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CIRRPC

Science Panel Report No. 5

REVIEW OF SCOPE 28 REPORT ON ENVIRONMENTAL CONSEQUENCES OF NUCLEAR WAR: VOLUME II, ECOLOGICAL AND AGRICULTURAL EFFECTS

March 1988

Committee on Interagency Radiation
Research and Policy Coordination

Office of Science and Technology Policy
Executive Office of the President
Washington, D.C. 20506

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NOTICES

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**Departments of Agriculture, Commerce, Defense, Energy, Health and Human Services, Housing and Urban Development, Interior, Justice, Labor, State, and Transportation; Environmental Protection Agency; Federal Emergency Management Agency; National Aeronautics and Space Administration; Nuclear Regulatory Commission; Office of Management and Budget; Veterans Administration; and the National Security Council.*

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EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20506

March 16, 1988

Dear Dr. Bentley:

I am pleased to transmit to the U.S. Department of Agriculture (USDA) the enclosed report "Review of SCOPE 28 Report on Environmental Consequences of Nuclear War: Volume II, Ecological and Agricultural Effects," prepared by an ad hoc panel of agricultural experts formed by the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC) and USDA. The panel was charged with reviewing and evaluating the conclusions reached in SCOPE 28, Volume II and, in particular, the assumptions and models used to reach those conclusions. The ad hoc panel did not evaluate the validity of data used in the models. Indeed, recently these data were acknowledged as faulty and have been modified. The panel did conclude that the methodology was sound. However, this does not mean that the conclusions in Scope 28 were endorsed.

The panel believes that several important factors were not adequately treated and should have received additional emphasis. Among these are the loss of large areas of irrigated agricultural land due to destruction of dams, the severe disruption of production, processing, and distribution caused by destruction of the complex infrastructure needed for the U.S. food and agricultural system, and the accurate response of major crops to a wide range of temperature and solar radiation. Given the large uncertainties in the physical hypothetical parameters affecting these studies and the significant changes in the SCOPE 28, Volume I source terms, updates will be needed to keep abreast of new developments.

Sincerely,

William R. Graham

William R. Graham
Science Advisor to the President

Dr. Orville G. Bentley
Assistant Secretary for Science and Education
U.S. Department of Agriculture
Administration Building, Room 217W
14th Street & Independence Ave., S.W.
Washington, D.C. 20250

COMMITTEE ON INTERAGENCY RADIATION RESEARCH
AND POLICY COORDINATION
1019 Nineteenth Street, NW, Suite 700
Washington, D.C. 20036

February 9, 1988

Dr. William R. Graham
Science Advisor to the President
Office of Science and Technology Policy
Executive Office of the President
Old Executive Office Building
Washington, DC 20506

Dear Dr. Graham:

Enclosed is the Committee on Interagency Radiation Research and Policy Coordination's (CIRRPC) Science Panel report entitled "Review of SCOPE 28 Report on Environmental Consequences of Nuclear War: Volume II, Ecological and Agricultural Effects." The review was conducted by an ad hoc panel of agricultural scientists formed through the coordinated efforts of CIRRPC and the U. S. Department of Agriculture (USDA). Dr. William H. Tallent, Assistant Administrator, Agriculture Research Service, USDA, served as Chairman of the ad hoc panel. The main charge to the panel was to review and evaluate the overall conclusions reached in SCOPE 28, Volume II, and, in particular, the assumptions and models used to predict the consequent effects on agriculture of "a large nuclear exchange."

The CIRRPC report has been reviewed by member agencies and it reflects their comments and suggestions. No substantive issues needing resolution were identified during CIRRPC's review of the panel's report. Therefore, as Chairman of CIRRPC, I am pleased to transmit the report. I believe the report will be an important contribution to the literature on this subject.

Sincerely,

Alvin L. Young

Alvin L. Young, Ph.D.
Chairman, CIRRPC

ALY/tc
Enclosure

COMMITTEE ON INTERAGENCY RADIATION RESEARCH
AND POLICY COORDINATION
1019 Nineteenth Street, NW, Suite 700
Washington, D.C. 20036

November 9, 1987

Dr. Alvin L. Young
Senior Policy Analyst for Life Sciences
Office of Science and Technology Policy
Executive Office of the President
Room 5005
New Executive Office Building
Washington, D.C. 20506

Dear Dr. Young:

I am pleased to provide the report of the ad hoc panel established by the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC) to review Volume II, Ecological and Agricultural Effects, of the SCOPE 28 report on Environmental Consequences of Nuclear War.

In its review, the panel focused its major attention on the effects of a large nuclear exchange on agriculture. The climatic perturbations described in SCOPE 28, Volume I, Physical and Atmospheric Effects, provided the general basis of the scenarios of cooling temperatures and solar insolation considered in Volume II and, thus, the panel's review. Simulation studies, using crop growth models for corn and soybean, were conducted by the panel and the findings compared to those described in SCOPE 28, Volume II.

The panel is in general agreement with the conclusions contained in the SCOPE 28 report that crops growing in the mid-latitudes of the Northern Hemisphere could be totally destroyed or production severely reduced for at least the first growing season after a nuclear exchange, if the resulting atmospheric perturbation were to cause temperature decreases on the order of 5 to 15°C for even short periods of time. However, the panel believes that several important factors were not adequately treated and should have received additional emphasis. Especially noteworthy are the loss of large areas of irrigated agricultural land due to destruction of dams, severe disruption of production, processing, and distribution caused by destruction of the complex infrastructure so necessary for the U.S. food and agricultural system.

To address gaps in our knowledge and other concerns, the panel recommends that comprehensive studies be designed to determine accurately the response of major crops to a wide range of temperature and solar radiation reductions and that the entire agricultural infrastructure be studied and modeled as to its response to a nuclear exchange.

On behalf of my colleagues and myself, we wish to thank you and CIRRPC for this opportunity to examine this important issue. Let me also express my personal thanks to the other panel members for their dedication and interest in completing this task.

Sincerely,

W H Tallent

William H. Tallent
Chairman
CIRRPC Ad Hoc Review Group for
SCOPE 28: Volume II

WHT:dcd
Enclosure

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Review of SCOPE 28 Report on Environmental Consequences of Nuclear War: Volume II, Ecological and Agricultural Effects

EXECUTIVE SUMMARY

The Scientific Committee on Problems of the Environment (SCOPE), a part of the International Council of Scientific Unions (ICSU), released a two volume report, The Environmental Consequences of Nuclear War, in September 1985 (SCOPE 28, 1985). Since this was number 28 in a series of reports issued by the Committee, it is commonly referred to as the SCOPE 28 Report. Volume I of the report concentrated on physical and atmospheric effects, whereas Volume II examined ecological and agricultural effects. A basic conclusion of Volume I was that a major nuclear exchange would inject huge amounts of smoke and dust into the atmosphere causing a reduction in the amount of solar radiation reaching the earth's surface. This would, in turn, cause a serious reduction in atmospheric and land surface temperatures. These effects can be divided into an "acute" phase involving a drastic reduction in light and temperature, lasting for days to weeks, and a "chronic" phase with slowly clearing skies and gradual recovery of warmth, lasting for a year or longer.

With the climatic changes predicted in Volume I, the authors of Volume II stated that essentially all agricultural production in the Northern Hemisphere would be lost in the first growing season after a war. Survivors would be forced to rely on stored food, but few countries would have enough stored food to last beyond a few weeks or months. Under these circumstances, the indirect effects of nuclear war could be far worse than the direct effects.

The agricultural implications of the SCOPE 28 report were sufficiently serious that an independent evaluation of Volume II was deemed imperative. Accordingly, through the coordinated efforts of the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC), a committee of the Federal Coordinating Council for Science, Engineering, and Technology, Office of Science Technology and Policy, and the U.S. Department of Agriculture (USDA), an ad hoc panel of agricultural scientists was formed and charged to conduct this review and evaluation (Appendix A). The charge to the panel was to review Volume II, which is based on the scenario described in Volume I; that is, a 6,000-megaton, 12,000-warhead exchange occurred, striking the targets described in Volume I, with the amount of smoke and dust generated and lofted into the atmosphere consistent with the magnitude of the exchange. The major emphasis of the review was to be the evaluation of the assumptions and models used to predict the consequent effects on agriculture and the conclusions reached in SCOPE 28, Volume II.

An adequate review of Volume II could not be accomplished without considering its connection to Volume I. Therefore, the panel examined this relationship, followed by a review of the three major parts of Volume II, i.e., Ecological Effects, Agricultural Effects, and Human Effects. The remainder of this summary outlines the observations and conclusions of the ad hoc review. Throughout this summary, reference to "panel" will mean the ad hoc panel assigned to review Volume II, not the authors of SCOPE 28.

Relationship of Volume I to Volume II

Volume I deals with the global atmospheric circulation problems which would follow a large number of nuclear explosions. The panel believes that Volume I's assessments of the atmospheric perturbations resulting from a major nuclear war leave room for uncertainties. These uncertainties are due not necessarily to inadequate war scenarios, but to limited knowledge of the atmospheric processes and inadequate physical-mathematical models of the global atmospheric circulation. This matter is discussed in greater detail in Appendix B.

Nonetheless, the wide range of possible catastrophes in life support systems resulting from a nuclear war, as discussed in Volume II, clearly establishes the vulnerability of agricultural and food-supply systems. For this reason, the panel believes that Volume II merits serious examination despite the great uncertainties about the long-range climatic effects of a major nuclear war, such as are advanced in Volume I.

Ecological Effects

Part I of Volume II is essentially a detailed review and evaluation of the scientific literature concerning the response of plants and animals to low temperatures, low light intensities, and other stresses anticipated to follow a nuclear war. These responses are fundamental to evaluation of predicted effects on agriculture, the panel's main concern. Therefore, the panel reviewed this part from the point of view of the adequacy of the literature from which the SCOPE 28 authors derived their material, and the soundness of their conclusions. Two significant inadequacies are noted: the treatment of potential synergism between the effects of low light and cold temperatures on plants and the interaction between chilling temperatures and drought stress. Noting these exceptions, the panel is in general agreement with the conclusions drawn by the authors of the SCOPE 28 report that low temperatures would be the most harmful post-nuclear climatic change to terrestrial ecosystems and that a spring- or summer-onset heavy frost induced by a nuclear exchange could kill all native and crop species in Northern Hemisphere temperate regions.

Agricultural Effects

Part II of Volume II addresses the potential effects of nuclear war on agricultural productivity. In addition to reviewing this part (Chapter 4) of Volume II of the SCOPE 28 report, the panel conducted simulation studies concerning the combined effects of low temperatures and low light on crop yields using crop growth models that were not available at the time of the SCOPE 28 review. Corn and soybean growth were modeled for several combinations of the time of year that a nuclear exchange occurred and the severity of the resulting reductions of temperature and light. The results of these simulations are given in the main body of the report and further details are provided in Appendix C.

The panel's simulation data and studies of recent literature lead to the following conclusions:

1. Rapid and severe temperature reductions (5-15°C) in the early days after a nuclear exchange, especially if it occurs during the growing season, would eliminate large areas of crop production in much of the Northern Hemisphere temperate zone.
2. Near- or below-freezing temperatures occurring for even short periods of time during the sensitive reproductive stages of crop development could sharply reduce crop yields.
3. Reduced light intensity would lower photosynthetic rates and crop yields because even under natural field conditions most crop canopies do not receive as much light as they can use for maximal photosynthesis.
4. A prolonged decrease in mean temperature would reduce the rate at which plants develop and mature, making them more vulnerable to the occurrence of fall frosts. This would be true even if the length of the growing season were not shortened by the climatic change.

5. Although not specifically simulated by the panel, literature studies show that tropical vegetation is vulnerable to small reductions in temperature. If climatic changes of the magnitude projected in Volume I ensue, serious losses in agricultural productivity could occur in the tropics.

Despite differences in crops and locations studied, the climatic severity imposed, and the timing of the climatic disruption, the results of the panel simulations are consistent with those of SCOPE 28, indicating that crops growing in the temperate zones of the Northern Hemisphere could be totally destroyed or their production severely reduced for at least the first growing season after a nuclear exchange. Subsequent recovery of this lost productivity would depend not only on the rate at which climatic conditions return to normal, but also on the rate at which agricultural infrastructure is redeveloped.

