CLIMATE IMPACT ANALYSIS IN COLD REGIONS

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FOREWORD

The field of *climate impact analysis* has grown tremendously in the last decade. IIASA has been in the forefront of this development, generating many new ideas [1] and acting as a focal point for an international network of investigators [2].

One of the important results of the IIASA project on Climate Impacts is represented herein. It deals with the sensitivity of crop yields to climate, particularly to seasonal anomalies in temperature and rainfall. The IIASA methodology is being tested by collaborators in ten countries.

The IIASA project is part of the UNEP World Climate Impact Programme and has been supported by UNEP, the Austrian Government, and the United Nations University.

R.E. MUNN
Program Leader
Environment Program

References

[1] See, for example, *Nature* 1985, **316**, 106–107.
[2] See, for example, *Climatic Change*, 1985, **7**(1).

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Among the many factors influencing agricultural and forest productivity worldwide, the effects of weather and climate are of considerable importance. Anomalous fluctuations of climate, particularly thermal conditions, can have a marked effect in high latitude regions where activities are already constrained by low temperatures and a short growing season. Moreover, a consideration of possible future climatic changes (e.g. those that may result from increased concentrations of atmospheric carbon dioxide) adds a further dimension to the problem of assessing the regional sensitivity of crop production to climate.

In many regions, the impacts of a climatic event extend well beyond the direct, physical response of crops. For instance, the resulting changes in crop production may affect farm incomes, regional food-based industries, employment and prices, with the ripple-effects filtering through to other sectors of an economy and society.

This paper outlines a methodology for assessing the sensitivity of crop productivity to climate, and shows how this may be elaborated to include a consideration of the economic and social implications of crop productivity changes. The approach utilizes a hierarchy of models, each one representing a stage in the cascade of responses induced by an anomalous climatic event. In particular, three sets of models are identified – of climatic changes, of climate impacts on potential and actual yield, and of the downstream economic and social effects of these. By considering a range of credible future climatic scenarios, it is possible to produce estimates of impact and to examine a range of adjustments that might be of interest to the agricultural planner or decision-maker.

The methodology is being tested in ten countries as part of a two year IIASA/UNEP research project. Full results will be published in two volumes in 1986.

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INTRODUCTION

For as long as man has cultivated crops or planted forests, the returns on these activities have been subject to the vagaries of weather and climate. In this paper we illustrate a methodology for assessing the sensitivity of agricultural and forest productivity to climate in high latitude regions and show how this may be extended to include a consideration of the economic and social implications of crop productivity changes.

The Earth's climate varies over both space and time. Most obvious is the spatial variation of climate which is vividly expressed in the regional pattern of the earth's natural terrestrial ecosystems. It is also fairly clear that most agricultural crops favour a natural range of climatic conditions to give optimum yields and are therefore best suited only to particular regions of the world.

Climate also varies over time. Our own experience tells us that the weather of one year is seldom similar to that of the next. These inter-annual fluctuations of climate may be superimposed on medium-term changes occurring over periods of years. For example, a sequence of predominantly cool years (relative to the long-term mean) may be followed by a series of mainly warm years, or wet years by dry years. The former situation is illustrated in Fig. 1 for the meteorological station at Stykkisholmur in Iceland, where one can observe a pronounced change in mean annual temperatures to warmer conditions shortly after 1920. Also noticeable are the strong inter-annual temperature variations, a characteristic of much of the high latitude zone, and of considerably greater magnitude than the variations recorded at lower latitudes (Kelly et al. 1982). Finally, over the long-term, we can identify climatic changes that have been more enduring and of greater magnitude still, such as the Medieval Warm Epoch (between about 1150 and 1250 A.D.) or the Little Ice Age (from the sixteenth to eighteenth centuries) in northwest Europe (Lamb 1977).

Given that climatic variations are known to have occurred in the past, does this knowledge offer us clues for the future? Because we cannot

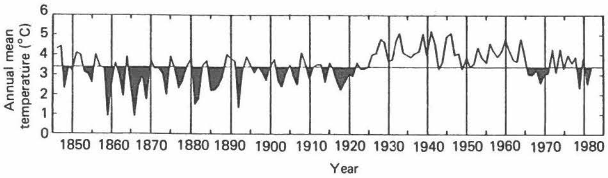

Fig. 1. Annual mean air temperature at Stykkisholmur, Iceland (1846–1982). Values below the mean are shaded. (Source: Bergthorsson 1985).

yet forecast the future climate we should, at the very least, assume that such variations will continue to occur, and use them as a basis for any assessment of impact.

One issue that is of global importance concerns the response of agroecological systems to climatic variations. Fluctuations in climate from year-to-year may, at some locations, contribute to large inter-annual variations of crop productivity, forest growth or grazing potential. Even accounting for long-term changes in farm management and technology which have brought about substantial increases in crop yields in many regions, these do not appear to have reduced crop sensitivity to climate. For example, Mukula (*In* Parry et al. (eds.) 1986a) has compiled a continuous yield series for barley in northern Finland from 1810–1983 (Fig. 2). Despite a significant rise in average yields since the second World War, inter-annual variability of yield, as measured by the coefficient of variation, has also increased (note, for instance, the contrast between yields recorded in the two pairs of consecutive years 1961–62 and 1980–81). Thus, present intensive production seems to be, in certain cases, more vulnerable than the earlier, extensive production.

