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Dear Professor Swaminathan,

You will probably have heard that we have been teamed up to co-chair the workshop on food security at the Toronto conference in June. I have not yet received a list of our workshop's participants though I believe these will be arriving soon. However since I shall be travelling for the next six weeks I thought I would make contact with you, both to let you have a list of my contact points up to April 25th (after which I return to Birmingham) and in order that we may start a process of thinking together about what items and emphasises we might wish to see emerging from our workshop.

To start the ball rolling I thought I would send you a draft of a recent summary paper which Tim Carter and I have written, drawing on the IIASA/UNEP project results. This contains some initial thoughts on where the impacts will come and what we might do about them.

Please drop me a line if you have any thoughts that you think would be worth exchanging at this stage. If I do not hear from you, I will still aim to be back in touch once I am back in Birmingham, by which time I imagine that we will have received a list of the participants in our workshop and will have a clearer picture of the sort of contributions to discussion that we can expect.

With best wishes.

Yours sincerely,

Martin Parry

enc: address list
draft summary paper

Martin Parry: addresses, March 14 to April 22

March 14 - 19	International Seminar on Climate Impact Assessment, at Ashok Hotel, New Delhi. Telephone: 600121 Telex: 3161835 insa i (c/o Professor Sinha, Indian Science Academy)
March 19-25	SCOPE-ENUWAR Meeting, at Salut Hotel, Leninsky Avenue 158, Moscow. Telephone: 438 6365 Telex: 411964A ans su (c/o N. Lukyanov, Computation Centre)
March 26- April 10	Zell-Am-See, Austria. Telephone: 6542 2884 (c/o Frau Fuchs, Appartment Haus Tirolerheim, Schmittenstrasse 68, 5700) Zell-am-See, Austria.
April 11-15	Scientific Advisory Committee of World Climate Impact Studies programme, UNEP, Nairobi. Telephone:254 2 333930, (c/o Mr Peter Usher) Telex: 22068 unep ke (c/o Mr Peter Usher)
April 16-22	Workshop on Global Vegetation Responses to Climatic Change, IIASA, Laxenburg, Austria. Telephone:2236 71521 (c/o Dr Al Solomon) telex: 079137 iiasa a (c/o Dr Al Solomon)

SOME STRATEGIES OF RESPONSE IN AGRICULTURE TO CHANGES OF CLIMATE

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1. INTRODUCTION

In this paper we review a number of potentially useful strategies in agriculture for responding to the impact of climatic changes resulting from increasing atmospheric carbon dioxide (CO_2). We will draw on experience from a number of case studies recently completed as part of a research project of the United Nations Environment Programme (UNEP) and the International Institute for Applied Systems Analysis (IIASA) (Parry _et al_., 1988a,b). Since our understanding of possible future changes in temperature is more detailed than for rainfall (for which information on changes in spatial pattern and seasonal distribution is, at present, extremely limited), any informed discussion must be limited to the effects (and responses) in agriculture in areas where temperature rather than rainfall is the major climatic determinant of agricultural production; in other words in cool temperate and cold areas at middle and high latitudes.

It is, however, largely in low latitude regions that there is the highest degree of vulnerability to climatic variability _now_ (for example, to droughts and tropical storms that occur as part of the range of events typical of _today's_ climate). These regions, particularly those characterised by precarious local food supplies and extensive degradation of land resources, are also probably the most vulnerable to long-term changes of climate _in the future_ simply because of their high degree of present-day marginality and their lack of resources either to combat the adverse effects or to take full advantage of the potentially beneficial effects of climatic change.

Rainfall, particularly its timing and geographical distribution, is critical for both crop and livestock farming in these vulnerable tropical regions. There is some indication that total annual rainfall may increase, averaged over the low latitudes as a whole, and that it may decrease in mid-continental mid-latitude regions such as central North America and Soviet Central Asia (Bolin, et al., 1986). But little is known about timing and pattern, and estimates of possible impacts is frequently reduced to unprofitable speculation.

For these reasons, then, we focus in this paper on those regions and issues where uncertainty is least and from these we try to draw lessons that may apply elsewhere. The paper has four sections: a summary of types of potential impact, a review of potential technical responses, a discussion of potential policy responses and a set of recommendations for future research.

2. SUMMARY OF POSSIBLE EFFECTS

The long-term climatic changes discussed below represent the difference between the present climate described by conditions during the period 1951-80) and the equilibrium climate estimated for atmospheric CO_2 levels that are double those of probable pre-industrial levels, the estimates being derived from an atmospheric general circulation model (GCM) developed by the Goddard Institute for Space Studies (GISS).[1] This is referred to as the GISS 2 x CO_2 climatic scenario. In addition, estimated effects of the GISS 2 x CO_2 scenario are compared with effects stemming from present-day climatic extremes, in order to help evaluate the magnitude of possible future effects.

We distinguish between two broad types of effect: first-order effects (i.e., the biophysical responses of plants and animals) and higher-order effects (i.e., those on farm-level production, regional output, national food supply, etc.). In the following sections we summarise some effects that might

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[1] The GISS model is one of a number of GCMs. A comparison of the models and the different estimates from them is given in Dickinson, 1986

occur if these were no effective technical or policy responses. Later we consider how much certain types of resource can serve to mitigate these effects.

2.1 First-order effects

a) On crop yields. Estimated increases in temperature for a 2 x CO_2 climate (which range from 1.5°C to 5.5°C imply substantial lengthening of the crop growing season at middle and high latitudes. In some areas temperature increases are so great that existing, early-maturing crop cultivars are heat-stressed by the altered conditions. In most areas, however, the warmer conditions can be expected to give higher yields at high latitudes : In northern Japan they are roughly equivalent to those of the best (i.e., warmest) year recently experienced; in Finland they are approximately double those during the best/warmest decade this century; in Iceland they are approximately four times the average for the best/warmest ten years since 1930 (Parry and Carter, 1988a).

However, where rainfall decreases (or increases insufficiently to compensate for increased evapotranspiration rates under the higher temperatures) yields may be adversely affected. In Saskatchewan (Canada), for example, they are as low as those which would occur under a repetition of the driest 5-year period on record (the years 1933-37) (Williams, et al., 1988).

In many parts of the world, particularly the semi-arid tropics, yields of the major cereal staples are much affected by rainfall. An example of this is given in Figure 1, which shows the relationship between rainfall and yields of maize and livestock forage in central and eastern Kenya. Relatively small changes in rainfall would, in these circumstances, have a substantial impact on yields. Indeed, if the annual rainfall total was unaltered (or even increased) while its distribution through the year was adversely altered, the effect on yields would also probably be negative. At present we know little about likely changes in average annual receipts of rainfall at low latitudes, and next-to-nothing about likely changes in rainfall pattern and duration, although this may affect not only quantity but also quality of yield. This is particularly true for the nutritive value of rangeland forage in semi-arid areas (Akong'a, et al., 1988).

b) On the geography of agricultural potential. Climatic change can be expected to bring about a spatial shift of crop potential. Areas which are, under present climatic conditions, judged to be most suited to a given crop or combination of crops or to a specified level of management will change location. At its simplest this kind of shift can be seen as a shift in limits of the cultivable area. This is illustrated in Figure 2 for northern Japan where the "safely cultivable" area for irrigated rice under the GISS 2 x CO_2 climate is more than double that under the present-day climate. Similar large-scale climate-related shifts of potential for maize and wheat have been investigated in North America (Blasing and Solomon, 1983; Rosenzweig, 1985).

