936 [illegible]
[illegible]
[illegible] 9695 6

Sensitivity of Agricultural Production to Climatic Change

P. A. Oram

Reprinted from *Climatic Change*, Vol. 7, 1985, pp. 129-152
Copyright © 1985 by D. Reidel Publishing Company,
Dordrecht, Holland

INTERNATIONAL
FOOD
POLICY
RESEARCH
INSTITUTE

SENSITIVITY OF AGRICULTURAL PRODUCTION TO CLIMATIC CHANGE

P. A. ORAM
International Service for National Agricultural Research, The Hague, The Netherlands

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

Climatic Change 7 (1985) 129–152. 0165-0009/85/0071-0129$03.60.
© 1985 *by D. Reidel Publishing Company.*

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

3

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 1). 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

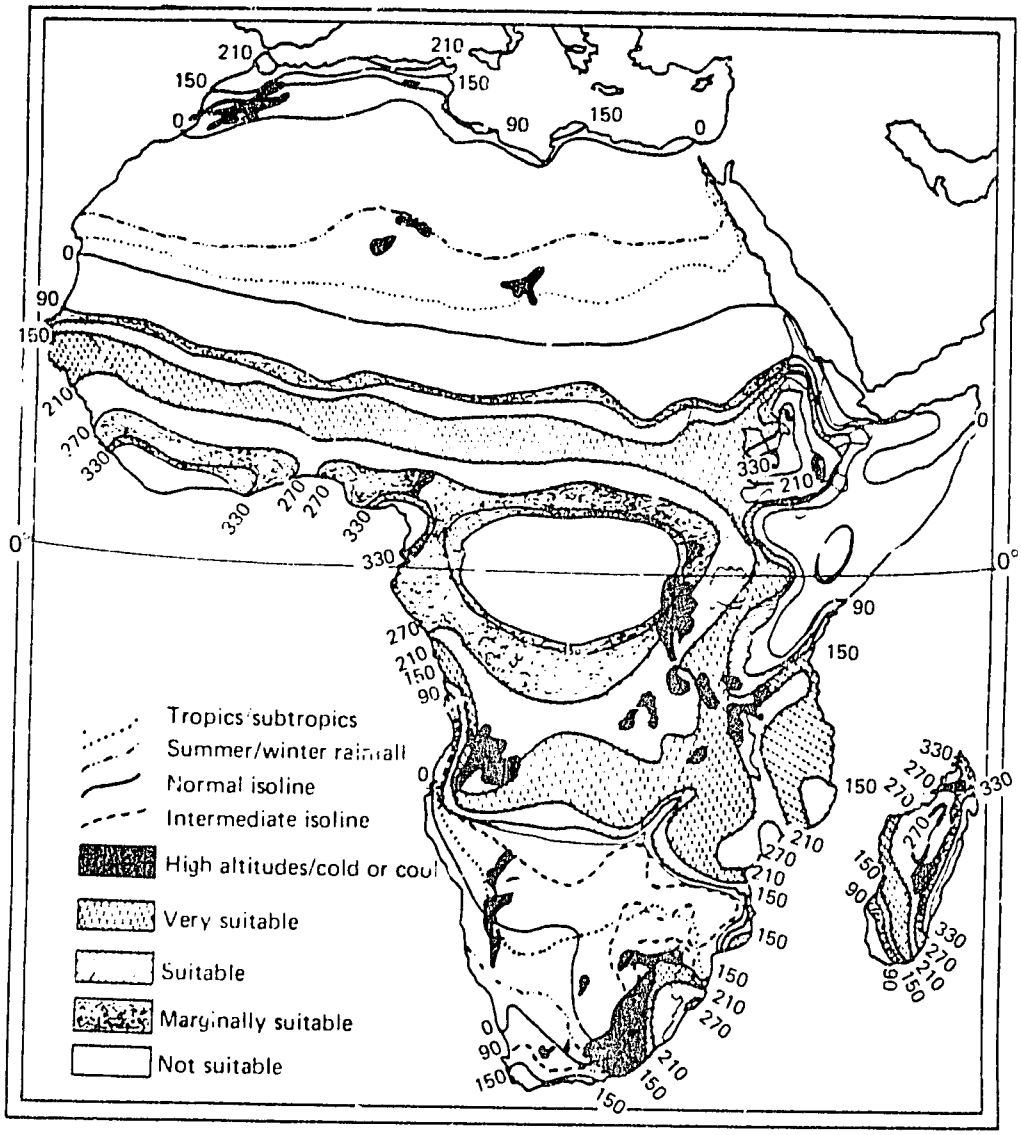

Fig. 1. Generalized agroclimatic suitability assessment for rain-fed production of the phaseolus bean (source: FAO, 1978, Vol. 1). Isolines show length of growing season.