In the following we will be examining this type of vulnerability, outlining an integrated approach to climate impact assessment in high latitude regions.

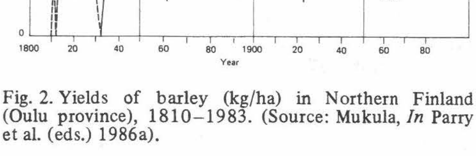

Fig. 2. Yields of barley (kg/ha) in Northern Finland (Oulu province), 1810–1983. (Source: Mukula, *In* Parry et al. (eds.) 1986a).

An integrated approach to climate impact analysis

One way of studying the interactions between climate and society is to attempt to trace the effects of a climatic event as these cascade through physical and social systems, and are disguised and modified by various sets of intervening factors. An example of this approach is offered by Warrick and Bowden (1981), tracking the impacts of drought occurrence in the U.S. Great Plains. They traced a variety of pathways that drought impacts could take, spanning a variety of spatial scales (from local to global) and a variety of systems (from agricultural to social). From the source of impact in the lower left of Fig. 3 the pathway can be traced from the first-order (direct) biophysical impact to the higher-order (less-direct) effects on society. What starts as meteorological drought, becomes agricultural drought, and subsequently perhaps a perturbation in the wider economy. While this example may not be particularly appropriate for high latitude regions, we could easily replace *drought* impact by the impacts of *cool periods, wet spells* or *severe frosts*.

The scheme presented above serves merely as a retrospective summary of the observed interactions between climate and society, but it is structured in such a way as to offer a logical framework for practical investigation of these. The cascade of effects stemming from an anomalous climatic event work their way through a hierarchy of responses (e.g. climatic anomaly → crop yield → farm production → farm income → regional agricultural sector → regional economy → national economy → society). In order to understand and evaluate each level of response, we need to develop a hierarchy of models that can simulate these impacts. In particular, we can idenfify three sets of models – of climatic changes, of climate impacts on potential and actual yield, and of the

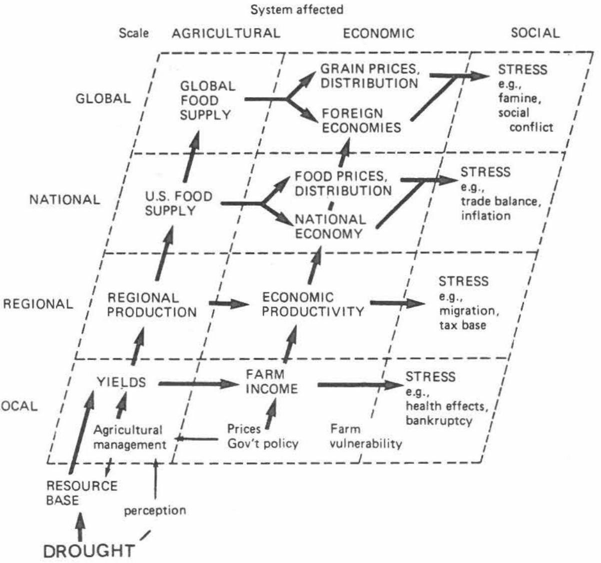

Fig. 3. The hypothetical pathways of drought impacts on society. (Source: Warrick and Bowden 1981).

downstream economic and social effects of these (Fig. 4).

Scenarios using outputs from climate models (e.g. atmospheric general circulation models) or data from instrumental climatic records, are used as inputs to agroclimatic models to predict potential or actual yield responses to climatic change. To trace the downstream effects of yield changes, outputs from the agroclimatic models are used as inputs to economic models (farm simulations, regional input–output models, etc.). It is then possible to consider what policies best mitigate certain impacts at specified points in the system.

This is the approach adopted by a two year project currently in progress at the International Institute for Applied Systems Analysis in Laxenburg, Austria, jointly funded by IIASA and the United Nations Environment Programme. The project has focused on climate-sensitive areas in the semi-arid, high latitude and high altitude zones. In this paper we draw on high latitude examples only, and concentrate on the top part of Fig. 4, namely first-order impacts, though we illustrate towards the end of the paper the value of the whole integrated approach.

Climate-sensitive regions as an appropriate laboratory

A useful focus for studies examining biomass responses to climatic fluctuations considers those regions where yearly productivity exhibits a high degree of sensitivity to inter-annual variability of climate. Such sensitivity may be especially marked close to the physiological limit of a plant's tolerance. If a plant is cultivated on a commercial basis, then a fluctuation in productivity is usually translated into profit or loss.

The criterion for selecting a region as being »climate-sensitive» is, of course, crop-related; the climate tolerances of one crop may be of a quite different character than those of another. For instance, in northern Japan the risk of damaging low summer temperatures makes rice cultivation a precarious activity at latitudes around 45° N (T. Uchijima, *In* Parry et al. (eds.) 1986a), while in Finland the northern limit of the boreal forest zone, also temperature-related, occurs close to 70°N (Hämet-Ahti 1981). Thus we choose our »laboratory» according to the climate tolerance of the major crops of the region.