In the tropics, where many zonation schemes for land-use management are based upon long-term mean values of climate (e.g., the FAO agro-ecological zones and estimates of population carrying capacity [FAO 1978a, 1978b, 1981]), changes in mean climate would be manifested in the long-term spatial shift of zones. The extent of these shifts (i.e., the sensitivity of such zones to climatic change) has yet to be investigated fully. However, some preliminary work in Ecuador indicates that agro-ecological potential may vary substantially with a hypothesized 10% increase and decrease of mean annual precipitation (a change that is well within the range of rainfall effects estimated by GCMs for a doubling of atmospheric CO_2) (Bravo, et al., 1988).

c) On other environmental processes. Further complexity is added by climatic effects that may occur concurrently on other physical systems, such as: on water resources, for example through changes in snowfall, spring snowmelt and groundwater re-charge; on soil fertility, for example through changes in rates of nutrient leaching that vary with amount of rainfall; on rates of soil erosion, which could be affected by changes in soil dryness and windspeed; and on the incidence of pests and diseases, whose survival and development can be influenced strongly by temperature and humidity.

2.2 Higher-order effects

The various effects that climatic changes could have on yields of crops and on the carrying capacity of rangeland could, through a web of reinforcing and countervailing circumstances, also influence regional food supply, farm income, rural economic activity rates and rural employment. We discuss these in turn.

a) Effects on regional food production. Changes in yield levels, soil fertility, level of farm input and types of management would almost certainly affect aggregate output of food. But the complexities in modeling these relationships mean that, thus far, estimates have only been made for single crops in certain regions, not for all crops grown there. Results indicate, for example, that under the GISS 2 x CO_2 scenario total wheat production in Sashatchensa falls by 18%, and total average rice production in Japan increases by about 5% (Williams, et.al., 1988; Yoshino, et.al., 1988). These estimates assume, most unrealistically, that the areas under different crops in these regions will remain the same as today, that crops types will not change and that management will remain unaltered. However, they give us an idea of what might happen if there was no technical or policy response to climate change; and they provide a starting point for considering what kinds of response can most effectively reduce the estimated effects.

b) Effects on farm income. The extent of these effects would depend, in addition, on what changes were to occur in the income of competing farmers and in costs of inputs. It is far from easy to predict the direction of income movement, even if yield changes are known. In instances of short-term impact, such as that of the 1979-80 drought in north-east Brazil, the price of staple foods may increase (in this instance by 90 to 100%) while the income and asset level of small landholders contracts (Magalhaes, <u>et al</u>., 1988).

c) <u>Effects on the regional economy</u>. Changes in farm income may often affect purchases of manufactured goods and thus activity rates in non-agricultural sectors. For example, in northeast Brazil purchases of clothing, footwear and processed food fell by about a third during 1983 (following two years' drought) as a consequence of increased expenditure by rural households on essential foodstuffs (Magalhaes, <u>et al</u>., 1988). The effects of changes in regional output on regional income can also be marked: For example, in some regions of Australia (where agricultural output contributes 30 per cent of total regional output) a drought-related fall in agricultural output of 10% can reduce regional output by 3% and regional income by 10% (Powell, 1978).

d) <u>Effects on rural employment</u>. It is possible to estimate the "knock-on" effects of agriculture on other sectors by simulating the exchanges between agriculture and other sectors in an input-output model. The only study of long-term climatic change that has, to date, followed this approach has been in Saskatchewan (Williams, <u>et al</u>., 1988). This indicates that yield reductions in spring wheat (due largely to increased moisture shortage under the GISS 2 x CO_2 climate) would reduce the overall purchasing power of the Saskatchewan agricultural sector by 3%. Consequent reductions in activity rates in other sectors were estimated to reduce province-wide employment by 0.5%. We must, however, be extremely cautious about these types of estimates because they make the unlikely assumption that present-day relationships between sectors will hold over the long-term future.

3. POTENTIAL TECHNICAL RESPONSES

The responses outlined below are limited to those for which the technology is at present available and which could be implemented now. There are, of course, likely to occur substantial changes in technology (and in factors which would affect its use, such as changes in demand and prices), but these are difficult to specify over the time-scales suggested for greenhouse gas-induced changes of climate. The technical responses we shall consider are of four types: change in crop variety; change in irrigation, fertilizing and drainage; change in crop management; and change in farm expenditure.

3.1 Change in crop variety

a) Change to crop varieties with high thermal requirements. There are firm indications that one of the most marked aspects of long-term climatic changes due to increases in greenhouse gases will be higher temperatures (both seasonal and annual) at middle and higher latitudes. In many areas where warmth during the growing season is the major constraint on crop yield this is likely to mean increases in output. However many of the early-maturing varieties at present grown in cool regions would fail to take full advantage of the longer and warmer growing seasons. In northern Japan, for example, yields of present-day rice varieties would probably increase by 4 per cent with the 35 per cent increase in growing-degree days estimated under the GISS 2 x CO_2 scenario (Yoshino, et al., 1988). However the substitution of late-maturing rice (at present grown in central Japan) might increase yields by 26 per cent (Figure 3). Similar increases have been estimated for spring wheat yields in Finland and the USSR. In each case only limited benefit would be derived from the present-day varieties, while substantial benefits are estimated for varieties with higher thermal requirements.

b) Change from spring to winter crop varieties. Increased temperature in some middle and high-latitude areas may increase rates of evapotranspiration to such an extent that, if there is no compensating increase in rainfall, there may occur an increased frequency of moisture shortage early in the growing period. This is the case in the Canadian prairies under the GISS 2 x CO_2 scenario (Williams, et.al., 1988). Spring-sown wheat crops, which are at present the predominant crop in the region, could be severely stressed under these conditions, but winter-sown crops (which would be well-established by May or June) would be less prone to damage. In fact, a switch from spring to winter-sown wheat in the southern Prairies has been evident over the past 10 years. An acceleration of this trend could be an effective response to possible warmer growing seasons in the future.

c) Change to crop varieties giving less variable yields. Long-term changes in temperature and rainfall could have a profound effect on yield stability. Long-term warming at high latitudes could reduce the interannual variability of crop yields (for instance, by reducing the frequency of cold-summer damage); or long-term reduction in rainfall (which is a possibility in mid-continental mid-latitude regions in the Northern Hemisphere), could increase the frequency of yield losses due to drought.[1] Careful choice of varieties could exploit the benefits of reduced extremes or serve to reduce losses from increased extremes. In Japan, for example, judicious crop selection would aim to balance the continued, though reduced, risks of cold summer damage to late-maturing varieties against the increased risk of poor yields from early-maturing varieties in unusually warm summers. This form of strategy is an age-old one in agriculture: the point here is simply that changes in the frequency distribution of different types of weather years will demand re-consideration of the best mix of crops and cropping strategies in a particular region.