Human Effects (Social and Infrastructural Issues)

Part III of Volume II projects unprecedented destruction and loss of life from direct effects of nuclear war and from massive food shortages that would take even more lives. However, factors not considered in the SCOPE 28 analysis concerning the impact of nuclear war on human populations would be equally as damaging as the factors which were included in the analysis. The SCOPE 28 projections give inadequate consideration to the fact that modern agriculture is an extremely complex system which is highly dependent on energy, irrigation water, pesticides, fertilizers, transportation, storage and marketing facilities, and skilled labor and management.

For all practical purposes, agricultural production would cease in developed countries if organized society were to be severely disrupted. Crops cannot be produced without fossil fuels to till the soil, control the pests, harvest the crops, process them for market, and transport them to markets. Furthermore, production cannot exist without a market structure to feed back necessary resources to the farmer. Production may approach zero after a nuclear exchange, even in the absence of climatic perturbations. Thus, the worst case scenario in Volume II may be a gross underestimation of the likely effects of a nuclear war on human populations.

Conclusions

The panel's simulation studies and analysis of recent literature led to conclusions concerning the effect of atmospheric perturbations on crop production that were in general agreement with those of the SCOPE 28 report. The panel's analysis indicated that crops growing in the mid-latitudes of the Northern Hemisphere could be totally destroyed or production severely reduced for at least the first growing season after a nuclear exchange, if the resulting atmospheric perturbations were to cause temperature decreases on the order of 5 to 15°C for even short periods of time.

The panel concluded that there were several factors which were not adequately treated in SCOPE 28, Volume II, and which should receive much more emphasis:

* Animal contributions to human food would be worthless for some period, perhaps decades in some areas, after a nuclear war.

* Radioactive fallout could result in severe contamination of some areas and impair normal farming operations.

* Destruction of dams and disruption of electricity supplies in a nuclear exchange could remove large areas of irrigated agricultural land from production for many years and greatly reduce postwar agricultural productivity.

* Destruction of the complex agricultural infrastructure would likely result in near-zero production independent of the projected climatic perturbations. The synergistic relationship of disruption of societal support systems for agriculture, due to the direct effects of nuclear exchange, and of the possible climatic effects that would follow, would likely result in total elimination of food supplies to a major portion of the survivors of a nuclear exchange.

Recommendations

Although state-of-the-art simulation models were used to evaluate crop response to climatic change, the models were, by necessity, extrapolated beyond their range of validation. The panel recommends that comprehensive studies be designed to determine accurately the response of major crops to a wide range of temperature and solar radiation reductions at varying stages of crop growth.

It is recommended that the entire agricultural infrastructure be studied and modeled as to its response to a nuclear exchange. Such a comprehensive quantitative assessment of agricultural production and food supply can be accomplished only by means of a fully interactive set of appropriate numerical models. Submodels would be required to deal with plant and animal production, ecological and environmental effects, and infrastructural factors such as energy supply, transportation, fertilizer sources, water supplies, skilled labor, markets, and a host of additional factors that affect a society's ability to produce and distribute food.

SECTION I: ECOLOGICAL EFFECTS

Main SCOPE 28 Conclusions

Part I of SCOPE 28, Volume II addresses the effects of a large-scale nuclear war on natural terrestrial and aquatic ecosystems. The report concludes that physiological adaptations do not protect organisms (plants and animals) from climatic extremes far beyond those they normally experience. Plants are more immediately susceptible to rapid changes in weather, but fauna would ultimately be more vulnerable to most stresses.

These conclusions have several repercussions for agriculture and food supplies. First, the principles upon which they are based apply to agricultural as well as native species. Secondly, with few exceptions, modern human populations do not rely on unmanaged ecological sources for food; agricultural productivity damaged by nuclear war could not be replaced by food from unmanaged ecosystems. Thirdly, changes in the ecosystems would impact on the effectiveness of insect and disease control in post-war exchange agriculture.

A. Terrestrial Ecosystems

SCOPE 28 concludes that low temperatures would be the most harmful post-nuclear climatic change to terrestrial ecosystems. The report predicts that a spring- or summer-onset frost of the type described in SCOPE 28 would kill all native and crop species in Northern temperate regions; even plants with the ability to acclimate probably would lack the proper cues to adapt.

Acclimated perennials and dormant seeds of annual plants, on the other hand, are very difficult to kill, so SCOPE 28 considers freeze-induced mortality unlikely during a nuclear war in winter. However, hardening is temporary and reversible. Thus, if temperatures increase after nuclear war, protection against a subsequent freezing event could be lost.

Tropical and subtropical plants lack the genetic capacity to frost-harden; an episode of -1 to -3°C would freeze and kill all aboveground tissue. Even chilling (low-temperature injury without freezing) could cause severe damage in the tropics. Tropical ecosystems which normally experience very slight seasonal fluctuations in temperature, rainfall, light intensity or photoperiod, such as evergreen rain forests in mangrove swamps, would be especially vulnerable and have very little capacity to recover. Seasonal tropical ecosystems (deciduous forests or grassland systems) would be less susceptible to cold during the dry season than at other times because of reduced metabolism and leaf area.

For grasslands and semiarid ecosystems, evapotranspiration may normally exceed precipitation, causing water deficit stress which limits primary productivity. In this case, SCOPE 28 postulates that a moderate decrease (1 to 2°C) in average temperatures could increase potential productivity, if freezing were not involved.

SCOPE 28 suggests that there would likely be little change in photosynthesis during reduced light episodes for plants which were already shade-tolerant. However, since adaptation to lower light levels usually requires a few weeks, plants probably would not have enough time to adapt. Plants already conditioned to slow growth, such as woodland species, would be less severely impacted.

In regard to the effects on fauna, SCOPE 28 concludes that if temperatures drop, homeotherms (animals such as birds and mammals with a constant internal temperature), if not adapted, would suffer more than poikilotherms (animals such as reptiles whose temperatures track those of their environments). Tropical animals would likely perish from cold or from loss of habitat and food. Most of the invertebrates existing in immature stages and virtually all soil organisms could survive nuclear war-induced low temperatures.

The SCOPE 28 authors assert that while temperate-zone animals can adapt to cold or avoid it by behavior, as well as by physiology, timing is critical for survival. Few species would hibernate or migrate in response to low temperatures alone; most would require other environmental cues and several weeks time to acclimate. As with plants, a nuclear war in spring would have the greatest impact, and many animals could starve or freeze.

B. Aquatic Ecosystems

SCOPE 28 concludes that the high specific heat of water would cause propagation of temperature changes to marine and estuarine systems to be delayed and considerably damped, resulting in negligible direct effects. However, changes in ocean currents could change spatial distributions of productivity, making it difficult for human survivors to find relocated fishing grounds.

The study predicts that because of reduction in light penetration due to the dust pall, a flux density of solar radiation sufficient to support photosynthesis in algae might reach a depth of only 10m, as opposed to 110m normally. Below this shallower depth (the light compensation point) many phytoplankton would die, though some species could adapt metabolically or encyst, thus enabling their survival.

Smaller heterotrophic species with no energy reserves, such as zooplankton, may not survive. Large animals, such as baleen whales, would probably not suffer mass mortality. The fate of medium-size fish is uncertain, but if larval stages are eliminated, species survival depends on the reproductive longevity of the remaining adults. On the other hand, some populations would increase because of the lack of human fishing. Deep or bottom systems would suffer minimal consequences of nuclear war.

SCOPE 28 recognizes that while coastal and estuarine systems have greater productivity and are more important to humans than other marine systems, they are also more vulnerable to cold, pollutants in runoff, and increased atmospheric turbulence after nuclear war. Consequently, there could be some killing of fish and shellfish needed for human food consumption.

The report concludes that although other environmental effects, such as radioactive fallout, could also disrupt natural ecosystems, climatic alterations have the greatest potential for severe, widespread, and unprecedented ecological effects.

Evaluation of SCOPE 28 Conclusions

Overall, SCOPE 28's conclusions as to impacts on terrestrial and aquatic ecosystems appear to be valid.

The panel's major disagreement with the SCOPE 28 report concerns the treatment of interactions between low light and low temperatures. Although the report says light could decrease by 90% for Northern mid-latitudes, it dismisses the significance of this reduction, citing "no known synergism between low light and cold." Such presumptions may be unwarranted in view of recent research which suggests that the combination of low light and chilling may be more harmful than either stress alone. Rose et al. (1986) found that chilling and light levels too low to support photosynthesis caused more damage than was previously reported for plants chilled in normal light. But if freezing temperatures prevail, the report correctly states that light intensity is of little concern.

Similarly, the impact of chilling on temperate zone plants is not adequately treated. Cold-induced water deficits are ignored by the report. Several researchers (Markhart, 1984; Rose et al., 1986; Rosenberg, 1969) have observed that chilled plants show an impaired ability to extract water from the soil. This phenomenon could add another injury to plants in the ecosystem after nuclear exchange.

SECTION II: AGRICULTURAL EFFECTS

Evaluation of SCOPE 28 Conclusions

A. Temperature Effects

SCOPE 28 concludes that in the aftermath of nuclear war a consequential atmospheric chilling will occur. Land surfaces will be cooled sufficiently to seriously disrupt crop production, particularly in the mid-latitudes of the Northern Hemisphere.

The sensitivity of crops to the occurrence of low temperatures at various stages of growth and development is reviewed in Part II, Chapter 4, of Volume II. Crops are classified as having high resistance to frost (e.g., spring wheat, barley), low resistance (e.g., corn, potatoes), and no resistance (e.g., buckwheat, peanuts). The fact that tolerance to low temperatures varies with stage of growth is emphasized. Temperature depressions deemed possible during the first days after a nuclear war are great enough to cause crops to freeze throughout much of the Northern Hemisphere. SCOPE 28 concludes that, even if plants are not killed outright during the early phases of chilling, production is likely to be severely restricted by a shortened growing season caused by the later occurrence of spring frosts and earlier occurrence of fall frosts. Further, the lower temperatures would reduce the rate at which growing degree days (thermal time) accumulate and, hence, the plants are less likely to reach maturity before the time that frosts normally end the growing season.

Review of the plant literature on low temperature effects supports the general conclusions of SCOPE 28, Volume II, if the scenarios of climate change used in this study are themselves realistic. The SCOPE 28 authors made one systematic mistake in their analyses, however. Since the normal mean monthly minimum temperature in June for most locations north of 32° latitude is near or below 15°C, it was assumed that a 15°C temperature drop at that time of year would devastate crops. Covey (1987) points out, however, that a smoke-induced climatic change large enough to cool mid-latitude Northern Hemisphere land areas by 15°C would probably damp the diurnal surface temperature wave considerably. Thus, weather simulation techniques which consider diurnal temperature variation should be used to predict daily maximum and minimum temperatures.

The panel agrees with SCOPE 28 that rapid and severe temperature reductions (5 - 15°C) in the early days after a nuclear exchange, especially if the exchange occurs during the growing season, would eliminate large areas of the Northern Hemisphere temperate zone from crop production. Near or below freezing temperatures, if they occur for even short periods of time during the sensitive reproductive stages of crop development, could sharply reduce crop yields.

A prolonged decrease in mean temperature would reduce the rate at which plants develop and mature, making them more vulnerable to the occurrence of fall frosts. This would be so even if the length of the growing season were not itself shortened by nuclear winter-induced climatic change. Tropical vegetation is vulnerable to even slight reductions in temperature. If such climatic effects as are projected in SCOPE 28, Volume I do occur, serious losses in agricultural productivity could occur in the tropics.

These consequences could be expected, whether the extreme climatic scenarios of Turco et. al. (1983), Covey et. al. (1984), and other early simulations or the less extreme "nuclear autumn" climatic scenarios (e.g., Thompson and Schneider, 1986) are used in the analysis.