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, 1976, 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

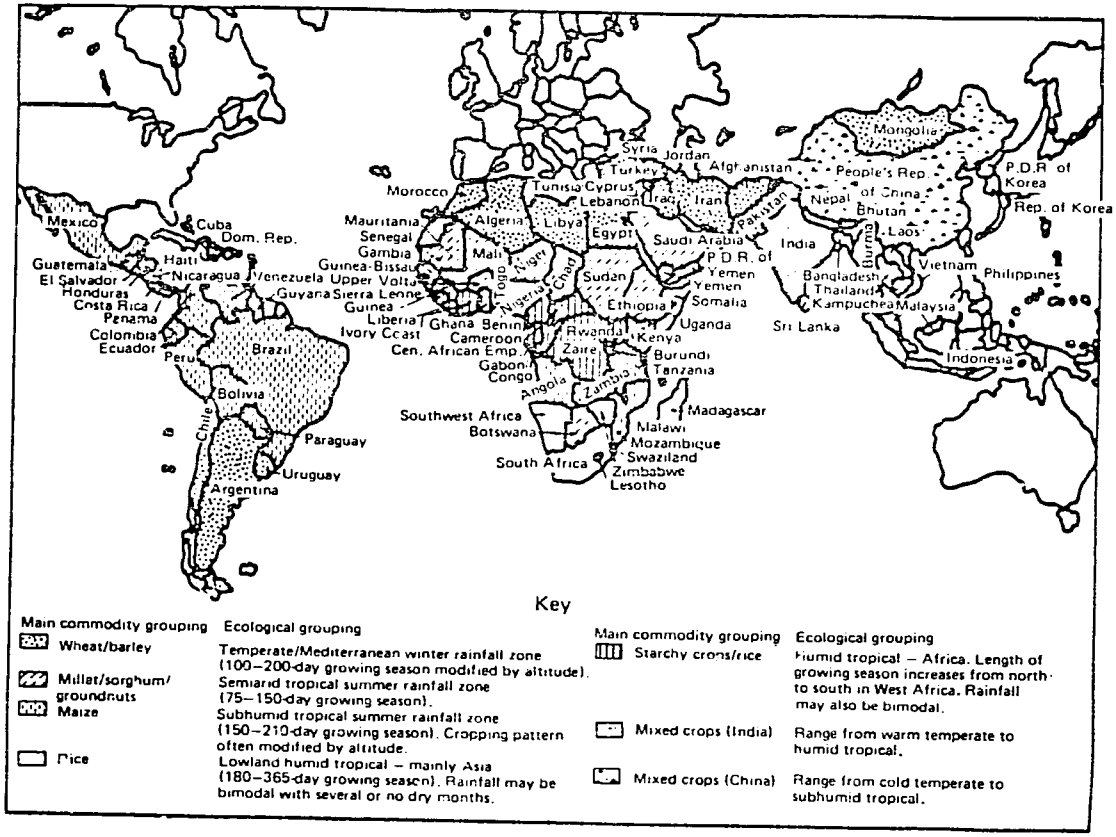

Fig. 2. Developing countries grouped by major commodities and ecological zones (source: Oram *et al.*, 1979). In the temperate or tropical highland regions, both cold and aridity may limit the length of the effective growing season. In the lowland tropics, rainfall and high temperature are the dominant 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

12

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	26.38	26.69	5.30	7.51	1.73 (14.07)	[illegible]	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.[illegible]	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	5.97	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 resarch 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 86% 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.

References

Barker, R., Gabler, E.C., and Winkelman, D.: 1981, 'Long-Term Consequences of Technological Change on Crop Yield Stability: The Case for Cereal Grain', in A. Valdes (ed.), *Food Security for Developing Countries*, Westview Press, Boulder, Colorado.

Bergthorsson, P.: 1985, 'Sensitivity of Icelandic Agriculture to Climatic Variations', *Climatic Change* 7, 111–127 (this issue).

Blaxter, K.: 1982, 'Food Animals and Climate', in K. Blaxter and L. Fowden (eds.), *Food, Nutrition, and Climate*, Applied Science Publishers, London.

Bunting, A.E., Dennett, M.D., Elston, J., and Speed, C.B.: 1982, 'Climate and Crop Distribution', in K. Blaxter and L. Fowden (eds.), *Food, Nutrition, and Climate*, Applied Science Publishers, London.

Buringh, P., van Heemst, J., and Staring, G.: 1975, 'Computation of the Absolute Maximum Food Production Potential of the World', The Agricultural University, Wageningen, Netherlands.