Although we cannot at present, make any useful predictions about likely long-term changes in location, quantity and seasonal distribution of rainfall in low-latitude semi-arid areas, it is probable that some regions will experience changes in rainfall. This strengthens the case for re-appraisal of the recent emphasis on high-yielding cultivars and crop production, which have discouraged forms of diversified, flexible and low-risk production systems

[1] We should note that in addition to these changes in yield variability (which could occur without any change in interannual climatic variability) changes in the interannual variability of climate could also occur as part of a greenhouse gas-induced change (and which might themselves have an effect on yield variability). However we know little at present about changes in climatic variability that might accompany changes in the average condition of the climate.

that often characterise traditional agriculture and provide it with some resilience to drought.

3.2 Changes in fertilizers, irrigation and drainage.

a) Fertilizer application. Some stability of crop production can be achieved by varying applications of fertilizer to offset anomalous climatic conditions. The efficacy of this strategy is severely limited, at present, by the low level of accuracy of seasonal weather forecasts. It is, however, being tested for feasibility by the government of Iceland, where increased applications of fertilizer in cool summers can maintain hay yields above a minimum necessary to feed the island's livestock; and where decreased applications in warm summers can reduce costs and help avoid over-supply (Figure 4).

Variations of fertilizer application may also be an appropriate technical response to climatic changes over the long-term. Experiments in Iceland indicate that savings of up to 50 per cent may be achieved in a warmer climate simulated for 2 x CO_2 conditions (Bergthorsson, et al., 1988). Where long-term climatic changes are less obviously beneficial it is possible that increased use of fertilizers may compensate for long-term decreases in yield - for example, experiments indicate that yields of winter rye in the Leningrad area of the USSR may fall by more than a quarter under a warmer 2 x CO_2 climate, but could be increased by about 15 per above present levels if fertilizer applications were increased by 50 per cent (Pitovranov, et al., 1988).

b) Irrigation. If large-scale shifts of rainfall patterns were to occur, particularly in the semi-arid tropics, then two broad responses are possible: large scale spatial shifts of farming activities (we discuss this later) and the large scale inter-temperal or inter-regional transfer of water. Large scale protective irrigation works of this kind were the mainstays of drought policy in much of the semi-arid tropics in the recent historic period up to about 1950, though more recently the emphasis has turned to smaller-scale developments such as the widespread construction of farm ponds or 'dug-outs'. The latter are seen as boosting farm-level resilience to drought when used in appropriate combination with drought-resistant crop types and crop management systems. Large scale water transfers, such as of the Nile in the 1960s and 1970s, require long lead-times in planning and construction, and may have increased vulnerability to water shortage over the longer-term. Given the extreme uncertainty at present about tropical rainfall in a high CO_2 world, plans for new large-scale irrigation schemes do not seem an appropriate response.

c) Soil drainage. Increased precipitation in some areas may lead to the increased incidence of waterlogging, with consequent losses in crop production, and also to increased rates of soil erosion. In these cases it might well pay to make improvements in soil drainage. This would be especially important as a means of more efficiently disposing of nitrate pollutants, if levels of fertilizer application were increased.

3.3 Change in crop management

All farmers adopt strategies to mitigate the effects of adverse weather which can occur as part of present-day climate, though these strategies vary considerably in degree of complexity. Much of the effort in agricultural development over recent years has been devoted to refining such strategies, particularly tuning them more closely to suit local climatic conditions. An appropriate response by crop management to long-term changes in climate would imply re-tuning some or all strategies to harmonize with the new set of climatic conditions. Paucity of our present knowledge about the details of these conditions make it quite impossible to speculate usefully about the kind of responses required, but it is quite likely that these would include:

- changes in the area cropped
- changes in the location of cropping

- changes in the extent of inter-cropping
- changes in planting density
- changes in use of crops with different needs for moisture and warmth
- changes in use of short-duration _versus_ long-duration crops
- changes in planting dates
- changes in use of fallowing
- changes in amount of tillage and mulching to limit erosion
- changes in amount of fertilizer application
- changes in amount and scheduling of irrigation

3.4 Changes in level of farm expenditure

Since _different_ crops growing in the _same_ region will probably respond differently to a given change in climate, there will probably occur substantial changes in the comparative advantage which one crop has over another. Some crops or crop mixes would become more profitable, others less; and changes in farm expenditure would be likely to reflect this, increasing in those areas and for those types of farming where profitability increased and _vice versa_. To illustrate, in an analysis which included an arbitrary 1°C increase in temperature around Moscow, an additional investment of 30m roubles[1] would increase grain production by 14 per cent and reduce the average cost per ton of production from 88 to 83 per cent of the baseline (present) cost (Figure 5). Under this scenario, substantial increases in agricultural investment might be expected.

4. POTENTIAL REGIONAL AND NATIONAL POLICY RESPONSES

In addition to the application of technology, there are some applications of potential policy responses that should be considered. Here we shall focus mainly on responses appropriate for long-term climatic change. It should be emphasized that few of these have yet been explored in any depth, and they are

[1] rouble = _ca_ U.S.$1

put forward here simply as an indication of the range of policy alternatives. Indeed it may reasonably be argued that, at this early stage in our understanding of the possible future climatic changes, it is more rewarding to concentrate on extending the range of policy options than on identifying and refining specific policies. Three types of option are considered here: change in land-use allocation, change in policies to maintain food security, change in policies to maintain farm incomes.

4.1 Change in land-use allocation

If long-term changes of climate were to include a widespread shift of the boundaries of present-day climate types (a matter on which there is some agreement between different GCMs) then we can reasonably expect some resultant shifts in the distribution of agricultural land use. It is unlikely, however, that present geographical patterns of agriculture would simply re-locate themselves to match the new geography of climate. This is considered in further detail below.

a) Changes of land use to optimize production. Because different crops respond differently to changes of climate and to varying levels of fertilizer application under those climates, any attempt to maximize output of each crop while minimizing production costs is likely to identify quite different allocations of land to alternative crops under different climates. For example, in the area around Moscow, an "optimal" land use for a climate that is on average 1°C warmer than the present one would have an expanded area under winter wheat, maize and vegetables and a reduced area under northern temperate-zone crops such as spring-sown barley, oats and potatoes (Figure 6). This pattern of land use begins to resemble that at present found farther south in the northern Ukraine and points to the value of using regional analogies to identify possible responses to climatic change.