B. Light Effects

SCOPE 28, Volume II, Chapter 4 does not deal as thoroughly with the impacts of reduced light intensity as with reduced temperature. However, the case is made that reductions of insolation received at ground level by 80 to 90% or more would drastically reduce photosynthesis. If sunlight levels at the top of the canopy are sharply reduced, as would occur if great amounts of dust and smoke spread throughout the atmosphere, photosynthesis would drop below the light compensation point--about 10% of full sunlight for most crop plants. Stored carbohydrates would be consumed by respiration in this circumstance. If light levels remain low, plants would eventually die.

Review of the literature cited in this chapter and other sources support the contentions stated above. There is ample evidence that reductions in light due to natural causes (e.g., protracted cloudy periods) reduce photosynthesis significantly. Since most crop canopies are light unsaturated under field conditions, any significant reduction in insolation would lower photosynthetic rates and probably reduce crop yields.

C. Combined Effects of Low Temperature and Reduced Insolation

SCOPE 28, Volume II draws heavily on the literature of ecology and crop physiology in which the separate effects of low temperature and reduced insolation are reported. No studies of plant performance under combined low temperature and low light intensity are cited in SCOPE 28. Indeed, there has been no good reason for researchers to study such an unlikely combination as cold and darkness during the normal crop growing season. However, there is reason to believe that the effects of low temperature and low light following a nuclear exchange would be synergistic and that, together, these stresses would probably be more deleterious than each is alone.

Our panel is aware, at this writing, of only one relevant study (Rose et al., 1986) that has investigated crop yields under conditions intended to simulate climatic conditions in the aftermath of a nuclear exchange. The results of this study suggest that the combination of low light and chilling are more harmful than is either stress alone.

D. Effects on Precipitation

Alterations in precipitation and/or storminess are deemed by SCOPE 28 as likely to be much less significant during the first days after a nuclear exchange than would be the effects of temperature and light reductions. Later, however, precipitation disruptions could be of greater importance. The most significant disruptions would occur if there is a suppression of monsoon circulation. This possibility was mentioned in SCOPE 28, Volume I and has been discussed further in more recent publications (Bach, 1986; SCOPE, 1987).

E. Regionality of Climatic Effects Due to Nuclear War

The foregoing discussion has dealt primarily with effects to be expected in the mid-latitudes of the Northern Hemisphere. SCOPE 28 does, however, attempt to evaluate what might happen to agriculture in other regions of the world in the aftermath of a nuclear war. A brief summary of its findings with respect to these regions follows:

1. The Tropics

According to SCOPE 28, Volume II, Chapter 4, a few days of significant chilling could cause considerable damage to plants growing in the tropics since these lack the evolutionary mechanisms of adaptation to cold. The degree of damage would depend on temperatures experienced, the duration of the low temperatures, and the species and stage of the annual or perennial growth cycle during which the chilling occurs.

2. Southern Hemisphere Mid-latitudes

In SCOPE 28, projected climatic effects for this region are similar to, but less drastic than, those that might occur in the Northern Hemisphere mid-latitudes. Some chilling and light reduction is possible. Pastoralism is of greater relative importance in Argentina and Australia than in much of the Northern Hemisphere. Cold damage to perennial grasses and legumes (many of Northern Hemisphere mid-latitude origin) should be relatively small.

It does appear from the analyses of Chapter 4 that agriculture in the Southern Hemisphere mid-latitudes is more vulnerable to nuclear exchange-induced reductions in precipitation than in temperature. Since much of Australia, Argentina, and southern Africa are quite dry and crops are grown in areas prone to frequent drought, reductions in precipitation could substantially limit Southern Hemisphere production. However, the mechanisms for reduced precipitation in the Southern Hemisphere mid-latitudes are less clearly evident than those for chilling and light suppression in the Northern Hemisphere. Thus, it is more difficult to assign as great a degree of certainty to the SCOPE 28 projection of impacts in this region.

Simulation Studies

A. The SCOPE Studies

Considerable space is given in SCOPE 28, Volume II, Chapter 4 to reporting results of crop simulation studies used to assess the likely effects of possible nuclear war-induced climatic changes. The changes considered are less severe than those predicted by Turco et. al. (1983), and are, in fact, roughly representative of the more moderate conditions predicted in subsequent models, including that of Thompson and Schneider (1986). Reduced temperature, reduced insolation, and altered precipitation are considered in these simulations. One simulation by R. B. Stewart of Agriculture Canada is used to assess the impacts of nuclear war-induced climatic effects on wheat and barley in the Prairie Provinces of Canada. The model is described in an appendix to Chapter 4 and was originally designed to evaluate long-term crop production capability under optimum management practices. The predictions of the effects of climatic change induced by a nuclear exchange developed with this model are optimistic, as the authors of Chapter 4 point out, since it is likely that management practices as we know them would be far less than optimum after a nuclear exchange.

The scenarios used in the Agriculture Canada model include reductions in temperatures of 1, 2, 3, 4, and 5°C and changes in precipitation of ±25% The daily minimum and maximum temperatures are altered uniformly by the specified temperature change. This has the effect of reducing the length of the growing season by delaying the initiation of the frost-free period and hastening the onset of the first freeze in the autumn. The model generated its own growing season length stochastically by having the probability of occurrence of a freezing event increase substantially when the average daily temperature falls below a threshold value. Changes in precipitation are assigned uniformly on the current monthly values, i.e., by assuming the normal pattern of precipitation remains unchanged over the growing season.

In another set of scenarios, seasonal temperatures are reduced by the same amounts, but the length of the growing season is fixed so that growing season average temperatures are reduced by the appropriate amount while the daily temperature on the days beginning and ending the growing season are not changed.

A third set of analyses involved changes in temperature, insolation, and daylength to simulate the passing of a nuclear exchange-induced smoke cloud. In this scenario, seasonal monthly values for temperature and insolation (intensity and daylength) were set below normal levels for the first month, with subsequent sequential improvements in the next two months. Total crop production was estimated as the product of the area in which crop growth was possible and the yield in such areas.

The Agriculture Canada simulations yielded the following conclusions:

- Growing season reductions in average temperatures of slightly more than 2°C for spring wheat and 4°C for barley results in total elimination of those crops from production in western Canada, regardless of any changes in light or precipitation.

- Each 1°C reduction in average temperature decreases the length of the growing season by 7-10 days, while lengthening the time required for wheat and barley to reach maturity by 4-6 days.

- For the areas that remain in production, reduced temperatures, if imposed alone, could result in increased per hectare yields 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.

- Transient episodes of chilling, if they occur at particularly sensitive stages of crop growth, could cause serious losses in grain production. The specifics of the sensitivity to temperature or light reductions also depend on location. Reductions of 10% in insolation and daylength in the Agriculture Canada model have little effect on production. Depending on timing, however, 20% reductions cause very substantial losses of production.

Chapter 4 also includes a simulation by Sinclair, USDA/ARS, of potential soybean yield in the midwestern United States resulting from exposure to temperature decreases of 2, 4, and 6°C. (The model was subsequently published by Sinclair 1986a, b.) The temperature decreases occur in conjunction with 10, 20, and 30% reductions in insolation. In most of the simulation runs, the soil was assumed to be fully charged with water. Varietal differences were also considered in these simulations by using model cultivars with varying maturity requirements, i.e., 40, 50, and 60 days to termination of leaf growth. This analysis was conducted for a site and climate typical of the soybean production area in the midwestern United States: a freeze-free period of 180 days; peak summer average diurnal minimum temperature of 20°C; and a daily temperature range of 12°C.

In this simulation, a moderate decrease in temperature had a small effect on yield for a short season (40-day to leaf maturity) cultivar, but for cultivars requiring a longer season, crop temperatures of less than 7°C occur, which is a critical temperature for carbon fixation and nitrogen assimilation. For 50- and 60-day cultivars at a temperature of 6°C below normal no pod set occurs. In the absence of precipitation, overall yield reductions were 20-25% under a 2°C temperature depression and 20-55% under a 4°C depression. With a 6°C depression, either the pods did not set or freezing was experienced prior to the end of the required growing season, meaning total crop loss.

B. Post-SCOPE Simulations

The results of the simulation studies described above are given great emphasis in Chapter 4. It is only through the use of such models that quantitative estimations of the climatic effects (other than total destruction) can be formulated. Hence, the review panel felt that additional simulation studies for other crops and locations should be attempted with other models. Detailed results of the simulations are given by J.W. Jones, C.A. Jones, and J.R. Williams in Appendix C. Highlights of these additional simulation studies are reported here.

Two independently-developed models, EPIC (Erosion-Productivity Impact Calculator, Williams et al., 1984) and SOYGRO V5.3 (Wilkerson et al., 1983; Jones et al., 1987) were used to simulate the climatic effects of nuclear exchange on corn and soybean yields at specific locations in the eastern half of the United States.

EPIC includes a stochastic weather generator which permits simulation of daily weather sequences throughout the United States. This component was modified to simulate a variety of weather scenarios that might occur following nuclear exchange. The model simulates the effects of temperature and/or insolation on crop phenological development, leaf area, dry matter accumulation and economic yield. The model also considers the impact of temperature and insolation on potential evapotranspiration, soil water content and drought stress.

SOYGRO is a physiological model that predicts crop development as well as growth and yield. Processes affected by temperature include photosynthesis, maintenance respiration, vegetative node development, leaf area growth, duration of reproductive stages, pod and seed addition rates, seed growth rates and evapotranspiration. Processes affected by radiation include evapotranspiration and photosynthesis, and processes affected by daylength include the duration of reproductive stages, pod and seed addition rates and partitioning of carbon to fruit. Hourly temperature is synthesized from daily maximum and minimum temperatures, assuming sinusoidal changes during the day and linear decreases in temperature after sunset. The SOYGRO model has been calibrated with data from Florida and has been tested using data from North Carolina, Georgia, Iowa and Indiana.

As is true of all models discussed in this report, neither the EPIC nor the SOYGRO models have been (or can be) validated over the entire range of temperature and insolation considered by SCOPE 28 as possible after nuclear war. However, in one study, simulations were also performed with SOYGRO to compare projected yields with the soybean yield responses to climate changes reported in SCOPE 28 that were based on the aforementioned simulations by Sinclair. The same sinusoidal temperature pattern and constant insolation were input to SOYGRO for the case of normal climate. Then, temperature decreases of 2, 4, and 6°C were imposed along with decreases in insolation of 10, 20, and 30%.

Results from SOYGRO (reported in Appendix C to this report), confirmed that the yield losses predicted in the SCOPE analyses are reasonable for the climate change conditions used by Sinclair (1986). Yield levels predicted by the two models under no-war conditions were similar. A 2°C drop in temperature resulted in about a 15% yield loss in both models, and a 6°C drop in temperature caused complete crop failure for the assumed weather patterns. However, yield loss predicted by SOYGRO for the 4°C drop in temperature was about 60% for the same conditions for which Sinclair reported a 30% loss. For intermediate decreases in temperature (and insolation) SOYGRO predicted delays in flowering and maturity which were not identified in the SCOPE simulations.

Additional simulations were conducted to evaluate the effect on results of the assumed normal climate variations instead of the sinusoidal temperature pattern. Fluctuating daily weather data for Jackson County, Illinois, were used as normal weather and the same decreases in temperature and insolation were imposed. In this case, yield losses were not as severe as those above, and the 6°C decrease in temperature resulted in a 40% yield loss. These results provided an indication that the model used in SCOPE 28, Volume II, Chapter 4 for soybean yield is reasonable, but that the choice of baseline climate conditions is critical.

The EPIC and SOYGRO models were also used to study the effects of four timing scenarios combined with three severity scenarios for several locations. The four timing scenarios were selected by assuming that nuclear exchange occurred on the first day of each calendar month after planting for four consecutive months (June, July, August, and September) before the time that harvest normally would occur. The climate severity scenarios used roughly mimic the projections of Thompson and Schneider (1986, Fig. 1) and Kondratiev and Nikolsky (1986), except that the recovery time is extended from 30 days to 3 months. The climatic severity scenarios are:

> <u>Scenario 1</u>: Reduction of temperatures in the first month by 15°C, in the second month by 7.5°C and in the third month by 3.7°C. These temperature reductions are accompanied by solar radiation reductions of 90% in the first month, 60% in the second month and 30% in the third month.
>
> <u>Scenario 2</u>: Same pattern with the first month reduction by 10°C, the second month by 5°C and the third month by 2.5°C. Solar radiation reductions are 80, 50, and 20% in the first three months, respectively.
>
> <u>Scenario 3</u>: Temperature decreases of 5, 2.5, and 1.2°C and solar radiation reductions of 70, 40, and 10% in the first, second, and third months, respectively.

