Environmental Consequences of Nuclear War Volume II:
Ecological and Agricultural Effects
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# CHAPTER 4
# *Potential Effects of Nuclear War on Agricultural Productivity*

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## 4.1 INTRODUCTION

The current human population on Earth is nearly $5 \times 10^9$ individuals, and the population continues to grow at least exponentially. Humans are almost totally dependent on biological activity for food and other sustenance, yet the human population now far exceeds the capacity of the natural ecosystems for support. Indeed, without any agricultural productivity, at least 90% to 99% of the current human population could not be maintained indefinitely, an issue discussed in more depth in Chapters 3 and 7.

Agricultural plants are largely derived species that evolved in tropical or subtropical areas, species capable of high seed production. They are especially sensitive to even brief periods of cold temperatures, to insufficient water availability, to insufficient nutrient supply, and to disruptions in their life cycles. Humans establish an artificial environment for most crop plants; this includes: 1.) reduction in competition against other plant species (e.g., through cultivation, weed removal, and applications of herbicides); 2.) supplements of nutrients and moisture (e.g., through fertilization, crop rotations to refurbish soil nutrient levels, and irrigation); 3.) protection against herbivory and disease (e.g., through applications of insecticides and fungicides); 4.) development of optimal genetic constitution (e.g., through artificial selection and controlled mixing of genomes); and 5.) protection from the vagaries of nature (e.g., by optimal timing of sowing to coincide with the weather conditions extant at a particular location). These, and many other, subsidies by humans for agricultural systems allow the high levels of productivity that are presently attained.

Humans, of course, cannot yet reliably control the weather, so the particular vulnerability of agriculture to adverse weather provides a constant back-drop to the production of substantial yields each year. But based on experience and selective breeding, the distribution of particular agricultural crops across the landscape reflects a deliberate reduction in the risk of failure, and, thus, indirectly provides protection of the crops from variations in the physical environment. Those years in which the conditions are adverse for crop production differ among crop species and locations; thus, there are few instances where disruptions in climate occur simultaneously on a global scale. Local- or regional-scale disruptions in productivity are usually compensated for via the economic system, involving trade from other areas (although this is not always the case for the poorer regions of the world). This complex interaction between human and biological systems, then, is largely successful in maintaining the modern human population, at least up to current population levels, because the scale of disruptive perturbations is relatively small compared to the total, global scale of the agricultural system, probably within $\pm 5\%$ globally in any single year.

But the possibility for global-scale disruptions in climate and the high probability for global-scale disruptions in human economic and societal systems resulting from a large-scale nuclear war for the first time offer the scale of perturbations that simultaneously could disrupt agricultural productivity world-wide. No other anthropogenic perturbation to the environment has this disruptive potential; consequently, little previous scientific investigation of the impacts of global disruptions on the agricultural system has been done. Previous work has focused on the possibility of an increase in global average temperatures by a few degrees in response to anthropogenically induced increases in atmospheric $CO_2$, and some work on small reductions in temperature has been done in the context of possible alterations in atmospheric ozone from human activities and the potential for general climate cooling at northern latitudes. However, these situations would develop gradually, with time for feedbacks from the human systems at least partially to compensate for climatic changes. Moreover, projections of these stresses do not invoke simultaneous, massive disruptions of societal systems. Therefore, while we will draw from these studies somewhat, there is essentially no precedent to the consideration of the types and scales of stresses potentially associated with nuclear war.

Previous assessments of the global environmental effects of nuclear war (e.g., Woodwell, 1963; Ayres, 1965; NAS, 1975; OTA, 1979; ACDA, 1979; UN, 1968, 1979, 1980, 1981; Lewis, 1979; Katz, 1982) and studies specific to agricultural effects of nuclear war (e.g., Brown and Pilz, 1969; Brown et al., 1973; Bensen and Sparrow, 1971; Haaland et al., 1976; Hill and Gardiner, 1979; FEMA, 1982; Hjort, 1982, 1984) did not consider the potential for large-scale climatic alterations. In many of these studies, agricultural effects were limited to consideration of radiation, since fallout was considered to be essentially the only global-scale stress requiring consideration. Many of the agricultural effects studies did consider some aspects of disruption of societal systems in their role of providing support to food production and distribution, but almost all examined only effects on the United States, often based upon a highly optimistic scenario of the post-nuclear war world. Katz (1982) and Hjort (1982, 1984) presented a more balanced picture of the societal constraints on post-nuclear war food production and distribution, and Hjort (1984) did extend the considerations to the global scale. Nevertheless, reading of the extensive literature on the effects of nuclear war that was prepared prior to considerations of climatic disturbances would not lead one to believe that agricultural effects were likely to be dominant.

In Ehrlich et al. (1983) the suggestion was made of the potential vulnerability of food production on a global scale following a nuclear war. This was examined more closely in Harwell (1984), and the conclusion was reached that globally the greatest vulnerability of humans to a nuclear war may be that associated with food availability. Here we will investigate the issue in considerably more depth, drawing upon a variety of information sources in order to make the best estimates of nuclear war-induced reductions in food production and availability. The approach is to examine first the vulnerability of world agricultural productivity to the potential climatic changes, including both acute and chronic stresses and considering effects on different crops and different parts of the Earth. We then consider, in the absence of climatic alterations, the effects on productivity from the loss of human subsidies to agriculture. These combined effects lead to at least the possibility of little or no agricultural productivity on up to a hemispheric scale during the acute phase response to a large-scale nuclear war, and to the severe reduction in agricultural productivity extending into the chronic period and beyond. The obvious next issue is the existence, availability, and duration of food stores on a global basis; this issue is examined in detail in Chapter 5 in order to translate the effects of nuclear war into effects on the large fraction of the human population that would not be victimized by the nuclear detonations directly.

## 4.2 VULNERABILITY OF AGRICULTURAL PRODUCTIVITY TO CLIMATIC PERTURBATIONS

### 4.2.1 General Issues Concerning the Effects of Climatic Perturbations on Agricultural Productivity

The SCOPE–ENUWAR team investigating the atmospheric and climatic responses to a major nuclear war (Volume I, Pittock et al., 1985) has estimated possible changes in air temperature, solar insolation, and precipitation that could occur on hemispheric or global scales (Table 2.1). There remains significant uncertainty in the specific projections (see also, NRC, 1985), and the projections differ considerably across locations and across seasons.

It is not possible for those of us examining the biological effects of climatic and other potential nuclear war-induced perturbations to select a single physical environmental scenario to be analyzed. This is because of 1.) the uncertainties in the physical analyses; 2.) the evolving nature of the detailed physical projections, as new analyses continue to be performed by the physical scientists; 3.) the complexity of the distribution of physical environmental conditions across the global landscape; and 4.) the complexity of distribution of biological systems and associated stress-response relationships across the global landscape.

For the purposes of the agricultural assessments in the present study, the possible climatic changes were categorized into groups of types of stresses based on their likely significances to biological systems and on the most appropriate methodology for use in making an assessment of those stress responses. Each of these categories has different implications for agricultural productivity, and different approaches to evaluating their effects were undertaken. The categories were not selected to represent the most likely outcome of a nuclear war, nor is there any implication in selecting these categories of the level of probability associated with their occurrence at any particular location or any particular point in time. Such estimations of probabilities and extent of occurrence of climatic disturbances are needed for more specific biological assessments to be conducted, but these remain for the physical scientists yet to resolve. The categorization used in the present analyses was: 1.) a climatic disturbance identified as being 'acute', characterized by transient, average land-surface air temperature extremes near or below freezing, and associated average light reductions of 90–99% below normal; 2.) a 'chronic' phase climatic disturbance, characterized by average annual land-surface air temperature reductions of a few degrees below normal (1°C, 3°C, 5°C, or even 10°C); and 3) an acute or chronic phase climatic disturbance characterized by precipitation reductions that could be 50% or greater below normal. Because the issue of patchiness in the post-nuclear war environment, e.g., having acute-type perturbations intermixed with more normal conditions, has not yet been resolved by the physical scientists, this issue was not analyzed explicitly; nevertheless, it is recognized that such an eventuality might lead to greater biological consequences than could follow from a single acute perturbation or from a monotonic, gradual decrease in temperatures, for which acclimatization might be possible.

We wish to emphasize again that the issue of probability for any or all of these climatic disturbances to occur at a particular location or region is not considered here. Thus, as an example, analyses of the potential effects on wheat production in Canada in response to an average growing-season temperature decrease of 3°C are presented in order to illustrate the vulnerability of that agricultural system to that level of perturbation. The specific level of temperature disturbance in those analyses is within the range of outcomes considered to be plausible based on Volume I; however, we are not predicting it would necessarily occur nor are we implying any specific level of probability of occurrence. By utilizing a systems vulnerability approach, the analyses presented in this volume should remain instructive, even as there continue to be adjustments in the projections of the physical scientists concerning the environmental responses to nuclear war. These cautions apply throughout the analyses in this chapter and the rest of this volume.

If an acute decrease in average temperatures down to near or below freezing were to occur during the growing season, the consequences on crop yields can be inferred from the types of physiological information discussed in Chapter 1. However, the other stresses require a closer examination for the potentially associated agricultural responses; we addressed these issues using physiological-level considerations, analyzing empirical data on crop-weather relationships, examining historical analogs, and utilizing simulation models. Each of these approaches is incorporated in the following sections. But we first need to examine the context of climatic changes on agriculture.

One key issue is the difference between average climatic conditions and actual weather experienced at a location and at a point in time. Except for the possibility of initial, transient 'quick freeze' phenomena, the projections from the atmospheric/climatic studies are for *average conditions*. For most of the analyses, these are averaged over diurnal cycles, over long periods of time, including seasonal cycles, and over large expanses of landscape. However, the understanding of the response of crops to the physical environment is based on far smaller scales of time and space. While it is important to know what the cumulative reduction in temperature over a growing season would be (i.e., the thermal time discussed below) at a particular location, a value that can be calculated from average climate predictions, it is also critical to know what the range of temperature variations and the incidence of brief cold events during the growing season would be. The average temperature drop may well define what crop yields would be, because a reduction in the available energy over the growing season translates into a reduction in crop yields. Averaged over time, this in large part determines what crops should be planted in specific regions. But it is the occurrence of short-duration episodes of low minimum temperatures that can lead directly to the death of plants or to the irreversible interference with maturation of the crop, i.e., can lead to total crop loss for that growing season. Both of these processes operate in the relationship between climatic alterations and crop productivity.

Consider a hypothetical example case, in which a projected chronic decrease in average temperature of, say, 3°C, occurred by having each and every daily maximum and minimum temperature decreased by 3°C. Over a growing season of, say, 100 days, that would translate into a loss of 300 degree-days, a value that could be used to estimate the yield responses of different crop species. Additionally, an average decrease in which the variance and autocorrelation of daily variance were unchanged would reduce the length of the growing season, if defined as the frost-free period, by an amount determined by the seasonal rate of warming in the spring and cooling in the autumn; i.e., if the average daily temperatures at the beginning of the growing season in our example are increasing at a rate of, say, 0.5°C per day, then a scenario having a 3°C reduction in average daily temperatures would correspond to an average delay in the onset of the growing season by 6 days.

The issue of changed variance in association with a nuclear war-induced change in average temperatures is an issue that has not been clarified to date. Changes in the variation of daily temperatures and the variation over diurnal cycles are possible in a nuclear war-altered climate. Suggestions have been made that the diurnal and monthly variance might decrease under a nuclear war-altered atmosphere for the mid-latitudes in mid-continental regions, and that variations at the periphery of a nuclear war-induced smoke cloud, such as at coastal zones and in tropical regions, might increase from current patterns (Volume I, Pittock et al., 1985). However, there does not appear to be a solid basis for such suggestions nor any quantification yet done. Thus, unless otherwise noted, the climatic analyses in the present volume were accomplished assuming no changes in weather variance after a nuclear war. It is clear that if an average cooling were to occur with an associated change in climatic variance over time, then the relationship between an average decrease in temperature and a reduction in the length of the growing season might differ from the pre-nuclear war situation. Likewise, if there were a differential reduction in temperature over a growing season, even without a change in the total variance, the reduction in the length of the growing season as a function of altered average conditions could be different from the estimates based on uniform application of a temperature decrease across the growing season, either extended or compressed in time.

As one method to estimate the present relationship between the reduction in the average temperature and the length of the frost-free season, a study that examined the potential effects from a 2°C reduction in global annual average temperature included an analysis of gradients of temperatures across latitude in comparison with the length of the growing season. Based on these assessments (Dale et al., 1975), it was reported that a 1°C change in the mean growing season temperature would result in reduction in the frost-free period by 10 days. Again, this assessment took no account of a change in the local weather variance or autocorrelation in daily temperatures.

We have performed similar evaluations by examining weather data from 38 stations across the continental United States to determine the relationship within a single year between the mean growing season temperatures and the length of the frost-free period, defined as the number of consecutive days with the minimum temperature above 0°C (Figure 4.1a) or above −2°C (Figure 4.1b). Two other plots were made for several weather stations over *different* years (Figures 4.1c,d). In all four situations, the estimate of about 10 days per 1°C average change in temperature was consistent.

In another set of evaluations performed in order to investigate this topic, a set of five stations was selected from a large climatological data base at the National Center for Atmospheric Research, which includes information recorded for weather stations throughout the United States and Canada. Each station has at least a 40-year record, and often many more years are covered by the data base. The long-term daily mean minimum temperatures for the selected stations were computed and subjected to harmonic analysis in a study performed by M. Verstraete for the SCOPE–ENUWAR project. This involved the decomposing of the seasonal temperature traces into Fourier components.

This procedure expresses the variance in the original records as a superpositioning of sine and cosine elementary signals, each with a particular amplitude, phase, and frequency. Since the annual temperature cycles are well defined for most of the stations in the survey, the first few components of the analysis accounted for most of the variance; over 99% of the total variance of the seasonal signal can be reconstructed from the first five harmonics. Therefore, it is possible to obtain for each station an analytical expression that very accurately reflects the long-term average seasonal cycle of the daily minimum temperatures.

This approach was used for examining the dates at which the daily minimum temperatures in May and September finally or initially crossed the threshold temperature of −2°C by analyzing the time derivative of the analytical expression at those points in time. The analysis is based on the seasonality component of the time series, with all other characteristics of the time–temperature signal, such as variance and autocorrelation, assumed to remain unchanged. The calculated slope value, as discussed above, represents the rate at which a change in average temperature translates into a change in the length of the frost-free period. For the selected weather

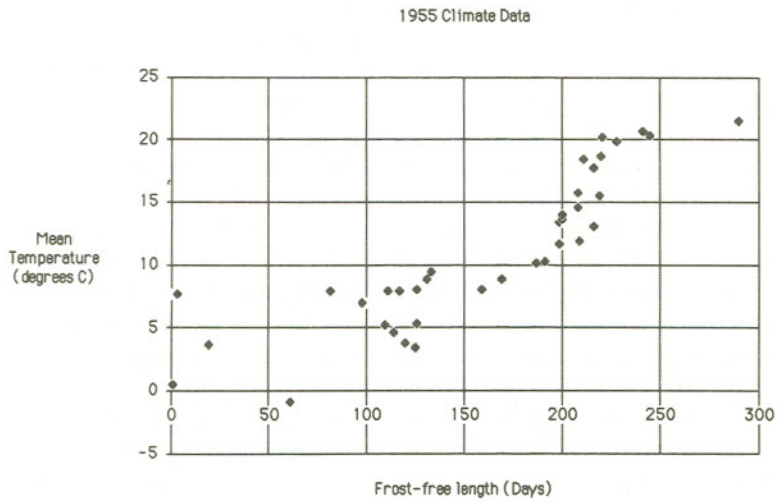


Figure 4.1a Consecutive days above 0°C for selected continental U.S. weather stations in 1955

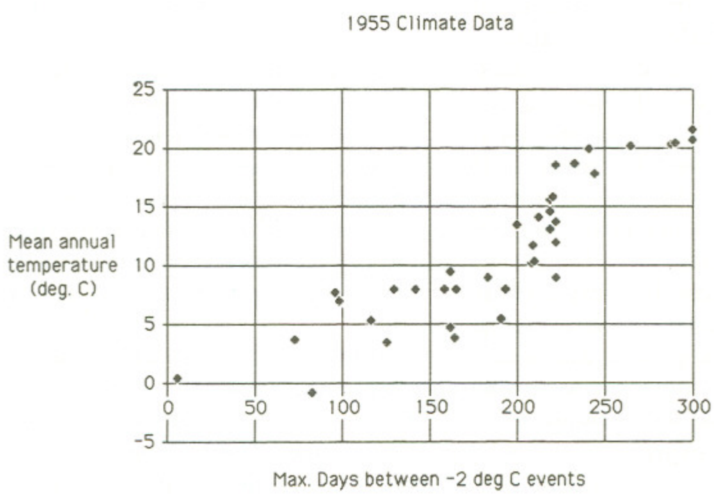


Figure 4.1b Consecutive days above $-2$°C for selected continental U.S. weather stations in 1955

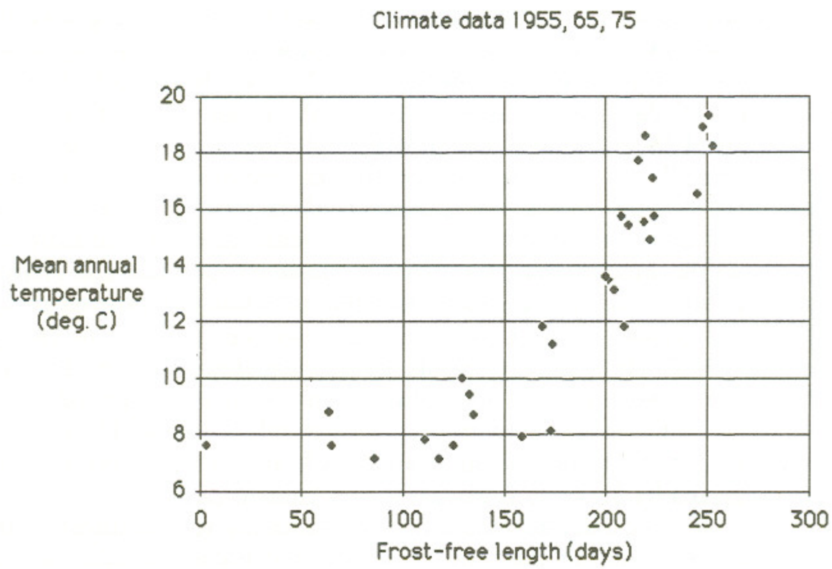


Figure 4.1c Consecutive days above 0°C for selected continental U.S. weather stations in 1955, 1965, and 1975

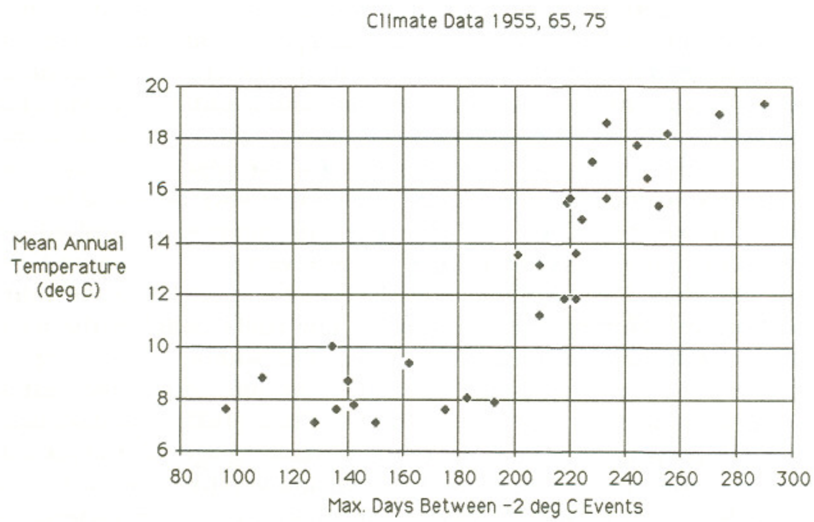


Figure 4.1d Consecutive days above −2°C for selected continental U.S. weather stations in 1955, 1965, and 1975

stations analyzed in the mid-latitudes, the sensitivity of the length of the growing season, as defined as the number of consecutive days during which the mean daily temperature remained above $-2°C$, was found to be approximately 10 to 12 days per degree C change in the mean temperature.

With respect to the sensitivities at other latitudes, stations in southern regions, especially into subtropical and tropical regions, never experience freezing, and this analysis is not applicable. More northerly stations were seen in this analysis to have a more marked seasonal cycle, reducing the sensitivity to this kind of change somewhat. However, Bollman and Hellyer (1974), in another analysis, concluded that the reduction in frost-free period per degree is greater in more northerly latitudes, i.e., the rate of change increases with shorter growing season. In Canada, they predicted that a 1 °C change translates into a 20 day reduction in the frost-free period, again assuming present average temperature-variance relationships. Their result, however, is contrary to the results from the wheat and barley productivity models analyzed by Stewart, as discussed in a later section.

Thus far, we have discussed the effect of decreasing temperatures by the same amount each day of the growing season; but there is another way in which a hypothetical chronic 3°C reduction in average temperature could occur: an increase in the frequency, intensity, and/or duration of cold episodes occurring within an otherwise normal growing season. This again relates to the variance in climate after a nuclear war, an issue for which we have little guidance from the climate analysts. On the one hand, it would seem that variance in temperature under a nuclear war-altered atmosphere would be decreased, because diurnal cycles might be dampened and because the atmosphere might be more stable vertically; on the other hand, the considerable disruption in current global atmospheric circulation patterns could possibly lead to historically unprecedented disruptions in weather patterns, increasing variance over time; also, those regions near the edge of a nuclear war-induced smoke cloud (e.g., the tropics) could experience increased temporal variability in weather. There is a strong spatial component involved here; e.g., monthly temperatures at a single location vary much more on a year-to-year basis than does the monthly temperature averaged over the entirety of the Northern Hemisphere. Thus, while one could establish the normal variation in temperatures on a global scale to be within 1°C in comparing growing seasons across years, the variation from one year to the next at a particular location is typically much greater. Clark (1985) also discussed in depth the importance of scale issues for understanding agricultural responses to climate, noting that several orders of magnitude differences in time and spatial scales are all potentially involved in stress-response characterization.