Delimiting impact areas

In some regions it may be valuable for planning

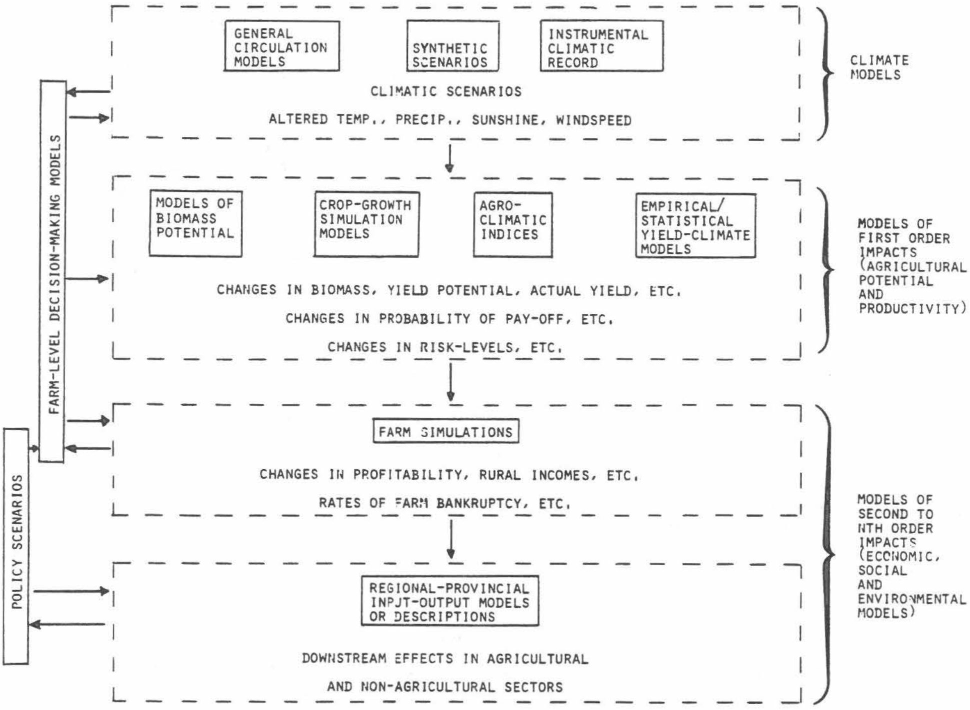

Fig. 4. A hierarchy of models for the assessment of climate impacts and the evaluation of policy responses. (Source: Parry 1985).

purposes to be able to locate those zones that are particularly sensitive to climate. We can delimit these margins as lines on a map. For example, there are several schemes that utilize long-term climatic averages to classify global vegetation zones, such as the well-known Köppen climatic classification (Köppen 1936) or the Holdridge Life Zones Classification (Holdridge 1964). The latter classification attempts to represent the broad distribution of terrestrial ecosystem complexes as a function of mean annual biotemperature (annual average biotemperature is defined as average annual temperature discounting unit-period temperature below 0°C) and mean annual precipitation. Given a sufficient regional coverage of climatic data these zones can be mapped geographically.

Similar mapping exercises have been conducted using various agroclimatic indices to provide measures of agricultural land suitability, or estimates of potential biomass productivity. The maps so obtained offer a useful geographical frame of reference within which to begin more specific assessments of plant responses to changes in climate.

Of course, most of these maps are based on climatic »normals», averaged over perhaps several decades. Yet we know that climate is not static but can be highly variable over time. Presumably the theoretical location of each mapped zone is shifting over space from year-to-year, from decade-to-decade and from one »normal» period to another. Obviously the inertia of vegetation ecosystems is such that they do not shift location from year-to-year. Nonetheless, there is abundant palaeoecological evidence to suggest that high and middle-latitude natural vegetation zones underwent long-term shifts during past glaciations.

When we turn to agricultural crops, however, we are normally dealing with annual plants the productivity of which will be influenced by climatic conditions within a single growing season.

If we were to map annual isolines of crop productivity or yield, these certainly *would* shift from year-to-year. Close to the limit of cultivation, these shifts could mean that crop production in one year may be satisfactory (i.e. yield a profit) but in another year may be inadequate (i.e. yield a loss).

Another way of viewing the sensitivity of crops to climatic variations is to consider the probability or risk of occurrence of adverse (or beneficial) events such as crop failure or shortfall from some critical level of output. In situations where crops are cultivated close to the limits of viability, such activities are likely to involve a high measure of risk. Furthermore, in high latitude regions it can be shown that while mean temperature changes in a broadly linear fashion with increasing latitude and altitude, the risk of occurrence of some critical level of temperature can have strongly non-linear aspects. There may thus be substantial differences over space in the probability of harvest failure or success, of profit or loss (see, for example, the case of oats cropping in the southern uplands of Scotland; Parry and Carter 1985).

DEVELOPING THE CLIMATIC SCENARIOS

If we are to undertake any assessment of crop sensitivity to climate, we require some realistic methods for evaluating both the present-day climate and the likely climatic changes that may occur in the future. Instrumental meteorological observations are today recorded regularly at a large number of locations. In high latitude regions the spatial coverage of stations is fairly good and some records extend back well into the last century or beyond. Thus, these records serve as a firm basis upon which to evaluate the impacts of medium- and short-term climatic fluctuations which have actually occurred in recorded history. Moreover, they provide the reference data against which to compare different climatic scenarios. In the IIASA project, the standard 30-year period, 1951–80, has been adopted as the reference (or baseline) period.

