Long-Term Biological Consequences of Nuclear War

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Summary. Subfreezing temperatures, low light levels, and high doses of ionizing and ultraviolet radiation extending for many months after a large-scale nuclear war could destroy the biological support systems of civilization, at least in the Northern Hemisphere. Productivity in natural and agricultural ecosystems could be severely restricted for a year or more. Postwar survivors would face starvation as well as freezing conditions in the dark and be exposed to near-lethal doses of radiation. If, as now seems possible, the Southern Hemisphere were affected also, global disruption of the biosphere could ensue. In any event, there would be severe consequences, even in the areas not affected directly, because of the interdependence of the world economy. In either case the extinction of a large fraction of the Earth's animals, plants, and microorganisms seems possible. The population size of *Homo sapiens* conceivably could be reduced to prehistoric levels or below, and extinction of the human species itself cannot be excluded.

Recent studies of large-scale nuclear war (5000- to 10,000-MT yields) have estimated that there would be 750 million immediate deaths from blast alone (*1*); a total of about 1.1 billion deaths from the combined effects of blast, fire, and radiation (*2*); and approximately an additional 1.1 billion injuries requiring medical attention (*1, 2*). Thus, 30 to 50 percent of the total human population could be immediate casualties of a nuclear war. The vast majority of the casualties would be in the Northern Hemisphere, especially in the United States, the U.S.S.R., Europe, and Japan. These enormous numbers have typically been taken to define the full potential catastrophe of such a war. New evidence presented here, however, suggests that the longer term biological effects resulting from climatic changes may be at least as serious as the immediate ones. Our concern in this article is with the 2 billion to 3 billion people not killed immediately, including those in nations far removed from the nuclear conflict.

We consider primarily the results of a nuclear war in which sufficient dust and soot are injected into the atmosphere to attenuate most incident solar radiation, a possibility first suggested by Ehrlich *et al.* (*3*), and first shown quantitatively and brought to wide attention by Crutzen and Birks (*1*). In a wide range of nuclear exchange scenarios, with yields from 100 MT up to 10,000 MT, we now know that enough sunlight could be absorbed and scattered to cause widespread cold and darkness [(*4, 5*); these papers are also collectively referred to as TTAPS]. In each of these cases the computations indicate very serious biological consequences. This is so even though all the scenarios are well within current capabilities and do not seem to be strategically implausible (*1, 2, 4–6*). Furthermore, the probability of nuclear wars of very high yield may have been generally underestimated (*7*). We also examine the consequences of the spread of atmospheric effects from the Northern to the Southern Hemisphere (*4, 5*).

As a reference case, we consider case 17 of the nuclear war scenarios discussed in TTAPS. This is a 10,000-MT exchange in which parameters describing the properties of dust and soot aerosols are assigned adverse but not implausible values and in which 30 percent of the soot is carried by fire storms to stratospheric altitudes. The resulting environmental perturbations, with their ranges of uncertainty, are listed for the Northern Hemisphere and the Southern Hemisphere in Table 1, A and B.

As an average over the Northern Hemisphere, independent of the season of the year, calculated fluxes of visible light would be reduced to approximately 1 percent of ambient, and surface temperatures in continental interiors could fall to approximately −40°C. At least a year would be required for light and temperature values to recover to their normal conditions. In target zones, it might initially be too dark to see, even at midday. An estimated 30 percent of Northern Hemisphere mid-latitude land areas would receive a dose ≳ 500 R immediately after the explosions. This dose, from external gamma-emitters in radioactive fallout, would be comparable to or more than the acute mean lethal dose (LD_{50}) for healthy adults (*8*). Over the next few days and weeks, fallout would contribute an additional external dose of ≳ 100 R over 50 percent of northern mid-latitudes. Internal doses would contribute another ≳ 100 R concentrated in specific body systems, such as thyroid, bones, the gastrointestinal

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tract, and the milk of lactating mothers (*9*). After settling of the dust and smoke, the surface flux of near-ultraviolet solar radiation (UV-B, 320 to 290 nm) would be increased severalfold for some years, because of the depletion of the ozonosphere by fireball-generated NO_x. Southern Hemisphere effects would involve minimum light levels < 10 percent of ambient, minimum land surface temperatures < −18°C, and UV-B increments of tens of percent for years. The potential impacts from the climatic changes that would be induced by nuclear war are outlined in Table 2.

