	12.8	30.5	–17.7	16.5	38.3	–21.8
Economic group[d]						
Developed	68.8	49.1	15.7	135.5	77.3	58.2
Developing	12.5	32.7	–20.2	17.6	46.0	–28.4

[a] Including all cereals; aggregated from country-level estimates of production and domestic use.
[b] Gross surplus minus gross deficit.
[c] For 130 countries with available data on cereal production and domestic use.
[d] Following the FAO classification.

political solutions can be found. However, because politicians tend to take a short-term view, it is likely to be easier to mobilize aid for immediate emergencies than to convince national planners of the need to take long-term and possibly costly measures to safeguard world food supplies against a change in climate, the direction of which is hard to demonstrate or to predict with any certainty. There is an urgent need for teamwork involving climatologists, agriculturalists, and economists to monitor and assess the implications of climatic change and variability, and to ensure that these are understood by national and international policy makers.

This analysis suggests that to determine where the main economic and social impacts of climatic change on agriculture might occur and who the principal beneficiaries and losers might be requires two complementary approaches. Simply to concentrate on marginal areas could be misleading because these are often relatively unimportant in the global production scene.

The first step would be to look at global supply and demand for food with emphasis on cereals for food and feed, and on the major consuming and exporting countries. It would be necessary to postulate scenarios of the present and likely future locations of the main producing areas and production systems on various assumptions of changes in temperature and precipitation. For example, since it is uncertain whether a northward extension of the frost-free limit in the corn belt of the United States consequent on a 1 °C warming would result simply in a larger area under corn, or whether it would lead to a shift of production around its southern margin into other crops – perhaps cotton, peanuts, or horticulture – these alternatives would have to be tested. However, maize or another C_4 crop bred for adaptation to cooler climatic conditions might replace wheat in some other areas. A similar trend might occur in the EEC, perhaps reducing its expensive wheat exports and its feed and exotic fruit and vegetable imports. The potential impact of climatic change in the U.S.A. on land now 'idled' from production (presumably marginal at present prices) ought also to be examined. The irrigation potential would also require evaluation. The supply analysis would have to be disaggregated to include the major producing countries and commodities to show how commercial demand could be met. In a world of plenty the main beneficiaries might be the urban consumers, and a sensitivity analysis of supply shifts using the producer and consumer surplus technique might help to clarify this. In a tight grain situation prices would rise and richer countries would have first call; little might be left for concessional sales or aid. Internationally the major food-exporting countries would probably benefit substantially; and importers with weak bargaining power, and the poor in those countries, especially the landless laborers, would be the chief sufferers.

While an analysis along these lines would help to delineate the main global socioeconomic effects of climatic change, a different approach, focusing on risk and uncertainty, would be needed to define the most vulnerable *producers*. *Four marginal producer groups at particular risk can be postulated.* The first is located in the humid tropics, in lowland areas of Asia at the mercy of excessive precipitation and flooding, and in the Pacific and Caribbean. While prone to periodic violent catastrophe these regions nevertheless seem less vulnerable to excessive year-to-year variability of yield and less likely to be severely affected by climatic change than producers in drier or colder marginal areas. The second group, in the arid and semiarid areas of the tropics in Africa and South Asia, and in the Mediterranean climate of West Asia and North Africa, exhibits the highest annual variability. Semiarid Africa has been the main focus of famine for many years. Population pressure and nationalism are exacerbating this, and reducing flexibility for traditional means of risk avoidance such as nomadism. The nomadic herdsmen are now at great risk, and declining in numbers; their situation in relation to any possible shift of the rainfall distribution at the dry margins north and south of the Sahara should receive special attention. A third group, estimated to comprise some 10% of the world's population, comprises the farmers at high altitudes. These have received relatively little attention until recently: they live in a wide range of conditions at varying altitudes and latitudes, and have an equally diverse range of production systems. In some regions altitude may modify harsh lowland climates favorably; in others, as in West Asia, it may compound summer heat with winter cold. In this region nomadism and transhumance are also important systems of livestock management. It is extremely difficult to predict how such diverse and complex situations would be affected by climatic change. Finally, there are the cold margins at higher latitudes. These are mostly located in developed countries and their people are therefore somewhat less vulnerable to destitution or starvation from climatic change than those in the marginal lands of the Third World. However, they are still not immune to economic loss, as Carter and Parry have pointed out. Again, it may be the herdsmen who are at most risk, since their living is often beyond the fringe of cultivation. Whether they would benefit from a warming trend in climate would depend greatly on how this affected their hay and grazing, since adequate nutrition of range animals is a crucial buffer against low temperature (Blaxter, 1982). Almost certainly a cooling trend would be detrimental. I see no alternative to studying the special problems of each of these groups and the potential effects of climatic change on their production systems separately, because except in the broadest economic sense as part of the global food situation they do not impinge on each other.

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In analyzing abrupt and important climatic changes in the time range of years to millenia, this book deals with variations which have a direct impact on our present as well as near future. By combining observational data from geological, paleoclimatic, historical, archaeological and instrumental records, together with modern models and theories relating to the background and origin of these changes, the authors are able to present a thorough analysis of the climatic changes as well as a scenario of their origin. The book demonstrates that the changes studied are not global but regional or hemispherical features, that they cover time ranges in the order of 50-150 years, and that they exhibit an amplitude spectrum ranging from some parts of a centigrade up to about 10°C (or even more). It is these changes that have set the character of our paleoclimatic records, formed the background to our major changes during the 'present' (instrumental) period, and will control and characterize our future climate.

Contents: I. The Deglaciation Period: Contributions by B. E. Berglund, N.-A. Mörner, G. Lemdahl, S. Björck, B. Ringberg, K. Petersen, B. Ammann, J.-L. de Beaulieu, M. Coûteaux, K. Heine, and M. Servant. **II. The Holocene:** Contributions by T. B. Kellogg, L. Starkel, M.-J. Gaillard, J. Birnie, B. Fredskild, S. Payette, R. W. Fairbridge, D. Jäkel, H. Faure, O. van de Plassche, A. Philip and E. Iregren. **III. The Last 1,500 Years:** Contributions by H. H. Lamb, P. Ambrosiani, I. Renberg, D. J. Schove, T. S. Bartholin, W. Karlèn, R. W. Aniol, J. A. Matthews, B. Holmgren, I. U. Olsson, C. Pfister, J. Munzar, A. E. J. Ogilvie, O. Heikkinen, S. Lindgrén, R. Heino, E. W. Peterson, R. Keränen, L. Makkonen and T. R. Carter. **IV. Models and Mechanisms:** Contributions by V. Bucha, J. L. Lean, T. Landscheidt, H. Flohn, R. E. Newell, H. Savijärvi, R. G. Barry and G. H. Petersen. **Epilogue. Index.**

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