The results obtained for corn and soybeans with the EPIC and Soygrow models are given in Appendix C. The most dramatic reductions in simulated yields occurred when freezing temperatures induced by nuclear exchange kill the crop before grain production can begin. This occurs most frequently when the nuclear exchange occurs during the first or second months after planting.

Severe yield reductions are predicted by the models even in the absence of killing frosts. Sharp temperature reductions (severity scenarios 1 and 2) often slow crop development sufficiently to prevent grain maturation before normal frost kills the crop in the autumn.

The models predict that some crops will mature in spite of low temperatures, but the harvest date is delayed. In such cases yields are low, usually due to low solar radiation during the crop growing period, especially during the sensitive grain-filling period.

In the SOYGRO simulation, water stress was reduced in two out of five years in this exceptional case because lower solar radiation and temperatures reduced evapotranspiration. However, these results show that there are high risks of crop losses for all scenarios, and risks of complete failure for severity scenarios 1 and 2. For crops that were not frozen, losses were greatest when nuclear exchange occurred during July and August because of delays in crop maturity that resulted in the freezing of the crop before maturity. Some seed growth had already occurred before the climate changed in a war that began in September.

Similar results were obtained with both models tested for soybean yield on three of the same sites (Barrow Co., WI; Jackson Co., IL; and Alamance Co., NC). If equal weighting is applied to each timing scenario or month of occurrence, average yield losses are 95, 91 and 42% for severities 1, 2, and 3, respectively, using SOYGRO whereas the EPIC simulations result in losses of 81, 79 and 53%. Overall average reductions are 75% for SOYGRO compared with 71% for EPIC.

An additional feature of the simulations done with SOYGRO, as compared with those in SCOPE 28, was the inclusion of a temperature damping factor. The effects of the three climate severity scenarios were studied with a 50% reduction in the amplitude of the daily temperature wave. A reduction in the daily variation caused minimum temperatures to be higher and greatly reduced the chance of occurrence of below-freezing temperatures at night. This resulted in yield losses less than those obtained with normal amplitudes of daily temperature.

The studies reported by J.W. Jones, C.A. Jones and J.R. Williams (Appendix C) make use of models that deal with important physical and physiological processes. Yet, these studies did not consider the climatic effects of reduced daylength on crop phenological development, nor did they consider changes in rainfall distributions. Dramatic reductions in daylength caused by intense smoke cover could change the development of crops such as soybeans that flower sooner under short days. If nuclear exchange were to occur near the time of flowering, it could cause severe pod and seed abortion due to decreased photosynthate supply and colder temperatures. The SOYGRO model includes the capability to predict changes in development of soybean under reduced daylengths.

Another scenario in need of further study is that involving a possible increase in diurnal temperature variation for a few days or weeks following the nuclear exchange. Such a situation could occur if the smoke is not yet evenly dispersed in the atmosphere and might result in more damaging localized frosts than those that were simulated in the study. After smoke cover becomes uniformly distributed, however, a reduction in diurnal temperature variation would probably occur. Major changes in rainfall amount and distribution would also be expected due to disruption of weather systems by smoke and by heating of the upper atmosphere, but this factor has not been considered in the Jones et al. simulations.

Over wide variations in crop and location studied, climatic severity imposed and timing of the climatic disruption, the SCOPE 28 simulations and the new ones described here are consistent and in general agreement in indicating that crops growing in the mid-latitudes of the Northern Hemisphere could be totally destroyed or their production could be severely reduced for at least the first growing season in the aftermath of a nuclear exchange. Depending on crop, location, and climate change scenario, losses range from total to moderate. Climate change scenarios of a so-called "nuclear autumn" are still severe enough to cause very great losses in the first crop growing season. Subsequent recovery would depend on the rate at which climatic conditions return to normal and on other, nonclimatic factors discussed in Section III ("Social and Infrastructural Issues") of this report.

Omissions in the SCOPE Analyses of Agricultural Effects

A. Animal Agriculture

An important deficiency in the Chapter 4 analysis is the almost total avoidance of the questions of impacts on animal agriculture. Some animals will be killed outright during a nuclear exchange; others could be exposed to lethal doses of radiation shortly thereafter. Not only would the initial toll be great, but also the surviving animals in large portions of the earth will face a hostile environment. Severe chilling after a nuclear exchange would seriously stress animals, even those adapted to colder climates. Shortages of grass, combined with the inability of surviving farmers to distribute hay and grain and to assure water and mineral supplements, would reduce animal endurance. Cows feeding on contaminated pasture or range would produce contaminated and perhaps unusable milk almost immediately and unusable meat later. Thus, animal contributions to human food would be worthless for some period (perhaps years in some regions) after a nuclear exchange.

B. Irrigation

Irrigated agriculture does not receive adequate attention in SCOPE 28, Volume II. In arid regions, virtually all crop production is achieved with irrigation. In semi-arid and humid areas irrigation is used to supplement rainfall, especially during droughts. The role of irrigation in such regions is to stabilize year-to-year production. The importance of irrigation to agricultural production is discussed further in Section III, "Social and Infrastructural Issues."

C. CO_2 Enrichment of the Atmosphere and the Greenhouse Effect

Neither volume of SCOPE 28 deals satisfactorily with a possible CO_2 enrichment of the atmosphere that might occur sometime after a nuclear exchange. In Volume I it is assumed that fires would add CO_2 to the atmosphere only to the equivalent of one (current) year's use of fossil fuel--an increase of about 1.36 ppm. Fossil fuel ignited in storage, fires in open pit coal mines, peatland fires and blast vaporization of soil organic matter are not considered in this estimate. Soon after a nuclear exchange the combined effects of CO_2, CH_4, N_2O and other radiatively active trace gases added to the atmosphere could offset cloud-induced insolation reduction to a small degree. Later, however, the loss of vast areas of forest would result in a great reduction in photosynthetic consumption of CO_2. Hence, a significant increase in atmospheric CO_2 concentration should not be ruled out. Most surviving plants would benefit from the increased concentration which stimulates photosynthesis. However, it is unlikely that this "CO_2-fertilization" effect would greatly improve agricultural productivity when all of the other limiting factors induced by nuclear exchange are still operative.

SECTION III. SOCIAL AND INFRASTRUCTURAL ISSUES

Evaluation of Scope 28 Conclusions

Scope 28, Volume II is based on the assumption that population centers of developed countries would be targeted in a nuclear war, resulting in unprecedented disruptions in societal organizations. The evaluation of infrastructural effects of a nuclear war is in Part III, "Human Effects."

Chapters 5 ("Food Availability After Nuclear War") and 7 ("Integration of Effects on Human Populations") of Part III project unprecedented destruction and loss of life from direct effects of nuclear war and the prospect of massive food shortages, which would take even more lives. Even so, these predictions are based on overly optimistic assumptions and on a simplified model of society. Factors not considered in the analyses on the impact of nuclear war on human populations would surely be equally as damaging as the factors which were included in the analyses.

Modern agriculture is highly dependent on societal structure because it is an energy-intensive industry requiring power to till the soil; pesticides to control insects, diseases and weeds; machinery and fuel to cultivate, harvest, process and market crops; and an orderly marketing structure to move food from the farms to the consumers. Thus, the conclusion of Scope 28, Volume II (page 361) that "... analyses indicate that food problems could be the single most significant contributor to human mortality following a nuclear war" seems valid. However, even that drastic conclusion is derived from a set of assumptions that are implausibly optimistic (every survivor would receive an equal amount of food, 2000 calories per day; food distribution would be optimal; no grain would be consumed by animals; and people would eat a 75% cereal diet). Most likely, none of those conditions would be possible in a society decimated by nuclear war. Nevertheless, the point is made in Part III that agricultural production would cease if the complex societal structure that supports it were disrupted. However, the point that agricultural production may be zero after a nuclear exchange, even in the absence of climatic perturbations, needs even greater emphasis than it is given in Scope 28.

Omissions from Scope 28

Several factors which could be devastating to agriculture are dealt with inadequately or omitted from Scope 28. For example, agricultural production and societal structure could be severely affected by striking specific targets, such as agricultural and municipal water supplies. Agricultural water supplies are derived from impoundment of surface waters in reservoirs and by pumping groundwater from aquifers. Municipal supplies are from the same sources, and municipal systems are frequently operated in conjunction with agricultural systems. Furthermore, most dams which are constructed to store water are also equipped with generating systems that produce electrical power. Most water delivery systems are controlled by electrical power. Thus, agricultural water supplies are inexorably linked to municipal supplies, and both are users and suppliers of electrical power.

A. Major Water Storage Facilities in the United States

Of the 100 major dams in the United States, 6 (2 on the Colorado River, 3 on the Missouri River, and 1 on the Columbia River) contain over 40% of the total water impounded, and produce about 5.4 million kilowatts of electrical power (Todd, 1970). Thus, six well-aimed missiles could remove a large portion of the surface water stored in the United States and cause a significant reduction in the availability of electrical power. Such an event would have long-term consequences; at least 5 to 10 years would be required to replace dams, even if money, materials, and manpower were available. After a nuclear war, their replacement may be impossible. Agencies responsible for dam safety have detailed Emergency Action Plans for possible disasters. However, these plans cover only the immediate consequences of dam failure (such as danger to human life and property) and do not address long term effects, such as the impact of the loss of food supplies previously derived from irrigated areas served by water from the failed dam.

B. Agricultural Water Supplies

Irrigated agriculture represents only 13 percent of the global arable land, but the value of crops from these lands is 34 percent of the world total (Jensen, 1980). As an example, assume that the two large dams on the Colorado River (Hoover and Glen Canyon) were destroyed: California's Imperial and Coachella

Valleys would be without irrigation water; farmlands along the Colorado River in Arizona, Nevada, and California would be forced out of production; and about 850,000 acres of productive land would revert to desert conditions (U.S. Bureau of Reclamation, 1981). Mexico would lose about 250,000 acres. Much of the power used to pump groundwater for irrigation in Arizona would be disrupted, at a cost of thousands of acres of productive land.

The 2.2 million kilowatts of electrical power generated at the two dams would no longer serve the western states. The more than 2 billion dollar Central Arizona Project (to carry Colorado River water to Central Arizona as far south as Tucson) would remain dry. Millions of people in the western states would be adversely affected by the loss of these dams, including those served by the Los Angeles Metropolitan Water District and by the County of San Diego municipal water supply.

C. Municipal Water Supplies

Cities obtain water from surface reservoirs and from wells. Water from either source is passed through electrically-operated treatment plants, and then pumped to holding tanks located above the elevation of the city, resulting in gravitational flow to users. The capacity of the holding tanks may vary from city to city, but the optimum size is typically sufficient to provide from 24 to 48 hours of water at an average use rate. Power outages in excess of 48 hours could initiate a water crisis, the seriousness of which would depend upon the size and location of the city. If a river were nearby, the population could obtain water (of questionable quality) by hand-carried containers. With an extended power outage, the quality of the river water would probably deteriorate because sewage treatment plants would not be operational and raw sewage may be dumped directly into the river.

In the arid and semi-arid states this problem may be more severe because some cities depend entirely on pumps to supply their water. No rivers or other surface water sources are available. Water would need to be transported from other locations.

The problem of water supply to cities would require a solution within a matter of a few days or weeks. If the supply is not restored within a short period, the inhabitants would need to move to a water source, establish a secondary source by truck or rail (if available), or face the ultimate consequence. People can go days without food, but only hours without water.

D. Electrical Generating and Distribution Systems

When a component failed in a power generating station in the Northeast a few years ago, the sudden loss of power from this station tripped switches along the network, causing a power outage over a large area. Although procedures have been implemented that should reduce the probability of a blackout of this magnitude reoccurring, even a limited nuclear strike could disrupt power networks to such an extent that power could not be restored at some locations for days or weeks, even if the supplies required to rebuild the system were available.