We can identify three types of climatic scenarios that are of particular use in climate impact analysis, representing the first level of the model hierarchy: instrumental scenarios, synthetic scenarios, and general circulation model scenarios.

Instrumental scenarios

Since we are interested in evaluating impacts of possible future climatic change, then one method of defining a future climate (scenario) is to examine the instrumental record. By searching the record for climatic anomalies: perhaps a sequence of particularly unusual weather-years (e.g. the anomalously warm »golden» 1930s in Finland) or a single extreme year (e.g. 1816, »the year without a summer» in the U.K.), we could use these events (which we know have occurred in the past and presumably could recur in the future) as scenarios of future climatic change. Such a procedure has also been used to identify past anomalies that may serve as analogues of typical conditions following a possible CO_2-induced climatic warming (Wigley et al. 1980).

Synthetic scenarios

An alternative method of simulating the climate is to use synthetic data. Depending upon the purpose for which they are required, these can be generated to simulate a variety of conditions. For example, stochastic procedures can be used to produce an artificial set of climatic data given prespecified values of the mean and variance. Synthetic scenarios are also of particular use for testing the sensitivity of impact models. For instance, we can simulate a climatic change by altering climatic data in a systematic, albeit unrealistic, way (e.g. increasing mean annual temperature in 0.5°C increments) and could study the plant responses to these changes. This approach has been adopted by Sirotenko (*In* Parry et al. (eds.) 1986a) for evaluating the sensitivity of spring wheat yields to temperature and precipitation in the U.S.S.R.

Scenarios from general circulation models

A third potential source for climatic data can be found as the outputs from models of the atmospheric general circulation (GCMs). These models are based on the fundamental dynamical equations describing large-scale atmospheric motion. By incorporating these, together with boundary conditions at the earth's surface (such as the sea surface temperature, sea ice distribution, surface elevation and albedo) and numerical methods which give a spatial resolution of a few hundred kilometers, GCMs have been reasonably successful in reproducing the large-scale features of the observed distribution of climatic variables (Gates 1984).

One use of GCMs has been to estimate the climatic changes that might be expected given an increase in the concentration of atmospheric carbon dioxide. Most experiments consider the effects of a doubling of CO_2 and the models produce outputs for the whole globe over a network of grid points, showing the simulated change in seasonally-averaged climatic variables (e.g. temperature, precipitation rate, cloud cover) between 1 x CO_2 and 2 x CO_2 equilibrium conditions.

To date, most GCMs estimate a mean annual global warming of between 1.5 and 4–5°C in response to a CO_2-doubling (Carbon Dioxide Assessment Committee 1983), but the models project increases that are considerably greater at high than at low latitudes, thus re-emphasizing the particular sensitivity of these regions to climate and suggesting quite substantial implications for agriculture and ecosystems.

MODELLING FIRST-ORDER IMPACTS

In order to estimate the impact on agriculture of the types of climatic scenarios defined above, we move to the next tier in the hierarchy, requiring the use of models of plant response to climate.

Estimating plant responses to climate

There is a range of agroclimatic models which can be utilized to estimate plant sensitivity to climate. These can be regarded as mathematical transfer functions of varied complexity used to translate climatic information into a measure of productivity or potential. We can identify three main categories of agroclimatic model.

The simplest method of relating agroclimatic resources to climate is to combine or manipulate meteorological variables into an *agroclimatic index*. Such derived variables can be quite useful as indicators for identifying areas suited for various crops, since they can incorporate, within a single term, those climatic variables to which plant growth and development is particularly responsive. However, indices can only be used quantitatively to evaluate the likely impact of climatic changes if they are related directly to yield data, as in the empirical statistical modelling approach described below. Such a procedure has been used in developing the agroclimatic resource index (ACRI) produced for Canada by G.D.V. Williams (Science Council of Canada 1976).

Empirical-statistical models are developed by taking a sample of annual crop-yield data from a certain area, together with a sample of weather data for the same area and time period, and relating them through statistical techniques such as multiple regression analysis. These models can have a high practical value for large-area yield prediction and usually require only modest quantities of data and little computational time. However, the approach does not easily lead to a causal explanation of the relationships between climate and crop yield, tending to identify only those variables that show a strong association with crop yield on short time scales. This can be a shortcoming where the climatic variable that is most limiting to a crop (e.g. temperature for spring wheat in the Canadian Prairies) is not the one that causes the main inter-annual variability (i.e. precipitation in the Prairies). Thus, in this example, the possible impact of a change in mean temperature might be underestimated because a model has been developed under conditions of particular sensitivity to precipitation, not temperature changes. Such models are probably most valuable for climate impact assessment in areas where crop yields are highly sensitive to a *single* variable, and where that variable is of particular interest in impact analysis (e.g. temperature and hay yields in Iceland; Bergthorsson 1985).