If we assume, for example, that agriculture is, in most regions of the world, closely tuned to its present-day climate, then present-day farming types are one indicator of a system (including crop types, expected yields, optimum levels of fertilization, etc.) that operates effectively in that climate. Whether that system is optimal for the climatic conditions would be a matter for further enquiry. Yet by mapping present-day analogues of (for example) a 2 x CO_2 climate we may thus gain some insight into the range of adjustments that may be required to match new uses of land to the new climate. Figure 7 illustrates present-day regional analogues for the GISS 2 x CO_2 climate estimated for five regions in the Northern Hemisphere: The climate of Finland is estimated to become similar to that of present-day northern Germany, of southern Saskatchewan to northern Nebraska, of the Leningrad region to the western Ukraine, of the central Ural mountains (Cherdyn region) to south-central Norway, of Hokkaido in northern Japan to northern Honshu, and of Iceland to north-east Scotland.

Following this approach we might, to adopt the Iceland-Scotland analogue, expect hay yields in Iceland to increase by about 50 percent to match levels which are more typical of north-east Scotland today. Model experiments tend to confirm this conclusion (Bergthorsson, et al., 1988). However, losses to pests and diseases, which are at present limited by winter cold in Iceland, might increase to up to the level of 10 to 15 per cent now faced by Scottish farmers. As for land use changes: whilst hay, potatoes and turnips are the only crops grown extensively out-of-doors in Iceland and sheep are the dominant stock, in north-east Scotland barley (stall-fed to cattle) is the main cash crop. Are the indications, then, that Iceland will see a shift from sheep farming to cattle rearing and fattening? And will the Leningrad region surplant the Ukraine as the wheat granary of the Soviet Union? Nothing is likely to be so simple, but indications are that the extent of the land-use changes may be substantial.

b) Changes of land use to stabilize production. Some changes of land use might be implemented not to optimize production (i.e., maximize the average return) but stabilize production. This strategy would seek to allocate land to uses in such a way that the risk of heavy losses due to climatic variations (either short- or long-term) is reduced, either by minimizing the variability or by striving for the best possible return under the worst possible conditions.

In some regions, and increasingly in the past decade, increasing variability of yield can be attributed to the intake of poor quality land for cropping. In years of average weather this land produces an average crop, but in adverse conditions its yields may be very low indeed, much lower than that of the medium quality arable land. If this marginal cropland were taken out of crop production and converted back to rangeland, the interannual variability of farm income can be reduced with only a small loss in overall production when averaged over several years.

4.2 Changes of policy to maintain food security

Warmer and longer growing seasons at middle to high latitudes would, ceteris paribus, generally lead to larger crop yields. Since many countries in these regions maintain price support policies to encourage home production, often at prices well above that of the world market, radical changes of policy will be necessary to avoid oversupply. On the basis of the few preliminary regional studies that have been completed it seems that this will be the case certainly in the Nordic countries, in the northern half of the European Community, in the central belt of the European USSR, and in Japan. In Europe, in particular, it is reasonable to envisage a growing problem of oversupply and an imperative to introduce further set-aside programmes to take cropland out of production.

For regions where moisture rather than temperature is the primary climatic constraint on present-day production (and these comprise the great majority of the world's farmed area) we simply do not have sufficient information, at this juncture, to indicate whether food supply at national levels would tend to increase or decrease as a result of changing climate. Much would depend on what changes were to occur in the regional and seasonal patterns of rainfall, something about which we know little at present. It is clear, however, that national food policies, whether presently designed to maintain strategic minimum levels of supply or to limit over-production, will need to be responsive to changes of climate, both (on the down side) to avoid national food shortfalls and avoid incurring potentially heavy foreign currency costs in food imports or (on the up side) to avoid unnecessary expense on food support and avoid incurring costs of excessive storage and disposal.

4.3 Change of policies supporting farm management and inputs

National farm policies which aim to increase resilience to short-term climatic variability (e.g., drought, flooding, cold spells, etc.) will often, incidentally, improve resilience to possible changes of climate over the longer term. However, it may be necessary to adapt these policies specifically to encourage different types of farm management and different levels of input to match climatically-induced changes in agricultural potential. For example, further support may be necessary in traditional areas of agricultural extension work such as in water management (e.g., in improving efficiency of water use), in land management (e.g., instituting new soil management practices to improve control of soil erosion), in pest control (e.g., adopting new crop varieties and cultivation practices to inhibit pests and diseases). Continued efforts in reorganisation of farm structure and rural infrastructure (such as improvements to systems of transport, marketing and credit) would be necessary, as they are today, to provide a suitable economic environment for the effective introduction of the new technologies.

5. RESPONDING WITH MORE INFORMATION

Throughout this paper we have emphasized the inadequacy of our present knowledge. While it is important that consideration of policy options should be made now, in spite of inadequacies of information about the future, it is quite clear that more information, particularly in some specific areas, would help us identify the full range of potentially useful responses and assist in determining which of these may be most valuable.

We may summarise our priorities for future research by referring to a diagram that includes the three orders of impacts we have distinguished in this paper : biophysical impacts at the level of individual plants and animals, impacts at the farm or village level, and impacts on the region or nation (Figure 8). The numbers below refer to points in the diagram that deserve our closer attention, as follows:

(1) More information is required about the nature of the changes in climate - its spatial pattern (particularly of rainfall); its seasonal pattern (again, particularly of rainfall); its rate of change in response to forcing factors such as CO_2 emissions, ozone depletion, etc (which would enable consideration of required rates of adaptation, such as the development or substitution of new crop varieties); and of likely changes in variability of climate as well as in its average condition.

(2) Improved understanding is needed of the effects of changes in climate on other physical processes, for example on rates of soil erosion and salinization; on leaching of soil nutrients; on pests and diseases, and their vectors.

(3) Improved knowledge is needed of effects of changes in climate on crop yields in different regions and under varying types of management. To date, less than a dozen regional studies have been completed, and these are insufficient as a basis for generalizing about effects on food production at the regional or world scale.

(4,5,6) An improved ability is required to "scale-up" our understanding of effects on crops, to effects on farm production, on village production and on national food supply. This is particularly important because policies must be designed to respond to impacts at the national level.

(7) Improved understanding is needed of the perception of (actual or potential) impacts from climatic change, particularly of the perception of risk and how this can be used to evaluate alternative policies which seek to reduce risk levels.

(8) Further information is needed on the range of potentially effective technical adjustments at the farm and village level (e.g., irrigation, crop selection, fertilizing, etc.).

(9) Further information is needed on the range of potentially effective policy responses at regional, national and international levels (e.g., re-allocations of land use, plant breeding, improved agricultural extension schemes, large-scale water transfers, etc.).