The destruction of generation facilities would result in power distribution to some areas being severely limited, if not totally eliminated. If limited power were available, municipal requirements would take precedence over irrigation needs. Cultivation of crops would be severely restricted, making the population more heavily dependent on imported food supplies. Without electrical power, cities, as we know them today, could not function. Without the supplies and marketing systems provided by cities, agriculture could not function.

E. Food Processing and Distribution

Disruption of transportation, electrical supply, and refrigeration capacity would eliminate fresh dairy products from the food chain immediately. That impact would be significant on children in developed countries. Fresh meat would also disappear if societal structure were severely impacted.

Cereal processing would be severely impacted by destruction of major cities. The impact of a sudden shift to an unprocessed cereal diet is difficult to imagine and perhaps impossible to attain. SCOPE 28 can be criticized as being simplistic in its projection of how mankind would survive on a 2000 calory diet if most normal processing of cereals were disrupted. A diet without animal products may not be a survival diet for societies grown accustomed to highly processed foods.

F. Radioactive Residues

Little consideration is given in Volume II to the possibility of widespread contamination of food supplies which survived an initial exchange of nuclear weapons. Since most fresh dairy products are produced near large cities, milk would be almost immediately contaminated by fallout if the cows were allowed to forage at all. Contamination of meat and egg products would soon follow. Vegetables would also quickly become contaminated if fallout occurred where they are produced. Experience gained from the aftereffects of the Chernobyl incident underscores the importance of this issue (DOE, 1987; IAEA, 1986; USNRC, 1987).

SECTION IV: RECOMMENDATIONS FOR ADDITIONAL RESEARCH

The panel's concern about uncertainties inherent in predictions of atmospheric perturbations following a nuclear exchange are indicated in the Executive Summary and Appendix B. However, the panel's recommendations for future research are confined to matters directly related to its charge to review and evaluate Volume II of SCOPE 28. These recommendations are as follows:

*Field and simulation experiments on effects of atmospheric stresses

A comprehensive research program is needed to increase our confidence in the ability of the crop models to accurately predict the effects of a given climate change on growth and yield and to project the changes in agricultural production at regional and national scales. A coordinated approach is needed in which experiments are conducted to expose plants to the combinations of conditions likely to occur after a nuclear exchange and the results are used to test and improve the crop models. These studies should include changes in solar radiation, temperature, daily temperature amplitude, precipitation, and daylength.

The efforts in experimentation and simulation should be a cooperative effort between biological and climatological scientists so that best estimates of climate change could be used to evaluate the probabilities of yield losses of major U.S. crops. In addition, sensitivity analyses should be performed by changing each climate factor individually and in combinations, to provide a better understanding of the individual and synergistic effects of various climatic variables. Geographic weather and soil data bases, weather simulators, and crop models exist for such studies and should be brought together to meet this objective. The developed models should then be used to evaluate yield changes over space by establishing climate and soil data bases at appropriate spatial scales.

In so far as possible, similar sequences of research efforts should be conducted for other components of the total agricultural industry and economy.

*Construction of comprehensive time-dependent numerical models for system analysis

For the comprehensive quantitative assessment of agricultural production and food supply after nuclear exchange, construction of numerical models of the total system will be required. These should consist of submodels for plant and animal production, socioeconomic systems, the ecological environment, and food supply management. These submodels should fully interact with each other. Each submodel may also include its own submodels so that the agricultural production and infrastructure may be properly simulated and experimented. This will be a major new task in many research units, and will involve researchers from the biological, economic, social and physical disciplines of agricultural science.

All factors involved must be explicitly formulated or parameterized in the numerical models. Such factors include climate, energy subsidies, nutrition level, trade and distribution, and perturbed biological environment (damaged ecosystem interactions, pest outbreaks and others). During a stress situation, these factors function in a very complicated manner through various feedback mechanisms at various time scales. The disruption of the agricultural and food-supply system can be assessed only with such comprehensive numerical models in fully interactive modes.

*Long-range atmospheric contamination

Patterns of long-range atmospheric contamination need to be clarified with fine-mesh global circulation models. Unlike the immediate fallout, delayed fallout would be controlled by the global atmospheric circulation pattern, and, thus, the areas and degrees of contamination would be expected to be selective.

*Food storage

In a major nuclear exchange, we should expect a loss of most of the open food stores. Studies are needed to assess the vulnerability of U.S. food stores, as currently geographically dispersed and physically housed.

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APPENDIX A

COMMITTEE ON INTERAGENCY RADIATION RESEARCH
AND POLICY COORDINATION
1019 Nineteenth Street, NW, Suite 700
Washington, D.C. 20036

July 30, 1986

MEMORANDUM FOR ALL CIRRPC MEMBERS

Al Young

FROM: Alvin L. Young

SUBJECT: SCOPE 28 Review

Dr. Mary Carter, Associate Administrator of the Agricultural Research Service and USDA's CIRRPC Representative requested CIRRPC to assist USDA in reviewing the SCOPE 28 Report Volume II: Ecological and Agricultural Effects (of Nuclear War). Following a recommendation from our Executive Committee, I have directed CIRRPC's technical assistance contractor to arrange for consultants and government agency experts in the appropriate scientific areas and to provide drafting, editing, clerical and meeting support for this effort. The review of the Report should be completed in six months.

cc: Dr. William Tallent

APPENDIX A

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20506

August 5, 1986

Dear Dr. Rosenberg:

The Committee on Interagency Radiation Research and Policy Coordination (CIRRPC) has been requested by the Department of Agriculture (USDA) to conduct a comprehensive scientific review of the SCOPE 28 Report, Volume II: Ecological and Agricultural Effects, which addresses the environmental impact of a wide-scale nuclear war (Executive Summary enclosed). CIRRPC is a Committee chartered by the Director, Office of Science and Technology Policy (OSTP) under the Federal Coordinating Council for Science, Engineering and Technology (FCCSET). Oak Ridge Associated Universities (ORAU) provides the necessary administrative and technical assistance for the Committee.

As Chairman of CIRRPC, I have asked Dr. William H. Tallent, Assistant Administrator for Cooperative Interaction, Agricultural Research Service, USDA, to serve as Chairman of an ad hoc group to conduct this review. The purpose of my letter is to inquire of your interest and availability to assist Dr. Tallent in this review. Your participation as an expert in this area of interest will greatly enhance the quality of the review.

We anticipate that the review will take about six months and would require at least three meetings of the reviewers. It would be expected that at least the first and last meetings of the group would be held in Washington, DC at the ORAU offices.

If you have an interest or questions concerning the review, please contact me at (202) 395-3125, or Dr. William A. Mills of ORAU at (202) 653-5505, no later than August 15.

Sincerely,

Alvin L. Young

Alvin L. Young, Ph.D.
Senior Policy Analyst for Life Sciences
Chairman, CIRRPC

Dr. Norman Rosenberg
Professor and Director
Center for Agriculture,
  Meteorology and Climatology
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cc: Dr. William H. Tallent, USDA

Similar letters sent to panel members shown on page A-5.

COMMITTEE ON INTERAGENCY RADIATION RESEARCH AND POLICY COORDINATION

AD HOC REVIEW PANEL FOR SCOPE 28: VOLUME II

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Appendix B

Relationship Between Volume I and Volume II of SCOPE 28

(E.C. Kung)

Environmental consequences of a major nuclear war are of genuine concern to serious scientists and the general public. Despite their contribution in the public opinion forum, however, most of the documents dealing with this subject have lacked rigorous scientific approach and deliberation. Volume I deals with global atmospheric circulation problems as a consequence of a nuclear explosion. Basic deficiencies in its assessments of atmospheric perturbations come not from inadequate scenarios of nuclear war, but from limited knowledge of the atmospheric processes and inadequate physical-mathematical models of the global atmospheric circulation. Any estimate of the smoke coverage of the earth and its eventual effects on circulation patterns through the alteration of the radiation balance depends on the area most poorly understood in today's meteorology--the diffusion processes between the micro and meso scales and between the meso and synoptic (global) scales. The Volume I study recognized this difficulty and uncertainty, but many necessary (and crucial) compromises had to be made for the perturbation assessment of the atmospheric circulation. The diffusion processes between the fire plumes and circulation environment were neglected; thus, the amount of smoke particles and their distribution in the atmosphere in the early stage of atmospheric perturbation were not properly described. This results in the subsequent numerical integration of models being biased to a strong positive feedback with grossly intensified perturbations of the circulation fields.

Concerning the simulation of the perturbed atmospheric circulation, all currently available studies are conducted with the coarse mesh models, whose horizontal resolution is approximately 4 to 7° of latitude and longitude. For the simulation, which requires proper non-linear interactions (i.e., feedback processes), it is mandatory to use high resolution models of at least 2 to 2.5° latitude-longitude, or finer, with as explicit as possible physical formulation. Future studies with fine-mesh general circulation models, which incorporate subgrid diffusion and microphysics, will result in a better description of diffusion, scavenging, thermodynamics, and mechanics of the motion. With these expected improvements in numerical experiments, we are most likely to have a projection of much more severe localized effects in the acute stress stage and much less long-range stress than is presented in Volume I.

Volume II was written to project the ecological and agricultural consequences of the perturbed atmosphere in the short range (acute phase) and long range (chronic phase), and, thus, Volume II is constrained within the framework of Volume I. Yet, in Volume II's analysis, the writers often treat or mention long-range atmospheric stresses only as an additional factor of the agricultural effects, implicitly rejecting long-range climatic stress as general grounds to consider agricultural effects. This is a reasonable approach in view of the uncertainties of Volume I projections. The long-range climatic effects of a nuclear war, although they may remain a remote possibility, cannot be the basis to deliberate the agricultural effects of a nuclear war.

The direct effects of a nuclear exchange would be devastating even without considering the atmospheric stresses, and the time scale of agricultural redevelopment (years to decades, depending on the level of redevelopment) would be far longer than that of long-range atmospheric stress. Even if the chronic climatic stress occurred, it would be only a secondary factor. Unlike the long-range climatic stresses, the short-range (immediately following the nuclear exchange up to one month or so) atmospheric perturbations are a real possibility with more significant local variations and more severe local stress than projected in Volume I.

Despite many deficiencies, Volume II does present a wide range of possible post-nuclear war catastrophes in our life-support system. It clearly establishes the probability of mass starvation for the surviving populations as a direct consequence of nuclear attack.

Appendix C

Complementary Modeling

(J.W. Jones, C.A. Jones, and J.R. Williams)

Quantitative estimates of climate change effects on agricultural production can best be made through the use of simulation models such as those discussed in Part II, Chapter 4 of the SCOPE 28, Volume II report. Because of the emphasis on simulation studies in the report, the review panel felt that additional simulation studies should be performed using other, existing crop models and for other locations. Experimental verification of the results presented in Chapter 4 was not possible in the time and resource restrictions of this review. If results from independent simulation studies were in agreement with those presented in the report, the panel would have more confidence in the range of estimates provided. Contradictions between new simulations and those in the report would help identify our level of uncertainty and results could be interpreted accordingly. The purpose of this appendix is to present results from those additional simulation studies as a basis for independent evaluation of the conclusions of Chapter 4.

OVERVIEW OF SELECTED CROP MODELS

The approach used in this study was to select two crop simulation models to analyze the climate effects of nuclear exchange on corn and soybean yields at specific locations in the eastern half of the United States. Models developed at two locations were selected so that results from each model could be compared with each other and with those from the SCOPE 28 report (SCOPE 28, 1985). Crop models have not been tested over the ranges of temperature and solar radiation that might occur after a nuclear war. However, it was felt that additional confidence in this simulation approach would be developed by comparing results from these independently developed models with results in Chapter 4. The two models selected were EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984) and SOYGRO V5.3 (Wilkerson et al., 1983; Jones et al., 1987).

The EPIC model was used to analyze the climate effects of nuclear exchange on both corn and soybean yields at 6 sites in the eastern half of the United States. EPIC is a computationally efficient, generally applicable mathematical model capable of simulating a number of important agricultural processes (Williams et al., 1984). It has nine major components: weather, hydrology, erosion, tillage, plant nutrients, soil temperature, plant environment control, plant growth, and economics. Simulation of the component processes is physically based, and the model is capable of computing the effects of weather, soil properties, erosion, and management on growth and yield of several crops.