Thermonuclear wars that would be less adverse to the environment are clearly possible, but climatic effects similar to those just outlined could well result from much more limited exchanges, down to several hundred megatons, if cities were targeted (*4, 5*). Even if there were no global climatic effects, the regional consequences of nuclear war might be serious (Table 3). We believe, however, that decision-makers should be fully apprised of the potential consequences of the scenarios most likely to trigger long-term effects. For this reason we have concentrated in this article on the 10,000-MT severe case rather than the 5000-MT nominal baseline case of TTAPS. Because of synergisms, however, the consequences of any particular nuclear war scenario are likely to be still more severe than discussed below. We still have too incomplete an understanding of the detailed workings of global ecosystems to evaluate all the interactions, and thus the cumulative effects, of the many stresses to which people and ecosystems would be subjected. Every unassessed synergism is likely to have an incremental negative effect.

Temperature

The impact of dramatically reduced temperatures on plants would depend on the time of year at which they occurred, their duration, and the tolerance limits of the plants. The abrupt onset of cold is of particular importance. Winter wheat, for

Table 1. Long-term stresses on the biosphere in (A) the Northern Hemisphere and (B) the Southern Hemisphere following a 10,000-MT severe Northern Hemisphere exchange (*4, 5*). Stresses occur simultaneously. Their geographic extent and severity would depend on many factors, including the number, distribution, and yield of the weapons detonated; height above the surface of the explosions and scale of the subsequent fires; degree of atmospheric transport of soot and dust (especially from the Northern to the Southern Hemisphere); and rate of washout of soot and dust, which determines their atmospheric residence times. Stresses in (B) are estimated effects which arise from 100-MT total detonations in the Southern Hemisphere plus particulates transported from the Northern Hemisphere primarily in the stratosphere. Data are from the "baseline 5000 MT" and "100-MT city attack" cases (*4, 5*). The Southern Hemisphere effects could be more severe if a heavy stratospheric soot burden resulted.

Physical parameter	Perturbed value*	Duration	Area affected†	Possible range
		A. Northern Hemisphere		
Sunlight intensity	× 0.01	1.5 months	NML	× 0.003 to 0.03
	× 0.05	3 months	NML	× 0.01 to 0.15
	× 0.25	5 months	NH	× 0.1 to 0.7
	× 0.50	8 months	NH	× 0.3 to 1.0
Land surface temperature‡	−43°C	4 months	NML land	−53° to −23°C
	−23°C	9 months	NH land	−33° to −3°C
	−3°C	1 year	NH land	−13° to +7°C
UV-B radiation§	× 4	1 year	NH	× 2 to 8
	× 3	3 years	NH	× 1 to 5
Radioactive fallout exposure‖	≳ 500 R	1 hour to 1 day	30 percent NML land	
	≳ 100 R	1 day to 1 month	50 percent NML	Factor of 3
	≳ 10 R	≳ 1 month	50 percent NH	
Fallout burdens§,¶	^{131}I, 4 × 10^5 MCi	8 days#	NML	
	^{106}Ru, 1 × 10^4 MCi	1 year	NH	
	^{90}Sr, 400 MCi	30 years	NH	
	^{137}Cs, 650 MCi	30 years	NH	
		B. Southern Hemisphere		
Sunlight intensity	× 0.1	1 month	SH tropics	0.03 to 0.3
	× 0.5	2 months	SH tropics and SML	0.1 to 0.9
	× 0.8	4 months	SH	0.3 to 1.0
Land surface temperature‡	−18°C	1 month	SML land	−33° to −3°C
	−3°C	2 months	SML land	−23° to +7°C
	+7°C	10 months	SML land	−13° to +13°C
UV-B radiation§	× 1.5	1 year	SH	× 1.2 to 2.0
	× 1.2	3 years	SH	× 1.0 to 1.5
Radioactive fallout exposure‖	≳ 500 R	1 hour to 1 day	Near detonation sites	
	10 to 100 R	1 day to 1 month	SH land	Factor of 3
Fallout burdens§,¶	^{90}Sr, 300 MCi	30 years	SH	
	^{137}Cs, 330 MCi	30 years	SH	