Simulation models generally incorporate, through a set of interrelated expressions, those mechanisms and interactions that are important for plant and crop growth. The explanatory nature of such models (a major virtue compared with other types) is based on an understanding of the basic processes, such as photosynthesis and transpiration, and their relationships with water supply, temperature, solar radiation and other factors. Certainly, many of the relationships are well-established and accepted, but inevitably there are some that are either little-understood, or of secondary interest to the modeller, and these tend to be represented as empirically derived relationships. Hence, the distinction between empirical-statistical models and simulation models tends to be somewhat blurred. A general disadvantage of the more process-oriented type of model is the requirement for quite detailed meteorological and physiological

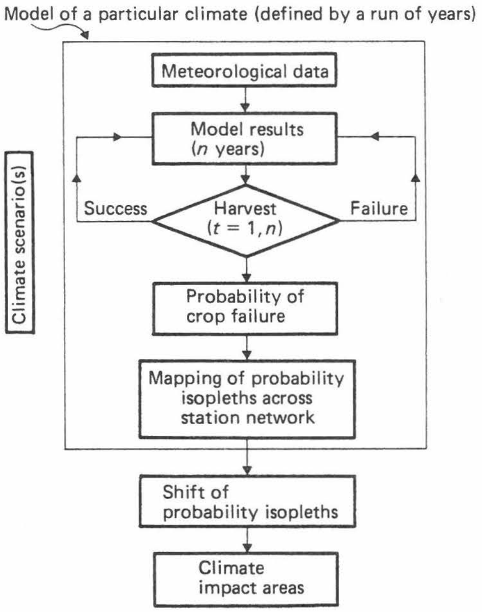

Fig. 5. Steps in the identification of climate impact areas using a spatial mapping approach. (Source: Parry and Carter 1984).

data, first to validate a model and then to apply it for specific locations (Carter et al. 1984).

Linking models of climate to models of plant response

A logical step towards estimating plant responses to climatic change is to use the data obtained for various climatic scenarios as inputs to agroclimatic models. Moreover, we can combine the use of agroclimatic models with the spatial mapping approach mentioned before in order to assess areas of impact. This is illustrated schematically in Fig. 5. In this case the weather for a number of years, described by a set of meteorological data, can be expressed as a probability of loss or reward using appropriate crop models. When calculated over a network of stations this probability level can be mapped as an isopleth.

The spatial impacts of climatic change can be assessed by using climatic scenarios as inputs to the same crop models, enabling us to re-map the boundary isopleths. The geographical shifts of the isopleths that are produced for the changed climate delimit areas of specific climate impact. The isopleth-shift approach can be applied to boundaries of vegetation zones, of agricultural suitability and of crop yield potential. We now consider some examples of the approach for a variety of climatic change scenarios.

The Boreal Forest Zone. Kauppi and Posch (1985) have related tree growth in the boreal forests of Finland to the effective temperature sum (ETS) above a base of 5°C in a simple empirical-statistical model. By delimiting the boreal forest zone according to minimum and maximum ETS requirements under Finnish conditions (600 and 1300 growing degree-days, respectively), they have mapped the zone across a 4° x 5° latitude-longitude grid for the entire latitude band 38° N to 70° N (Fig. 6). Comparison of this zonation with a published vegetation map (Hämet-Ahti 1981) shows that although the calculated northern boundary fails to include forest areas in Kamchatka and Alaska, the match is reasonable for land areas extending from Western Canada eastwards to Western Siberia.

Using the results from a GCM experiment for a 2 x CO_2 climate (Hansen et al. 1984), they re-mapped the ETS boundaries for the same grid network. Preliminary results (Kauppi and Posch, *In* Parry et al. (eds.) 1986a) indicate a substantial shift in the zone, displaced northwards by between 500 and 1000 km (Fig. 6). In Finland it would mean that the location of the northern timberline today would mark the southern boundary of the boreal forests under a 2 x CO_2 climate, implying dramatic consequences for Finnish forestry and forest-based activities.

Canadian Spring Wheat and U.S. Corn Belts. The isopleth bounding the wheat-maturing zone in Canada (the area suited to wheat production not constrained by soil or terrain) has been estimated by Williams and Oakes (1978) and is based on biophotothermal timescale equations which consider the date of first fall freeze, growing season temperature and radiation conditions. Newman (1980) defined the limits of the U.S. Corn Belt in terms of minimum frost-free period for maturity, minimum and maximum thermal requirements, and moisture constraints. Both crop zones are shown as shaded areas in Fig. 7. In this example, a synthetic scenario of a 1°C cooling throughout the year has been used to simulate the shift of crop zones. In Canada, the shift would mean a reduction in the area suited

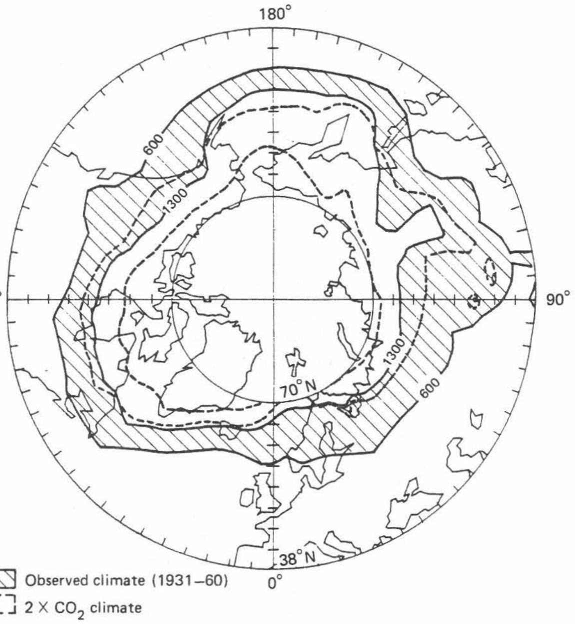

Fig. 6. Hypothetical shift of the boreal forest zone for a doubled CO_2 climate scenario. The zone is delimited between effective temperature sum isopleths of 600 and 1300 degree-days. (Source: Kauppi and Posch, *In* Parry et al. (eds.) 1986a).