6. CONCLUSIONS

There are certainly a number of strategies that can be adopted to mitigate the effects of climatic changes. The question is not "Can agriculture adapt?" but "How best can agriculture adapt?" Our task over the next decade is to explore the full range of options available and to evaluate their relative efficacy with respect to different types and rates of climatic change. We have stressed that much critical information is lacking concerning the regional detail of changes in temperature and rainfall, and possible changes in the distribution of rainfall through the year. However, it is evident that while we cannot, at present, forecast how the climate will change, we can estimate the potential consequences of each of a number of possible climatic changes. In this way we can improve our understanding of effects and explore appropriate responses. Later, when sufficiently precise forecasts of climatic change are available we shall thus have acquired the ability both to assess their impact and to determine the best response.

CAPTIONS TO FIGURES

Figure 1. Estimated response of a) maize yield and b) livestock forage to rainfall in different agroclimatic zones in central and eastern Kenya. Source: Akong'a et al., 1988.

Figure 2. Safely cultivable area for irrigated rice in northern Japan under four climatic scenarios. The safely cultivable area (shaded) is the minimum level of accumulated temperatures during the growing season required for the crop to complete its normal life cycle. Source: Yoshino et al. (1988).

Figure 3. Simulated year-to-year variations in rice yield under the observed and 2 x CO_2 scenario climates for the period 1974-1983 in Hokkaido, northern Japan. Estimates are for current technology (including an early-maturing rice variety) and adjusted technology (including a late-maturing rice variety). Source: Yoshino et al. (1988).

Figure 4. Effects of adjustments to fertilizer application on hay yields in Iceland. Source: Bergthorsson et al. (1988).

Figure 5. Cost of increased grain production in the Moscow area (Central Region), N. USSR. Changes in total grain production are plotted in percentages relative to the baseline (vertical axis) as a function of additional expenditure (roubles) on harvesting capacity, equipment and labour (horizontal axis). The resultant costs per ton are shown on the graph as percentage values relative to the baseline for (a) the baseline climate (1931-1960) and (b) an arbitrary increase in mean annual temperature of +1 C Source: Pitovranov et al. (1988).

Figure 6. Effects of adjustments to crop allocation in the Moscow area (Central Region, USSR). Source: Parry and Carter (1988a).

Figure 7. Present-day regional analogues of the GISS 2 x CO_2 climate estimated for four regions : Saskatchewan, Iceland, Finland, Leningrad and Cherdyn regions (USSR) and Hokkaido and Tohoku districts (Japan). Source: Parry and Carter (1988a).

Figure 8. Research priorities in the assessment of effects of climatic variations : The schema of the IIASA/UNEP project's approach, with priority tasks identified by numbers that are described in the text. Source: Parry and Carter (1988a).

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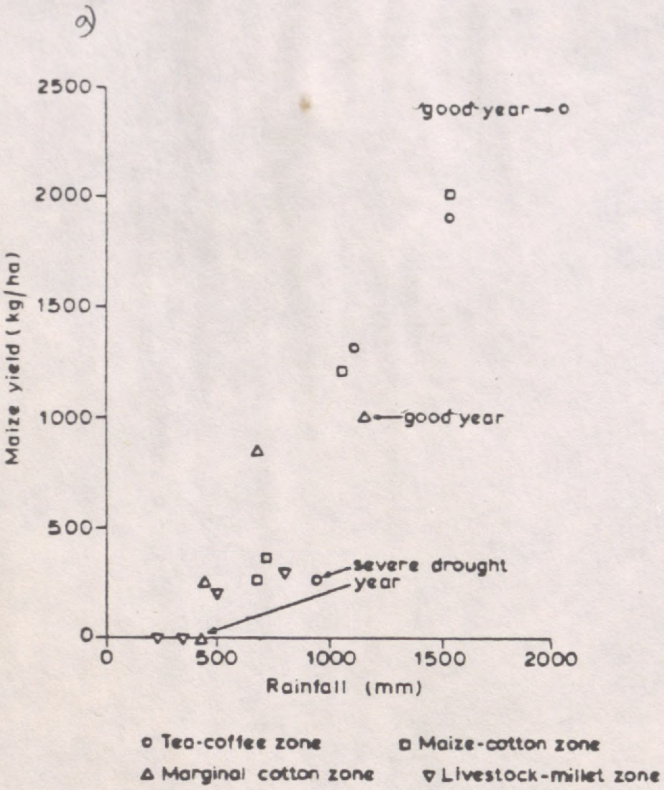
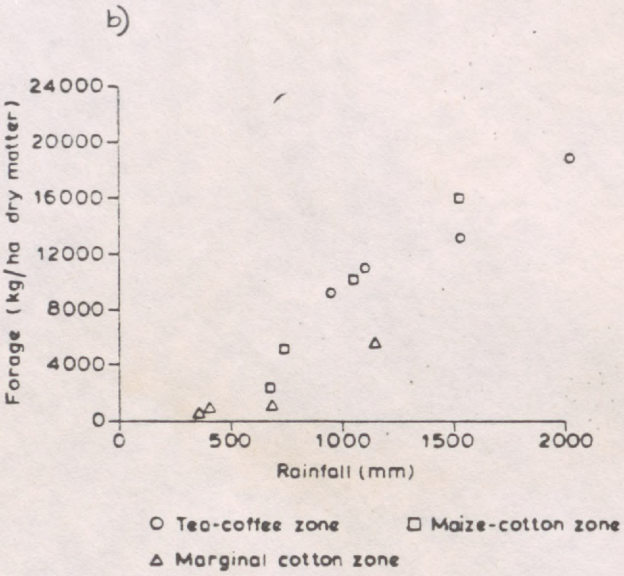
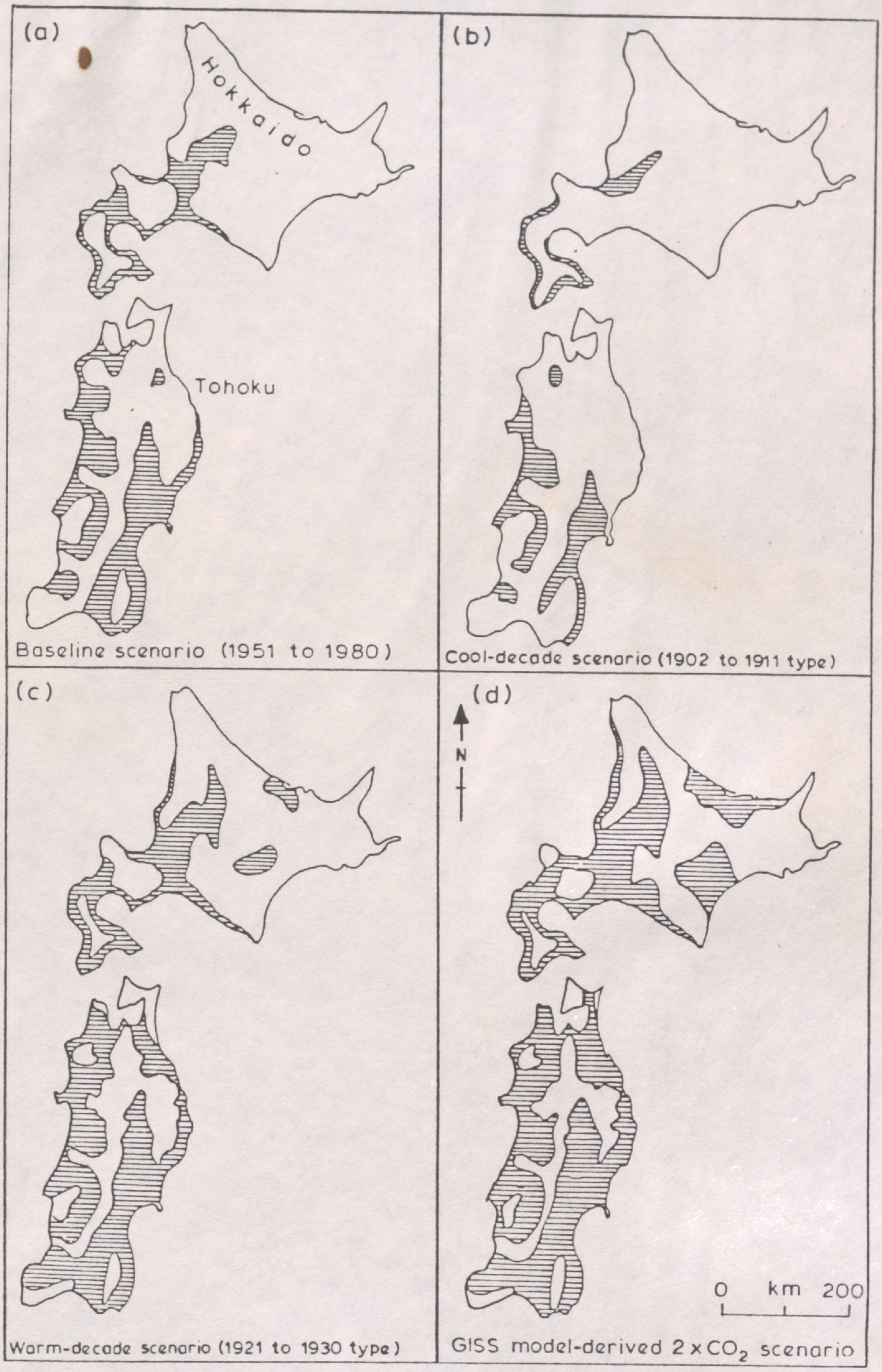