Carter, T.R. and Parry, M.L.: 1984 'Strategies for Assessing Impacts of Climatic Change in Marginal Areas', in N. A. Mörner and W. Karlén (eds.), *Climatic Changes on a Yearly to Millennial Basis*, D. Reidel, Dordrecht, Netherlands, pp. 401–412.

Clark, W.C., *et al.*:1982, 'The Carbon Dioxide Question: A Perspective for 1982', in W.C. Clark (ed.), *Carbon Dioxide Review*, Clarendon Press, Oxford, U.K., pp. 3–44.

Delrymple, D.D.: 1978, 'Development and Spread of High-Yielding Varieties of Wheat and Rice in the Less Developed Nations', USDA/USAID Report 95.

Food and Agriculture Organization: 1978–80, 'Report on the Agroecological Zones Project', Vols. 1–4, FAO, Rome.

Food and Agriculture Organization: 1982, 'Potential Population Supporting Capacities of Lands in the Developing World', FAO/UNFPA/IIASA Report FPA/INT/S13, Rome.

Grainger, J.: 1981–82, 'What are the Factors Causing Different Patterns of Crop Production?', *World Crops*, Parts 1–7.

Hazell, P.B.R.: 1982, 'Instability in Indian Foodgrain Production', Research Report 30, International Food Policy Research Institute, Washington, D.C.

Hough, M.N.: 1981, 'A Weather-Dependent Yield Model for Silage Maize,' *Agric. Meteor* **23**.

International Livestock Centre for Africa:, 1983, 'Livestock and Drought', Annual Report, ILCA, Addis Ababa, Ethiopia, p. 29.

Lamb, H.E.: 1981, 'Effects of Climatic Change on the People of Europe in the Past', and 'The State of the Art in Climatology', in S.W. Burrage and M.K.V. Carr (eds.), *Climatic Change and European Agriculture*, Centre for European Agricultural Studies, Wye College, Kent, U.K.

Mehra, S.: 1981, 'Instability in Indian Agriculture in the Context of the New Technology', Research Report 25, International Food Policy Research Institute, Washington, D.C.

Monteith, J.L. and Scott, R.K.: 1982, 'Weather and Yield Variation of Crops', in K. Blaxter and L. Fowden (eds.), *Food, Nutrition, and Climate*, Applied Science Publishers.

National Defense University: 1978, 'Climate Change to the Year 2000', Joint Study with the U.S. Department of Agriculture, the Defense Advanced Research Project Agency, the National Oceanic and Atmospheric Administration, and the Institute for the Future, Washington, D.C.

National Defense University: 1980, *Crop Yields and Climate Change to the Year 2000*, Vols. 1 and 2, U.S. Government Printing Office, Washington, D.C.

Ollerenshaw, C.B.: 1981, 'Climatic Change – Its Likely Effect on Some Animal Diseases', in S.W. Burrage and M.K.V. Carr (eds.), *Climatic Change and European Agriculture*, Centre for European Agricultural Studies, Wye College, Kent, U.K.

Oram, P.A.: 1982, 'The Economic Cost of Climatic Variation', in K. Blaxter and L. Fowden (eds.), *Food, Nutrition, and Climate*, Applied Science Publishers, London.

Oram, P.A., Zapata, J., Alibaruho, G., and Shyamal, R.: 1979, 'Investment and Input Requirements for Accelerating Food Production in Low-Income Countries by 1990', Research Report 10, International Food Policy Research Institute, Washington, D.C.

Palutikof, J.P., Wigley, T.M.L., and Farmer, G.: 1983, 'The Impact of CO_2-Induced Climate Change on Crop Yields in England and Wales', Paper presented at Symposium on Climate and Biosphere, Osnabrück, F.R.G., March.

Parry, M.L.: 1978, *Climatic Change, Agriculture and Settlement*, Dawson, Folkestone, U.K.

Sundquist, W.B., Menz, K.M., and Neumeyer, C.F.: 1982, 'A Technology Assessment of Commercial Corn Production in the United States', Bulletin 546, Agriculture Experimental Station, University of Minnesota.

Valdes, A. and Konandreas, P.A.: 1981, 'Assessing Food Insecurity Based on National Aggregates in Developing Countries', in A. Valdes (ed.), *Food Security for Developing Countries*, Westview Press, Boulder, Colorado.

Williams, G.D.V. and Oakes, W.T.: 1978, 'Climatic Resources for Maturing Barley and Wheat in Canada', in K.D. Hage and E.R. Reinelt (eds.), *Essays on Meteorology and Climatology: In Honour of Richmond W. Longley*, Studies in Geography Monograph 3, University of Alberta, Edmonton, Canada, pp. 367–385.

World Bank: 1982, 'World Development Report 1982', World Bank, Washington, D.C.