As a simple illustration of the spatial and temporal components of temperature variance, consider the hypothetical situation depicted in Figure 4.2. In Case 1, some perturbation is applied to the normal pattern for an entire

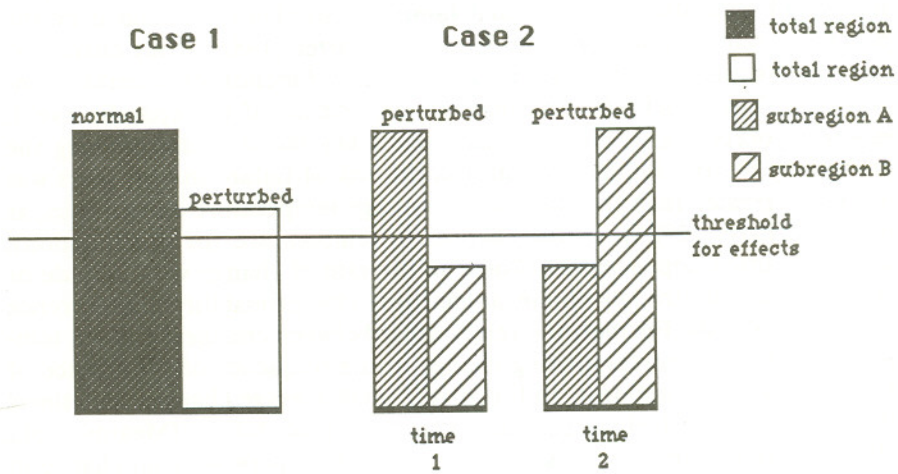


Figure 4.2 Idealized representation of effect of spatial and temporal scale on evaluating effects from average conditions. See text for discussion

region. In Case 2, the total region is subdivided into two halves. Twice as intense a perturbation occurring over half the area would give the same regionally averaged value as the first case. Alternatively, to add a temporal component, consider two time periods in Case 2, where one half of the region experiences the perturbation for half the time, followed by the other half being perturbed for the other half of the time. Again, the time- and region-averaged perturbation would be the same as in Case 1. However, if there is a threshold for effects, then the actual consequences would be quite different from the averaged case to the more local-scale situation. As an example, in the regionally average case of Figure 4.2, no effects at all would be predicted, since the threshold would never have been exceeded. In the other case, 50% or even 100% of the area could suffer total effects, depending on the time pattern of imposing the perturbation (e.g., having half the region perturbed for the total time, or having each half of the region perturbed for half the time). Thus, if exceeding some threshold for brief periods of time can result in an impact, then a spatially and temporally averaged picture of the perturbation cannot reliably predict the consequences that would be felt. And that is precisely the situation with respect to agricultural impacts from climatic changes. For example, in the acute period there is the possibility of experiencing sudden freezes that move across large areas of landscape, even though only a relatively small area would be perturbed at any one point in time; likewise, in a chronic period, episodes of extreme temperatures could be a part of a generalized reduction in average temperatures.

One approach to dealing with these issues is to identify the probability of experiencing conditions exceeding the threshold for effects. A detailed analysis of agricultural success and failure in southern Scotland over the past three centuries was done by Parry and Carter (1985). They characterized the frequency of failure of oat crops as a function of monthly temperatures. The conclusion was that the importance of the episodic event, especially occurring in extreme years, was a key factor in determining the probability of crop failure. The shift in the risk of failure in cool years was markedly greater than the shift in the average temperature alone. Thus, as noted by Parry (1985), spatial changes in temperature (or precipitation), which are often approximately linear in the rate of change with latitude or altitude, result in strongly nonlinear changes in the probability of occurrence of extreme events. Further, the relationship between changes in mean temperatures and the corresponding change in the frequency of occurrence of extreme events is nonlinear, and relatively small average changes sometimes translates into relatively large changes in event probabilities (Mearns et al., 1985; Warrick, in press). This might occur even if there were no change in the variance–average temperature relationship, such as after a nuclear war compared to the present. This will have implications in our later discussions of the post-nuclear war chronic period with respect to the planting strategies by survivors in order to reduce the probabilities of crop failure in an uncertain environment.

Another aspect of the disturbed climate projections is a measure of the magnitude of the stresses. For instance, a 1°C change in average temperatures over a growing season may seem relatively small, yet major climatic consequences can follow from global average temperatures that are below normal by smaller or even nonexistent levels The average annual Northern Hemisphere temperature has been within about $\pm 0.75$°C over the past century, and differences between current hemispheric temperatures and the warmest interglacial periods of the last half million years are only about 2–3 °C (IIASA, 1981). In 1816 killing frosts continued through the summer in much of North America and Europe (Stommel and Stommel, 1979), even though there was probably less than 1°C or 2°C difference in global temperature. As another example, consider the extreme weather responses to the most recent El Niño episode, in which large regions experienced record-breaking low or high temperatures, and extremes of rainfall or drought; changes in global average temperatures were essentially irrelevant to this large, regionally important anomaly.

Similarly, projections of precipitation possibly being reduced on a regional scale by 25% or 50% need to be perceived within the context of normal year-to-year variation. Figure 4.3 shows the current rainfall variability on Earth (IIASA, 1981, citing Petterssen, 1969). Large portions of the agriculturally productive areas of North and South America, Europe, and Asia experience annual rainfall deviations from normal of less than

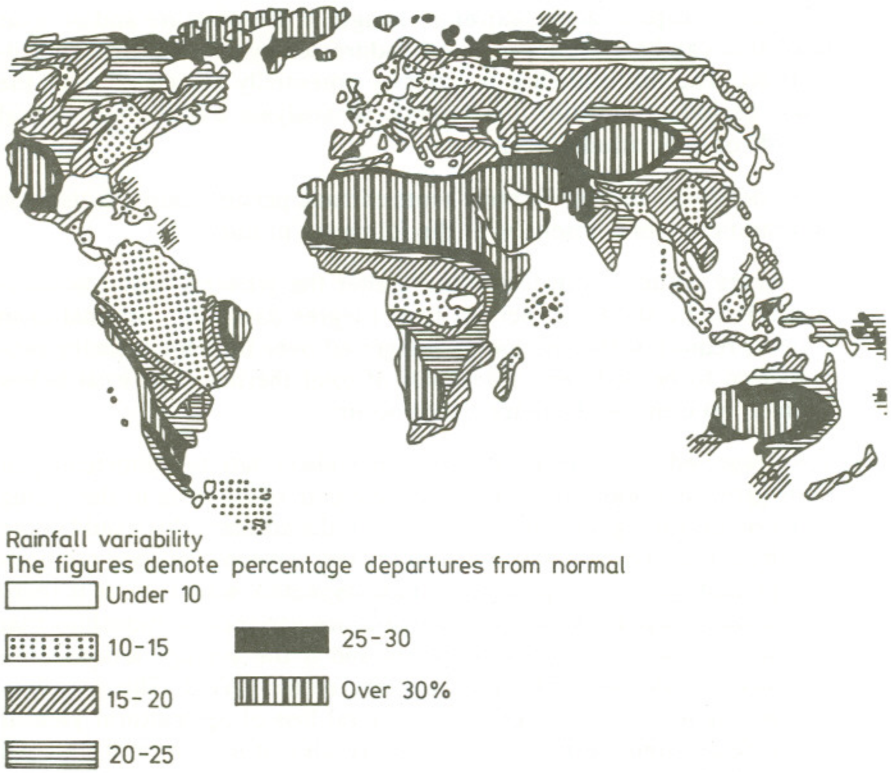


Figure 4.3 Annual variability of rainfall. After IIASA (1981)

20%, according to this reference, and only the more arid regions of Africa, the Arabian Penisula, Australia, the Arctic, and the deserts of America and Central Asia experience deviations of 30% of more, reflecting a general trend of greater variation occurring in areas of lower average precipitation. Thus, changes in precipitation of the magnitude projected as potentially occurring over at least a regional scale following a large-scale nuclear war are unprecedented for those regions for which agricultural productivity is high.

### 4.2.2 Summary

These preceding considerations guide us in our approach to evaluating the agricultural effects of nuclear war. The potential responses of agricultural productivity to altered climatic conditions may involve one or more of the following factors, discussed in detail in the subsequent sections:

1.) Effects on crops of acute, extreme changes in temperature and/or solar insolation can be most appropriately addressed by physiological considerations. The extreme climatic stresses potentially associated with the acute period are outside the bounds of analyses based on historical records or simulation models.

2.) Chronic effects and less extreme acute climatic perturbation effects must be examined more closely, with the following in mind:

   - Average reductions in temperature alter the growing season as characterized by the total thermal time (degree-days); i.e., optimal crop yields require sufficient energy integrated over time for primary production to be high, and thresholds of total thermal time exist below which no crop productivity would occur.

   - Average reductions in temperature may also relate to a shortening of the growing season by delaying the last date of freezing in the spring and/or advancing the onset of freezing in the autumn; this would occur if there were no change in the average temperature-variance relationships that exist in an unperturbed atmosphethis would occur if there were no change in the average temperature-variance relationships that exist in an unperturbed atmosphere and if the average temperature reduction extended uniformly over the entire period. This growing-season reduction factor can lead to total loss of agricultural yield if insufficient time exists for the crop to reach maturity, even if the total thermal time as characterized by the degree-days is adequate.

   - The reduction in average temperatures over a growing season typically results in a reduction in the rate of the crop maturation processes; this tends to extend in time the length of a growing period required for completion of crop maturation, thereby exacerbating the effect of shortening the growing season.

   - Episodes of extreme temperatures are often associated with changes in the average temperatures over a growing season; thus, within a growing season there is an increased probability of crop failure on a regional scale resulting from even a brief period of extreme weather;

   - Because agricultural plants have distinct thresholds for survival and/or production of a usable crop, exceeding the threshold can lead to non-linear effects that are irreversible for that growing season;

- Precipitation on at least a regional scale might be changed by unprecedented amounts following a large-scale nuclear war; most grain crops, the major basis for human support, are grown in water-limited areas under normal precipitation patterns, so they are especially vulnerable to reductions in precipitation.

In the following sections we examine the effects of nuclear war-induced climatic perturbations on agricultural production in the Northern Hemisphere, in the tropics, and in the Southern Hemisphere. Our primary emphasis is on the grain crops as providing the most important component globally in the human diet. Secondary consideration is given to animal productivity, especially in those areas (e.g., New Zealand) where animals provide a major food resource.

## 4.3 POTENTIAL VULNERABILITY OF NORTHERN TEMPERATE AGRICULTURE

### 4.3.1 Response to Acute Extreme Climatic Perturbations

The mid-latitudes of the Northern Hemisphere are highly productive agriculturally, providing a large fraction of the grain production in the world. Of particular interest here is the production of wheat, maize (corn), and rice. Figures 4.4 a–c illustrate the current distribution of the growing areas for these three grains in North America, the U.K., and Eurasia. These growing areas are the region potentially most subject to the direct and the climate-induced indirect effects of nuclear war. Based on the discussions in Volume I, it is likely that the Northern mid-latitudes would have the highest probability of any region on Earth of experiencing acute climatic perturbations, particularly from a summer-onset nuclear war. With respect to the biological analyses, the acute, extreme climatic perturbation of at least brief periods of near- or sub-freezing temperatures, with concomitant light level reductions, is instructive for examining the vulnerability of Northern temperate agricultural to the potential effects of a large-scale nuclear war.

The response of crop plants to freezing events during the growing season is discussed in Chapter 1. A synopsis of some of the minimum temperatures that various crops can endure without either death or the irreversible interruption in the production of yield is listed in Table 4.1. It is apparent from these data that any of the crops of substantial value for human food production would be killed outright or the yield considerably reduced or even lost for a growing season in which freezing occurred.

By considering this simple, direct response at the physiological level, the response of agriculture in the Northern mid-latitudes to the potentially extreme temperature excursions of the acute period of nuclear war-induced

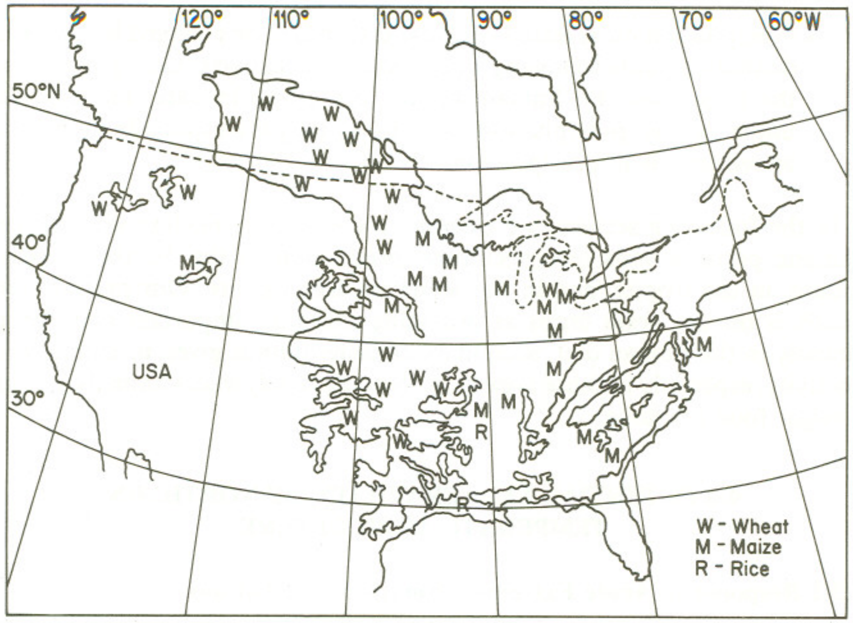


Figure 4.4a Current growing areas for wheat (W), maize (M), and rice (R) in North America. Maps prepared by J. Porter

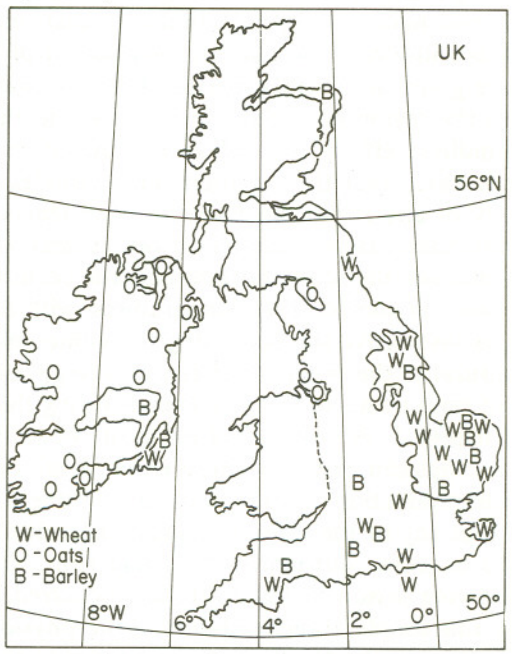


Figure 4.4b Current growing areas for wheat (W), oats (O), and barley (B) in the U.K.

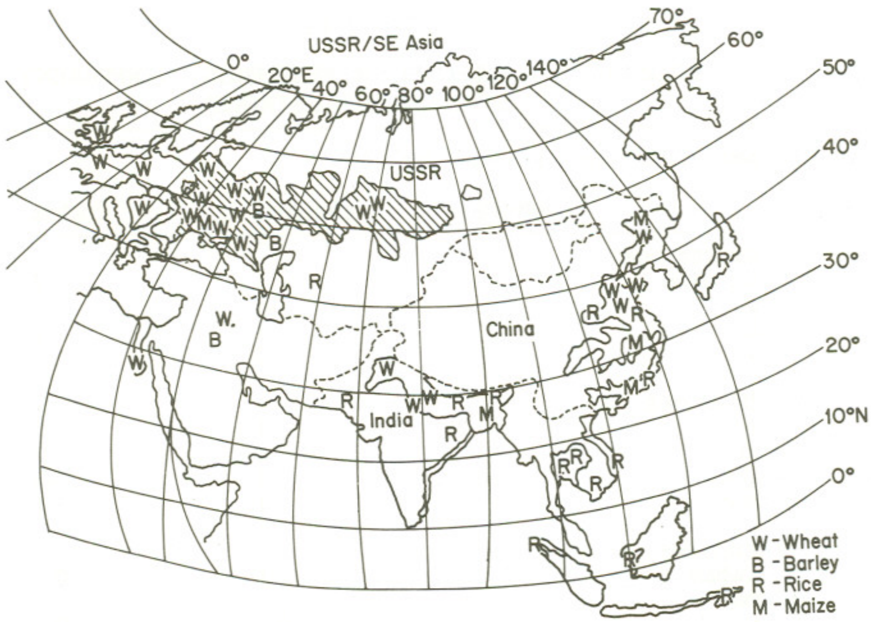


Figure 4.4c Current growing areas for wheat (W), rice (R), barley (B), and maize (M) in Eurasia

climatic disturbances can be determined by knowing the spatial extent of such freezing episodes. The best information from the climatic analyses is that most inland continental areas of the Northern mid-latitudes could experience subfreezing minimum temperatures after a summer- or a winter-onset nuclear war of sufficient magnitude to inject about $2 \times 10^8$ tonnes of smoke into the atmosphere, and by inference following such a war at other times of the year. For example, Table 4.2 illustrates the mean minimum daily temperature during June at a number of locations above 30°N latitude, indicating the vulnerability of those locations to a drop of 15°C below the daily minimum levels. If such a temperature excursion were to occur below average normal June conditions, each location would be near or below freezing and, thus, subject to the types of chilling or freezing effects discussed in Chapter 1. Likewise, if a climatic perturbation induced by a nuclear war were to occur in the spring, summer, or early autumn, then any subfreezing episodes that did occur would coincide with the growing season, and essentially no agricultural crop production in that location would occur that year. In short, a transient acute, extreme climatic perturbation would lead to the loss of a crop for the year for all Northern temperate areas in which such an event

TABLE 4.1

RESISTANCE OF SELECTED CROPS TO FROST IN DIFFERENT DEVELOPMENTAL STAGES[a]

| Temperature (°C) harmful to plant in phases of: | Germination | Flowering | Fruiting |
|---|---|---|---|
| HIGHEST RESISTANCE | | | |
| Spring wheat | -9 | -1 | -2 |
| Oats | -8 | -1 | -2 |
| Barley | -7 | -1 | -2 |
| Peas | -7 | -2 | -3 |
| LOW RESISTANCE | | | |
| Corn | -2 | -1 | -2 |
| Millet | -2 | -1 | -2 |
| Sorghum | -2 | -1 | -2 |
| Potatoes | -2 | -1 | -1 |
| NO RESISTANCE | | | |
| Buckwheat | -1 | -1 | -0.5 |
| Cotton | -1 | -1 | -2 |
| Rice | -0.5 | -0.5 | -0.5 |
| Peanuts | -0.5 | ------ | ------ |
| Tobacco | 0 | 0 | 0 |

[a] Data from Oliver (1973).

occurred. In the case of a major, hemispheric-scale transient acute cooling response to nuclear war, such as the higher ranges of the possible outcomes projected from Volume I, agricultural productivity in the Northern temperate regions would be lost if a nuclear war occurred in about a six-month window of vulnerability, during the spring/summer/early autumn.

In the event of a war occurring in the autumn immediately after harvesting of the previous summer's crops, then the issue with respect to responses to acute perturbations is one of the duration of the acute period. If the acute period were to extend into the following growing season, then the same effect would apply, and no production could occur the following summer. However, based on Volume I, it seems more likely that the acute period would already be passed prior to the onset of the following summer months; thus, the potential effects on agricultural productivity can be assessed using the approaches for the chronic period, discussed in detail in the following sections.

TABLE 4.2

SUSCEPTIBILITY TO SUBFREEZING TEMPERATURES BASED ON A 15°C DECREASE IN MEAN TEMPERATURES IN JUNE FOR SELECTED NORTHERN HEMISPHERE LOCATIONS[a]

| Weather Station | Latitude | Mean June Minimum Temp. (°C) | Mean June Minimum Temp. -15°C (°C) |
|---|---|---|---|
| Irkutsk, U.S.S.R. | 52°N | -1 | -16 |
| Vladivostok, U.S.S.R. | 43°N | +7 | -8 |
| Krasnovodsk, U.S.S.R. | 40°N | +16 | +1 |
| Rome, Italy | 42°N | +13 | -2 |
| Brno, Czechoslovakia | 49°N | +6 | -9 |
| Munich, F.R. Ger. | 48°N | +5 | -10 |
| Madrid, Spain | 40°N | +9 | -6 |
| London, U.K. | 51°N | +7 | -8 |
| Osaka, Japan | 34°N | +12 | -3 |
| Nanking, China | 32°N | +16 | +1 |
| Oak Ridge, TN, U.S. | 36°N | +17 | +2 |
| Fort Wayne, IN, U.S. | 41°N | +16 | +1 |
| Bismark, ND, U.S. | 47°N | +11 | -4 |

[a] Data from Rudloff (1981).

The consensus, then, reached among the large number of agricultural scientists considering this issue, is that, on the basis of temperature perturbations alone, the initial growing season in the Northern Hemisphere mid-latitudes following a nuclear war in which major climatic perturbations ensued would have essentially no agricultural productivity for a nuclear war occurring within, at a minimum, a several month period. Further, significant productivity might be unlikely for a large-scale nuclear war occurring at any other time of the year, again considering only the effects of transient, acute reductions in temperature.

Added to this could be the effect of reduced solar insolation. As discussed in Chapter 1, the net photosynthetic response of a single plant is typically for saturation to be reached at levels of light input well below full sunlight;

however, an entire crop canopy's light levels often do not reach saturation. This is because the leaves in a crop canopy are an assemblage of leaves at different ages, different physiological states, and different degrees of shading. The plant leaves in the context of the rest of the canopy receive but a fraction of full sunlight, and many of the leaves may photosynthesize at rates below that of respiration (i.e., have no net photosynthesis). This response means that reduction in insolation often leads to a direct decrease in productivity.