*The following definitions apply: ×, multiplicative factor; R, rad ≃ rem; MCi, megacurie. †Abbreviations: NH, Northern Hemisphere; NML, northern mid-latitudes; SH, Southern Hemisphere; SML, southern mid-latitudes. ‡Average surface temperatures should be compared to the normal ambient value of 13°C. §From (*4, 5, 22*). ‖These figures are rough estimates of whole-body gamma-ray doses and apply only to exposed organisms, particularly near or downwind of the 10^4 explosion sites. Exposures are due to fallout on "prompt" and "intermediate" time scale; ingestion of biologically active radionuclides is not taken into account, but could double the dose in body organs (for instance, the thyroid for ^{131}I), where these radionuclides tend to accumulate. Doses are larger than in some conventional models which scale from high-yield atmospheric tests; such models assume much more radioactivity carried into the stratosphere and decaying before falling out than is appropriate for a war with a wide mix of yields (*4, 5, 40*). ¶The principal modes of deposition are fallout and washout. In airbursts, the radionuclides settle out slowly over several years. In surface bursts, ≃ 60 percent falls out promptly, ≃ 40 percent over 1 to 2 years. In subsurface water bursts, ~ 100 percent is deposited in the water. During the atmospheric nuclear tests of the 1950's and 1960's, ~ 200 MT of fission yield produced an average ^{90}Sr deposition ~ 50 millicuries per square kilometer. #These are essentially the radionuclide lifetimes. Other radionuclides contribute mainly to the prompt fallout exposure.

example, can tolerate temperatures as low as −15° to −20°C when preconditioned to cold temperatures (as occurs naturally in fall and winter months), but the same plants may be killed by −5°C if exposed during active summer growth (*10*). Even plants from alpine regions, *Pinus cembra* for example, may tolerate temperatures as low as −50°C in midwinter but may be killed by temperatures of −5° to −10°C occurring in summer (*11*). In the TTAPS calculations, temperatures are expected to fall rapidly to their lowest levels (Table 1); it is unlikely under these circumstances that normally cold-

Table 2. Potential impacts on humans and ecosystems from climatic changes induced by a major nuclear war at various time periods after the war.

First few months	End of first year	Next decade
	Natural ecosystems: Terrestrial	
Extreme cold, independent of season and widespread over the Earth, would severely damage plants, particularly in mid-latitudes in the Northern Hemisphere and in the tropics. Particulates obscuring sunlight would severely curtail photosynthesis, essentially eliminating plant productivity. Extreme cold, unavailability of fresh water, and near darkness would severely stress most animals, with widespread mortality. Storm events of unprecedented intensity would devastate ecosystems, especially at margins of continents.	Many hardy perennial plants and most seeds of temperate plants would survive, but plant productivity would continue to be depressed significantly. As the atmosphere clears, increased UV-B would damage plants and impair vision systems of many animal species. Limited primary productivity would cause intense competition for resources among animals. Many tropical species would continue to suffer fatalities or reduced productivity from temperature stress. Widespread extinction of vertebrates.	Basic potential for primary and secondary productivity would gradually recover; however, extensive irreversible damage to ecosystems would have occurred. Ecosystem structure and processes would continue to respond unstably to perturbations and a long period of time might follow before functional redundancies would reestablish ecosystem homeostasis. Massive loss of species, especially in tropical areas, would lead to reduced genetic and species diversity.
	Natural ecosystems: Aquatic	
Temperature extremes would result in widespread ice formation on most freshwater bodies, particularly in the Northern Hemisphere and in mid-latitude continental areas. Marine ecosystems would be largely buffered from extreme temperatures, with effects limited to coastal and shallow tropical areas. Light reductions would essentially terminate phytoplankton productivity, eliminating the support base for many marine and freshwater animal species. Storms at continental margins would stress shallow-water ecosystems and add to sediment loadings. Potential food sources would not be accessible to humans or would be contaminated by radionuclides and toxic substances.	Early loss of phytoplankton would continue to be felt in population collapses in many herbivore and carnivore species in marine ecosystems; benthic communities would not be as disrupted. Freshwater ecosystems would begin to thaw, but many species would have been lost. Organisms in temperate marine and freshwater systems adapted to seasonal temperature fluctuations would recover more quickly and extensively than in tropical regions.	Recovery would proceed more rapidly than for terrestrial ecosystems. Species extinctions would be more likely in tropical areas. Coastal marine ecosystems would begin to contain harvestable food sources, although contamination could continue.
	Agroecosystems	
Extreme temperatures and low light levels could preclude virtually any net productivity in crops anywhere on Earth. Supplies of food in targeted areas would be destroyed, contaminated, remote, or quickly depleted. Nontargeted importing countries would lose subsidies from North America and other food exporters.	Potential crop productivity would remain low because of continued, though much less extreme, temperature depressions. Sunlight would not be limiting but would be enriched with UV-B. Reduced precipitation and loss of soil from storm events would reduce potential productivity. Organized agriculture would be unlikely, and modern subsidies of energy, fertilizers, pesticides, and so on, would not be available. Stored food would be essentially depleted, and potential draught animals would have suffered extensive fatalities and consumption by humans	Biotic potential for crop production would largely be restored. Limiting factors for reestablishment of agriculture would be related to human support for water, energy, fertilizers pest and disease protection, and so on.
	Human-societal systems	
Survivors of immediate effects (from blast, fire, and initial ionizing radiation) would include perhaps 50 to 75 percent of the Earth's population. Extreme temperatures, near darkness, violent storms, and loss of shelter and fuel supplies would result in widespread fatalities from exposure, starvation, lack of drinking water, and synergisms with other impacts such as radiation exposure, malnutrition, lack of medical systems, and psychological stress. Societal support systems for food, energy, transportation, medical care, communications, and so on, would cease to function.	Climatic impacts would be considerably reduced, but exposure would remain a stress on humans. Loss of agricultural support would dominate adverse human health impacts. Societal systems could not be expected to function and support humans. With the return of sunlight and UV-B, widespread eye damage could occur. Psychological stresses, radiation exposures, and many synergistic stresses would continue to affect humans adversely. Epidemics and pandemics would be likely.	Climatic stresses would not be the primary limiting factors for human recovery. Rates of reestablishment of societal order and human support systems would limit rates of human population growth. Human carrying capacities could remain severely depressed from prewar conditions for a very long period of time, at best.