EPIC has several characteristics which facilitate its use in a study of this sort. It includes a stochastic weather generator which permits simulation of daily weather sequences throughout the United States. This component can be easily modified to simulate a variety of weather scenarios which might occur following nuclear war. The model simulates the effects of temperature and/or solar radiation on crop phenological development, leaf area, dry matter accumulation, and economic yield. Temperature and solar radiation also interact to affect potential evapotranspiration, soil water content, and drought stress. The model is sensitive to soil properties such as depth, organic matter content, texture, pH, aluminum and calcium saturation, bulk density, and nitrogen and phosphorus fertility. Input data are available for over 800 important United States soils.

A soybean simulation model, SOYGRO V5.3 (Wilkerson et al., 1983; Jones et al., 1987), was used to simulate the effects of transient climate changes on yield for three of the same sites used for EPIC. SOYGRO is a physiological model that predicts crop development as well as growth and yield. Temperature and solar radiation affect various development and growth processes differently. For example, the effect of temperature on vegetative development is linear between 7 and 30°C whereas flowering and reproductive development are insensitive to temperatures between 21 and 28°C and pod formation is dramatically reduced when temperatures are below 14°C. Table 1 shows the processes in SOYGRO that are affected by temperature, solar radiation, and daylength. Temperatures are calculated hourly in SOYGRO using daily maximum and minimum temperatures as input and assuming sinusoidal changes during the day and a linear decrease in temperature after sunset. Most temperature-sensitive processes respond to hourly temperatures. This is important because none of the temperature functions are linear over all ranges of temperatures. This model has been calibrated and tested using data from five years in Florida and tested using data from North Carolina, Georgia, Iowa, and Indiana. Further tests are in progress for Georgia, Illinois, Hawaii, Minnesota, Nebraska, and Taiwan.

Table 1. Processes affected by temperature, radiation, and daylength in SOYGRO V5.3.

1. Temperature
   - a. Photosynthesis (Hofstra and Hesketh, 1975)
   - b. Maintenance Respiration (McCree, 1974)
   - c. Vegetative Node Development (Hesketh et al., 1973)
   - d. Leaf Area Growth (Thomas and Raper, 1978)
   - e. Duration of Reproductive Stages (Parker and Borthwick, 1943)
   - f. Pod and Seed Addition Rates (Thomas and Raper, 1981)
   - g. Seed Growth Rates (Egli and Wardlaw, 1980)
   - h. Evapotranspiration (Priestly and Taylor, 1972)

2. Radiation
   - a. Evapotranspiration (Priestly and Taylor, 1972)
   - b. Photosynthesis (Ingram et al., 1981)

3. Daylength
   - a. Duration of Reproductive Stages (Thomas and Raper, 1976)
   - b. Pod and Seed Addition Rates (Fisher, 1963)
   - c. Partitioning of Carbon to Fruit (Cure et al., 1982)

METHODS

EPIC was used to simulate corn and/or soybean growth at six locations in the eastern United States. The sites, soils, normal planting and harvest dates, and mean annual temperatures and precipitation are given in Table 2. Normal planting and harvest dates were taken from Agriculture Handbook 628 (United States Department of Agriculture, Statistical Reporting Service, 1984).

Table 2. Sites, soils, normal planting and harvest dates, and mean annual temperatures and precipitation used in the study.

Crop	Site	Soil	Normal Dates		Mean Annual Temperature	Mean Annual Precipitation
			Planting	Harvest		
					°C	mm
Corn/ Soybean	Barrow Co. Wisconsin	Fine-loamy, mixed, Typic Glossoboralf (Santiago)	5/11 6/1	9/8 (corn) 10/5 (soybean)	5.8	782
Corn/ Soybean	Jackson Co. Illinois	Fine, montmorillonitic, mesic, Vertic Haplaquoll (Darwin)	5/1 5/5	9/2 (corn) 9/20 (soybean)	14.2	1094
Corn	Macon Co. Alabama	Fine-loamy, siliceous, thermic, Typic Paleudult (Orangeburg)	3/11	8/15	18.6	1309
Corn	Tioga Co. Pennsylvania	Coarse-loamy, mixed, mesic, Typic Fragiochrept (Lackawanna)	5/11	9/18	9.1	942
Soybean	Carroll Co. Mississippi	Fine-silty, mixed, thermic, Typic Fragiudalf (Loring)	5/5	9/20	18.0	1328
Soybean	Alamance Co. North Carolina	Clayey, kaolinitic, thermic, Typic Hapludult (Cecil)	5/5	10/15	15.7	1100

For each site and crop, a standard simulation was performed using the normal planting and harvest dates. This consisted of a continuous simulation of five years with either continuous corn cropping or continuous soybean cropping. Weather data were generated stochastically; therefore, daily precipitation, temperature, and solar radiation varied among years at each location. After the standard run was performed for a location, the thermal time required for crop maturation under normal climate conditions was used for simulations of crop maturity dates under various nuclear war scenarios. Four "timing" scenarios were combined with three "severity" scenarios for each location and crop. For each nuclear winter scenario, harvest was simulated in EPIC when accumulated thermal time reached the mean thermal time at harvest for the control run. If this value had not been reached by December 15, harvest of the immature grain was simulated.

Three locations were chosen for comparing the SOYGRO model results with those from EPIC: Barrow Co., Wisconsin; Jackson Co., Illinois, and Alamance Co., North Carolina. These sites were at 45° 30'N, 37° 45'N, and 36°N latitudes, respectively. The weather (5 years) and soil data used to simulate soybean yield in SOYGRO were the same as those used in the EPIC simulations for those sites. In addition, the same "timing" and "severity" scenarios were used for these locations. These combinations of weather, "timing", "severity" and locations resulted in 195 season simulations with SOYGRO for comparison with results from EPIC.

Because SOYGRO has genetic coefficients that are used to simulate the effects of environment on different cultivars, varieties were chosen so that crops would mature at the right date for each location under normal weather conditions. Phenological development is predicted in SOYGRO based on temperature and photoperiod, and, thus, SOYGRO predicts delays in maturity due to changes in climate. Bragg (maturity group 7) was selected for North Carolina and Wayne (maturity group 3) was used for Illinois and Wisconsin. Preliminary simulations with normal weather (no war) showed average maturity dates of mid-October, first week in September, and mid October for Wisconsin, Illinois, and North Carolina, respectively. These dates compared reasonably well to the dates assumed in EPIC for soybean grown at these three locations. In Wisconsin, however, the maturity date was one to two weeks later with SOYGRO. To demonstrate the effects of cultivar choice, genetic coefficients for a hypothetical photoperiod insensitive cultivar (maturity group 00) were estimated simply by changing a photoperiod sensitivity coefficient for Wayne cultivar. This cultivar was simulated for Barrow Co., Wisconsin and resulted in physiological maturity in early September followed by harvest maturity in mid to late September, slightly earlier than the maturity of October 5 assumed in EPIC.

Photoperiod durations were not changed for any of the sites or severities.

Timing Scenarios

For each site and crop, four timing scenarios were selected by assuming that nuclear exchange occurred on the first day of each calendar month after planting for four consecutive months before normal harvest would occur. Thus, four timing scenarios are described for each site. For timing scenario I, exchange was assumed to occur the first day of the first calendar month after planting. For timing scenario II, it occurred on the first day of the second calendar month after planting, etc. For example, for Jackson County, Illinois, soybeans were planted May 5, and (in the absence of simulated war) they were harvested September 20. Therefore, for timing scenarios I, II, III, and IV, nuclear war was simulated to begin on the first day of June, July, August, and September, respectively.

Severity Scenarios

For each timing scenario, three severity scenarios were simulated. Severity I caused mean daily temperatures to be reduced by an average of 15, 7.5, and 3.7°C in the first three months of the war, respectively. Mean solar radiation was reduced by an average of 90, 60, and 30% for the three months, respectively. Severity II used less severe assumptions: 10, 5, and 2.5°C reduction in mean daily temperatures and 80, 50, and 20% reductions in solar radiation. Severity III was the least severe: 5, 2.5, and 1.2°C reductions in temperature and 70, 40, and 10% reductions in solar radiation. These severity scenarios correspond approximately to the projections made by Thompson and Schneider (1986, Fig. 1), except that recovery time is 3 months compared with about 1 month in their paper.

Each of the above climate-change scenarios had both maximum and minimum daily temperatures decreased. Since there is some question as to how the daily fluctuations in temperature would be modified, SOYGRO was used to investigate the effects of reducing the magnitude of daily temperature fluctuations to one-half of the normal values. The average daily temperature reductions were the same as in the original severity scenarios. Five years of weather, three severities, and two war timing scenarios were used for the Illinois site (30 seasons).

We assumed that weather effects lasted no more than three months after nuclear exchange, CO_2 concentrations remained at normal levels, and rainfall probabilities and diurnal temperature variations did not change (with the exception of the 30 runs made with SOYGRO to demonstrate diurnal effect). Changes in such parameters could be simulated with the current models in future studies; however, collaboration with climate modelers would be required to develop realistic scenarios.

The climate severity scenarios are summarized below:

SCENARIO I. - reduction of temperatures in the first month by 15°, in the second month by 7.5°, and in the third month by 3.7°; reduction of the solar radiation by 90% of the original in the first month, by 60% in the second, and by 30% in the third.

SCENARIO II. - reduction of temperatures in the first month by 10°, in the second month by 5°, and in the third month by 2.5°; reduction of the solar radiation by 80% of the original in the first month, by 50% in the second, and by 20% in the third.

SCENARIO III. - reduction of temperatures in the first month by 5°, in the second month by 2.5°, and in the third month by 1.2°; reduction of the solar radiation by 70% of the original in the first month, by 40% in the second, and by 10% in the third.

Comparative Simulations

None of the climate-change scenarios in the SCOPE 28 report are the same as those outlined above. Additional simulations were made with SOYGRO V5.3 to compare to soybean yield responses to climate changes in the report based on the work of Sinclair (1986).

In Sinclair's study, temperature and solar radiation for a hypothetical midwestern site were calculated as follows. Solar radiation was constant at 20 million Joules per square meter per day (20 MJ/m^2-day). Minimum daily temperatures were calculated with a sine function assuming a maximum value of 20°C in mid-summer, and a 180 day frost-free period. Daily maximum temperatures were 12° higher than minimum values each day. Simulations were started on the day when the minimum temperature reached 10°C. Three climate-change scenarios were chosen. Daily maximum and minimum temperatures were decreased by 2, 4, and 6°C and solar radiation was decreased by 10, 20, and 30%, respectively.

In SOYGRO V5.3, we selected Jackson County, Illinois as the site at which the changes in temperatures and solar radiation occurred. The latitude of the site (37° 45'N) was needed to compute day lengths used in predicting the timing of critical developmental stages. In addition, the time scale for the sine function was adjusted so that the 10°C minimum temperature occurred on the previously selected planting date of May 5. Simulations were then performed using Wayne cultivar.

After the simulations with the sine function temperatures were completed, additional simulations were made using the 5 years of generated daily weather data for Jackson County, Illinois, with the climate changes used by Sinclair (1986) imposed on those data, i.e., T-2, T-4, and T-6°C with 10, 20, and 30% reductions in solar radiation, respectively.

RESULTS

EPIC Model

The effects of four timing and three severity scenarios for both corn and soybean are summarized in Tables 3-10. Yields are given in millions of grams per hectare (Mg/ha). Relative yields of all scenarios are summarized for northern and southern sites in Table 11. The most dramatic reductions in simulated yields occurred when nuclear war-induced freezing temperatures killed the crop before grain production could begin. This happened most frequently when nuclear exchange occurred during the first or second months after planting (timing scenarios I and II). It occurred for southern as well as northern sites, but early frost damage was more frequent for northern sites.