During periods in the acute phase of potential nuclear war-induced climatic disturbances, if sunlight levels at the top of the crop canopy were reduced by 90% or more, insufficient sunlight would reach the canopy as a whole for the crop system to be above the light compensation point. If this circumstance were prolonged, the crop would essentially starve to death as the carbohydrate energy reserves became depleted by respiration. The length of period required for this to occur is not easily determined, but would be a function of the crop type, the level of maturation reached prior to the onset of reduced light, and interactions with the effects of temperature. With respect to the latter, if conditions were not so extreme that the temperature killed the plants (e.g., after a relatively mild nuclear war-induced climatic disturbance, at the margins of a nuclear war-induced smoke cloud, or in the chronic period at some point later in time), then reduced temperatures would reduce respiration rates and perhaps compensate somewhat for the effect of reduced light levels.

The other stresses that could be associated with nuclear war-induced climatic disturbances, specifically, areas of reduced precipitation and perhaps increased storminess, would appear to be much less significant with respect to reductions in agricultural productivity during the acute period than the potential reductions in temperature and light. If temperature minimums were not so extreme, such as following a nuclear war that resulted in less disturbance to the atmosphere, then precipitation could become limiting to crop production, as discussed in more depth in the sections on chronic responses.

### 4.3.2 Responses to Potential Chronic Climatic Perturbations

#### *4.3.2.1 Analytical Approaches*

The projections for the chronic phase of nuclear war-induced climatic stresses include the possibility of average temperatures over the growing season being decreased below normal levels by 1°C, 3°C, 5°C, or even 10°C. The light levels assumed to have induced these temperature reductions are projected to be, respectively, approximately 5%, 13%, 16%, and 26% below normal insolation at the surface. The Volume I analysts also suggest that at least on a regional scale, there could be precipitation decreases of 25% to 50% for at least the Northern Hemisphere continental regions, although the uncertainties on these estimates are larger than for the other physical parameters and local increases in precipitation are possible, especially on windward coasts. In order to evaluate the potential consequences of these stresses on agricultural productivity, a number of approaches are utilized.

One basis is historical precedent, examining the past years of extreme low temperatures or precipitation levels for effects on crop yields. While it is clear that there are no historical precedents to the acute onset of extreme nuclear war-induced climatic disturbances, the potential conditions of a chronic phase or a particularly mild climatic disturbance during the acute period may appropriately be analyzed by limited extrapolation and predictions based on the historical record. This approach tends to be anecdotal, and the issues of scale become important, as years in which there were poor yields in some regions may have had good yields elsewhere. In addition, historical extreme years typically had environmental conditions less severe than most of the range of perturbations projected to be possible for even the chronic period after a nuclear war. For example, a decrease in the hemispherically averaged temperature of 3°C or higher is essentially unprecedented within the historical record (Budyko, 1982).

The second approach is to use statistical models, i.e., also to look at the historical record, but to look across years for patterns and relationships rather than at a single year's situation. Again, this approach is limited by the range of physical parameters actually encountered in the past, as much of the variation of possible nuclear war-induced climatic disturbances is unprecedented, and, therefore, is outside the bounds of a statistical approach. Nevertheless, this does provide one additional line of reasoning as a part of the collective analyses.

Another approach is to use empirically based models of plant metabolism in response to environmental parameters, such as ambient temperature, light availability, and moisture stress. This approach is based primarily on laboratory experiments conducted to examine the physiological responses of plants, especially crop species, and follows much of the considerations presented in Chapter 1. Where in the discussions of the consequences of extreme climatic disturbances in an acute case, we relied on the physiological response of crop plant death or crop yield loss in response to near- or sub-freezing temperatures, the physiological approach here uses other indicators of metabolic activity, such as rates of photosynthesis.

The fourth approach is to use simulation modelling, based on models that have been constructed from mechanistic and empirical principles relating the various factors controlling primary production to physical parameters and that have been subsequently validated against actual crop yield data. This approach goes beyond the simple physiological approach by placing the crop plant in the context of the total environment, and, thus, provides a technique to examine multiple perturbations simultaneously. This method also has its limitations, however, especially at the outer bounds of the physical parameters for which the model is appropriate; nevertheless, these simulation models can be very instructive in projecting chronic agricultural responses.

### *4.3.2.2. Historical Approach*

The first consideration for chronic effects of nuclear war-induced climatic disturbances on temperate agriculture is the historical approach. One instance of particular relevance is the year without a summer, 1816, on the food production in the Northeastern United States, Canada, and Western Europe. A detailed account of the consequences is given in Stommel and Stommel (1979) and in Post (1977). These authors examined the temperature records for several locations in the Northeast U.S., with evidence of abnormal cold on average over the summer months. For example, New Haven, Connecticut, had a mean monthly temperature in June, 1816, that was about 3°C below the normal level experienced over the first third of the 19th Century. This translated into a considerable delay in the onset of summer conditions, with the occurrence of several frosts in May. However, warm temperatures at the beginning of June were followed by an extreme cold episode lasting for about a week, during which killing frosts occurred.

The same pattern was seen twice more that summer, with warm periods being abruptly terminated by cold episodes and nighttime frosts in early July and in late August. Inspection of the *average* daily temperatures, however, shows these values did not go below 11°C in June, 14°C in July, and 13°C in August. Nevertheless, the occurrence of frosts during brief periods at night was sufficient to lead to severe impacts on crop yields. Most of the crops that had germinated in late May were killed by the June episode, and much of the subsequently planted crops were killed by the July episode. In many locations, crops that had survived the initial frosts succumbed to the August episode; for instance, it was said that maize production in the region was eliminated in all but the most protected locations because of the effectively two-week early termination of the growing season.

Maize was apparently most affected among the grains, with wheat less severely impacted. Plants grown for hay fared better with respect to temperature decreases, but the reduction in precipitation that occurred simultaneously apparently reduced yields by one-half. On the other hand, those hay yields that were harvested were qualitatively better than normal because of better curing in the drier weather. One important synergistic effect was that the reduced temperatures on average over the growing season prolonged the time required for crop maturation, especially the filling and ripening of the grains; this made the effect worse when the early onset of frost occurred, since the crops were in a less mature, and therefore, less consumable state.

The net effect of the climatic perturbations is difficult to quantify based on anecdotal information. However, one objective measure of the effects was the market price of the food commodities and the incidence of famine. The prices for grains, potatoes, hay, and livestock were reported to increase by factors of two to six, although meat prices fell precipitously because of farmers' killing off their stock for meat rather than try to maintain the herds in the face of high feed prices. Food shortages were not reported for the North American regions that were impacted, since the economic and agricultural systems extant there were adequately buffered; however, urban areas in Europe, such as in Switzerland and France, did suffer famine and associated societal disruptions. This resulted because much of Europe was still stressed from the recently ended Napoleonic Wars, and the societal systems' resistance to perturbation was low (Stommel and Stommel, 1979; Post, 1977). The potential similarity here to a post-nuclear war situation hardly needs further emphasis.

Another set of historical analogs is found in the period known as the 'Little Ice Age'. This period extended from the late 16th Century through the end of the 17th Century, with dendrochronological evidence indicating prolonged periods of regional-scale adverse weather during the 1590s, 1620s, 1640s, 1650s, and 1690s (Parker, 1980). Parker reports that this climatic change is reflected in the vineyard records in France, and in written records from observers at the time. A large variety of anecdotal pieces of information support the general response to an estimated 1°C reduction in average summer temperatures, including shifts in the ranges of crops (e.g., citrus production being eliminated in south China), lower snow lines in mountainous areas, extension of glaciers, and increased incidences of drought. It is estimated by Parker (1980) that the average growing season was reduced in length by three or four weeks. In response, grain yields fell by up to 75% in parts of Europe over the period, and human population growth, which had been rapid for the previous century, was reportedly slowed or even reversed into a population decline for many areas. The mechanism by which the reduced yields translated into human population impacts was apparently largely economic, in which the prices of grains increased substantially during the periods of low harvests, making food beyond the economic resources of the poorer constituents of society, a pattern seen consistently seen in historical and modern famines. It also seems likely that there was a linkage between the reduced food support for humans and the epidemic outbreaks of diseases, such as the bubonic plague, as well as interactions between limited resources and warfare.

#### *4.3.2.3 Statistical Approaches*

As an example of the use of statistical models to relate agricultural productivity to climatic change, Björnsson and Helgadottir (1984) examined in detail the record of hay production in Iceland on the same experimental plots that have been studied for the past five decades. The fertilizer treatments were constant over the experimental period, although there were differences in cutting treatments that had to be compensated for statistically. Yields and seasonal mean temperatures were found to be linearly related with a slope of about a 10% reduction in yield per decrease of 1°C for the Akureyri site in Northern Iceland (loss of about 600 kg $ha^{-1}$ $°C^{-1}$), with greater losses in more southerly locations in Iceland (up to 1100–1200 kg $ha^{-1}$ $°C^{-1}$ at Skriduklaustur). In similar studies, Bergthorsson (1985) reported on a statistical model of hay yield in relation to temperature averaged over the year. The result, corrected for fertilizer differences, is a curvilinear relationship between the annual average temperatures of 1.5°C to 5°C (Figure 4.5). From about 4.5°C to 2.5°C, yields fell about 25%; however, another 1°C decrease in temperature would result in an additional loss of 25%, illustrating the nonlinearity of the response.

The use of linear statistical models based on historical data was explored in detail in the analyses of the Climate Impact Assessment Program (U.S. Department of Transportation, 1975). This study was designed to examine the potential effects of an average temperature reduction or increase of 3°C and

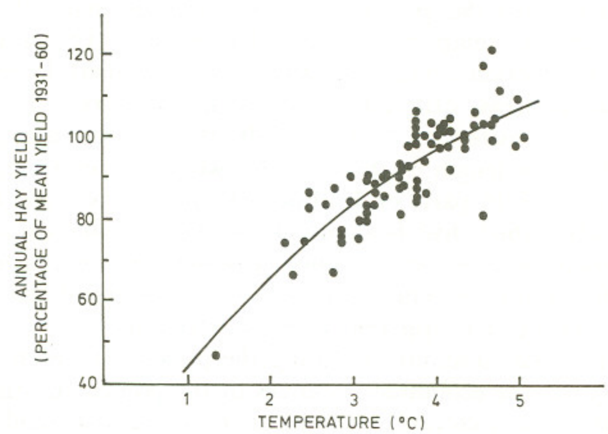


Figure 4.5 Hay yields in Iceland in 1901–1975 as percent of average yields (1931–1960) as a function of average air temperature at Stykkisholmur during October–April. After Bergthorsson (1985)

±30% change in precipitation in the Northern Hemisphere associated with hypothesized impacts from anthropogenic disturbance to the ozone layer in the stratosphere. Variance in temperature and precipitation was assumed not to change, allowing the researchers to use the historical record for relationships between climate and agricultural productivity (see Thompson, 1969a, 1969b, 1970). These statistical models were based on multiple regressions relating crop yield to mean monthly climate data over the growing season. Account was made in time trends for the increased yields attained historically in response to improvements in agricultural technology and energy subsidies. Because the regression models are based on high-energy agricultural production, their applicability for a post-nuclear war world is limited. (See the discussion of the potential effects from the loss of human subsidies to agricultural production, Section 4.6.)

The statistical models of wheat yield indicated a variable response to climatic change. Lower temperatures (1°C or 2°C below normal) were shown actually to *increase* production in those areas normally experiencing limitations of precipitation. This relationship, to be seen again in the results from simulation models and in the discussions of ecosystems effects, reflects a reduced rate of evapotranspiration under reduced temperature, and, therefore, a reduction in soil moisture stress. Since this, rather than low temperatures, is a limiting factor for grain production in many areas, decreasing soil moisture stress allows primary production and crop yields to increase. These statistical models also indicated that in other areas, relatively small decreases in temperatures decreased projected wheat yields; however, the greatest sensitivity to changes in the physical parameters was to precipitation, with reduced precipitation resulting in marked reductions in wheat yields (Thompson, 1975). Similar results were reported for statistical analyses of maize production in the United States (Thompson, 1969a; U.S. Department of Transportation, 1975).

The use of statistical crop yield models to predict the agricultural consequences of climatic change has been strongly criticized. For example, Katz (1977) points out that statistical crop yield models are limited by the small amount of reliable historical data available. Further, these models use a large number of predictor variables, none of which have a high impact if acting in isolation. The multiple linear regression models used in the CIAP evaluation of potential climatic change consist of a number of coefficients relating mean monthly variables, such as temperature and precipitation, as well as technology trends to crop yield. However, it is clear from much evidence that crop yield responses to these and other environmental parameters are not linear; therefore, model extrapolations of climatic changes beyond the narrow limits of the historical data base are tenuous at best (Katz, 1977). Consequently, these types of statistical models are not relied upon for the present analyses.

### *4.3.2.4 Physiological Analysis Approach*

The third approach to evaluating the effects of chronic stresses on agricultural production relies on empirical relationships determined primarily by laboratory experimentation. This mechanistic approach has the particular advantage of relating crop plant development to physical parameters acting independently and under controlled conditions. The qualitative responses of crops to altered light and temperature regimes can then be deduced from simple physiological relationships and the known requirements of the plants. An example of this approach is found in Clark (1985a), who pointed out that for most crop plants that have been studied in detail, the responses of growth and development to temperature can be diagrammatically represented by Figure 4.6. A measure of the rate of growth (e.g., the rate of increase in leaf length in mm $hr^{-1}$) or the rate of development (e.g., the inverse of the time period required for an event to occur, such as germination) increases essentially linearly with temperature above some minimum threshold value ($T_{min}$) up to some optimum value ($T_{opt}$). Above $T_{opt}$ there is a sharper, but also approximately linear, decrease in the rate of growth or development, back down to the zero level above some maximum threshold level ($T_{max}$). Clark reports that for crops of tropical origin (e.g., rice), $T_{min} \approx 10°C$; $T_{opt} \approx 35°C$; $T_{max} \approx 45°C$. For crops of temperate systems (e.g., wheat and barley), $T_{min} \approx 0°C$; $T_{opt} \approx 25°C$; $T_{max} \approx 35°C$. In the case of a nuclear war-induced climatic disturbance imposed on temperate climates, we are only interested in the lower levels of these ranges, i.e., below optimum conditions and perhaps below minimum levels.

One characterization of this response is the concept of degree-days (or Day-Degrees of Thermal Time in the terminology of Monteith, 1981). This suggests that the development time of a plant is a function of the duration and the magnitude of temperature above the minimum level; specifically,

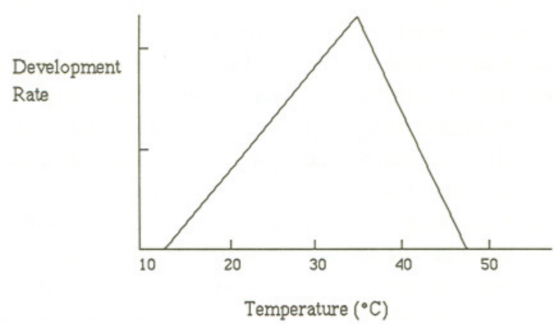


Figure 4.6 Idealized representation of effect of temperature on plant development rates. See text for discussion

the rate of growth or development is directly proportional to ($T$–$T_{min}$), but that the rate is zero below $T_{min}$. If temperatures are warm, the rate of development and growth are high; if they are low, it takes longer for the crop to complete its life cycle. This reproductive cycle for crops in the U.K., and for much of the rest of the Northern mid-latitudes, takes between 1000 and 2000 degree-days; below that there is insufficient time for the crop to reach maturity. As an example of this approach in describing the limits of crop ranges, Clark examined the temperature values for a station in the low Midlands of the U.K. The mean minimum monthly temperature in January and February is about 3°C, reaching a level of about 17°C in July. The mean annual thermal time above 10°C is just under 1000 degree-days; consistent with this, crops of tropical origin are marginal at this location. Thermal time above 0°C is about 3500 degree-days, sufficient for all temperate crops to be grown.

In an analysis based on the mechanistic approach, Clark (1985a) predicted the effects of chronic reductions in temperature on agricultural productivity in the U.K. A 7°C decrease in average temperature over the growing season was projected to produce a climate in the U.K. similar to Iceland, with a mean thermal time above 0°C of only about 1000 degree-days; consequently, only grasses and the shortest season cereal crops could be grown at low altitudes, and then only marginally. A 3°C decrease in temperature over the growing season would preclude yields from tropical and vegetable crops. In the English lowlands, the thermal time above 0°C would still be large enough (about 2500 degree-days) to support most temperate crops, but in northern and upland areas, the thermal time would be insufficient. Consequently, a 3 °C reduction in temperature would reduce the crop ranges of the temperate crops, according to the physiological approach. Finally, a 1°C drop was projected to be near the range of normal variation in the U.K., with little or no effect on the ability of temperate crops to reach maturity. It may be that a 1°C decrease, in the absence of any other perturbations, could result in an increase in yields, not because of reducing evapotranspiration rates, as the case for moisture-limited grain production in North America, but because the metabolic activity of the crops would be slowed down somewhat, making the crop more efficient in capturing solar energy into a useful form (i.e., biomass).

The mechanistic approach can also be used to examine the effect of reduced light levels on crop productivity. As discussed previously, whereas light is not limiting for individual leaves in sunlight, within the context of a crop canopy, photosynthesis is not light-saturated, and reductions in insolation can lead to reductions in productivity. At the higher levels of insolation, the reduction would not be directly proportional, and a 10% reduction in insolation would produce less than a 10% reduction in photosynthesis and in yield. In the middle ranges of the response curve, the relationship would be approximately linear, so that a 50% reduction in sunlight would give about a 50% reduction in productivity. At the lower levels of insolation, threshold levels are reached, specifically the light compensation point, at which level photosynthesis just matches respiration. Clark (1985a) suggests that point for most crops is at about the 10% level of normal light. Light reductions below the compensation point would lead to crop plant death from exhaustion of the carbohydrate reserves if maintained for a prolonged amount of time.

In the context of the present consideration, i.e., the climatic perturbations that might occur during chronic period of the post-nuclear war environment, the mechanistic, physiological approach suggests that the projected reductions in insolation by 5–25% would not reduce crop yields more than proportionately and, therefore, would seem to be minor compared to the corresponding temperature reductions. However, other considerations discussed below indicate that a nonlinear response could occur at less severe light reductions because of insufficient total sunlight time for crop maturation processes to be completed.

### *4.3.2.5 Simulation Model Approach*

#### *4.3.2.5.1 Canadian wheat and barley simulations*

The final approach used in evaluating the potential chronic climatic disturbances that could follow a large-scale nuclear war is the utilization of simulation models. As with other methodologies, there are limits to this approach, specifically extending projections beyond the range to which the model reliably predicts the response of the real system; the limitations of input data to the model; the propagation through the model of uncertainties associated with those data; the site-specificity versus site-generality of the models and, therefore, the potential for extrapolation to other locations or other crops; and the ability of the model to consider other physical parameters that could affect crop yield predictions. Nevertheless, insofar as validated models can be identified that are sensitive to the changes of temperature, precipitation, and light levels being projected, this approach does offer promise for analyzing the chronic period.

With this in mind, we selected the simulation model of Agriculture Canada for analysis of wheat and barley production in the western provinces of Canada. This work, under the direction of R.B. Stewart, relied on a model developed initially by FAO (1978) and later modified by Stewart (1981) for Canadian conditions. This model is based on the de Wit (1965) methodology for estimating net biomass production. The model was used to evaluate long-term crop production capability under optimum management practices; this means that effects on agricultural productivity from disruptions in human subsidies and other factors leading to less-than-optimal management would result in further reductions in yields from those predicted by the model. Input data include monthly averages of temperature, precipitation, solar insolation, wind speed, and vapor pressure. A photosynthesis equation describes constraint-free yields, i.e., yields under optimal conditions, with a sigmoidal cumulative growth curve incremented up to the number of days required for the crop to mature. Net biomass production is calculated by taking into account the gross biomass production capacity of the crop as influenced by this temperature- and insolation-dependent photosynthesis term, subtracting the respiration losses resulting from another temperature-dependent function. A description of the model is provided in the appendix to this chapter.

The scenarios simulated using the Agriculture Canada model included:

1.) Changes in temperature by 1°C, 2°C, 3°C, 4°C, and 5°C, and changes in precipitation by ±25% respectively. This was done by decreasing the daily minimum and maximum temperatures uniformly by the specified amount. As discussed previously, this has the effect of reducing the length of the growing season by delaying the initiation of the frost-free period and enhancing the onset of the first freeze in the autumn. However, the relationship inferred from the statistical relationships of growing season length as a function of average temperature, discussed previously, was not explicitly incorporated into the model. Rather, the model generated its own growing season length stochastically by having the probability of a freezing event occurring increase substantially when the average daily temperature fell below a threshold value. Changes in precipitation were made to the monthly values, i.e., assuming the pattern of precipitation was unchanged over the growing season.

2.) Changes in seasonal temperatures by the same amounts, but holding the growing season length fixed; that is, the growing season average temperatures were reduced by the appropriate amount, but the daily temperature on the days beginning and ending the growing season were not changed (Figure 4.7).

3.) Changes in temperatures, insolation, and daylength to simulate the passing of a nuclear war-induced smoke cloud; for this scenario, the seasonal monthly values for temperature and insolation (intensity and daylength) were below normal by amounts that decreased over a three-month period.

To estimate the overall effect on Canadian wheat production, the total areal extent of spring wheat and barley production was estimated based on model-calculated changes from the actual ranges for the past two decades; crop yields per area were calculated by the model.