a)
Maize yield (kg/ha)
2500
2000
1500
1000
500
0
good year
good year
severe drought year
0
500
1000
1500
2000
Rainfall (mm)
o Tea-coffee zone
□ Maize-cotton zone
△ Marginal cotton zone
▽ Livestock-millet zone


b)
Forage (kg/ha dry matter)
24000
20000
16000
12000
8000
4000
0
0
500
1000
1500
2000
Rainfall (mm)
O Tea-coffee zone
□ Maize-cotton zone
△ Marginal cotton zone

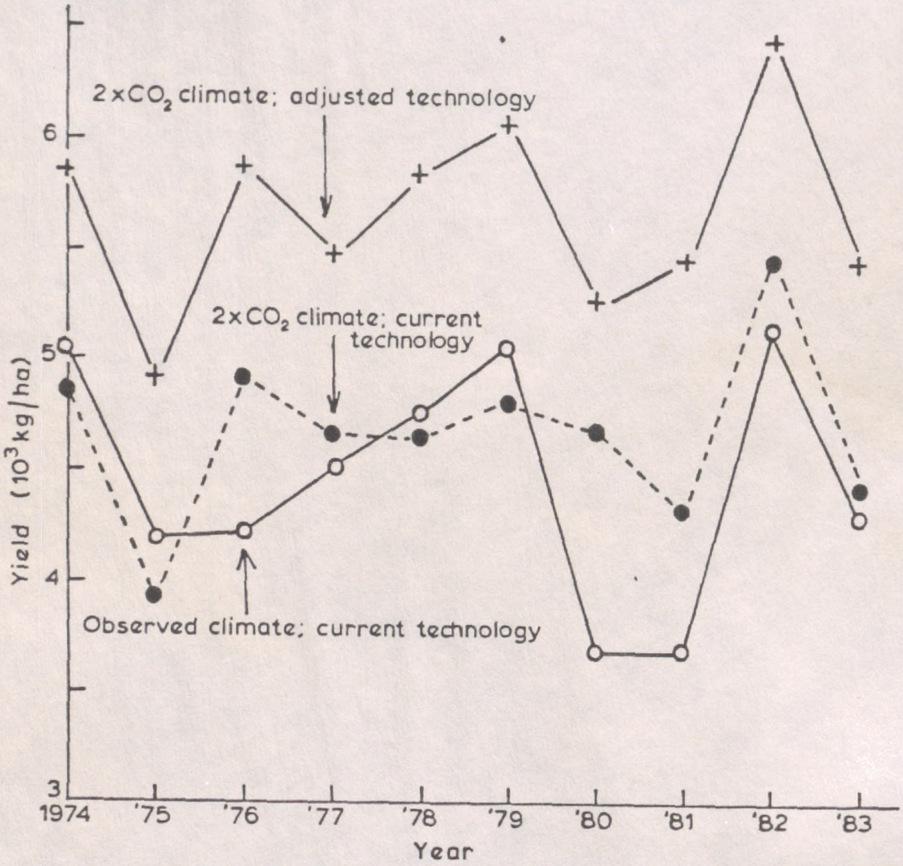


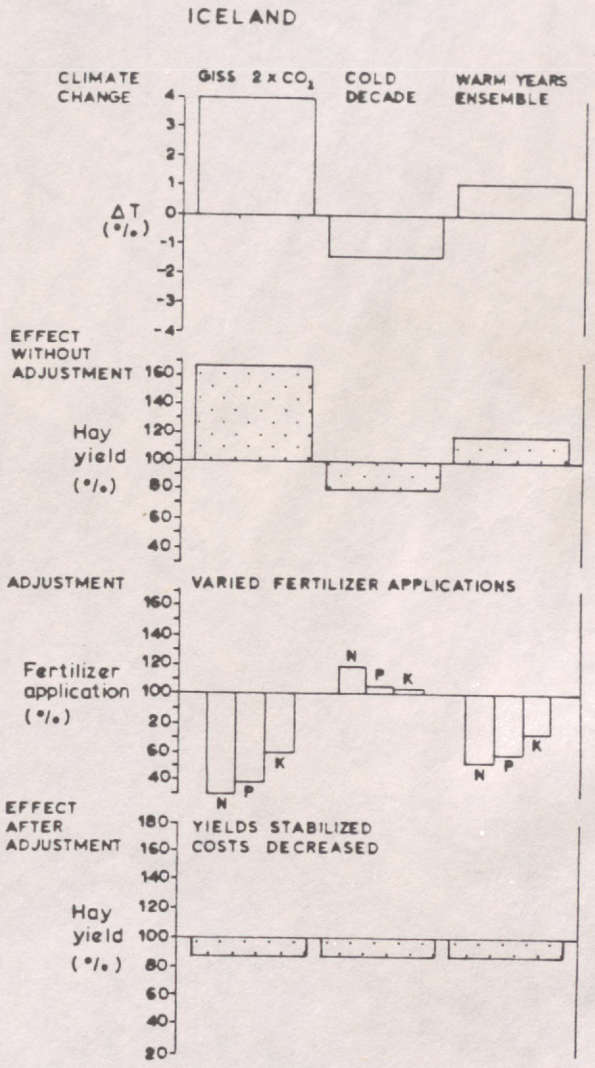
(a) Baseline scenario (1951 to 1980)