to spring wheat of about one-third. In the Corn Belt, a 1°C cooling with no change in precipitation would reduce moisture stress at the drier margin, while reducing the growing season at the cool margins. The combined effect would be a shift of the belt in a southwesterly direction of about 175 km.

Presumably, although not depicted in Fig. 7, since the Spring Wheat Belt extends southwards over the border into the United States, there would be a shift of the southern limit also, probably into regions where winter wheat is presently the dominant cultivar, or into areas vacated by corn.

Spring wheat yields in Saskatchewan. Within the Spring Wheat Belt of Canada, the province of Saskatchewan is the major wheat producer, accounting for about one-eighth of the world's traded wheat. Recently, some experiments have been conducted to estimate the effect of CO_2-induced climatic change on potential spring wheat yields in Saskatchewan (Blackburn and Stewart 1984), using a crop growth simulation model developed by FAO (1978) and modified by Stewart (1981).

The »normal» period 1941–70 was adopted as a reference against which to compare estimates of future climate and production. The climatic scenarios utilize GCM computations of temperature change obtained by Manabe and Stouffer (1980) and adjusted to represent a 2 x CO_2 atmosphere. These temperature changes were added to the 1941–70 monthly climatic normals and used in the yield computations. Monthly precipitation changes were simulated synthetically at three levels: normal (100 %), and at 70 % and 130 % of normal (for the whole year).

The experiments indicate yield decreases for all three scenarios: 40 to 50 percent for a 2 x CO_2 temperature increase (with no changes in precipitation), 70 to 80 percent with 70 % precipitation, and up to 20 percent with 130 % precipitation (Fig. 8). These results, while preliminary, suggest that drought, not temperature, would be the most important limiting factor for spring wheat production in southern Saskatchewan. However, the temperature increases, by lengthening the frost-free growing season by about 30 days, would probably render present-day varieties ineffective and poorly adapted to the changed conditions.

Rice cultivation in Japan. Rice is grown in most

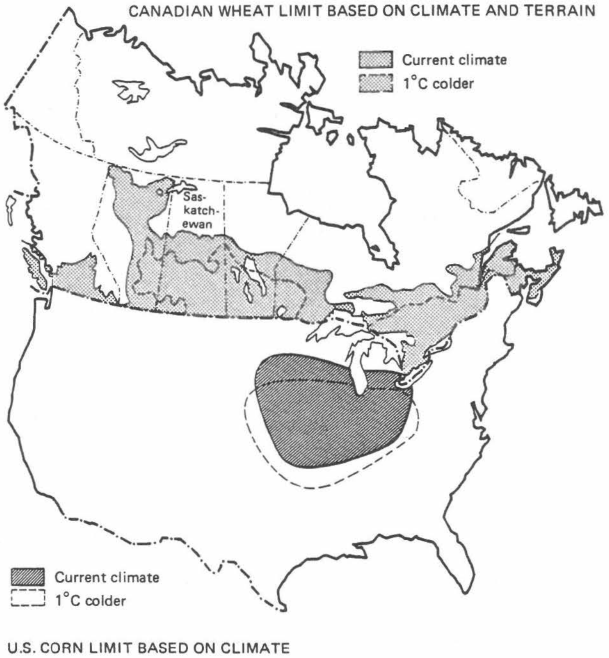

Fig. 7. Estimated shift of the Canadian Spring Wheat Belt and the U.S. Corn Belt in response to a 1°C cooling of annual temperature. (Sources: Williams and Oakes 1978, Newman 1980).

parts of Japan and field experiments indicate that potential rice yield relates closely to temperature conditions and sunshine duration during the growing period. Combining these effects into a climatic index of rice productivity, T. Uchijima (*In* Parry et al. (eds.) 1986a) has conducted tests to determine the sensitivity of potential rice yields to below average summer temperatures and radiation. For example, temperatures in the summer of 1980 were below average across the whole country. The climatic index for that year is mapped in Fig. 9 and shows how the relative impact of cool summer temperatures on potential yields increases markedly from south to north. In the northernmost