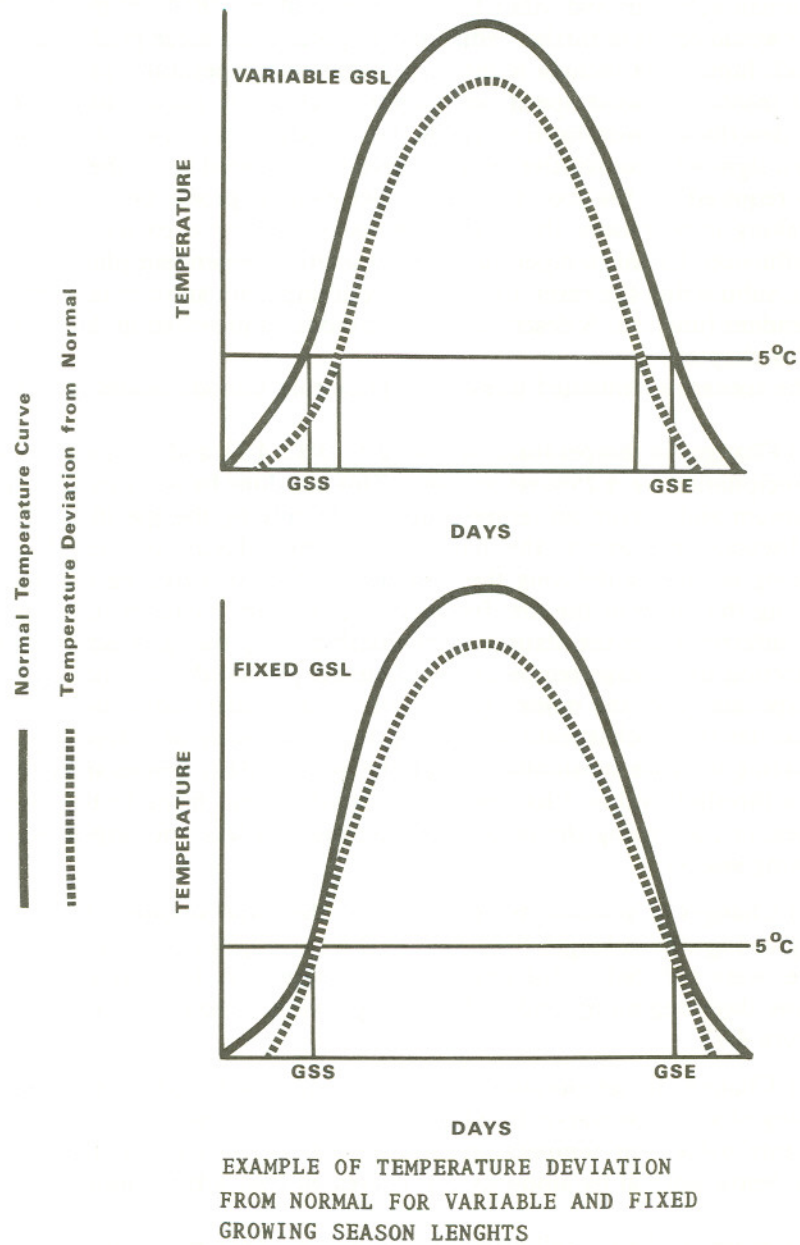


Figure 4.7 Representation of two approaches to reducing temperatures with variable- and fixed-length growing seasons used in the Agriculture Canada wheat and barley simulations. From Stewart, 1985

*4.3.2.5.2 Effects of reductions in average growing season temperature*

The results from the first set of simulations are presented in Figures 4.8a and 4.8b, and the data are summarized in Tables 4.3 and 4.4. Figure 4.8a illustrates that for wheat production in Canada, a 1°C decrease in annual temperature does not substantially change the area in which wheat can be grown; however, the model predicts that a 2°C decrease in mean growing season temperature would eliminate all of the potential area for wheat production in Alberta and most of the area in Saskatchewan and Manitoba. A 3°C reduction would totally eliminate wheat production in Canada. Barley is not quite as sensitive, with little areal reduction for a 1°C or 2°C decrease in average temperatures; however, by 4°C, almost all barley production would be eliminated in Canada.

The reduction in the areal extent of potential grain production follows from two factors: 1.) The decrease in temperatures applied to every daily maximum and minimum value results in a shortening of the growing season at a rate of about 7 to 10 days per °C; this is the same rate seen from several sources of estimation, as discussed previously; 2.) The decrease in average temperature reduces the rate of crop development and growth, also as discussed previously; here, the model predicts that the time required to reach maturation is increased by 3 to 5 days per °C decrease in temperature. It is the combination of these two factors that results in the nonlinear response to decreased temperatures.

In the model simulations for either the base or alternate period, total crop production losses associated with the sudden decrease in the range over which the grain crops could be grown were partially compensated for at the lower temperature values by increased yields per hectare on those areas in which the grain could reach maturity. This resulted because of the reduction in the evapotranspiration rate and, therefore, a reduction in the soil moisture stress, which is important to productivity in precipitation-limited areas. This sensitivity to precipitation levels is highlighted by Table 4.4 for the 0°C difference case. The simulations indicate that crop yields would decrease by about 50% for wheat and 40% for barley in response to a 25% reduction in precipitation. Also, there is a disproportionately greater effect by reducing precipitation by 25% versus increasing it by 25%, suggesting a nonlinear response. This has implications for the effects from a greater decrease in precipitation, in that crop yields may decrease even more than would be estimated by mere extrapolating from the 25% case; i.e., there is the potential for the essential elimination of wheat production in Canada in response to a 50% reduction in growing season precipitation.

*4.3.2.5.3 Effects of reducing thermal time only*

In order to test the effect on crop yields of reducing only the thermal time

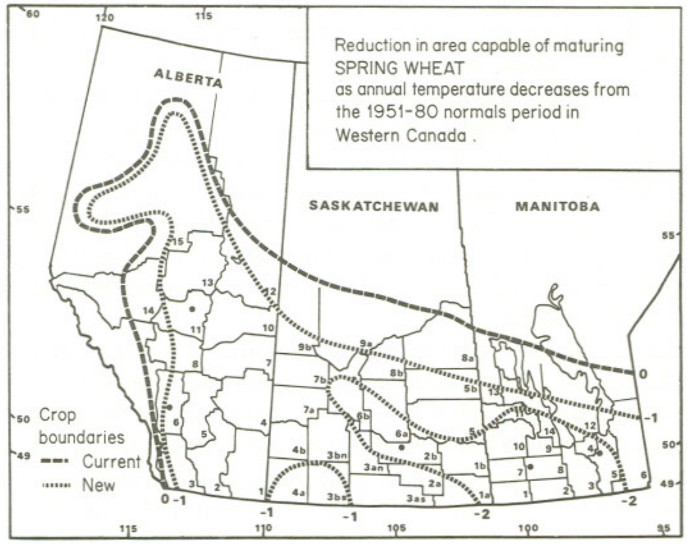


Figure 4.8a Reduction in area capable of maturing spring wheat as average temperatures are reduced by 1°C and 2°C from normals of 1951–1980. Based on Agriculture Canada model simulations by Stewart (1985)

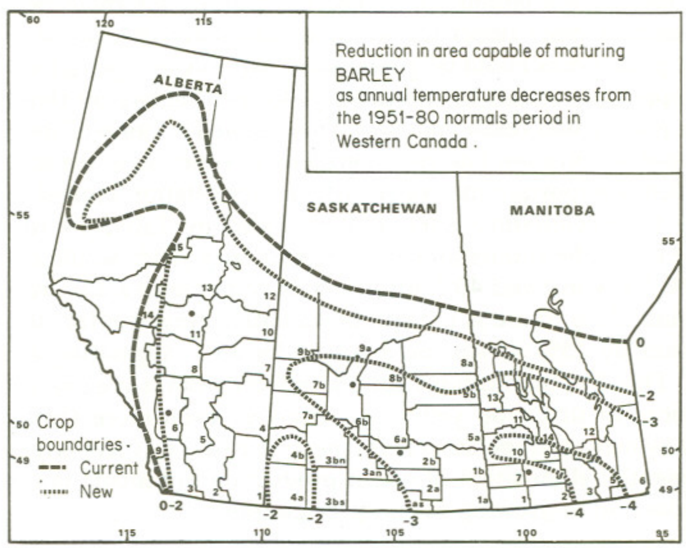


Figure 4.8b Reduction in area capable of maturing barley as average temperatures are reduced by 1°C and 2°C from normals of 1951–1980. Based on Agriculture Canada model simulations by Stewart (1985)

TABLE 4.3

PERCENT OF 1961-1981 AVERAGE WHEAT AREA AND PRODUCTION BASED ON TEMPERATURE DECREASES OF 1°C, 2°C, AND 3°C; PRECIPITATION LEVELS OF 75%, 100%, AND 125% OF THE 1951-1980 NORMALS[a]

| | Normals | | | -1°C | | | -2°C | | | -3°C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRECIPITATION | 75 | 100 | 125 | 75 | 100 | 125 | 75 | 100 | 125 | 75 | 100 | 125 |
| MANITOBA | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 97 | 97 | 97 | 94 | 94 | 94 | 0 | 0 | 0 |
| Production | 68 | 100 | 136 | 82 | 120 | 149 | 103 | 150 | 169 | 0 | 0 | 0 |
| SASKATCHEWAN | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 83 | 83 | 83 | 25 | 25 | 25 | 0 | 0 | 0 |
| Production | 56 | 100 | 137 | 63 | 106 | 140 | 27 | 41 | 56 | 0 | 0 | 0 |
| ALBERTA | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 98 | 98 | 98 | 0 | 0 | 0 | 0 | 0 | 0 |
| Production | 56 | 100 | 137 | 73 | 123 | 164 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTAL | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 88 | 88 | 88 | 28 | 28 | 28 | 0 | 0 | 0 |
| Production | 58 | 100 | 137 | 68 | 112 | 147 | 32 | 45 | 57 | 0 | 0 | 0 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model.

TABLE 4.4

PERCENT OF 1961-1981 BARLEY AREA AND PRODUCTION BASED ON GROWING SEASON TEMPERATURE DECREASES OF 1°C, 2°C, 3°C, AND 4°C; PRECIPITATION LEVELS OF 75%, 100% AND 125% OF THE 1951-1980 NORMALS[a]

| | Normals | | | -1°C | | | -2°C | | | -3°C | | | -4°C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | 75 | 100 | 125 | 75 | 100 | 125 | 75 | 100 | 125 | 75 | 100 | 125 | 75 | 100 | 125 |
| MANITOBA | | | | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 100 | 100 | 100 | 94 | 94 | 94 | 94 | 94 | 94 | 45 | 45 | 45 |
| Production | 64 | 100 | 130 | 79 | 120 | 140 | 95 | 130 | 140 | 118 | 142 | 148 | 69 | 78 | 78 |
| SASKATCHEWAN | | | | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 100 | 100 | 100 | 97 | 97 | 97 | 45 | 45 | 45 | 0 | 0 | 0 |
| Production | 62 | 100 | 133 | 78 | 122 | 154 | 101 | 144 | 173 | 61 | 87 | 101 | 0 | 0 | 0 |
| ALBERTA | | | | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 100 | 100 | 100 | 97 | 97 | 97 | 0 | 0 | 0 | 0 | 0 | 0 |
| Production | 62 | 100 | 125 | 77 | 115 | 140 | 93 | 132 | 154 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTAL | | | | | | | | | | | | | | | |
| Area | 100 | 100 | 100 | 100 | 100 | 100 | 96 | 96 | 96 | 29 | 29 | 29 | 6 | 6 | 6 |
| Production | 62 | 100 | 128 | 78 | 118 | 145 | 96 | 135 | 158 | 35 | 47 | 52 | 9 | 10 | 10 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model.

(i.e., *not* including the effects of a reduced growing season acting against an increased maturation requirement), a sensitivity analysis was completed by holding the growing season length constant, but imposing the same average decrease in temperatures within the growing season. This scenario is not considered to be likely in the aftermath of a nuclear war, if the relationship between reduced average temperature and the reduction in the frost-free period, which has been demonstrated for a non-perturbed atmosphere, is assumed to remain after a nuclear war. Nevertheless, it is instructive to understanding the relative importance on crop productivity of the two major factors, growing season sufficiency versus thermal time sufficiency.

Results are shown in Figures 4.9 and 4.10 and Tables 4.5a,b and 4.6a,b for wheat and barley, respectively, indicating a decreased sensitivity to the reduction in average temperatures. For wheat, a 2°C change does not reduce the area of wheat production, and a 3°C reduction does not affect the area of barley production. But another 1°C reduction or so eliminates production of both crops, again indicating a strong nonlinearity in response. These results suggest that both the thermal time and the growing season length factors are important in determining the response of Canadian agriculture to climatic disturbances.

### *4.3.2.5.4 Effects of transient climatic perturbations*

The final set of simulations using the Agriculture Canada model were designed to test the sensitivity of the model predictions to changes in insolation and to simulate the temporal response of a passing nuclear war-induced smoke cloud. These computer runs simulated the movement of a debris cloud by assuming that temperatures were reduced by 5°C the first month, 3°C the second month, and 1°C the third month, beginning at various times between April and August. Corresponding to these temperature reductions, solar insolation and day length were decreased by 22%, 15%, and 8%, in one simulation and by 11%, 8%, and 3% in another. All other climatic input data, including precipitation, were consistent with the 1951–1980 levels. Tables 4.7a–c show the impact on the area capable of maturing spring wheat based on production averages for 1961–1980. The months listed in the table indicate the month the transient effects are assumed to begin. For each month, it is assumed that the smoke cloud moves rapidly into the region, with gradual reduction of effects over the subsequent three months. Results are based on: 1.) effects of temperature reductions alone; 2.) effects of light and daylength reductions alone; and 3.) combined temperature, light, and daylength effects.

Temperature reductions alone are seen to cause substantial impacts on spring wheat, except for the case of initiation of the perturbation in April. For all areas except Manitoba, temperature reductions beginning at

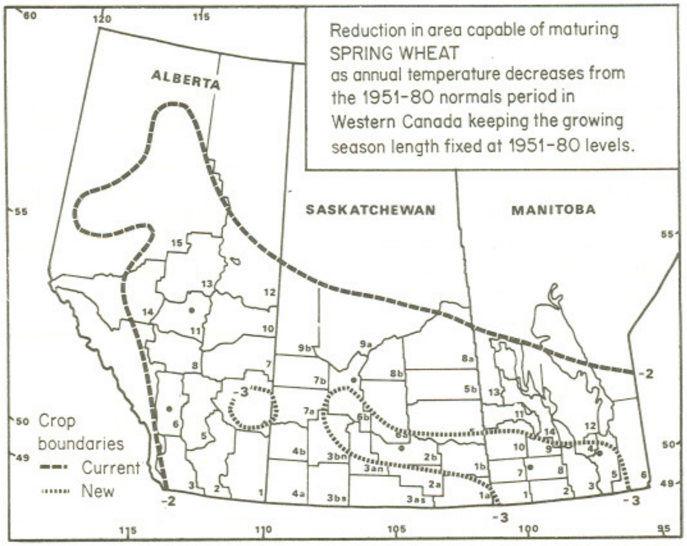


Figure 4.9 Reduction in area capable of maturing spring wheat as average temperatures are reduced by 1°C, 2°C, and 3°C from normals of 1951–1980 but keeping growing season length fixed. Based on Agriculture Canada model simulations by Stewart (1985)

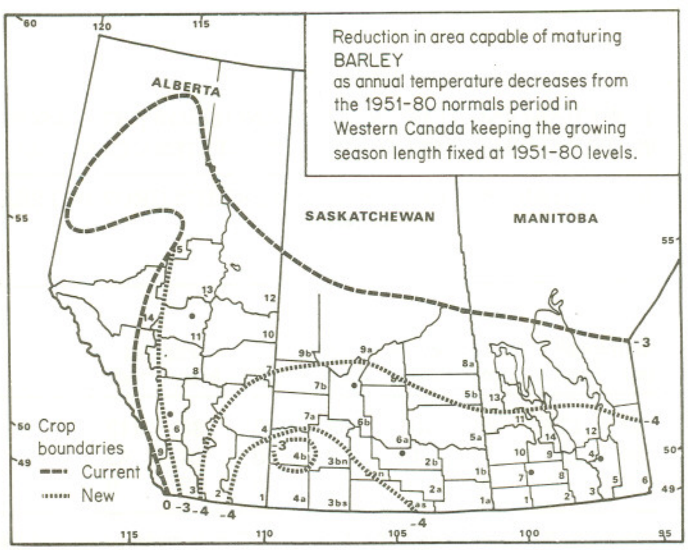


Figure 4.10 Reduction in area capable of maturing barley as average temperatures are reduced by 3°C and 4°C from normals of 1951–1980 but keeping growing season length fixed. Based on Agriculture Canada model simulations by Stewart (1985)

TABLE 4.5a

THE EFFECT OF CHANGING TEMPERATURE AND GROWING SEASON LENGTH ON SPRING WHEAT PRODUCTION IN WESTERN CANADA[a]

DECREASING TEMPERATURE AND FIXING THE GROWING SEASON LENGTH AT THE 1951-1980 NORMALS LEVEL

| Temp. Normal | Manitoba[b] | | Saskatchewan | | Alberta | | Prairies | |
|---|---|---|---|---|---|---|---|---|
| | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| -1°C | 100 | 122 | 100 | 122 | 99 | 121 | 99 | 121 |
| -2°C | 97 | 146 | 77 | 117 | 88 | 130 | 82 | 124 |
| -3°C | 83 | 156 | 20 | 38 | 10 | 14 | 25 | 47 |
| -4°C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Area and production are expressed in terms of percent of the 1961-1981 average.

[b] Area and production figures represent the 1961-1976 average. A change in the crop district boundaries in 1977 does not allow comparison of production data beyond 1976.

TABLE 4.5b

THE EFFECT OF CHANGING TEMPERATURE AND GROWING SEASON LENGTH ON SPRING WHEAT PRODUCTION IN WESTERN CANADA[a]

DECREASING TEMPERATURE AND VARYING THE GROWING SEASON LENGTH

| Temp. Normal | Manitoba[b] | | Saskatchewan | | Alberta | | Prairies | |
|---|---|---|---|---|---|---|---|---|
| | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| -1°C | 97 | 120 | 83 | 106 | 98 | 123 | 88 | 112 |
| -2°C | 94 | 150 | 25 | 41 | 0 | 0 | 28 | 45 |
| -3°C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Area and production are expressed in terms of percent of the 1961-1981 average.

[b] Area and production figures represent the 1961-1976 average. A change in the crop district boundaries in 1977 does not allow comparison of production data beyond 1976.

TABLE 4.6a

THE EFFECT OF CHANGING TEMPERATURE AND GROWING SEASON LENGTH ON BARLEY PRODUCTION IN WESTERN CANADA[a]

DECREASING TEMPERATURE AND FIXING THE GROWING SEASON LENGTH AT THE 1951-1980 NORMALS LEVEL

| Temp. | Manitoba[b] | | Saskatchewan | | Alberta | | Prairies | |
|---|---|---|---|---|---|---|---|---|
| Normal | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| -1°C | 100 | 115 | 100 | 112 | 100 | 121 | 99 | 121 |
| -2°C | 100 | 130 | 100 | 131 | 100 | 130 | 82 | 124 |
| -3°C | 100 | 144 | 99 | 156 | 97 | 14 | 25 | 47 |
| -4°C | 94 | 158 | 50 | 113 | 8 | 0 | 0 | 0 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Area and production are expressed in terms of percent of the 1961-1981 average.

[b] Area and production figures represent the 1961-1976 average. A change in the crop district boundaries in 1977 does not allow comparison of production data beyond 1976.

TABLE 4.6b

THE EFFECT OF CHANGING TEMPERATURE AND GROWING SEASON LENGTH ON BARLEY PRODUCTION IN WESTERN CANADA[a]

DECREASING TEMPERATURE AND VARYING THE GROWING SEASON LENGTH

| Temp. | Manitoba[b] | | Saskatchewan | | Alberta | | Prairies | |
|---|---|---|---|---|---|---|---|---|
| Normal | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| -1°C | 100 | 121 | 100 | 122 | 100 | 115 | 100 | 117 |
| -2°C | 94 | 130 | 97 | 144 | 97 | 132 | 96 | 135 |
| -3°C | 94 | 142 | 44 | 87 | 0 | 0 | 29 | 47 |
| -4°C | 45 | 78 | 0 | 0 | 0 | 0 | 6 | 10 |
| -5°C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Area and production are expressed in terms of percent of the 1961-1981 average.

[b] Area and production figures represent the 1961-1976 average. A change in the crop district boundaries in 1977 does not allow comparison of production data beyond 1976.

any other time (May through August) would devastate crop production (Table 4.7a); Manitoba seems only sensitive to an event initiated in June. For an episode beginning in that month, essentially all areas that normally grow wheat in Canada would be precluded from any crop production. Clearly, there are strong seasonality components to the response of crops to temperature excursions.

The reductions in light and daylength levels are seen not to cause major yield reductions at the lower levels (11% peak decrease) (Table 4.7b) for anywhere in Western Canada, although larger light reductions essentially eliminates yields if initiated in the mid-growing season. The marked difference between results of light and daylength reductions of 11% versus 22% suggests that the growing season as defined as cumulative hours of incident sunlight within the frost-free period can be a critical parameter. This is further indicated by the data on the combination of effects, which indicate strongly synergistic responses.

The results for barley production (Tables 4.8a–c) show considerably more resistance to temperature or light effects when applied independently, but the synergism of the combined perturbations leads to much greater impacts of some combinations of temperature, light, and daylength reductions. Again, a strong seasonality is apparent, and the occurrence of peak events in June would be devastating, according to the simulations.

TABLE 4.7a

EFFECTS ON AREA CAPABLE OF MATURING WHEAT AND TOTAL PRODUCTION IN WESTERN CANADA CORRESPONDING TO SEQUENTIAL MONTHLY TEMPERATURE REDUCTIONS OF -5°C, -3°C, AND -1°C RESPECTIVELY, BEGINNING IN THE MONTH INDICATED[a]

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 101 | 94 | 97 | 99 | 102 | 96 | 100 |
| May | 97 | 100 | 53 | 59 | 17 | 21 | 51 | 55 |
| June | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| July | 95 | 110 | 33 | 39 | 0 | 0 | 34 | 39 |
| August | 94 | 99 | 20 | 22 | 0 | 0 | 25 | 26 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Percent of 1961-1981 average production; all climatic input other than temperature was held constant at the 1951-1980 levels.