Table 3. Simulated effects of three levels of climatic change and four dates of nuclear war on corn growth and yields on Santiago soil in Barrow Co., Wisconsin, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield		Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
		Mean	Range			
	°C	------------Mg/ha------------			MJ/m^2	°C·d
June	15	0.0	0.0-0.0	0.2	493	158
	10	0.8[1/]	0.0-3.8	2.5	892	391
	5	3.9[1/]	3.3-4.6	11.4	2060	1217
July	15	0.0	0.0-0.0	0.2	532	158
	10	1.9[1/]	1.0-3.1	9.7	2163	1055
	5	2.9	2.4-3.2	10.6	2116	1215
August	15	2.1[1/]	0.9-3.3	11.8	1965	924
	10	2.8[1/]	2.2-3.4	12.5	2114	1031
	5	4.2	3.4-4.9	13.0	2283	1226
September	15	5.2	4.7-5.6	13.4	2454	1225
	10	5.4	4.9-5.8	14.0	2455	1227
	5	5.5	4.9-5.9	14.1	2455	1228
Control	0	5.5	5.0-5.9	14.1	2457	1228

[1/] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 4. Simulated effects of three levels of climatic change and four dates of nuclear war on corn growth and yields on Darwin soil in Jackson Co., Illinois, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield Mean	Grain Yield Range	Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
	°C	Mg/ha			MJ/m^2	°C·d
	15	1.2[1/]	0.0-6.0	3.5	1092	737
June	10	6.3	5.9-6.7	17.0	2405	1983
	5	6.3	5.4-6.7	17.1	2273	1986
	15	3.4[1/]	0.1-5.1	14.2	2317	1700
July	10	4.5	3.9-4.5	15.8	2501	1983
	5	4.5	4.0-4.9	15.4	2315	1983
	15	4.4[1/]	3.2-6.7	18.8	2474	1719
August	10	6.1	5.3-6.9	19.7	2612	1962
	5	6.5	6.0-7.3	20.0	2532	1987
	15	9.0	7.5-9.5	22.7	2852	1986
September	10	9.1	7.6-9.7	22.9	2852	1987
	5	9.2	7.7-9.8	23.2	2854	1987
Control	0	9.3	7.8-9.9	23.4	2857	1987

[1/] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 5. Simulated effects of three levels of climatic change and four dates of nuclear war on corn growth and yields on Orangeburg soil in Macon Co., Alabama, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield		Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
		Mean	Range			
	°C	Mg/ha			MJ/m^2	°C·d
	15	0.0	0.0-0.0	0.2	340	180
June	10	1.6[1/]	0.0-8.0	4.3	902	585
	5	4.1[1/]	0.0-8.1	11.3	1825	1490
	15	0.0	0.0-0.0	0.8	939	395
July	10	6.8	5.8-7.8	6.8	2738	2297
	5	6.7	5.2-7.6	18.3	2684	2300
	15	6.5	5.7-7.2	20.1	2808	2297
August	10	6.2	5.1-6.9	19.7	2761	2302
	5	5.9	4.6-6.4	18.9	2699	2298
	15	5.0	4.2-5.5	18.2	2912	2295
September	10	5.1	4.3-5.6	18.2	2848	2296
	5	5.4	4.4-6.0	18.1	2807	2298
Control	0	7.6	5.6-8.6	20.1	3259	2299

[1/] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 6. Simulated effects of three levels of climatic change and four dates of nuclear war on corn growth and yields on Lackawanna soil in Tioga Co., Pennsylvania, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield Mean	Grain Yield Range	Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
	°C	--------------Mg/ha	--------------	--------------	MJ/m^2	°C·d
	15	0.0	0.0-0.0	0.2	477	176
June	10	0.7[1]	0.0-3.3	2.2	864	439
	5	3.3	2.9-3.9	10.0	2130	1371
	15	0.0	0.0-0.0	3.4	1183	535
July	10	2.2	1.7-2.9	9.8	2188	1279
	5	2.9	2.6-3.2	10.4	2178	1369
	15	1.1[1]	0.5-1.6	9.3	1872	964
August	10	1.7[1]	1.3-2.0	10.1	2023	1084
	5	2.8	1.9-3.5	10.8	2284	1283
	15	4.1	3.7-4.6	11.6	2464	1343
September	10	4.2	3.7-4.6	11.5	2472	1353
	5	4.3	3.7-4.7	11.6	2491	1378
Control	0	4.3	3.7-4.8	11.6	2509	1380

[1] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 7. Simulated effects of three levels of climatic change and four dates of nuclear war on soybean growth and yields on Santiago soil in Barrow Co., Wisconsin, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield		Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
		Mean	Range			
	°C	Mg/ha			MJ/m^2	°C·d
	15	0.0	0.0-0.0	0.0	3	4
June	10	0.0	0.0-0.0	0.0	28	14
	5	0.8[1/]	0.4-1.1	6.3	1767	908
	15	0.0	0.0-0.0	0.3	742	276
July	10	0.1[1/]	0.0-0.1	2.0	1303	532
	5	0.5[1/]	0.3-0.8	5.1	1829	902
	15	0.1[1/]	0.1-0.3	4.9	1473	646
August	10	0.1[1/]	0.1-0.3	5.1	1553	685
	5	0.7[1/]	0.4-1.1	6.7	1943	923
	15	1.3[1/]	0.9-1.6	8.0	2097	966
September	10	1.3[1/]	0.9-1.7	8.2	2106	972
	5	1.4	1.1-1.8	8.2	2158	1003
Control	0	1.8	1.4-2.1	8.1	2499	1117

[1/] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 8. Simulated effects of three levels of climatic change and four dates of nuclear war on soybean growth and yields on Darwin soil in Jackson Co., Illinois, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield		Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
		Mean	Range			
	°C	Mg/ha			MJ/m^2	°C·d
June	15	0.3[1/]	0.0-1.7	2.1	992	566
	10	2.2	2.0-2.3	10.6	2494	1739
	5	2.3	2.0-2.6	10.2	2415	1830
July	15	0.7[1/]	0.0-1.6	6.7	2010	1220
	10	1.6	1.4-1.9	9.8	2587	1734
	5	1.7	1.5-1.8	9.2	2457	1830
August	15	0.7[1/]	0.3-1.0	9.3	2217	1316
	10	1.6	1.2-2.1	10.5	2687	1721
	5	1.8	1.4-2.1	10.2	2613	1829
September	15	2.3	1.6-2.8	10.9	2795	1743
	10	2.4	1.5-2.7	10.7	2879	1805
	5	2.5	1.5-2.8	10.7	2856	1829
Control	0	2.6	1.5-3.8	10.9	2916	1830

[1/] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 9. Simulated effects of three levels of climatic change and four dates of nuclear war on soybean growth and yields on Loring soil in Carroll Co., Mississippi, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield		Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
		Mean	Range			
	°C	-------------	-Mg/ha-	-------------	MJ/m²	°C·d
June	15	1.8[1]	1.4-2.0	11.3	2289	1906
	10	2.5	2.3-2.8	11.7	2473	2123
	5	2.5	2.1-2.8	11.3	2398	2169
July	15	1.5[1]	1.1-1.8	11.1	2390	1889
	10	2.0	1.8-2.3	11.3	2545	2118
	5	2.1	1.7-2.3	10.9	2449	2170
August	15	1.4[1]	1.1-1.7	12.0	2604	1919
	10	1.9	1.5-2.2	11.9	2705	2126
	5	2.0	1.6-2.2	11.8	2592	2172
September	15	2.4	1.9-2.8	12.9	2780	2024
	10	2.7	2.1-3.2	12.9	2900	2163
	5	2.7	2.1-3.2	12.9	2849	2167
Control	0	2.8	2.1-3.2	12.9	2956	2171

[1] Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Table 10. Simulated effects of three levels of climatic change and four dates of nuclear war on soybean growth and yields on Cecil soil in Alamance Co., North Carolina, using EPIC.

Month of War	Mean Monthly Temperature Decrease in First Month	Grain Yield		Mean Biomass (root + shoot)	Mean Solar Radiation	Mean Thermal Time
		Mean	Range			
	°C	Mg/ha			MJ/m^2	°C·d
June	15	0.3[1/]	0.0-0.7	3.5	1303	840
	10	1.4[1/]	1.3-1.6	10.2	2481	1796
	5	2.1	1.8-2.4	10.0	2645	2031
July	15	0.6[1/]	0.3-0.9	8.9	2346	1530
	10	1.3[1/]	1.1-1.6	10.4	2546	1788
	5	1.9	1.5-2.1	10.2	2689	2030
August	15	0.6[1/]	0.4-0.9	9.4	2518	1571
	10	1.1[1/]	0.9-1,4	10.2	2700	1807
	5	1.6	1.2-1.7	9.8	2807	2035
September	15	1.6[1/]	1.1-1.9	10.2	2664	1767
	10	1.7	1.5-2.0	10.2	2910	1917
	5	2.1	1.6-2.5	10.9	2966	2064
Control	0	2.3	1.7-2.9	10.2	3118	2082

1/ Harvestable yield probably lower due to insufficient (<0.9 of normal) thermal time accumulation for grain maturation.

Severe yield reductions also occurred in the absence of killing frosts. Severe temperature reductions (temperature scenarios I and II) often slowed crop development and prevented grain maturation before normal frosts killed the crop in the autumn. In some cases significant amounts of dry matter accumulated in the grain.

Crops often matured in spite of low temperatures; however, the date of harvest was delayed. In such cases, low yields were usually associated with low solar radiation during the growing season especially during the sensitive grain-filling period. The effects of simulated nuclear exchange were least severe when it occurred late in the crop cycle after grain was almost mature (Table 11, timing scenario IV).

Table 11. Effects of timing and severity scenarios on simulated grain yields[1/] for northern (Wisconsin, Illinois, Pennsylvania) and southern (Mississippi, Alabama, North Carolina) sites, using EPIC.

Severity Scenario	Timing Scenario			
	I	II	III	IV
	(percent of control)			
Northern Sites				
I	5	13	29	89
II	37	40	45	92
III	70	52	63	95
Southern Sites				
I	26	27	54	74
II	57	72	66	79
III	78	82	73	86

[1/] Harvestable yields would probably be lower in some cases due to insufficient thermal time accumulation for grain maturation.

SOYGRO Model

Table 12 presents soybean yield averages and ranges of yields simulated over five years for each month of nuclear exchange and each severity level for the Wisconsin site. Table 13 shows the relative yield for each case, normalized by the average, control yield. Average simulated yield was 2.01 million grams per hectare (MT/ha) with a variation of 1.03 to 2.70. In all cases but one, yield was reduced due to the assumed climate changes. At the lowest severity level (III), where temperatures dropped by 5, 2.5, and 1.2°C for the three months after an exchange, a slight yield increase occurred for two years when the exchange occurred in June. Water stress was reduced in these two years because of lower radiation and temperatures. A similar, small increase in soybean yield was simulated in the Sinclair (1986) study when a 2°C decrease in temperature and 10% reduction in solar radiation reduced the effect of an imposed water stress in July. Our results show that there are high risks of crop losses for all scenarios and risks of complete failure for scenarios I and II. Losses were greatest when nuclear exchange occurred during July and August because of delays in crop maturity that resulted in the freezing of the crop before maturity. When nuclear exchange occurred in September, some seed growth had occurred before the climate changed.

Table 12. Simulated average soybean yields and ranges of yields that occurred over a five year period for each hypothetical month of war and severity of climate change using SOYGRO. (Barrow Co., Wisconsin, Santiago soil series using Wayne cultivar of maturity group 3).

	Month of War			
Severity	June	July	August	September
	Mg/ha			
I Yield	0.09	0.0	0.0	0.35
(Range)	(0.00-0.32)	(0.0-0.0)	(0.0-0.0)	(0.20-0.50)
II Yield	0.15	0.19	0.00	0.38
(Range)	(0.0-0.57)	(0.0-0.57)	(0.0-0.0)	(0.2-0.56)
III Yield	1.68	1.45	0.78	0.74
(Range)	(0.80-2.88)	(0.86-2.17)	(0.37-1.20)	(0.29-1.01)
Control	2.01			
(Range)	(1.03-2.70)			

Similar results were simulated by the EPIC model. If equal weight is applied to each timing scenario or month of occurrence, average yield losses were 95, 91, and 42% for severities I, II, and III, respectively, using SOYGRO, whereas the EPIC simulations resulted in average losses of 81, 79, and 53%. Overall average reductions were 75% for SOYGRO compared with 71% using EPIC. The SOYGRO and EPIC results compared very well with only one exception. EPIC predicted that a September nuclear exchange would have little effect in Wisconsin on yield (average of 26% loss, Table 7), whereas the SOYGRO estimate was 76% loss (Table 13). Predicted maturity dates from SOYGRO were later than the October 5 date used in EPIC. Thus, more of the seed filling period was affected by a September exchange in SOYGRO than in EPIC. This was confirmed by the analysis using the hypothetical photoperiod- insensitive cultivar. It matured mid-to late September and resulted in only 12, 9, and 2% yield losses for September exchange for severities I, II, and III, respectively.