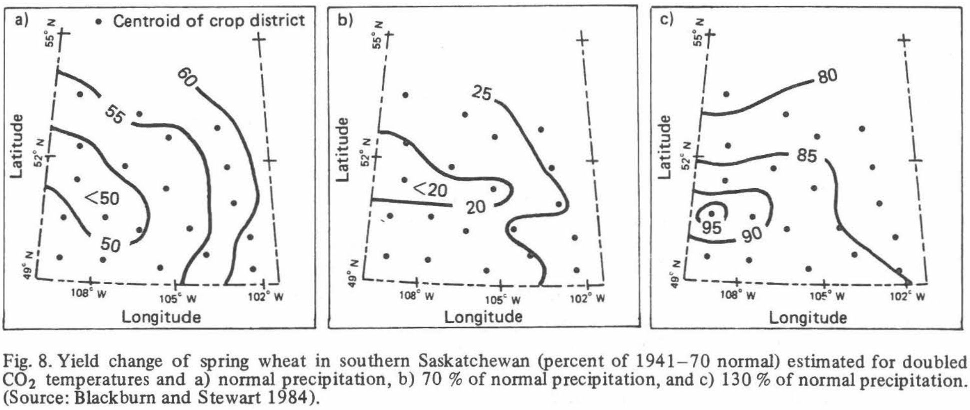

Fig. 8. Yield change of spring wheat in southern Saskatchewan (percent of 1941–70 normal) estimated for doubled CO_2 temperatures and a) normal precipitation, b) 70 % of normal precipitation, and c) 130 % of normal precipitation. (Source: Blackburn and Stewart 1984).

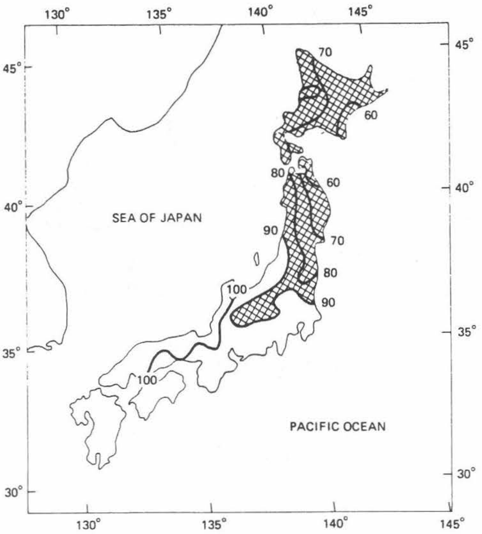

Fig. 9. Changes in the climatic index (percent of normal) during a cool summer damage year (1980) in Japan. (Source: Sugihara 1982).

island, Hokkaido, this high sensitivity of rice production to climate is accentuated by a high inter-annual variability of summer temperatures (the coefficient of variation is more than twice that in southern districts; Uchijima 1978). Moreover, the return period of a 1980-type anomaly in Hokkaido (calculated from a temperature record extending back to 1889) is as high as about one year in eight. In terms of national agricultural planning, Uchijima (1978) notes that a small reduction in rice production could be expected to be balanced by technological progress, but this »seems to be very difficult in the northernmost part of Japan, where severe declines in temperature occur».

Oats cultivation in Scotland. In maritime upland areas of northwestern Europe (as in Japan), relatively small increases in altitude generally result in marked foreshortening of the growing season and a great reduction in the intensity of accumulated warmth. Using the long Central England temperature record, adjusted to Southern Scotland, along with a knowledge of the temperature lapse rate in this region, Parry and Carter (1985) have calculated annual accumulated temperatures at different elevations for the period 1659–1981. Assuming crop failure to occur when accumulated temperatures fail to achieve a minimum threshold value (970 GDD for oats) it is possible, from the 323-year record, to represent the mean probability of failure for different elevations as a »risk surface».

By delimiting a high-risk zone as the area where the frequency of crop failure lies between 1 year-in-10 and 1-in-50, they have mapped its location for the region by constructing isopleths of these risk levels. However, this zone represents long-term mean conditions only and does not reflect the climatic perturbations that have occurred during the last three centuries. When the risk isopleths are re-drawn for the warm (1931–80) and the cool (1661–1710) periods (two instrumental scenarios), the geographical shift of the high-risk zone is lineated. This produces an altitudinal movement of about 85 m such that whereas »in the late seventeenth century a large proportion of the foothills (above about 280 m) was submarginal with respect to 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» (Parry and Carter 1985).

INTEGRATING THE BIOPHYSICAL, ECONOMIC AND SOCIAL IMPACTS OF CLIMATIC CHANGE

Up to this point we have considered only two stages of impact assessment, namely the selection (from several types) of a scenario of climatic change (climate model) which supplies climatic information to one of a variety of agroclimatic models in order to evaluate first-order biophysical plant responses to climatic change. The work, in progress in the IIASA/UNEP project, has demonstrated that it is possible to add additional tiers to this model hierarchy, using yield changes as inputs to one or more economic models. It then becomes possible to generate estimates that may be more meaningful to the policy and planning community. In particular, it permits a consideration of appropriate policies that may be available for mitigating or exploiting certain impacts. The following gives a foretaste of the approaches employed in high latitude regions. Published results will be available in 1986 (Parry et al (eds.) 1986a).