TABLE 4.7b

EFFECT ON AREA CAPABLE OF MATURING WHEAT AND TOTAL PRODUCTION IN WESTERN CANADA CORRESPONDING TO SEQUENTIAL MONTHLY SOLAR INSOLATION AND DAYLENGTH REDUCTIONS OF I.) -22%, -15%, AND -8%; AND II.) -11%, -8%, AND -3% RESPECTIVELY, BEGINNING IN THE MONTH INDICATED[a]

I.) INSOLATION AND DAYLENGTH (-22%, -15%, -8%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 102 | 100 | 101 | 100 | 101 | 100 | 100 |
| May | 97 | 102 | 87 | 93 | 99 | 106 | 91 | 97 |
| June | 11 | 15 | 0 | 0 | 0 | 0 | 1 | 2 |
| July | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| August | 94 | 89 | 66 | 66 | 81 | 82 | 73 | 72 |

II.) INSOLATION AND DAYLENGTH (-11%, -8%, -3%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| May | 100 | 103 | 96 | 99 | 99 | 101 | 97 | 100 |
| June | 97 | 101 | 82 | 88 | 99 | 105 | 87 | 94 |
| July | 97 | 99 | 82 | 87 | 99 | 104 | 87 | 92 |
| August | 100 | 98 | 96 | 96 | 99 | 98 | 97 | 96 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Percent of 1961-1981 production average; all other climatic inputs than solar insolation and daylength were held constant at the 1951-1981 level.

TABLE 4.7c

EFFECT ON AREA CAPABLE OF MATURING WHEAT AND TOTAL PRODUCTION IN WESTERN CANADA CORRESPONDING TO SEQUENTIAL MONTHLY TEMPERATURE DECREASES OF -5°C, -3°C, AND -1°C AND SOLAR INSOLATION AND DAYLENGTH REDUCTIONS OF I.) -22%, -15%, AND -8%, AND II.) -11%, -8%, AND -3% RESPECTIVELY, BEGINNING IN THE MONTH INDICATED[a]

I.) INSOLATION AND DAYLENGTH (-22%, -15%, -8%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 97 | 97 | 94 | 98 | 99 | 105 | 95 | 101 |
| May | 52 | 61 | 0 | 0 | 0 | 0 | 6 | 8 |
| June | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| July | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| August | 92 | 92 | 38 | 39 | 0 | 0 | 36 | 37 |

II.) INSOLATION AND DAYLENGTH (-11%, -8%, -3%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 102 | 94 | 99 | 99 | 103 | 96 | 100 |
| May | 96 | 103 | 38 | 43 | 0 | 0 | 37 | 40 |
| June | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| July | 53 | 65 | 13 | 16 | 0 | 0 | 15 | 18 |
| August | 94 | 97 | 33 | 34 | 0 | 0 | 34 | 34 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Percent of 1961-1981 average production; all other climatic input was held constant at the 1951-1980 level.

TABLE 4.8a

EFFECT ON AREA CAPABLE OF MATURING BARLEY AND TOTAL PRODUCTION IN WESTERN CANADA CORRESPONDING TO SEQUENTIAL MONTHLY TEMPERATURE REDUCTIONS OF -5°C, -3°C, AND -1°C, RESPECTIVELY, BEGINNING IN THE MONTH INDICATED[a]

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 103 | 99 | 104 | 100 | 102 | 100 | 103 |
| May | 100 | 102 | 97 | 102 | 97 | 100 | 97 | 101 |
| June | 94 | 99 | 26 | 28 | 0 | 0 | 22 | 22 |
| July | 94 | 104 | 83 | 94 | 66 | 73 | 76 | 84 |
| August | 94 | 94 | 95 | 93 | 97 | 90 | 96 | 92 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Percent of 1961-1979 average production; all climatic input other than temperature was held constant at the 1951-1980 level.

TABLE 4.8b

EFFECT ON AREA CAPABLE OF MATURING BARLEY AND TOTAL PRODUCTION IN WESTERN CANADA CORRESPONDING TO SEQUENTIAL MONTHLY SOLAR INSOLATION AND DAYLENGTH REDUCTIONS OF I.) -22%, -15%, AND -8%, AND II.) -11%, -8%, AND -3% RESPECTIVELY, BEGINNING IN THE MONTH INDICATED[a]

A) INSOLATION AND DAYLENGTH (-22%, -15%, -8%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 101 | 100 | 101 | 100 | 98 | 100 | 99 |
| May | 100 | 104 | 100 | 103 | 100 | 102 | 100 | 103 |
| June | 100 | 108 | 97 | 105 | 100 | 105 | 99 | 106 |
| July | 100 | 97 | 99 | 99 | 100 | 96 | 100 | 97 |
| August | 100 | 99 | 100 | 98 | 100 | 96 | 100 | 97 |

B) INSOLATION AND DAYLENGTH (-11%, -8%, -3%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 100 | 100 | 100 | 100 | 98 | 100 | 99 |
| May | 100 | 102 | 100 | 101 | 100 | 99 | 100 | 100 |
| June | 100 | 103 | 100 | 102 | 100 | 101 | 100 | 101 |
| July | 100 | 101 | 100 | 100 | 100 | 98 | 100 | 99 |
| August | 100 | 100 | 100 | 100 | 100 | 98 | 100 | 99 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Percent of 1961-1981 average production; all other climatic input was held constant at the 1951-1980 level.

TABLE 4.8c

EFFECT ON AREA CAPABLE OF MATURING BARLEY AND TOTAL PRODUCTION IN WESTERN CANADA CORRESPONDING TO SEQUENTIAL MONTHLY TEMPERATURE DECREASES OF -5°C, -3°C, AND -1°C AND SOLAR INSOLATION AND DAYLENGTH REDUCTIONS OF I.) -22%, -15%, AND -8%, AND II.) -11%, -8% AND -3% RESPECTIVELY, BEGINNING IN THE MONTH INDICATED[a]

A) INSOLATION AND DAYLENGTH (-22%, -15%, -8%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 103 | 99 | 105 | 100 | 102 | 100 | 103 |
| May | 94 | 97 | 95 | 105 | 90 | 98 | 92 | 100 |
| June | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| July | 94 | 100 | 56 | 61 | 60 | 69 | 64 | 71 |
| August | 94 | 94 | 95 | 94 | 97 | 90 | 96 | 92 |

B) INSOLATION AND DAYLENGTH (-11%, -8%, -3%)

| | Manitoba | | Saskatchewan | | Alberta | | Total | |
|---|---|---|---|---|---|---|---|---|
| MONTH | Area | Prod. | Area | Prod. | Area | Prod. | Area | Prod. |
| April | 100 | 103 | 99 | 104 | 100 | 102 | 97 | 103 |
| May | 100 | 103 | 95 | 101 | 95 | 99 | 96 | 100 |
| June | 94 | 106 | 12 | 14 | 0 | 0 | 17 | 18 |
| July | 94 | 101 | 68 | 75 | 63 | 71 | 69 | 76 |
| August | 94 | 94 | 95 | 93 | 97 | 90 | 96 | 92 |

[a] Based on simulations by R.B. Stewart using the Agriculture Canada model. Percent of 1961-1981 average production; all other climatic input was held constant at the 1951-1980 level.

*4.3.2.5.5 Conclusions from Canadian grain analyses*

These simulations suggest the following conclusions:

- Chronic (growing season) reductions in average temperatures of slightly more than 2°C for spring wheat and 4°C for barley would result in the total elimination of those crops from production in Western Canada, irrespective of any changes in light or precipitation.
- The growing season decreases at a rate of 7–10 days per °C decrease in average temperature at the same time that the maturity requirements for wheat and barley are increased by 4–6 days.
- For those areas remaining in crop production, reduced temperatures, if imposed alone, could result in increased yields per hectare in response to reduced soil moisture stress. However, in almost all cases, the area in which crops can mature decreases more substantially than the per hectare yields increase, resulting in a net reduction in total production.
- Analyses of transient episodes indicate high sensitivity to temperature reductions at particular times of initiation of the episode; the specifics of the sensitivity to temperature or light reductions also depend on location.
- There is a high sensitivity to reduction in solar inputs (insolation and daylength) if these exceed a threshold, resulting in no losses at 10% reductions and total losses (depending on timing) at 20% reductions. The light sensitivity apparently relates to having enough hours of daylight for crop maturation;
- Combinations of temperature and light reductions are synergistic, with the combined sensitivities being highly dependent on location and timing of the onset of a climatic perturbation.

These results provide the most convincing evidence thus far of the tremendous potential agricultural consequences from the occurrence of even the milder cases of a nuclear war-induced climatic disturbance. This reflects on the conclusions for the acute period, in that if the acute perturbations occurred in the part of the year immediately after the autumn harvest, we previously were unable to state unequivocally that the following summer's crop would be essentially eliminated, because of not knowing precisely enough from the climatic analysts how long the acute period would last. However, we can now see that relatively mild continued repercussions of climate in the first growing season following a nuclear war could also lead to the substantial or complete loss of crop yields, based on the physical environmental constraints alone (i.e., not considering the effects on the agricultural system itself, discussed later).

#### *4.3.2.6 Soybean Simulation Analyses*

Another major crop of particular interest for the effects of nuclear war is soybeans (*Glycine max*); this crop is potentially of enhanced importance after a nuclear war, because its cultivars are self-pollinating inbreds, i.e., not requiring commercial sources for hybrid seed stocks. Soybean is a legume, and therefore does not require nitrogen fertilization. It has high content of both protein and oil, potentially providing a major source of protein in replacement of the potential loss of animal sources.

A physiologically based simulation model was used by Sinclair (1985a) for simulation of a nuclear war-induced climatic perturbation. The model uses climatic information, including daily minimum and maximum temperatures, solar insolation, and precipitation, to calculate carbon and nitrogen accumulation. These elements were apportioned between vegetative tissue and seeds; physiological response is limited by soil moisture stress. The model has been verified against field observations with respect to both seasonal development and total seed yield (Sinclair, 1985b; Muchow and Sinclair, 1985).

The normal temperature values were selected to be representative of the soybean production area in the midwestern United States, based on a sine function fixed with a 180 day freeze-free period, a peak summer average diurnal maximum of 20°C, and a daily range of temperatures set at 12 °C. Perturbed simulations were based on a 2°C, 4°C, or 6°C reduction in the daily maximum and minimum values throughout the growing season. The model simulations began after the unifoliate leaves emerged, and crop growth began 10 days following the attainment of a daily minimum temperature of 10°C (approximately day 40 of the normal simulation), following the physiological evidence that soybeans exhibit a 10°C minimum temperature for most growth processes (Da Moto, 1978). Other temperature thresholds were incorporated into the model; for instance, soybean pods are not formed if the minimum temperature falls below 13°C (Hume and Jackson, 1981), so the simulations were terminated if this condition was met at the critical time. Carbon fixation and nitrogen assimilation rates were set to zero if the minimum temperature fell below 7°C, and the simulations were terminated if temperatures reached 0°C.

Solar inputs were also reduced in these simulations by 10%, 20%, and 30% for the 2°C, 4°C, and 6°C cases, respectively. Moisture stress was simulated by additional runs, in which drought was imposed for either three weeks in July (simulation days 80 to 100) or in August (simulation days 110 to 130); otherwise, the soil was assumed to be fully charged with water. Crop maturation times reflecting different cultivars were imposed in the model at 40 days, 50 days, and 60 days, with 50 days being the normal value.

Results are shown in Table 4.9. For the shortest season crops and a July drought, temperature reductions increased yields, as seen previously in re-

TABLE 4.9

SIMULATION RESULTS OF POTENTIAL SOYBEAN YIELD WHEN SUBJECTED TO CLIMATIC PERTURBATIONS OF DIFFERING SEVERITIES[a]

| | Yield ($g\ m^{-2}$) | | | |
|---|---|---|---|---|
| Drought | Normal | T -2°C | T -4°C | T -6°C |
| | Termination of Leaf Growth on Day 40 | | | |
| None | 336 | 304 | 238[b] | 146[c] |
| July | 260 | 283 | 236[b] | 146[c] |
| August | 310 | 284 | 230[b] | 144[c] |
| | Termination of Leaf Growth on Day 50 | | | |
| None | 445 | 378[b] | 265[b] | NPS[d] |
| July | 385 | 366[b] | 265[b] | NPS |
| August | 357 | 328[b] | 250[b] | NPS |
| | Termination of Leaf Growth on Day 60 | | | |
| None | 556[b] | 417[b] | 246[c] | NPS |
| July | 525[b] | 412[b] | 246[c] | NPS |
| August | 415 | 352[b] | 239[c] | NPS |

[a] Based on simulations by T. Sinclair.

[b] Crop subjected to temperatures less than 7°C

[c] Crop subjected to end-of-season temperatures less than 0°C.

[d] NPS = No pod set because of temperatures less than 13°C.

sponse to reduced soil moisture stress, since the drought period coincided with the maximum leaf area development and, therefore, the maximum evapotranspiration rates. In all other simulations, yields decreased in response to temperature decreases. The yield reductions in the absence of precipitation changes were 10% to 25% for the different season length cultivars under the 2°C simulation, and 30% to 55% under the 4°C simulation. At 6°C reductions, either the pods did not set or freezing was experienced prior to the end of the required growing season, implying crop loss.

Sinclair (1985a) concluded that soybean production during the acute phase of a nuclear war-caused climatic perturbation would be impossible, and temperatures would have to return to within 4°C of normal for there to be any production at the modelled locations. Having shorter-season cultivars would be necessary for production at those temperatures, so that in double-cropped areas, it might be possible for production to occur in a 4°C temperature reduction scenario if a single crop was grown over the warmest period and if seed sources were available. However, actual yields would be more sensitive than even this shows because of uncertainty in optimal planting time, the possibility of extreme cold events during the growing season, and the loss of subsidies to agriculture, as discussed in a later section.

In a different study, another simulation model was used to examine the effects of climatic perturbations on soybean production. To assess the potential impacts of temperature diverging from normal levels by ±2°C, Curry and Baker (1975) used the SOYMODI model for three sites in the midwestern United States; their model was subject to only limited validation for the three sites. This model is also physiologically based, including plant development factors as functions of the physiological day, analogous to the thermal time of Monteith (1981), i.e., based on the integrated heat units above 10 °C and below 30°C. The results of these simulations, which were not done with the nuclear war-induced climatic disturbances in mind, indicated that a 2°C decrease in average growing season temperatures would reduce yields in the majority of years simulated. Using climatic data from 1971 to 1974 for an Ohio site, Curry and Baker (1975) found reduced yields predicted by SOYMOD I for both a 1°C and a 2°C reduction, except for the simulation based on 1974 climatic data. In this case, yield increases were predicted to result from a 1°C or 2°C decrease in air temperatures because that year was subject to particularly hot conditions; therefore, the response was again seen of soil moisture stress being reduced by lowered temperatures and thereby increasing yields.

These two sets of soybean simulations again reflect the great sensitivity of crops to reductions in temperature. Whereas the Canadian situation was more thoroughly analyzed, it alone is not sufficient evidence of crop sensitivity in warmer agricultural regions. However, the simulations with the soybean models suggest the high vulnerability of warm-climate crops to a reduction in a few degrees of average growing season temperatures. This sensitivity is seen to be even greater for the crop that is of greatest importance to global food supplies, rice, as discussed in the tropical agricultural section later.

### 4.3.3 Consensus of Temperate Agricultural Workshop

The SCOPE–ENUWAR project convened a workshop at the University of Essex to address the issues associated with the potential effects of nuclear war on the agricultural systems of the Northern mid-latitudes. This workshop focused on agricultural productivity effects in response to acute and chronic scenarios of climatic perturbations. Many of the crops discussed at the workshop were subsequently further analyzed, and the resultant discussions appear in previous sections of this chapter. In the present section is presented a synopsis of expected impacts on temperate agriculture for those crops not previously discussed.

Consideration was given to the major crops and farm animals of the Northern Hemisphere, including tropical and subtropical regions; the latter are reported on in a later section. Crops in marginal areas were distinguished from their counterparts nearer the center of the crop distribution, where crops would presumably have increased resistance to climatic disturbances. For each case, consideration was given to how climatic changes would alter the areas where traditional crops could grow and how the productivity of those crops might alter. No consideration was given to substantial replacement of crops by other crops in the aftermath of a large-scale nuclear war, since it was the consensus of the workshop participants that in the Northern midlatitudes, the area most likely to be directly affected by nuclear devastation, it was unlikely that seed or expertise would be available in the first years after a nuclear war. The group wished to emphasize that the *potentials* for crop growth and production were assessed, but that there are many factors that could combine to ensure that these potentials could not be attained, and that total production of major crops would be but a small fraction of current levels, even under the most benign of climatic disturbances, primarily in response to disruptions in societal systems and subsidies to agriculture, a topic discussed in Section 4.6.

The group concentrated on temperature and precipitation reductions, although the lack of detailed information from the climatic scientists concerning precipitation levels and patterns, temperature variances, atmospheric circulation alterations, and duration of effects limited the discussions. Reductions in insolation were not considered to be of primary importance, except that under relatively small temperature reductions, cold hardiness could interact with reduced light levels; likewise, radiation and air pollutants were considered to be important only for combatant zones, but on a global scale would not be the limiting factor on food productivity.

Tables 4.10 and 4.11 summarize the results of the group evaluations. It was concluded that a nuclear war causing significant climatic perturbations during the period of February to August would probably eliminate any useful crop yields from Northern temperate zones. A nuclear war-induced climatic perturbation after August might produce climatic alterations after the crops had been harvested, but the possibility of continued reduced temperatures the following spring, if they were to occur, would limit potential production the subsequent growing season.

For wheat and barley, the previous discussions apply. In addition, it is felt likely that seasonal average temperatures of 1–2°C below normal are within

TABLE 4.10

CROP AND ANIMAL RESPONSES TO ACUTE CLIMATIC PERTURBATIONS OCCURRING IN JANUARY

| ZONE | |
|---|---|
| Northern Temperate: | Winter wheat would survive all except extreme temperatures (e.g., -50ºC in Canada or U.S.S.R.), especially if snow-covered, but low average temperatures in the growing season would not allow grain to develop except at a few low latitudes (e.g., N. India, N. Africa, Southern U.S., provided that there was adequate rainfall). Yields might also be possible in coastal areas if mean temperatures there were warmer (e.g., W. Europe).<br>Spring sowings of wheat, barley, and maize might be possible, but, except in coastal zones, seasonal mean temperatures would be too low for grain to form. Most crops of these cereals in N. America, U.S.S.R., and China would fail. Rice in Japan and China would fail. Potatoes would produce no yield (e.g., Europe, U.S.S.R.). Rye in E. Europe would survive cold but would fail because of season length. Spring sown soybeans at low latitudes (e.g., Southern U.S.) would have the potential to yield effectively provided that there was adequate rainfall. Grasslands would survive the cold with some leaf damage. Intensively housed animals would not survive failure of mechanical ventilation and feeding. Most healthy adult ruminants would survive the cold outdoors; food and water would be limiting factors for their potential survival. Young animals would die of cold stress. Low light levels could affect the fertility of animals such as sheep. |
| Tropics: | Rice, maize, sorghum, and millet would be killed if even short cold spells occurred during susceptible stages. Better estimates of temperature means and variations are necessary to improve conclusions. Staple crops of semi-arid zones (millet, sorghum in Africa and India) would fail if rainfall decreased substantially. Maize currently planted at the lower limit of its rainfall requirement (≈500 mm) would also be susceptible to drought (parts of Central Africa, Central and S. America). Tropical grasslands would also be cold sensitive but recovery would be likely when temperatiure and rainfall reached adequate levels. Animals would survive cold periods and their ultimate survival would depend on food availability. Changes in the general circulation, as well as influencing temperature and rainfall, would also modify the range of major migratory pests. Possibilities of more than one crop in a year in the humid tropics would probably be lost. |
| Southern Hemisphere: | Lack of clear climatic predictions limits the ability to estimate effects. |

TABLE 4.11

CROP AND ANIMAL RESPONSES TO ACUTE CLIMATIC PERTURBATIONS OCCURRING IN JULY

| Zone | |
|---|---|
| Northern Temperate: | Some winter and spring-sown cereals would have been harvested by July (e.g., in India, China, N. Africa, U.S.), but harvest operations in Canada, U.S.S.R., and W. Europe would be severely affected. Cold and darkness would cause maize, soybeans, potatoes, and rice to fail. Adult ruminants would survive, but young animals and shorn sheep would die of cold. Grasslands would probably be killed by cold although recovery later might occur. |
| Tropics: | All crops are susceptible to cold. Areas where agriculture is closely linked to timing of monsoon rains (e.g., India, Indonesia) would be strongly affected by alterations in general circulation. Effects in N. tropics would be likely to be more severe than in the January scenario because of the timing of planting of millet, sorghum, and rice in June-July. Multiple crop possibilities in one year in the humid tropics would probably be lost. |
| Southern Hemisphere: | Cold would lengthen the period for maturation of wheat and maize in Australia, S. Africa, and S. America, and would slow growth of grasslands, but water would be more likely to limit production. Animal production would be limited by food availability, but would not be significantly affected directly by temperature decreases. |

the range of natural variation, and any effect on yields to be seen would probably relate to increased yields in response to reduced moisture limitations. However, even that level of temperature reduction would shorten the growing season, based on present temperature variance relationships, while increasing the crop maturation times. At the margins of these grain crops, such as in Canada and the U.S.S.R., this could have a marked effect on potential crop ranges. A reduction of 2°C or more would reduce the area for which wheat could develop by perhaps 50%; a 5°C reduction would adversely affect essentially all wheat-producing regions of the Northern Hemisphere, and grain production everywhere would be extremely low.

Effects of shifts in rainfall patterns could also be considerable. Increases of rainfall in combination with cooler temperatures could lead to increased crop loss to disease; decreased precipitation, of the order of 50%, would lead to substantial crop failures in wheat growing areas of the U.S. and U.S.S.R., where rainfall is already limiting.