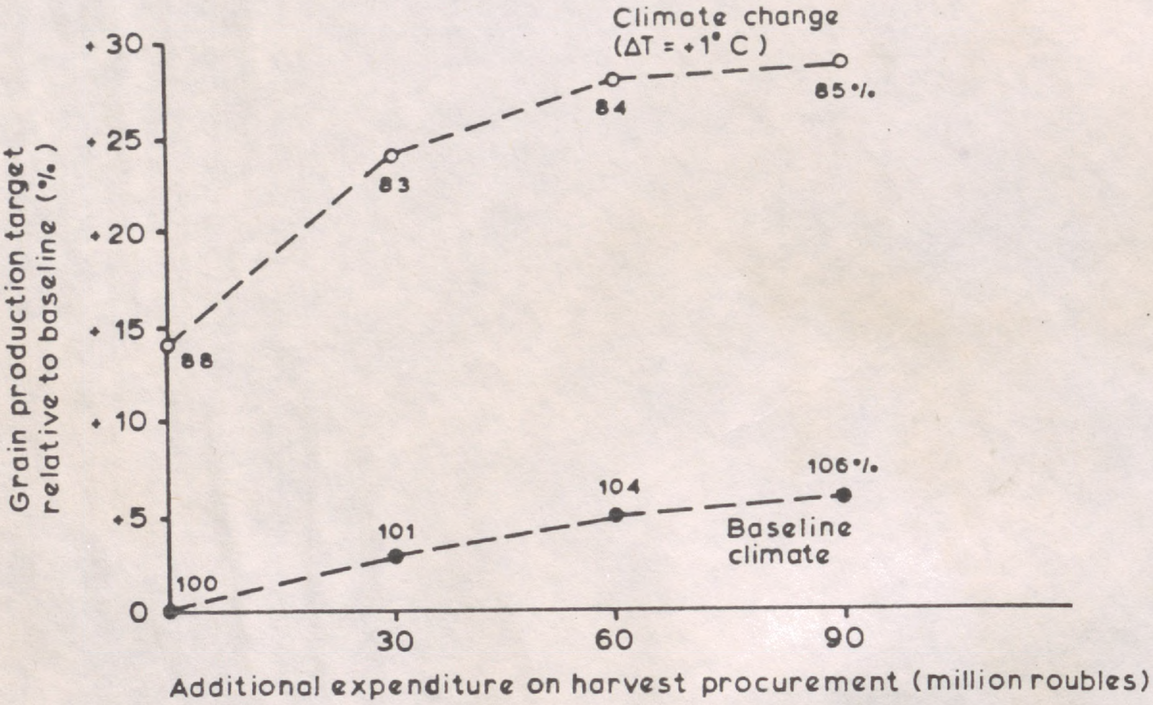
(b) Cool-decade scenario (1902 to 1911 type)

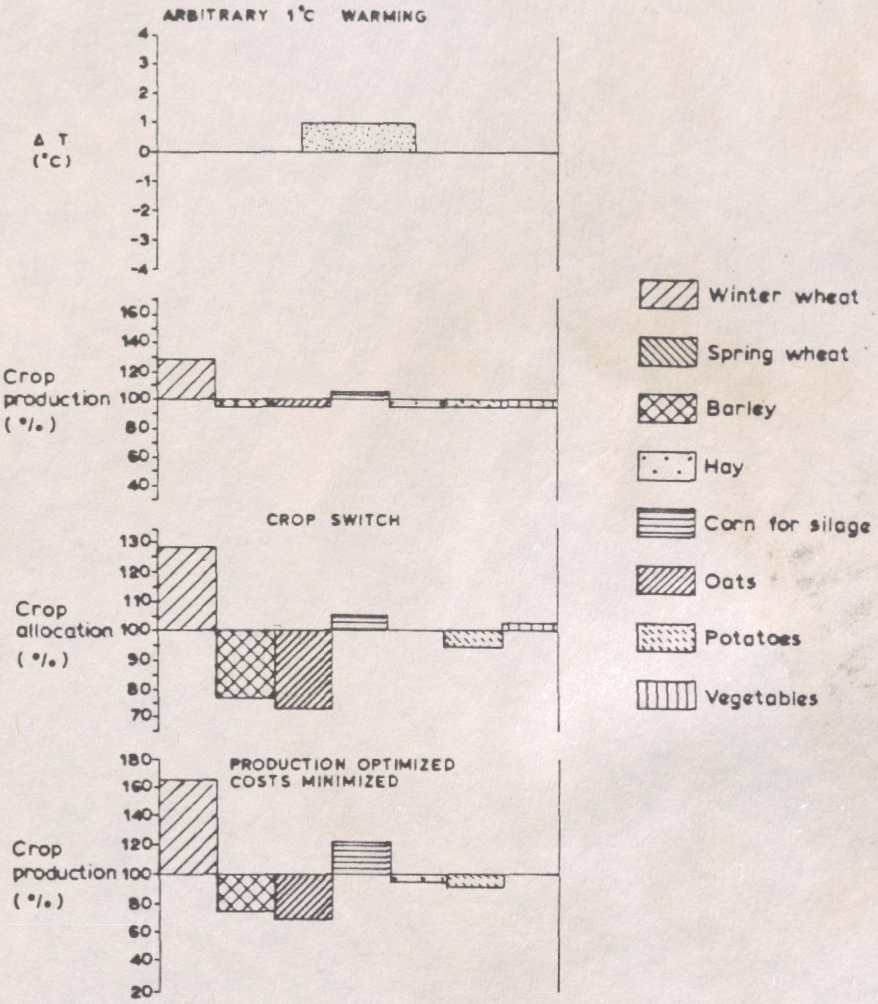
(c) Warm-decade scenario (1921 to 1930 type)