For example, in Saskatchewan further climatic

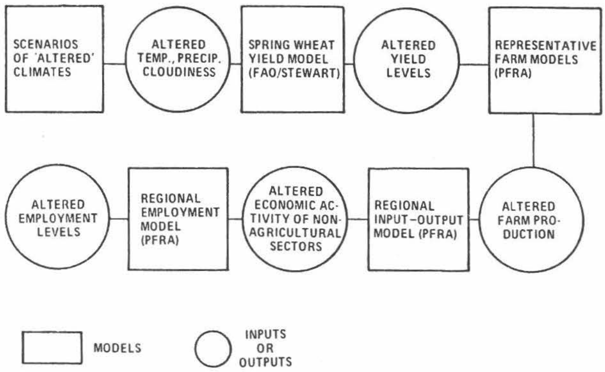

Fig. 10. Hierarchy of models for assessing impacts of climatic change in Saskatchewan (Source: Fautley, *In* Parry et al. (eds.) 1986a).

scenarios of altered temperature and precipitation have been used to estimate altered yield levels of spring wheat using the FAO/Stewart model (described above). The altered yields are input to farm level models and converted to production figures, categorized according to soil zone and cereal farm size. These are then aggregated to give provincial production and commodity changes which are suitable as inputs to a regional input–output model. Finally, changes in output levels for various economic sectors are translated into changes of employment using a third, employment model (Fig. 10). All three models are used operationally by the Prairie Farm Rehabilitation Administration (PFRA) based in Regina, Saskatchewan, and the experiments are being conducted by R. Fautley.

In Japan a similar procedure has been adopted whereby rice yields are estimated using empirical-statistical agroclimatic models (Z. Uchijima, H. Seino, and T. Uchijima) for a number of climatic scenarios and are input to a National Rice Model for Japan (H. Tsujii). This is an integrated regional model incorporating technological, economic, fiscal and political factors. The model has been disaggregated into regional models in order to identify regional differences in climatic effects on production. The inclusion of fiscal and political variables should allow investigators to inspect some of the policy implications of climate impacts in Japan.

The profitability of crop cultivation on farms in Finland has been examined by Varjo (1973) for barley and oats. He utilizes a measure of »gross margin» which represents the income that remains for a farmer once his variable expenditure (i.e. costs of machinery, seed, fertilizer, wages paid to outside workers, etc.) has been deducted.

Calculation of the gross margin requires data on marketable yield of a crop, its market price and the variable expenditure involved in its cultivation. Varjo has developed regression equations relating crop yield to climate and has estimated the crop yields that could be expected in two contrasting regions of Finland, given a number of climatic scenarios. Fixing the market price and variable expenditure at 1980 levels, he has determined the gross margin that would result under each climatic scenario.

Of particular concern to planners in the U.S.S.R. is the adaptation of agriculture to a changing climate, since adverse future changes in crop production will require a centrally coordinated and purpose-oriented system of mitigation measures. Experiments are currently being conducted by V. Kiselev, using a regional agricultural optimization model to assess the impacts of specified climatic changes. The model provides estimates of the regional impacts of climatic conditions simulated by a number of production scenarios in terms of the necessary adjustments in area-planted and productivity (compared with the present-day) required to maintain output at prescribed levels. Model outputs include the estimated impacts of climatic change on the structure of agriculture, crop-mix and altered crop requirements, and should facilitate an examination of some of the possible options available to planners and decision-makers for responding to future climatic change.

An assessment of the sensitivity of livestock production to climate is, if anything, more complicated than a consideration of crop sensitivity. Investigators in Iceland, where sheep and cattle account for about three-quarters of the value of agricultural production, have concentrated on three important aspects: grass growth and hay production, winter fodder requirements, and grazing conditions. Temperature is the dominant constraint on agricultural production in Iceland, and the implications of short-term fluctuations of temperature (see e.g. Fig. 1) are a major policy concern. Using the results of empirical-statistical models simulating crop and livestock production under present and possible future climatic conditions, B. Gudmundsson (Ministry of Agriculture) has evaluated some of the policy adjustments that could stabilize production over the short-term while accommodating credible longer-term climatic changes.

CONCLUSIONS

There is little doubt that crop productivity worldwide is influenced by the climate. The more dramatic impacts invite prominent media coverage, reporting the effects of anomalous climatic events as costs (or benefits) to economies and societies. However, even after the events have occurred, national bookkeeping is rarely reliable enough to give a precise estimate of the real impact. The connections between a climatic event, crop responses, the economic costs of prevention or compensation, and the social impacts of these are not well understood. In an attempt to investigate these links, we have proposed a scheme that utilizes a hierarchy of models that are capable of simulating environment-society interactions. Each model represents one stage in a cascade of responses induced by an anomalous climatic event. By considering a range of possible future climatic scenarios, it is possible to produce estimates of impact that will be of use to the planner.

We have argued that this method of analysis may be more effectively applied to those areas that exhibit a particular sensitivity to climate, since these represent zones where the impacts are likely to be most readily detectable. This we have illustrated using examples from regions in high latitudes where low temperatures and s short growing season restrict the opportunities for cultivation of crops. One virtue of the approach, however, is that it can be applied to *any* region assuming that appropriate models are available. Work is in progress in ten countries as part of the IIASA/UNEP project (cf. below) and it is hoped that governments and agencies in other countries will recognize the potential of the approach as a planning and decision-making tool. Moreover, each regional case study represents a building block for a more ambitious effort in the future, examining impacts of climatic change at an integrated *global* scale.

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Full results of the project will be available in 1986 as two volumes (Parry et al. (eds.) 1986a, 1986b).

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