Maize production could be difficult because only limited supplies of hybrid seeds would probably be available after a nuclear war, forcing many to use open-pollinated seeds which have increased variation in productivity. For those fields with adapted, pure line seeds, the general response of maize to a chronic climatic alteration would be similar to other grains, with slight increases in yields for 2°C reductions associated with no change in precipitation in many areas, but reduction in productivity in regions nearer the margins of the normal range. Greater temperature reductions, 2°C to 5°C, would decrease yields in virtually all areas, with total crop failures in northern regions, but with high yield potential remaining in the southern extremities.

About 80% of the total potato production annually occurs in Northern Europe and the U.S.S.R. Calculations were performed using a model developed by Ingram and McCloud (1984) for climates in two regions: the Northwest U.S. and the Midlands of England. A 5°C reduction in England was found to result in about a 50% reduction in production, with other physical parameters left unchanged, and 2°C reductions could occur without any major impact. In the U.S.S.R. and Poland, where potatoes grow nearer their temperature limit, it is estimated that a few degrees reduction in temperature would severely reduce production, and that a 5°C reduction would eliminate yields. Because potatoes are vegetatively propagated, it is unlikely that stocks would be available if the previous year's crop were lost in an acute, extreme climatic disturbance following a nuclear war. Potato limitations in North America would likely be more related to reductions in human subsidies than to changes in climatic conditions in a chronic period.

## 4.4 POTENTIAL VULNERABILITY OF TROPICAL AGRICULTURE

### 4.4.1 General Considerations

Tropical agroecosystems are vulnerable to the same types of perturbations that could impair temperate agricultural production following a nuclear war. Tropical agriculture, however, requires special consideration because of the unique crops and climates within this region and because of differences in the magnitudes of stresses that would be experienced. Further, the disproportionate fraction of humans surviving the immediate consequences of a large-scale nuclear war would likely be in tropical and subtropical regions.

The following section is primarily based on contributions to, and conclusions of, the agricultural working group of the ENUWAR tropical workshop.

**4.4.2 Temperature Stresses**

Direct experience of freezing conditions in lowland tropical agroecosystems is very limited. It is possible to predict some of the consequences of temperature reduction for tropical crops based on laboratory determinations of physiological tolerances (Chapter 1), and from records of exposures of tropical plants growing in climates that experience freezing events. The Florida peninsula of the United States is an example of a subtropical region with documented frost events that damage plants of tropical origin. Although freezing occurs at low frequencies in southern Florida, those episodes that do occur are responsible for severe damage to citrus, tropical fruits, and sugar cane. Five major freezing events in Florida between 1977 and 1985 caused huge losses of vegetable crops and fruit, with a period of several years required for recovery of damaged trees (Myers, 1985).

Tropical tree crops would not exhibit the cold acclimation exhibited by Florida citrus trees. Even acclimated plants of the most cold-tolerant varieties are killed by temperatures below −10°C (Davies et al., 1981; Wiltbank and Oswalt, 1983). These cultivars are not grown in tropical regions.

The major tropical and subtropical agricultural plants are quite sensitive to chilling injury, and are killed by brief periods of freezing (Chapter 1). Rice, the principal grain crop in many tropical countries, is damaged by exposures to temperatures as high as 15°C during certain phenological-stages (an extensive discussion of rice and climatic stress is found in Section 4.4.6). The tropical workshop group on agricultural effects concluded that climatic events of brief duration, producing minimum daily temperatures of 10°C to 15°C , would substantially reduce yields of most crops grown in the tropics. Additional temperature decreases would eliminate the possibility of producing others. Some cultivars of potato, barley, and rye were considered to be the most cold tolerant, but there are generally grown at high elevations in the tropics.

Temperature decreases throughout the growing season were also considered. Mean temperature reductions between 3°C and 10°C would cause widespread yield decreases, and could reduce the area of land suitable for certain crops. Brazil is an example of a tropical country that could experience serious perturbations to its agricultural system following a mean temperature decrease of 3°C. Lopes et al. (1985) considered the production of soybeans, coffee, and sugar cane during the potential climatic alterations for the chronic post-nuclear war period. Based on consideration of current climate-production relationships and limits on these crops, Lopes et al. (1985) calculated that as much as 165 million $km^2$ would be lost from the area capable of producing these crops.

### 4.4.3 Vulnerability to Precipitation Stress

Although many weather stations in tropical regions report annual rainfall levels between 2 and 4 meters, precipitation reductions following a nuclear war are a potential problem. Even the wettest regions often exhibit a highly seasonal distribution of precipitation, and altering the initiation and duration of rainy seasons could result in the planting of crops unable to mature. Arid and semi-arid tropical regions are of course particularly vulnerable to decreased precipitation, as evidenced by the poor agricultural production found in the Sahel. Long-term changes in atmospheric and oceanic circulation patterns could lead to impacts as severe as desertification. The climatic changes associated with El Niño events demonstrate the vulnerability of tropical agriculture to even small temporary changes in circulation patterns.

### 4.4.4 Energy Subsidy Losses

Many tropical countries, particularly those dependent on imports, would experience impaired agricultural production as a result of diminished energy subsidies following a nuclear war. (A more thorough discussion is presented in Section 4.6, and analyses of representative countries are in Chapter 5.) Some of the acute phase disruptions would decrease yields for an extensive time period. Many tropical countries require large inputs of draught animal power for agricultural production. If these animals were consumed as food during an acute-phase crisis, potential crop production would be reduced to that maintained in handpowered agricultural systems. In the seasonal tropics, many of the most important crops are grown during the dry season under irrigation. Shortages of power and maintenance capability for irrigation could cause massive crop failures. Loss of international trade in petroleum products, machinery, and inorganic fertilizers could not be easily compensated for in many tropical countries.

### 4.4.5 Potentially Ameliorating Factors

Broad geographical and climatic diversity within tropical regions ensure that some type of agriculture would be possible under most of the nuclear war scenarios considered. In regions with high temperatures and precipitation, nuclear war-induced climatic stresses might produce climates similar to sub-tropical or temperate regions. Although productive agriculture would be possible in these regions, matching the correct crops and farming practices to the new climate could be quite difficult. Similarly, transporting seed or rootstock and new cultural knowledge needed for planting and preparing crops from high-elevation or temperate regions to affected tropical farmers could be difficult.

Following climatic shifts, tropical farmers might increase the use of intercropping. Crop failures involving only one species would not be as serious with an intercropping system. It would also be possible to compensate for reduced yields by increasing the land area used for food crops. Many tropical countries use a substantial fraction of their arable land for the production of non-food and export crops (Table 4.12a). This additional land represents a potential for greatly increased food production levels under conditions of adequate temperature and precipitation. Assuming the climate allows any agriculture, flexible responses are possible to these stresses; however, the time lag before successful implementation would be significant, and societal responses could determine the extent of such implementation.

TABLE 4.12a

AREAS UNDER CURRENT PRODUCTION OF SELECTED CROPS

| | (x 1,000 ha)[a] | | |
|---|---|---|---|
| | FOOD CROPS[b] | SUGAR CANE | EXPORT CROPS[c] |
| Brazil | 32,851 | 3,370 | 10,667 |
| Costa Rica | 220 | 51 | 1,159 |
| Indonesia | 15,431 | 24,531 | 13,281 |
| Philippines | 7,248 | 480 | 4,395 |

[a] Source: FAO Production Yearbook (1983).

[b] Cereals, pulses, roots and tubers, soybeans.

[c] Coffee, tea, cocoa, bananas, cotton and other fibers, tobacco, hops, coconuts.

TABLE 4.12b

CRITICAL TEMPERATURES FOR RICE DEVELOPMENT[a]

| GROWTH STAGE | Minimum | Maximum<br>Temperatures (°C) | Optimum |
|---|---|---|---|
| Germination | 16-19 | 45 | 18-40 |
| Seedling Emergence | 12-25 | 35 | 25-30 |
| Rooting | 16 | 35 | 25-28 |
| Leaf Elongation | 7-12 | 45 | 31 |
| Tillering | 9-16 | 33 | 25-31 |
| Panicle Initiation | 15 | -- | -- |
| Panicle Differentiation | 15-20 | 30 | -- |
| Anthesis | 22 | 35-36 | 30-33 |
| Ripening | 12-18 | >30 | 20-29 |

[a] Data from De Datta (1981).

### 4.4.6 Vulnerability of Rice to Climatic Perturbations

#### *4.4.6.1 General Characteristics of Rice Production*

The responses of rice production to the effects of climatic change and other stresses require separate attention because of the important role rice plays in world food balances. More than $4 \times 10^8$ metric tons of rice are produced annually (FAO, 1982), and rice currently supplies over one-half the energy requirements and an important part of the protein intake, in the diets of more than a billion people. After a nuclear war, a disproportionate fraction of the survivors would probably exist initially in the areas of current rice production; therefore, if rice could be grown under the post-nuclear war conditions, it would probably provide the major cereal crop for survivors in non-combatant countries. Because of this tremendous potential for human support after a nuclear war, it is necessary to evaluate its particular vulnerability to the environmental perturbations projected to occur.

Rice is currently grown under irrigation and as a rainfed crop. The rainfed upland rice constitutes about 10% of the world production, and rainfed lowland rice another 30% (De Datta, 1981). Irrigated, deepwater, and floating rice constitute 45%, 11%, and 4%, respectively. Paddy rice is the dominant type in the U.S., the U.S.S.R., Japan, China, Egypt, Indonesia, and Southeast Asia; upland rice is common in South America (particularly Argentina, Brazil, Columbia, and Paraguay) and in Africa. However, all of Latin America's areas under rice cultivation are less than Bangladesh's, and West Africa's rice land constitutes only 1.4% of the world's area under rice cultivation (De Datta, 1981). Clearly, Asia's rice production is the most important in terms of area, crop production, and human support.

Climatic conditions largely control rice production. For upland rice crops, such as in West Africa and South America, the amount and annual distribution of precipitation are of critical importance. Because of the lack of adequate irrigation facilities, most of the rice here is grown as a wet-season crop, and no production is possible in other parts of the year. The development of monsoonal rains is the key to crop production in many upland rice regions. In many rice-growing regions, especially in South and Southeast Asia, there is a strong seasonality in precipitation, and rice is grown in the wet season; in these situations, rice production is typically rainfall limited. Rainfall in the dry season is insufficient for rice production, so those times of the year and locations must have irrigation for production of a dry-season crop.

Variability in rainfall is also the primarily controlling factor for rainfed rice in Asia, which constitutes about 80% of the rice grown in that area (De Datta, 1970, 1981). Most of tropical SE Asia receives about 2000 mm of rain per year, which is adequate for one rice crop if the precipitation is evenly distributed over the year; if rainfall is more seasonal, such as monsoonal areas, as little as 1200–1500 mm of rain per year is adequate for a single crop. However, the two largest rice-growing countries in the world, India and China, receive less than this amount of rainfall; in the case of China, almost all rice is grown under irrigation; India often has too little, or too much, rainfall, and crop production is frequently adversely affected. In Thailand, widespread crop failure from either drought or excessive flooding occurred during 8 of the 58 years between 1907 and 1965, and at least 10% of the crop area was not even harvestable in 24 of the 58 years (i.e., over 40% of the time) (Yoshida, 1981).

Variability in the onset of the monsoon season determines the time of planting for transplanted rainfed rice; to reduce the effects of this uncertainty, many farmers hold water in the fields by bunds, with concomitant loss of seedlings and with lodging in the later stages of crop development reducing productivity. If rainfall extremes coincide with critical periods in the rice life cycle, yield reductions can be severe. For upland rice, rainfall variability is even more important than for lowland cultivation, and moisture stress often kills plants that receive large amounts of rain in one day and none for the subsequent few weeks. Varieties of rice that can mature in less than 100 days are an advantage in mitigating the effects of precipitation variability.

The availability of sunlight is also important to rice maturity and yields, although not nearly as critical as precipitation. The correlation between insolation and grain yield in the tropics has been found to be highly significant, especially during the last 30 days of rice growth (De Datta and Zarate, 1970). The amount of insolation received from panicle initiation until the later stages of crop maturation is particularly important (Stansel, 1975; De Datta, 1981).

Of considerable importance to the production of rice in many areas is the temperature regime. Mean growing season temperatures, temperature sums (e.g., degree-days), temperature ranges and extremes, seasonal distribution of temperatures, and diurnal ranges have each been shown to be correlated with rice yields (Moomaw and Vergara, 1965; De Datta, 1981). Critical temperatures for germination, tillering, inflorescence initiation and development, dehiscence, and ripening have been empirically derived (Table 4.12b)(De Datta, 1981). In northern areas, rice is sown when temperatures are low, and the crop begins its growth cycle in a period of rising temperatures; after flowering, maturation occurs during the period of declining temperatures. In lower latitudes, sowing occurs at high temperature periods, with slowly declining levels until maturation; near the equator, little temperature change occurs annually. In tropical regions, slightly lower temperatures during the ripening period increase yields in response to slower ripening and longer time for grain filling (De Datta, 1981).

Growing seasons, and the number of crops per year, vary among countries. In Japan, the growing season typically is May to September. Southern China and Taiwan have two rice crops each year, April to September and October to December. The latter crop in particular is affected by climatic conditions because of the marginality of growing conditions under the climate and variability of that time period. Indonesia is a major example of a location where rice is grown essentially year-round, but here seasonality in precipitation often limits yields. Such continuous cropping countries, more often occurring in tropical regions, are less subject to temperature fluctuations than more northerly latitudes; however, the crops in the tropical regions are more sensitive to those temperature excursions that do occur (Uchijima, pers. comm.).

Cold-temperature injury to rice occurs in many temperate and tropical regions, and rice is clearly more temperature sensitive than the other grains considered in this report. Rice production in northern latitudes in particular is limited by low temperatures; e.g., low rice yields from low temperatures often occur in Korea (Chung, 1979). In California, seedling establishment and vigor have been reduced in response to temperatures under 18°C; sterility has been found following night-time temperatures below 15°C if within two weeks of heading (Rutger and Peterson, 1979).

Japanese rice production provides a substantial data base for estimating temperature effects on rice production, since its crops are frequently reduced considerably in yields because of cool weather. For example, for 25% of the years over the last century in Hokkaido, rice yields have been low because of cool temperatures during the growing season (Satake, 1976), and this district, along with the Tohoku district, frequently suffer yield losses in excess of 50% (Horie, in press). These districts in good years account for 40% of the total Japanese crop. In 1980 as a result of only about a 0.5°C reduction in average temperatures over the growing season, the overall Japanese rice yield averaged about 5,100 kg $ha^{-1}$, compared to an average yield for the 1974–1976 period of 5,850 kg $ha^{-1}$ (FAO, 1982). In some regions during 1980, the July and August temperatures were reduced by less than 2°C, but one-third reduction in rice yields occurred (Horie, in press). In general, historical data indicate that a 1°C to 2°C decrease in temperatures averaged over the growing season result in rice crop failure, and that any brief temperature excursions below about 15°C would result in the loss of at least one-third of the crop (Uchijima, pers. comm.).

Meiosis is a phase in the rice life cycle that is particularly susceptible to reductions in temperature. Sterility can occur at temperatures falling below 15°C–17°C in the highly cold-tolerant varieties, and 17°C–19°C in the cold-sensitive varieties, a result primarily of injuries occurring in anthesis (Satake, 1976; De Datta, 1981). Cool temperatures can also lead to poor germination, slow growth, stunted growth, delayed heading, incomplete panicle exsertion, prolonged flowering periods because of irregular heading, degeneration of spikes, irregular maturity, and formation of abnormal grains (Kaneda and Beachell, 1974; De Datta, 1981). Often effects that lead to a loss of rice yield will not kill the plant outright, but since rice is an annual rather than a perennial, loss of the grains means that crop will never produce a usable yield.

Sensitivity to temperature varies among the major cultivars of rice. Japonica cultivars are primarily the ones used in Japan and other temperate regions, and the temperature minima listed above relate particularly to this type (Uchijima, pers. comm.). A more tropical cultivar, Indica, grown in SE Asia and India, would have significant yield reductions at temperatures a few degrees higher than those for Japonica (Uchijima, pers. comm.). Javanica rice, grown in Indonesia, is intermediate between the two in temperature sensitivity, but on a global scale its production is not as important as the others.

A final physical effect often limiting to rice production is the presence of winds. A gentle wind improves grain yields by increasing turbulence in the canopy, replenishing the $CO_2$ supply before it becomes depleted (De Datta, 1981). However, strong winds can dessicate panicles, increasing floret sterility; strong winds enhance certain bacterial leaf diseases; they can dessicate and cause mechanical damage to rice leaves, reducing photosynthetic capability; and, if occurring after heading, strong winds can cause severe lodging and shattering (De Datta, 1981).

#### *4.4.6.2 Potential Vulnerability of Rice to Nuclear War-Induced Climatic Perturbations*

In considering the potential impacts of a nuclear war-induced climatic disturbance on rice production in the world, it is clear from the above discussions that brief episodes of subfreezing temperatures during the growing season would kill the rice outright, and even with temperature minima well above freezing, there still would be the loss of the current growing season's crop. In short, it can be stated that during the acute period of a significant nuclear war-caused climatic event, rice production would be essentially eliminated in at least the Northern Hemisphere, and the Southern Hemisphere could experience the same fate, depending on the nature of the temperature excursions in that part of the world.

In the potential climatic disturbances associated with a chronic phase, the effects of temperature reductions would also cause severe or total rice crop loss. Having a mean growing season temperature below 15°C would be expected to preclude rice production (Stansel and Huke, 1975). The critical mean growing season temperature for Japan, below which yields would be reduced, is 19°C–25.5°C, depending on the regional variety of the rice (Uchijima, 1981). These results follow from having insufficient thermal time over the growing season (Uchijima 1981, 1982; Yoshida, 1981), and are in addition to the effects that would result from brief temperature reductions over a day or more during the growing season.

A simulation model has been developed based on dynamic crop-weather relationships using daily solar insolation and temperature data to simulate rice growth and yield (Horie, in press). This model was validated to simulate final crop biomass dry weight and rice yield to within 10% of actual values for most cases of different locations, seasons, and climate. Importantly, the model was found to be accurate in simulating rice production in the northern limits of production in Japan, where annual yield variation is large, and where severe crop losses occur approximately once every three or four years (Horie, in press). Using this model for simulations of reducing temperatures over the growing season by an average of 2°C lead to a loss of 70% of the rice yield in an area calibrated to Sapporo, Japan.

Based on the model and the mechanistic-physiological considerations discussed above, it is concluded that a chronic average decrease in growing season temperatures by 2°C–3°C would likely result in the loss of rice production over the Northern Hemisphere through the combined effect of the loss of thermal time and of the occurrence of cold temperature episodes. The rice-growing areas of the Southern Hemisphere are dominated by upland rice cropping, as noted above. These are the more sensitive to changes in temperature and precipitation. Therefore, those rice-growing areas of lesser climatic perturbations are also the areas of greater sensitivity to such climatic alterations, and would also appear to be vulnerable to the temperature effects of nuclear war.

With respect to the issue of possible reductions in precipitation, in those areas where irrigation systems are sophisticated, such as in Japan, a reduction in precipitation during the chronic period would not result in reductions in rice production because the water stores in the system is sufficient to last a year, especially if water demand were reduced by having a loss of industrial activity. Timing of the nuclear war would be important, e.g., as in the case of Japan, the rains come primarily in June, providing the charging to the water storage system; if the nuclear war were to happen prior to that and if there were a subsequent major reduction in precipitation, insufficient recharging of the s9stem would occur and insufficient water would be available for crop production. Over a longer period, precipitation decreases of 50% or more would be expected to be the point at which the irrigation system would have insufficient water, and crop yields would suffer (Uchijima, pers. comm.). For countries with less sophisticated or non-existent irrigation systems, such as in Africa, reductions in precipitation would translate directly into crop yield losses, as there is essentially no buffer against water loss. Those areas in which rainfed upland rice is grown would also be directly sensitive to reductions in precipitation, and a 50% reduction in precipitation would be expected to reduce yields by an even greater amount (i.e., >50%).

Light reductions would not seem to be significant in causing loss of yields from having too short a photoperiod, as was felt to be the case for other grains, discussed previously. However, prolonged periods of reduced light levels would result in comparable reductions in total rice production, based on the highly significant correlation of grain yields to light levels (De Datta and Zarate, 1970). The effects of light reductions, however, would likely be secondary to the effects of temperature and precipitation reductions.

## 4.5 POTENTIAL VULNERABILITIES OF EXTRA-TROPICAL SOUTHERN HEMISPHERE AGRICULTURE[1]

### 4.5.1 Introduction

The potential effects of climatic disturbances following a nuclear war on the agricultural productivity of the Southern Hemisphere was a topic of consideration at the SCOPE–ENUWAR workshop in Melbourne, Australia. As in the case of the ecological effects, the emphasis at this workshop was on extra-tropical Australia and New Zealand as representing the Southern Hemisphere continental and large island situations Those issues associated with tropical agricultural systems are discussed in the section on the tropics (Section 4.4). Those issues associated with temperate agriculture in Africa and South America have not explicitly been addressed, but it was felt among the workshop participants that the situation in southern Africa would most be analogous to Australia.

The projected perturbations to the physical environment in the Southern Hemisphere are substantially different from those projected potentially to occur in the Northern Hemisphere after a Northern Hemisphere nuclear war. This difference relates to several key factors: 1.) isolation from the particulate inputs to the atmosphere from the major fires and dust that would result from nuclear detonations in the Northern Hemisphere; this isolation is because of the spatial separation of the areas and, particularly, because of the limited exchange of the troposphere across the equator; 2.) few, if any, nuclear detonations in the Southern Hemisphere; 3.) much greater expanse of the hemisphere being covered by ocean as opposed to continental areas.