Table 13. Normalized yields, average yield for a particular scenario divided by the average yield for no war for Barrow Co., Wisconsin, simulations using SOYGRO.

	Month of War				
Severity	June	July	August	September	Average
I	0.04	0.00	0.00	0.17	.05
II	0.07	0.09	0.00	0.19	.09
III	0.84	0.72	0.39	0.37	.58
Average	0.32	0.27	0.13	0.24	.24

Simulations with SOYGRO in Jackson Co., Illinois (Tables 14 and 15) showed that there was a risk of early season freeze if nuclear exchange occurred in June at the -15°C severity. However, if a freeze did not occur, the delay in maturity would help offset the delay in early season growth. August nuclear exchange caused the greatest average yield reductions because of delays in the onset of pod fill. At this site, SOYGRO simulated an overall average yield decrease of 35% when considering all months of nuclear exchange and severities compared with 34% using EPIC.

Table 14. Simulated average soybean yields and ranges of yields that occurred over a five year period for each hypothetical month of war and severity of climate change using SOYGRO. (Jackson Co., Illinois, Darwin soil series using Wayne cultivar of maturity group 3).

		Month of War			
Severity		June	July	August	September
		Mg/ha			
I	Yield	0.00	1.20	0.55	2.66
	(Range)	(0.00-0.00)	(0.0-2.21)	(0.23-1.44	(2.36-2.90)
II	Yield	3.05	2.09	1.87	2.84
	(Range)	(2.74-3.33)	(1.61-2.67)	(1.46-2.40)	(2.51-3.14)
III	Yield	3.21	2.30	2.06	2.90
	(Range)	(2.81-3.49)	(1.76-3.02)	(1.64-2.57)	(2.51-3.37)
No	Yield	3.17			
War	(Range)	(2.69-3.68)			

Table 15. Normalized soybean yields, average yield for a nuclear war scenario divided by the average yield for no war, for Jackson Co., Illinois, simulations using SOYGRO.

	Month of War				
Severity	June	July	August	September	Average
I	0.00	0.38	0.17	0.84	0.35
II	0.96	0.66	0.59	0.90	0.78
III	1.01	0.73	0.65	0.91	0.82
Average	0.66	0.59	0.47	0.88	0.65

Tables 16 and 17 show simulated results for Alamance Co., North Carolina. The longer growing season and normally warmer temperatures allowed time for soybeans to recover if the exchange occurred early (June or July), provided a freeze did not occur. In several cases when war started in June, and temperatures dropped 15°C, plants froze and all yield was lost. However, no freezes occurred at lower severities in August. Yields under September exchanges were greatly reduced. In contrast to the more northern latitudes, seed fill occurred in September and into October. The cultivar simulated for this location was Bragg (MG-7) which is highly photoperiod-sensitive. Water stress occurred in three out of five years at this location, and small reductions in temperature caused yield increases due to decreases in water stress. There was an overall average yield reduction of 18% (average) to 34% (minimal water stress) as compared with 42% reduction estimated by EPIC. There was, however, more variability in yields simulated by SOYGRO depending on month of nuclear exchange than EPIC, meaning that the risk of yield loss was greater.

Table 16. Simulated average soybean yields and ranges that occurred over a five-year period for each hypothetical month of war and severity of climate change, using SOYGRO. (Alamance, North Carolina, Cecil soil series, using Bragg cultivar of maturity group 7).

	Month of War			
Severity	June	July	August	September
	Mg/ha			
I Yield	0.69	3.13	1.96	0.13
(Range)	(0.00-3.43)	(2.62-3.52)	(1.81-2.26)	(0.05-0.25)
II Yield	3.47	3.21	2.58	1.41
(Range)	(3.18-3.68)	(2.59-3.73)	(1.96-2.82)	(1.07-1.71)
III Yield	3.35	3.25	2.72	1.92
(Range)	(2.58-3.73)	(3.25-4.02)	(2.06-3.28)	(1.25-2.52)
No Yield	2.81			
War (Range)	(1.47-3.62)	(3.62 for minimal water stress year)		

Table 17. Normalized soybean yields, average yield for a nuclear war scenario divided by average yield for no war, for the Alamance, North Carolina, simulations using SOYGRO. The results in parentheses are for the first simulated weather year where there was very little water stress.

	Month of War				
Severity	June	July	August	September	Average
I	0.25(0.00)	1.11(0.90)	0.70(0.44)	0.05(0.01)	0.53(0.34)
II	1.23(0.99)	1.14(0.93)	0.92(0.70)	0.50(0.42)	0.95(0.76)
III	1.19(1.02)	1.16(0.96)	0.97(0.85)	0.68(0.70)	1.00(0.88)
Average	0.89(0.67)	1.14(0.93)	0.86(0.66)	0.41(0.38)	0.82(0.66)

In order to show the influence of daily temperature variations, SOYGRO was used to simulate the effects of the three severities of climate change, but with a 50% reduction in the daily variation in temperature. Mean temperatures were the same as for scenarios I, II, and III, and June and August nuclear exchanges were simulated for Illinois. Table 18 shows that June exchange caused 28% reduction in yield for severity I(-15°C) whereas there was a 100% decrease shown in Table 14. A reduction in the daily variation caused minimum temperatures to be higher and greatly reduce the chance of freezing nighttime temperatures.

Table 18. Relative yield results from SOYGRO simulations in which average daily temperature dropped as in the "severities" cases originally, but the daily fluctuation in temperatures were reduced to 0.5 of the normal daily fluctuations. (Jackson Co., Illinois site, June and August wars only).

Month of War	Mean monthly temperature decrease in first Month, °C 15	 10	 5	Average
June	0.72	0.84	0.95	0.84
August	0.61	0.56	0.60	0.59
Average	0.66	0.70	0.78	0.71

Direct Comparisons with Soybean Results in SCOPE 28

The predicted dates of flowering and physiological maturity using the sine function weather and the Illinois latitude were within 3 days of the predicted dates derived from the original daily weather pattern. Planting to flowering required 56 days and flowering to physiological maturity required 64 days. Yield levels predicted by the two models under no-war conditions were similar (Table 19). A constant drop of 2°C resulted in the same percentage yield decrease (15%), and a 6°C drop caused crop failure to be predicted by both models. However, for a 4°C decrease in temperature, SOYGRO predicted a greater loss in yield (59 compared to 30% loss) than did the Sinclair model. This occurred because the beginning of seed growth was delayed by 14 days in SOYGRO which decreased the seed-filling period. The 6° decrease in temperature caused a 28-day delay in the beginning of seed growth in SOYGRO and resulted in complete crop failure. The Sinclair model did not include the capability to predict delays in development due to temperature changes and thus may have underestimated the impact of intermediate temperature changes on yield loss.

Table 19. Comparison of simulated results from SOYGRO V5.3 with those reported by Sinclair (1986) on soybeans and used in the SCOPE 28 book.

	Climate Change Scenario			
Case	Normal	T-2	T-4	T-6
	Mg/ha			
From Sinclair (1986)[1]	4.45	3.78(0.85)[2]	2.65(0.60)[2]	0.0(0.0)[3]
SOYGRO V5.3 with Sinclair climate	4.01	3.41(0.85)[3]	1.25(0.31)[3]	0.07(0.02)[3]
SOYGRO V5.3 with[4] Jackson Co., Illinois Climate	3.00	3.12(1.04)	2.86(0.95)[5]	1.80(0.60)[3]

[1] From his Table 1, no water stress, termination of leaf growth on day 50. The termination of leaf growth in SOYGRO V5.3 was 56 days after emergence under the normal weather specified by Sinclair.

[2] Numbers in parenthesis are fraction of normal yield.

[3] Crop terminated by freezing temperatures before normal maturity dates.

[4] Average of 5 years of simulations.

[5] In 2 out of 5 years, crop terminated by freezing temperatures before normal maturity dates.

There were considerable differences in the results using the sine function temperatures from those using daily, randomly generated data for the Illinois site (Table 19). Since the two models were in reasonable agreement for the sine function temperatures, these results were interpreted as an indication that the sine function temperatures and constant solar radiation are not adequate representations of weather for the Illinois location. This finding emphasizes the sensitivity of the models to weather and the need to have accurate baseline weather conditions before imposing likely climate change scenarios.

DISCUSSION

The soybean simulation studies performed with SOYGRO and EPIC for three locations predicted similar yield loss results. When averaged across locations, simulated yield losses were 43% by SOYGRO and 44% by EPIC.

When the same weather data were used as inputs, there was very good agreement between the results in the SCOPE 28 report and SOYGRO results for small (<2°C) and large (≥6°C) changes in temperature. However, for intermediate changes, yield losses could be greater than those in SCOPE 28. Because the baseline weather data in the soybean simulations in that report are for a hypothetical site, they cannot be interpreted in a broad context. When the same climate change scenarios were applied to daily fluctuating weather conditions generated for Jackson County, Illinois, simulated losses in yield were lower than from those using the sine function. These results and those in SCOPE 28 suggest that a decrease in temperature of 6°C during the chronic phase would likely eliminate crop production as far south as 37° 45'N latitude. Our results for the transient, acute effects also suggest that there is a high chance of complete crop failure if temperatures drop by 15°C even for one month during a crop season, as far south as 36°N latitude. At higher latitudes, crop failure would occur at smaller changes in temperatures, which is in agreement with the report (ie., 10°C acute case in Wisconsin, 45° 30'N).

The yield reductions predicted by the models resulted from one or more of the following: (1) frost damage killed the crop prior to grain maturation, (2) chilling temperatures prevented grain maturation before normal frosts in the fall killed the crop, (3) low solar radiation and (sometimes) chilling temperatures reduced dry matter accumulation, and (4) low temperature prevented normal seed setting. The study did not address several other potentially important effects of nuclear war discussed in SCOPE 28. These include the effects of increased ionizing radiation and air pollutants, effects of reduced daylength on crop phenology, or changes in rainfall distribution. Increased ionizing radiation and air pollutants could cause yield reductions, though it would probably be confined to areas near targets, especially cities. If reduction in daylength are caused by intense smoke cover, change in development could occur in crops such as soybeans that flower and mature sooner under short days.

Diurnal temperature variation would probably increase for a few days or weeks at the beginning of a war because smoke would not be evenly dispersed in the atmosphere. This might cause localized frosts to be more damaging than those simulated in this study. After smoke cover becomes uniformly distributed, a reduction in diurnal temperature variation would probably occur. Major changes in rainfall amounts and distribution would be expected due to disruption of weather systems by smoke and heating of the upper atmosphere.

Yield response to climate change depends on location, crop, the timing and magnitude of changes in climate variables, and the duration of changes. If nuclear exchange occurred at a time after the crop was planted, then yield losses in that year would be affected to a major extent by the transient changes in climate. In addition to changes in plant growth and yield, field operations could be impaired in such a way that harvested yield would be considerably lower than field yields. Contamination of crops could further reduce effective yields over large areas. Therefore, model simulations represent an upper limit on yields and a somewhat conservative estimate of yield losses if nuclear exchange were to occur within a growing season. Similarly, if the simulated results are for the chronic phase (if the exchange occurred in the winter or in the previous season), they would also represent an upper limit because of additional constraints imposed by dramatic changes in agricultural infrastructures and the availability and distribution of resources. Dramatic crop failure in one year could drastically reduce seed stock for the following year and further reduce effectiveness of agriculture in post-war years.

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