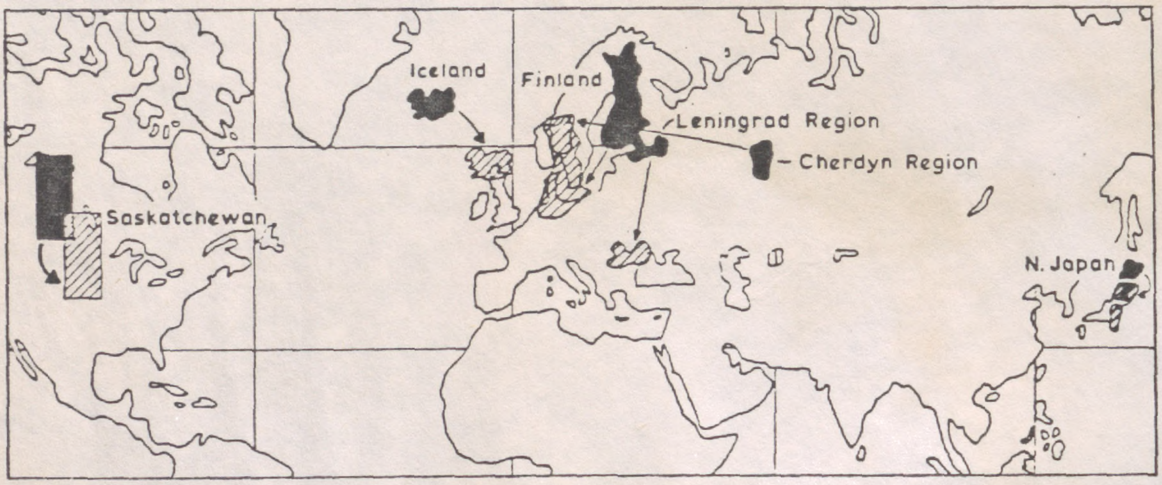
(d) GISS model-derived 2 x CO_2 scenario

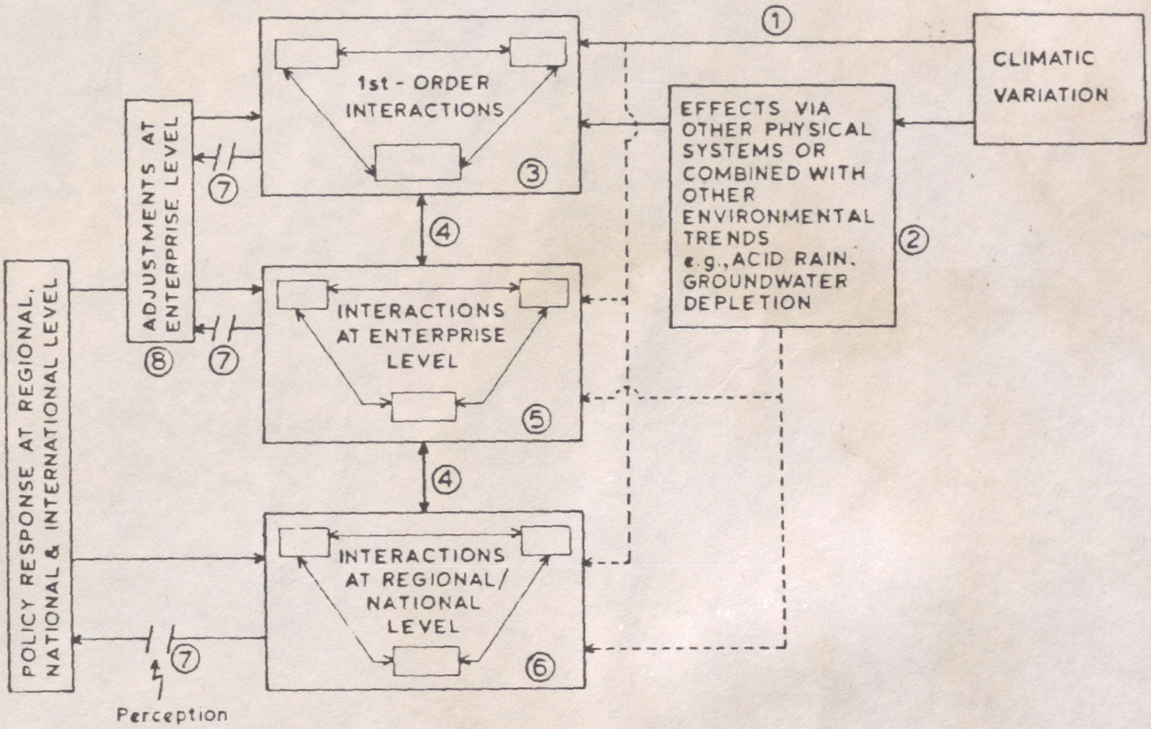

2×CO_2 climate; adjusted technology
2×CO_2 climate; current technology
Observed climate; current technology
Yield (10^3kg/ha)
3
4
5
6
1974
'75
'76
'77
'78
'79
'80
'81
'82
'83
Year


ICELAND
CLIMATE CHANGE
GISS 2 x CO_2
COLD DECADE
WARM YEARS ENSEMBLE
ΔT (°/.)
4
3
2
1
0
-1
-2
-3
-4
EFFECT WITHOUT ADJUSTMENT
Hay yield (°/.)
160
140
120
100
80
60
40
ADJUSTMENT
VARIED FERTILIZER APPLICATIONS
Fertilizer application (°/.)
160
140
120
100
20
60
40
N
P
K
N
P
K
N
P
K
EFFECT AFTER ADJUSTMENT
YIELDS STABILIZED
COSTS DECREASED
Hay yield (°/.)
180
160
140
120
100
80
60
40
20


Climate change
(ΔT = +1° C)
88
83
84
85 %
Baseline climate
100
101
104
106 %
Grain production target relative to baseline (%)
+30
+25
+20
+15
+10
+5
0
30
60
90
Additional expenditure on harvest procurement (million roubles)


ARBITRARY 1°C WARMING
Δ T (°C)
4
3
2
1
0
-1
-2
-3
-4
Crop production (%)
160
140
120
100
80
60
40
CROP SWITCH
Crop allocation (%)
130
120
110
100
90
80
70
PRODUCTION OPTIMIZED COSTS MINIMIZED
Crop production (%)
180
160
140
120
100
80
60
40
20
Winter wheat
Spring wheat
Barley
Hay
Corn for silage
Oats
Potatoes
Vegetables


Iceland
Finland
Leningrad Region
Cherdyn Region
Saskatchewan
N. Japan


①
CLIMATIC VARIATION
1st - ORDER INTERACTIONS
③
EFFECTS VIA OTHER PHYSICAL SYSTEMS OR COMBINED WITH OTHER ENVIRONMENTAL TRENDS e.g., ACID RAIN, GROUNDWATER DEPLETION
②
ADJUSTMENTS AT ENTERPRISE LEVEL
⑦
④
INTERACTIONS AT ENTERPRISE LEVEL
⑤
⑧
⑦
POLICY RESPONSE AT REGIONAL, NATIONAL & INTERNATIONAL LEVEL
④
INTERACTIONS AT REGIONAL/ NATIONAL LEVEL
⑥
⑦
Perception