As discussed in Volume I (Pittock et al., 1985), there is an increased assurance from recent atmospheric analyses that the particulate inputs to the atmosphere in the Northern Hemisphere could be elevated to high altitudes, almost irrespective of the initial height of injection of the smoke plumes. This could tend to increase transport into the Southern Hemisphere atmo-

[1] This section was written by M.J. Salinger and is primarily based on the biological working group discussions at the Melbourne conference, with input from N. Cherry, H. Hughes, N. Nicholls, B. Pittock, and D. Potter.

sphere because of the much greater exchange across the equator by the stratosphere than by the troposphere. Further, other analyses indicate that for a Northern Hemisphere summer-onset nuclear war, the strong differences in absorptive properties of the Northern Hemisphere atmosphere in the early period after the nuclear war compared to the Southern Hemisphere could establish altered global atmospheric circulation patterns. The current inhibitions against trans-hemispheric transport could be reduced or eliminated, and a new circulation pattern that includes atmospheric circulation extending from the Northern mid-latitudes down to 30°S latitude or so could become established. In this circumstance, climatic perturbations following a summer-onset nuclear war could extend through the tropics of the Southern Hemisphere and perhaps to even more southerly latitudes. Such an atmospheric response would apparently not occur if the nuclear war were to occur in the Northern winter, unless the particulates were to remain in the atmosphere in sufficient quantities so that on the following summer the altered circulation patterns would then become established.

For our purposes, these possibilities suggest that there is a great deal of uncertainty concerning the environmental perturbations that could be experienced in the Southern temperate regions. There also might be an increase in the variance about whatever climatic effects were felt there, in that the boundary of a nuclear war-induced cloud could tend to have periods of obscuration alternating with periods of clearing of the skies. These factors also suggest a particularly strong seasonality effect for the timing of the nuclear war as affecting the Southern Hemisphere environment, more so than for other parts of the Earth. Finally, the predominance of ocean areas in the region would mean lessened intensities of temperature drops, but there might be more effects on precipitation in response to relatively subtle changes in ocean currents and sea-surface temperatures. That the latter substantially controls periods of drought in at least Australia was demonstrated by Nicholls (in press). Because of these uncertainties, the approach taken for the Australian and New Zealand estimations was to consider the sensitivities of these agricultural systems to the various climatic disturbances, rather than concentrate on one or a few specific climatic disturbance scenarios.

The land areas that fall into this region include southern Africa, southern South America, Australia, and New Zealand. The Melbourne, Australia workshop focused discussions on the latter two countries. It is believed that southern Africa's agricultural responses would be similar to those experienced in Australia, but these have not been specifically analyzed. Southern Hemisphere extra-tropical agricultural systems differ from those in comparable latitudes in the Northern Hemisphere by the emphasis placed on pastoral agriculture for meat and wool production. The emphasis is demonstrated by the percentage of agricultural land devoted to this activity. Although grain crops, especially wheat, are important in Argentina and Australia, pastoral farming is still the dominant agricultural activity.

There are several different features of Southern Hemisphere grassland agricultural systems compared with equivalent Northern Hemisphere systems. They are not based upon indigenous species, but largely utilize exotic species that have either been introduced from the Northern Hemisphere or are cultivars that have been selected from breeding programs. Another difference is that in many of the Southern Hemisphere countries (e.g., New Zealand), the pasture swards introduced by the European settlers have replaced the indigenous vegetation, including grassland and bush. On the basis of the above differences of the pastoral ecosystems of the Southern Hemisphere and the specialized management of this system that is practiced, the grassland ecosystems here are considered under agriculture, rather than in the ecosystem chapter. This also recognizes the importance placed on livestock production, a characteristic of agriculture in this hemisphere.

### 4.5.2 Vulnerabilities to Possible Acute Climatic Effects

Extra-tropical Southern Hemisphere agricultural systems are unlikely to experience severe acute climatic effects according to modelling studies (Volume I). As most of the smoke would be injected in Northern latitudes, the initial circulation state of the atmosphere, where the circulation of both hemispheres only meets in the tropics, prevents any immediate atmospheric effects from spreading rapidly south. However, with the lofting of smoke plumes into the upper troposphere and lower stratosphere, and under favorable circulation, smoke streamers might travel south for short durations and must be considered as possible consequences, especially for the north of this zone (Covey et al., 1984). The incidence of frosts in the growing season (usually September to May, depending on the latitude) could be very damaging to some aspects of agriculture. Such an event, especially at a critical crop growth stage, could decimate the current year's production of frost-sensitive crops. However, the grassland systems which dominate are largely resistant even to such an extreme event.

### 4.5.3 Vulnerabilities to Potential Chronic Climatic Effects

The greatest potential effects seen for Southern Hemisphere extra-tropical agriculture would be in the chronic time period. In order to evaluate vulnerabilities to a potential chronic climatic disturbance, the effects of a few degree reduction in average temperature (1°, 2°, or 5°C, depending on location), with associated 5–20% reductions in insolation, and the potential for large (up to 50%) reductions in precipitation were considered.

Given that much of Australian rangeland and cereal cropping activities are inland from the coast, the environmental stresses would be akin to that of continental Southern Hemisphere areas. The bulk of agricultural production is from pastoral farming and cereal cropping activities. Several studies are relevant to potential chronic phase stresses. As a first-order investigation of the sensitivity of Australian biological systems to such effects, Pittock and Nix (1985) ran the 'Miami Model' of net primary production for various disturbed climate scenarios. Because the Miami Model uses non-linear regression relationships between mean temperature, annual precipitation, and net primary production at any one place, it assumes that whichever relationship gives the lowest primary production is the limiting factor (Lieth, 1975). Therefore, the model has limitations, discussed below. However, it is still useful in providing indications of responses to stresses lasting through one or more growing seasons.

The results pertinent to this study are the scenarios of 2°C and 5°C temperature reductions with 50% of normal precipitation. As might be expected, the major effects occur in response to a 50% reduction in precipitation. Biomass was predicted to be reduced by 25% in high rainfall zones, 33% in subhumid zones, and 50% in arid zones. Temperature reductions were seen to have very little effect north of 30°S, but a 5°C degree temperature drop could cause up to a 20% reduction in production in the coldest parts of Australia, according to the model.

Production estimates based on the Miami model, as with other regression models, should be used with caution. Although this technique can be used to illustrate the potential sensitivity of an ecosystem type to climatic change, the model does not represent a mechanistic description of physiological processes or vegetation dynamics. The Miami model was developed using data collected from the dominant or "climax" vegetation at a large number of locations. The relationships between geographical variation in annual climate and predicted productivity are not analogous to responses of plants to rapid or severe climatic change. In addition, predictions using normal climatic parameters may be inaccurate at any specific unperturbed location. The Miami model can be used as a first-order approximation of relative sensitivity to climatic change, but it probably underestimates the actual sensitivity of vegetation to the rapid climatic perturbations that could follow a nuclear war.

In another analysis, Harris and Stapper (1985) found it difficult to detect possible effects of climatic change on wheat yields because of inherent variability in yields. However, their methods did not adjust yield data for trends. The workshop discussions identified rainfall as the critical determinant of wheat yield as it is required in the sowing stage in autumn and again during the grain filling period in spring. Other studies support these conclusions. Wigley and Tu (1984) identified precipitation as the main determinant of wheat yields in the inland areas of Western Australia. Such a conclusion is further strengthened by the work of Nicholls (1985a,b). The El Niño–Southern Oscillation phenomenon is an important mode of climatic variation affecting the Australasian region; therefore, inter-annual fluctuations of some Australian crops might be expected to be closely related to this phenomenon. Nicholls demonstrated that total production anomalies of all cereal crops, once allowance is made for trends, is significantly related to an index of the Southern Oscillation index. A typical wheat yield is 1.2 t $hectare^{-1}$, so anomalies of up to 0.5 t $hectare^{-1}$ represent substantial inter-annual variability in yield. A drought index was further defined by Nicholls, representing rainfall in inland New South Wales, Victoria, and southern Queensland, for June to November. This index had both high correlations with the total value of Australian crop production over a 32-year period ($r = 0.72$) and El Niño–Southern Oscillation indices ($r = -0.76$ for Darwin pressure) over a 47-year period.

A final piece of evidence relating grass growth to aspects of rainfall and water balance comes from New Zealand studies. Maunder (1974) demonstrated that pasture growth over the warm season in New Zealand is determined by precipitation through soil moisture levels.

Therefore, it is reasonable to conclude from all these studies, and because present day Australian agricultural activities are located in climatic zones where temperature reductions would not likely be a significant factor, that nuclear war-induced reduction in precipitation, if that occurred, would be the dominant effect on Australian pastoral and cereal cropping production. Similar conclusions can be extrapolated to South Africa and the northern agricultural areas of Argentina. Depending on what the precipitation reduction would be, the workshop tentatively estimated that grassland and cereal production could drop from between 0 and 50% at the beginning of a chronic phase. Persistence into the chronic phase would cause a further decrease with loss of fertilizer support. If stresses were to last only a year, then production would return to normal, followed by a decline when agricultural systems lost their fertilizer support. However, adaptation would likely occur, and Australia could still be a net food producer, though with dramatically lower production.

In contrast, effects in New Zealand would be more in response to possible temperature reductions in the chronic phase than to possible changes in precipitation. In New Zealand and Tasmania, there are areas which are precipitation limited, and reductions in precipitation would produce proportionate drops in yield. Maunder (1974) demonstrated that monthly dairy production in New Zealand is related to weighted indices of water deficit. However, better understanding of regional airflow is required, because wind direction fundamentally determines topographic precipitation patterns. Temperature effects on productivity would be more important in the chronic phase. If effects are assumed to persist through at least one and possibly more growing seasons, in contrast to the hotter continental climate of Australia where plants are often heat stressed, in the cooler maritime climates of the islands, plants are more often closer to their threshold temperature for growth. Thus, yield is temperature limited and colder temperatures would significantly reduce yields.

This point is illustrated by Salinger (1985) in a study examining the effect of various temperature decrease scenarios on the length and intensity of the New Zealand growing season for various start times. Chronic phase scenarios modelled ranged from a temperature reduction of 3°C for six months, then 1°C for another six months, to a 1°C reduction for twelve months (Table 4.13). For Ruakura, a location typical of agricultural areas in northern New

TABLE 4.13

EFFECT OF DIFFERENT TEMPERATURE SCENARIOS ON THE GROWING SEASON IN NEW ZEALAND

| | Scenarios | | | |
|---|---|---|---|---|
| Starting Time | -3°C 6 mo.<br>-1°C 6 mo. | -3°C 3 mo.<br>-1°C 9 mo. | -1°C 12 mo. | -1°C 6 mo. |
| September | 828[a]<br>••[b,c] 67[d] | 1003[a]<br>••[b,c] 33[d] | 1113[a]<br>40[c] 22[d] | 1215[a]<br>27[c] 17[d] |
| November | 783<br>•• 80 | 942<br>•• 39 | 1113<br>40 22 | 1200<br>32 13 |
| December | 808<br>•• 44 | 938<br>•• 40 | 1113<br>40 22 | 1211<br>23 10 |
| March | 957<br>•• 15 | 983<br>12 14 | 1113<br>40 22 | 1274<br>3 0 |
| May | 977<br>•• 22 | 1087<br>40 14 | 1113<br>40 22 | 1289<br>6 3 |
| June | 977<br>•• 32 | 1087<br>40 14 | 1113<br>40 22 | 1278<br>9 7 |

[a] GDD above 10°C. Average during normal climate is 1376 growing degree days (GDD) above 10°C.

[b] •• indicates that the crop would not reach maturity.

[c] Reduction in the growing season (days) for the time period over which crops requiring 1000 GDD would be grown.

[d] Reduction in the growing season (days) for the time period over which crops requiring 700 GDD would be grown.

Zealand, almost 1400 growing degree-days are normally accumulated above 1°C. The largest change scenario gave reductions in growing degree-day accumulations to 800–900. This represents a reduction in growing season length by 3 to 5 weeks for plants requiring 700 growing degree-days to mature. Thus, plants requiring 1000 growing degree-days for maturity would not mature under this scenario. Even the smallest temperature reduction scenario (Table 4.13 and Figure 4.11) gave a reduction in length of the growing season by 1 to 3 weeks.

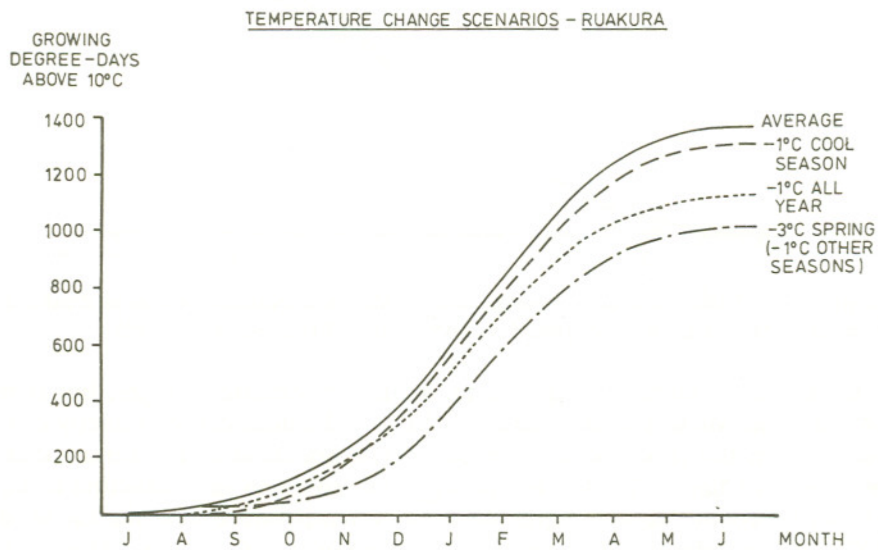


Figure 4.11 Effect of different temperature reduction scenarios at Ruakura, New Zealand, on growing degree-days above 10°C. From Salinger, 1985

This study also demonstrated the significance of timing of the effects of climatic disturbances from a nuclear war. For the 3°C reduction for three months, followed by a 1°C reduction for nine months (Table 4.13 and Figure 4.12), the maximum impact occurred when effects occurred in spring or early summer. In this case, 3 to 4 weeks were lost from the growing season, and many crops would be unable to reach maturity because of insufficient thermal time. However, a war producing such effects in autumn or winter would have much less impact. Warm weather crops would be able to reach maturity, and the reduction in growing season length was predicted to be about two weeks.

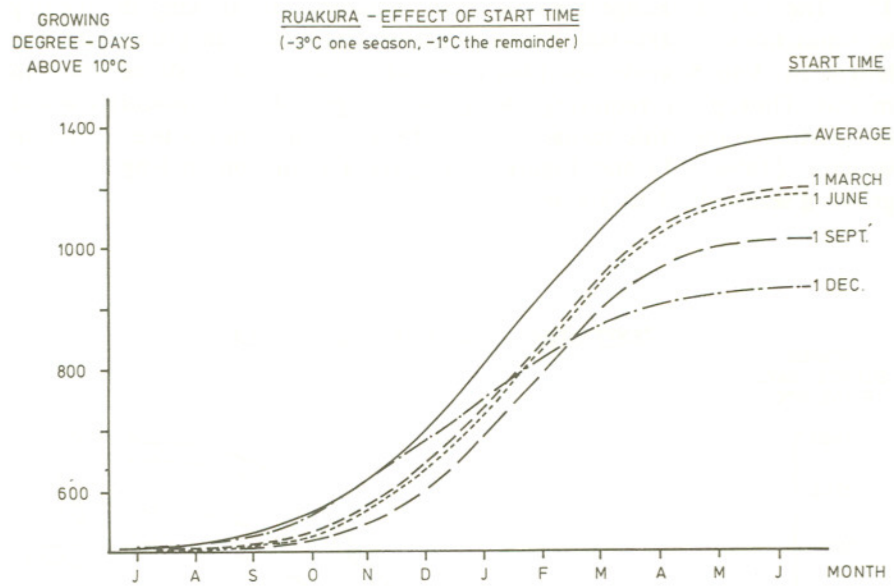


Figure 4.12 Effect of different temperature reduction initiation times at Ruakara, New Zealand, on growing degree-days above 10°C. From Salinger, 1985

Grassland production responds to mean temperature changes, but it is probably not subject to frost damage. Yield reductions can be directly estimated from the results seen from the SPUR grassland model simulations, reported in Chapter 2. The results suggest a reduction in production of $C_4$ grasses by about 7% per degree decrease in temperature over the range of 0°C–6°C and about a 3% per degree reduction for $C_3$ grasses. However, in drylands precipitation would also be a significant factor. Lower temperatures and reduced pasture yield would limit livestock carrying capacity. At the present, the summer excess in pasture production is harvested and stored for winter feed (Levy, 1970). This could be lost for at least one season following climatic perturbations from a nuclear war, leading to moderate-to-severe winter livestock feeding problems. Cold stress on newborn lambs, exacerbated by food shortages, could reduce animal numbers.

Effects on New Zealand cropping and horticultural activities are illustrated by growing degree-day reductions for two scenarios calculated by Salinger (1985). In the greater temperature reduction scenario (reductions of 3°C in spring, and 1°C for other seasons), thermal time accumulations would decline by 200 to 470 growing degree-days (Figure 4.12 and Table 4.14). Crops requiring 1000 growing degree-days or more would be unable to reach maturity in much of the North Island, areas where they currently

TABLE 4.14

EFFECT ON GROWING SEASON LENGTH AND
GROWING DEGREE-DAYS OF CHRONIC SCENARIO

| | Growing Degree-Days(GDD) Above 10°C | | Reduction in Growing Season Length (Days) | |
|---|---|---|---|---|
| | Normal | Perturbed[a] | 1000 GDD[b] | 700 GDD[c] |
| North Island[d] | | | | |
| Kerikeri | 1441 | 970 | ••[e] | 25 |
| Tauranga | 1215 | 796 | •• | 27 |
| Ruakura | 1003 | 630 | •• | •• |
| New Plymouth | 916 | 604 | •• | •• |
| Gisborne | 1183 | 786 | •• | 27 |
| Havelock North | 969 | 621 | •• | •• |
| Waingawa | 917 | 691 | •• | •• |
| Palmerston North | 929 | 564 | •• | •• |
| Levin | 907 | 539 | •• | •• |
| South Island | | | | |
| Appleby | 865 | 530 | •• | •• |
| Christchurch Airport | 781 | 495 | •• | •• |
| Blenheim | 1066 | 825 | •• | 17 |
| Ashburton | 714 | 439 | •• | •• |
| Oamaru | 569 | 319 | •• | •• |
| Earnscleugh | 644 | 399 | •• | •• |
| Roxburgh | 677 | 408 | •• | •• |
| Otautau | 381 | 177 | •• | •• |

[a] Scenario 1 includes a 3°C reduction in average temperature during the spring, 1°C reduction for all other seasons.

[b] Reduction in length of growing season for the time period in which 1000 GDD crops are normally grown.

[c] Reduction in length of growing season for the time period in which 700 GDD crops are normally grown.

[d] Locations aranged in order of increasing latitude from north to south.

[e] •• indicates that the crop would be unable to reach maturity under the chronic perturbation because of insufficient GDD.

can mature. For crops requiring only 700 growing degree-days, as is the case for many cereals, maturation would be from 4 to 6 weeks later, and in the south, crops would be unable to reach maturity. In the case of a less severe reduction of 1°C for 12 months, growing season reductions by 2–4 weeks would cause delayed maturation of crops, and some heat-demanding crops would not reach maturity in northern New Zealand. Other considerations are important for cereal crops. Wheat is the main crop grown in the South Island. Frosts during emergence, low temperatures delaying germination, shortening of the growing season, and low temperatures during grain formation all cause severe problems for the production of wheat (and other cereals), with growing season drops of 2°C or more.

Because of the dominant contribution of grasslands, food production in New Zealand could drop by around 20 to 50%, depending on the severity of temperature drop and frost occurrence in New Zealand (with similar declines probable in Tasmania). Since New Zealand agriculture presently supports over twice its population, it would continue to be able to support its present population through the first and subsequent years with such reductions. However, critical to continuing effects would be the length of the chronic phase, an aspect which is of great importance to all the Southern Hemisphere extra-tropical agricultural systems.

## 4.6 POTENTIAL EFFECTS ON AGRICULTURE OF ALTERATIONS IN HUMAN SUBSIDIES

### 4.6.1 Introduction

Many agricultural production systems could be altered dramatically or even eliminated for a period of several years following a nuclear war. Possible climatic stresses, the direct effects of nuclear weapon detonations, and the disruption of economic and societal systems would be some of the principal problems in the first post-nuclear war year. In subsequent years, redevelopment of agricultural production in combatant countries, and adjustment of production levels in non-combatant countries, could continue to be affected by climatic disturbances. In addition, agricultrual production could be affected in varying levels of intensity by a reduction of the technological and energy subsdies that could be delivered. Impairment of most of the industrial and transportation systems of major exporting countries, as well as fundamental alterations of the current international economic structure, would likely leave the survivors of a nuclear war with destabilized food production capabilities. The climatic disturbances could cause significant decreases in world-wide agricultural yields, but even with no climatic perturbations, technological simplification and reduced fossil fuel subsidies would lower production levels. The vulnerability of agricultural productivity to technological simplification and reduction of energy subsidies of agriculture is considered in this section as *independent* of any potential climatic stresses.

Agricultural production technologies that depend on high energy inputs are characteristic of developed nations such as Canada, United Kingdom, Australia, and U.S.S.R. In the U.S. about 6% of total energy in the economy is used for food production, about 6% for processing and packaging, and 5% for distribution and preparation. This represents 17% of total U.S. energy, or about 1500 liters (400 gals) of fuel per person annually.

Other agricultural systems, particularly in developing countries, are not nearly so dependent on high energy subsidies for production. On an areal comparison basis, they are not as productive, but their lowered reliance on largely imported subsidies in the form of direct energy inputs, and indirect inputs through manufacture of machinery, fertilizers, and pesticides, renders them less susceptible to large alterations in levels of productivity in the context of post-nuclear war pertubations.

Petroleum refineries, ports, railroad facilities, and oil fields could all be severely damaged in major nuclear war. This destruction would not only impair agricultural production in combatant countries, but also in developing countries that depend on energy imports. In addition to crop production, industrial fishing fleets, food transportation and storage capability, and timber harvesting would be severely affected by the destruction associated with nuclear war. Refrigeration of food could be a limiting factor in combatant countries and countries highly dependent on energy imports.

It is through examination of the various levels and types of subsidies that an interpretation can be made of the relative vulnerabilities of agricultural production systems and crops to the types of disturbances that could be experienced in the aftermath of a large-scale nuclear war.

### 4.6.2 Fossil Fuel Energy Subsidies of Agricultural Production

The new technologies that have been adopted by agriculture during the last century depend primarily upon fossil energy subsidies. Examination of potential effects of massive alterations in agricultural production systems from the effects of a major nuclear war should focus on how these energy inputs affect current agriculture and, therefore, how vulnerable the system is to disruption of that process.

Direct fossil fuel use and indirect energy subsidies, such as through the production and transportation of fertilizers and pesticides, in particular, are strongly related to the increased agricultural yields experienced during the past 45 years. In developed countries, yields have increased 3- to 4-fold since 1940 and have increased about 2-fold in developing countries.

One of the obvious areas for possible severe disruption in a post-nuclear war agricultural production system would be in the supply of fossil fuel products. These are used currently, in a direct form, to run and lubricate the machinery which aids in the planting, cultivation, and harvesting to produce crops on a large scale. The amount of diesel fuel currently consumed per hectare in raising grain crops in developed countries is approximately 100 liters $ha^{-1}$ (Pimentel, 1985). During the past two decades, liquid fuel inputs have declined somewhat as larger, more energy efficient farm machinery came into use.

In combatant countries, once local centers of supply became depleted, it could be difficult to obtain fuel for agricultural purposes. In non-combatant regions, supplies of fuel which were traditionally imported from the combatant regions would be imperiled; where supplies originated from within a region not directly affected on a large scale by nuclear detonations, availability would be dependent on a number of factors external to the actual agricultural system.

Direct energy subsidies to agricultural production in the form of fuel for use in agricultural machinery are relatively easy to trace. In contrast, the indirect energy subsidies to agricultural production are less visible; they are, however, key factors in the production levels of agriculture which allow the support of the current world population. The energy-intensive agriculture of developed countries is particularly vulnerable to reductions in the level of subsidies available following a nuclear war. Combatant countries suffering direct destruction, as well as other countries dependent on imports from them, would be affected. Widespread yield declines are possible, independent of any potential climatic effects. A detailed analysis of each country or region is required to describe the specific responses and redevelopment potentials (see Chapters 5 and 7).

Though direct fuel inputs to farming in developed countries have fallen somewhat in the last years, fossil enery inputs for farm machinery construction have risen as larger farm equipment is used. Large farm equipment can till, plant, and harvest more efficiently and over larger areas than small equipment. One area of vulnerability for redeveloping agricultural systems would be the continuing availability of equipment and replacement parts, which would be dependent on the availability of energy for use in manufacture and repair, among many other considerations.

The use of fertilizers in crop production is extremely important in determining the levels of productivity in regions to high energy subsidy of agriculture, i.e., largely the developed countries. For example, in 1983, nitrogen application rates for maize grown in the U.S. had reached a high of 152 kg $ha^{-1}$, typical of developed countries (Table 4.15). Application rates of phosphorus, potassium, and lime were also high, but these inputs do not require as much fossil energy in production as nitrogen. Wheat and rice production also received relatively heavy applications of fertilizers.

TABLE 4.15

ENERGY INPUTS IN U.S. MAIZE PRODUCTION IN 1983[a]

| INPUTS | QUANTITY HA$^{-1}$ | KCAL HA$^{-1}$ |
|---|---|---|
| Labor | 9.88 hr | -------- |
| Machinery | 56.1 kg | 1,025,781 |
| Fuel | 112.3 liters | 1,264,798 |
| Manure | 1.12 ton | -------- |
| Nitrogen | 151.6 kg | 3,216,770 |
| Phosphorus | 75.2 kg | 475,544 |
| Potassium | 95.4 kg | 241,506 |
| Lime | 426.6 kg | 134,447 |
| Seeds | 21.3 | 522,850 |
| Insecticides | 2.8 kg | 301,261 |
| Herbicides | 7.9 kg | 806,682 |
| Irrigation | -------- | 2,265,682 |
| Drying | 3332.3 kg | 664,766 |
| Electricity | 99,590 kcal | 99,590 |
| Transport | 323.3 kg | 89,631 |
| TOTAL | | 11,109,308 |
| OUTPUTS | | |
| Corn Yield | 6,539 kg | 26,207,214 |
| KCAL OUTPUT/KCAL INPUT = 2.36 | | |

[a] Data from Pimentel (1985).

About 10% of the total energy employed in developed nations' maize production is involved in the use of pesticides (Table 4.15), with slightly lower proportions of pesticides used in wheat and rice production; in all cases, herbicides dominate the pesticide inputs. When maize is harvested as grain directly, it contains 25% to 30% moisture. The maize must be dried and cannot contain more than 13% to 15% moisture before being placed in storage. About $0.7 \times 10^6$ kcal of energy is required to dry 6,500 kg of maize (Table 4.15). Harvesting maize as cobs and then drying it in maize cribs by wind or solar energy has been calculated to use 33% less fossil energy than harvesting the maize as grain and drying it using fossil energy (Hudson, 1984).

There has been a steady increase in the application of irrigation water for maize and other grain production in developed countries. The quantity of water used is now slightly more than $2.2 \times 10^6$ liters per hectare and requires an energy input of $2.3 \times 10^6$ kcal for pumping. During 1945, less than 1% of the maize area was irrigated; now an estimated 18% is irrigated (Table

4.15). Rice production often requires a significant fuel input for moving water. Gravity-fed irrigation systems require less energy for pumping, but do use energy inputs for construction and maintenance.

Although argicultural systems in many developing countries are relatively low levels of indirect fossil fuel subsidies, major production systems of developing countries currently have high input levels. In China, for example, the level of fertilizer application per hectare exceeds the average for developed countries (FAO, 1982). For Indian paddy rice production, more energy can be used in one season for nitrogen fertilizer ($2.0 \times 10^6$ kcal $ha^{-1}$) than for human labor and bullock power combined ($0.95 \times 10^6$ kcal $ha^{-1}$) (Hameed and Parimanam, 1983).

Rice production in developing countries is often based on energy-intensive inputs, particularly of N-fertilizer, resulting in a doubling of yield since 1950 (Figure 4.13). There is an approximately linear relationship between crop yields and energy (fertilizer) inputs (Greenwood, 1981; Schlichter et

TABLE 4.16

ENERGY INPUTS FOR RICE PRODUCTION IN DAWA COUNTY LIAONING PROVINCE, CHINA[a]

| INPUTS | QUANTITY $HA^{-1}$ | KCAL $HA^{-1}$ |
|---|---|---|
| Labor | 3,045 hr | -------- |
| Horses | 332 hr | 1,517,173 |
| Tools | 4.50 kg | 93,204 |
| Machinery | 14.6 kg | 263,160 |
| Diesel | 72.9 liters | 832,195 |
| Electricity | 122 kw hr | 348,914 |
| Nitrogen | 191 kg | 2,292,600 |
| Phosphorus | 96.7 kg | 290,190 |
| Insecticides | 0.90 kg | 78,219 |
| Herbicides | 1.88 kg | 187,831 |
| Seeds | 164 kg | 482,800 |
| Irrigation | 184 cm | 1,170,013 |
| Transportation | 81.1 kg | 720,840 |
| TOTAL | | 7,577,139 |
| OUTPUTS | | |
| Rice Yield | 8,094 kg | 23,906,477 |
| KCAL OUTPUT/KCAL INPUT = 3.16 | | |

[a] Annual average for 1979-1981; data from Wen Dazong and Pimentel (1984).

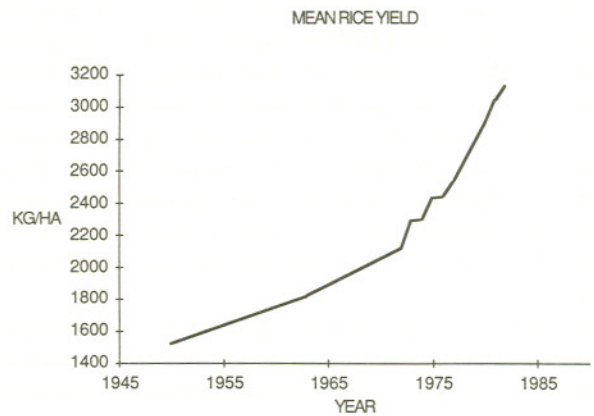


Figure 4.13 Average rice yields (kcal • $ha^{-1}$) for China, India, the Philippines, and Indonesia. Data from FAO Production Yearbooks, 1950–1983

al., 1985), particularly for low- to intermediate-subsidy levels. Almost one-third of the total world fertilizer consumption occurs in developing countries (Greenwood, 1981). In Central American agriculture, fertilizer inputs account for more than 50% of the energy subsidies, and essentially all of the inorganic fertilizers, pesticides, farm machinery and fuels are imported (Schlichter et al., 1985).

Loss of nitrogen fertilizer would not be immediately catastrophic in areas with fertile soils or a long history of prior fertilization. Simulations of wheat production in the U.K under post-nuclear war climatic alteration conditions indicate that reduced levels of crop growth and nitrogen mineralization rates are expected with temperatures 5°C–10°C lower than normal; under that circumstance, soil nitrogen supplies would be adequate without additional fertilization (Addiscott and Whitmore, 1985). In general, however, the nutrients supplied by unfertilized soild are a small fraction of the requirements for maximum growth, and most arable soils in the world can supply fewer nutrients than soils in the United Kingdom (Greenwood, 1981).

In sum, the current productivity levels of agricultural systems worldwide are heavily dependent on the use of indirect sources of energy, particularly through application of fertilizers and pesticides. Disruption or cessation of such subsidies would force a fundamental alteration in the methodologies of agriculture and the resultant outputs.

### 4.6.3 Human and Animal Labor Inputs to Production

The use of engine power has made tremendous differences in developed societies as well as elsewhere in the world. This can be illustrated by analyzing the human labor equivalent present in a gallon of fuel. One gallon (3.79 liters) of fuel fed to a small gasoline engine will provide 20% of the heat energy produced in the form of mechanical energy. Thus, from about 31,000 kcal in a gallon of fuel, about 6200 kcal of mechanical energy can be produced. This is the equivalent of about 10 horse power-hours or 100 human power-hours of power (Pimentel and Pimentel, 1979). Thus, 1 gal of gasoline can provide about 2.5 weeks of human power equivalents. This is part of the reason for the dramatic reductions in labor inputs that have occurred in agricultural production in industrialized nations (Pimentel and Wen Dazong, 1985).

With the current heavy mechanization of agriculture in developed countries, the labor input in maize production is about 10 hr per hectare (Table 4.15). This is less than 1% of the input required to produce maize by hand (Pimentel, 1985); however, this does not take into account all the indirect labor inputs that go into agricultural production. If these are taken into consideration, then, for example, current U.S. maize production uses about 2% of the labor input for hand-grown maize. This is still a dramatic reduction in total amount of labor required to produce maize compared with producing maize by hand.

In most industrialized nations today, insufficient human labor exists to subsitute for the tractor power that is present on farms. Even if the human labor were available, this labor is inexperienced in crop agriculture. The most productive agricultural systems would be most vulnerable to the disruptions and energy input losses expected after a nuclear war.

In some countries like China and India, both draft animals and small tractors supplement human labor, though the labor input in these systems is still quite high, ranging from 700 to 1252 hr $ha^{-1}$, which is similar to some hand-produced maize systems (Pimentel and Pimentel, 1979). Rice is an example of an often labor-intensive agricultural system (e.g., 3,045 hrs $ha^{-1}$ in Liaoning Province, China).

Although most food crops in the world are produced using tractor or draft animal power, a significant quantity of food crops (estimated to be 10%–15%) are produced using only humanpower. Over 90% of the global agricultural labor force is in developing countries (Figure 4.14)(FAO, 1982). The hand labor required to produce a hectare of maize, wheat, and rice crops by hand is approximately 1200 hrs of labor per hectare (Pimentel and Pimentel, 1979). About one-third of the labor is required to till the soil for planting, and about half of the labor is for weeding. The remaining 17–20% is for harvesting. Overall, about 100- to 120-fold more labor is required to produce a grain crop by hand than using heavy mechanization.

The technological and fossil fuel inputs used in hand-powered agriculture are usually a small fraction of the total energy inputs (Tables 4.17, 4.18). Although fertilizer and other subsidies are sometimes used in these systems,

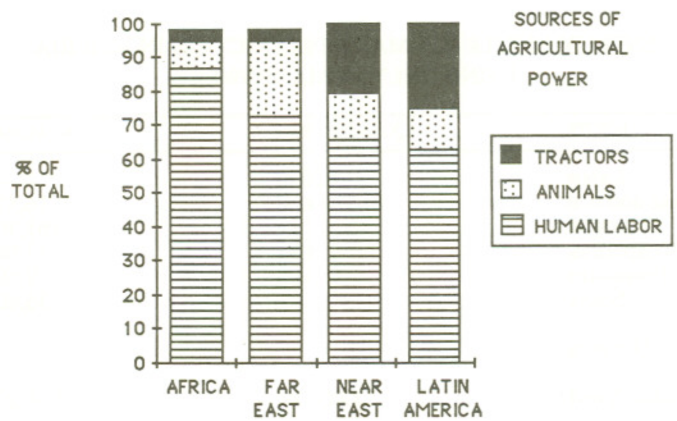


Figure 4.14 Sources of agricultural power (tractors, animals, and human labor). Data from FAO, 1982a

TABLE 4.17

ENERGY INPUTS FOR RICE PRODUCTION BY THE IBAN OF BORNEO USING ONLY HUMANPOWER[a]

| INPUTS | QUANTITY $HA^{-1}$ | KCAL $HA^{-1}$ |
|---|---|---|
| Labor | 1,186 hr | ------- |
| Axe and hoe | 16,570 kcal | 16,570 |
| Seeds | 108 kg | 392,040 |
| TOTAL | | 408,610 |
| OUTPUTS | | |
| Rice Yield | 2,016 kg | 7,318,080 |
| KCAL OUTPUT/KCAL INPUT = 17.91 | | |

[a] Data from Pimentel and Pimentel (1979).

TABLE 4.18

ENERGY INPUTS FOR MAIZE PRODUCTION IN NIGERIA
USING ONLY HUMANPOWER[a]

| INPUTS | QUANTITY HA$^{-1}$ | KCAL HA$^{-1}$ |
|---|---|---|
| Labor | 620 hr | ------- |
| Axe and hoe | 16,570 kcal | 16,570 |
| Nitrogen | 11 kg | 161,700 |
| Phosphorus | 4 kg | 12,000 |
| Potassium | 6 kg | 9,600 |
| Seeds | 10.4 kg | 36,608 |
| OUTPUTS | | |
| Corn Yield | 1,004 kg | 3,564,200 |
| KCAL OUTPUT/KCAL INPUT = 15.07 | | |

[a] Data from Pimentel and Pimentel (1979).

the quantities are minimal and relatively little yield reduction would occur if these were removed.

### 4.6.4 Veterinary Subsidies

Many countries rely on imported veterinary expertise and supplies or imported feedstocks for domestic production of medicines. The direct effects of a nuclear war, and the associated disruptions in societal systems and the physical environment, could be expected to reduce severely the supplies and availability of critical veterinary support.

As an example of the potential vulnerability of loss of veterinary support, consider the case in Africa of rinderpest, a potentially devastating disease of livestock. This disease is currently under substantial control through the institution of an intensive inoculation program (McNaughton, 1985). However, prior to the use of attenuated-virus inoculations in the extensive program initiated in mid-1960s, rinderpest virtually eliminated pastoral agriculture throughout the Serengeti plains. Rinderpest continues to remain endemic in many wild animal species of the Serengeti (McNaughton, 1985), and there thus remains a serious vulnerability to large-scale losses from this disease in the instance of loss of veterinary support.

It seems highly likely that many other diseases that currently are well controlled by intensive veterinary regimes also offer high vulnerability to loss of such support.

### 4.6.5 Conclusions

Considerable quantitative and qualitative changes in energy dependence have evolved over the period of modern agricultural development. Clearly, without the technological inputs of diesel and gasoline fuel, fertilizers, pesticides, and hybrid seed, agriculture in both developed and developing countries would be severely altered. Technologies in developed countries would suffer disproportionately more because they are more sophisticated and are more heavily dependent on fossil fuels than the technologies in developing countries. In developed countries, about 1000 liters of oil equivalents are used to raise one hectare of food, whereas in a developing country employing primarily hand labor, only about 10 liters of fuel per hectare are used. Labor inputs for grain production in developed countries average about 10 hours $ha^{-1}$, but in developing countries it often averages 1200 hours $ha^{-1}$ for hand-produced grain.

Considering *only* the perturbations of the disruption or severing of supplies of fuel and fuel-based agricultural subsidies, it is clear that agricultural systems in countries that currently experience high levels of energy inputs would be extremely vulnerable to such perturbations. Their adaptability over the long run would be variable in different situations and would depend on many factors, including the suitability of the soil type to different types of crops and different methods of cultivation, the availability of different types of seeds in response to altered agricultural methodologies, and the availability and efficacy of draft animal and human labor to replace machines and methodologies when there would not be adequate energy inputs to maintain prior production activities.

In areas of the world that would not have their supplies and sources of energy destroyed or severely impaired, agricultural production could continue to be subsidized by fuel and fuel-produced applications. In those regions that are not now heavily dependent on high energy subsidies, agricultural practices could revert to prior methodologies, though with a concomitant lowering of productivity. It seems clear that both of the latter areas would be less vulnerable to the loss of human subsidies to agriculture than would energy-intensive combatant countries.

## APPENDIX

### Model Descriptions

### 4A.1 Canadian Wheat and Barley Model

The model used to analyze the effects on yields of wheat and barley in Canada was developed initially by FAO (1978) and later modified by Stewart

(1981) for Canadian conditions; it is currently implemented at Agriculture Canada under the guidance of R.B. Stewart. This model is based on the de Wit (1965) methodology for estimating net biomass production under optimum management practices. Input data include monthly averages of temperatures, precipitation, solar insolation, wind speed, and vapor pressure. A photosynthesis equation describes constraint-free yields, i.e., yields under optimal conditions, with a sigmoidal cumulative growth curve incremented up to the number of days required for the crop to mature. Net biomass production is calculated by taking into account the gross biomass production capacity of the crop as influenced by this temperature- and insolation-dependent photosynthesis term, subtracting the respiration losses resulting from another temperature-dependent function. This relationship is:

$$B_{\mathrm{n}} = 0.36 B_{\mathrm{gm}} (1/N + 0.25 C_{\mathrm{T}})^{-1} \tag{4A.1}$$

where:

$B_{\mathrm{n}}$ = net biomass production
$B_{\mathrm{gm}}$ = gross biomass production
$N$ = number of days required for the crop to mature
$C_{\mathrm{T}}$ = maintenance respiration coefficient

The value for $N$ was based on the biometeorological time scale (Robertson, 1968), and $C_{\mathrm{T}}$ follows an expression developed by McCree (1974). Crop dry matter yield is then derived as:

$$B_{\mathrm{y}} = B_{\mathrm{n}} H_{\mathrm{i}} \tag{4A.2}$$

where:

$B_{\mathrm{y}}$ = crop dry matter yield
$H_{\mathrm{i}}$ = harvest index.

The harvest index is defined as that fraction of the net biomass production that is economically useful. Here $H_{\mathrm{i}}$ is based on Major and Hamman (1981), who calculated the index for Neepawa wheat at a location in Alberta, Canada. They found that $H_{\mathrm{i}}$ is inversely related to moisture availability, such that under moisture-limiting conditions, a greater percentage of the biomass is converted into yield than under moist conditions. In the current simulations, the moisture stress was indicated by the ratio of actual evapotranspiration to potential evapotranspiration (AET/PET) (calculated as outlined in Stewart, 1981), and the value for $H_{\mathrm{i}}$ was set as follows:

If (AET/PET) $\geq$ 0.75, then $H_{\mathrm{i}}$ = 0.35; if (AET/PET) $\leq$ 0.36, then $H_{\mathrm{i}}$ = 0.52; for (AET/PET) between the two limits, a linear interpolation of $H_{\mathrm{i}}$ was done between 0.35 and 0.52.

Values of $B_y$ computed by equation 4A.2 are for constraint-free (i.e., genetic potential) yields, neglecting the effects of physical stresses, presence of weeds or pests, field condition, etc. For this study, correction was made for a moisture-stress yield reduction factor:

$$B_{ye} = B_y \mathrm{MSF} \tag{4A.3}$$

where:

$B_{ye}$ = estimated dry matter biomass corrected for moisture stress
MSF = moisture stress factor.

This factor was derived using an expression relating the relative yield decreases to relative evapotranspiration deficit as:

$$Y_a = Y_p(1 - K_y(1 - \mathrm{AET/PET})) = Y_p \mathrm{MSF} \tag{4A.4}$$

where:

$Y_a$ = actual yield
$Y_p$ = potential yield
$K_y$ = empirically derived crop yield response factor to moisture deficits = 1.10 (based on Doorenbos and Kassram, 1979).

The planting date is defined as the date at which the mean minimum temperature exceeds 5°C, representing the average date (50% probability) for the last spring killing frost calculated by the technique of Sly and Coligado (1974) from the 30-yr climatic normals data (Atmospheric Environment Service, 1982). After the planting date, the biometeorological time scale of Robertson (1968) was used to estimate the length of time required to reach maturity based on minimum and maximum air temperatures and daylength.

The climatic data were based on the record for 1951–1980, computed as monthly averages for the crop districts of three western provinces, using the procedure of Stewart (1981). Daily information for all climatic parameters except precipitation were generated from these monthly data by the technique of Brooks (1943). Precipitation data were converted to weekly averages, distributed as 60%, 30%, and 10%, respectively, for the first three days of the week, with none thereafter.

The model was validated against the data of Major and Hamman (1981) and Onofrei (pers. comm.) for seven locations in Manitoba and Alberta;

predicted results were generally within 15% of actual yields. It should be reemphasized that the model results are for optimal conditions, not for those conditions actually experienced commercially; therefore, the results are normalized to the average yields reported for 1961–1980.

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