tolerant plants could "harden" (develop freezing tolerance) before lethal temperatures were reached. Other stresses to plants from radiation, air pollutants, and low light levels immediately after the war would compound the damage caused by freezing. In addition, diseased or damaged plants have a reduced capacity to harden to freezing conditions (*11*).

Even temperatures considerably above freezing can be damaging to some plants. For example, exposure of rice or sorghum to a temperature of only 13°C at the critical time can inhibit grain formation because the pollen produced is sterile (*11*). Corn (*Zea mays*) and soybeans (*Glycine max*), two important crops in North America, are quite sensitive to temperatures below about 10°C.

While a nuclear war in the fall or winter would probably have a lesser effect on plants in temperate regions than one in the spring or summer, tropical vegetation is vulnerable to low temperatures throughout the year. The only areas in which terrestrial plants might not be devastated by severe cold would be immediately along the coasts and on islands, where the temperatures would be moderated by the thermal inertia of the oceans. These areas, however, would experience particularly violent weather because of the large lateral temperature gradient between oceans and continental interiors.

Visible Light

The disruption of photosynthesis by the attenuation of incident sunlight would have consequences that cascade through food chains, many of which include people as consumers. Primary productivity would be reduced roughly in proportion to the degree of light attenuation, even making the unrealistic assumption that the vegetation would remain otherwise undamaged.

Many studies have examined the effects of shading on the rate of photosynthesis, plant growth, and crop yield (*12*). Although individual leaves may be saturated by light levels below one-half of unattenuated sunlight, entire plants that have several layers of leaves oriented at different angles to the sun and partially shading each other are usually not light-saturated. Thus, while only a 10 percent reduction in light might not reduce photosynthesis in a fully exposed leaf, it might well reduce it in the entire plant because of the presence of unsaturated leaves within the canopy. Because plants also respire, most would, in fact, be unlikely to maintain any net growth if the light level fell below about 5 percent of the normal ambient levels in their habitats (the compensation point) (*12, 13*). At the levels expected in the early months following a substantial nuclear exchange, plants would be severely affected and many would die because of the substantial reductions in their net productivity caused by reduced light alone.

Ionizing Radiation

Exposures to ionizing radiation in a nuclear exchange would result directly from the gamma and neutron flux of the fireball, from the radioactive debris deposited downwind of the burst, and from the component of the debris that becomes airborne and circulates globally.

The degree of injury to organisms would depend on the rate and magnitude of the exposure, with higher rates and larger total exposures producing more severe effects. The mean lethal exposure for human beings is commonly thought to be 350 to 500 R received in the whole body in less than 48 hours. Most other mammals and some plants have mean lethal exposures of less than 1000 R. If the rate of exposure is lower, the mean lethal dose rises.

The area subject to intense radiation from the fireball would also be affected directly by blast and heat (*9, 14*). The radius within which the pressure from the blast exceeds 5 pounds per square inch has been defined as the lethal zone (*9*) for blast, and the area within which the thermal flux exceeds 10 cal/cm^2 as the lethal zone for heat. The radius within which ionizing radiation from the fireball would be expected to be lethal for human beings is less than the radii for mortality defined by pressure or heat (*1, 9*). No special further consideration has been given here to the effects of ionizing radiation from the fireballs.

One estimate, based on the *Ambio* scenario (*1*) and similar to the TTAPS baseline case, involves an exchange of 5742 MT and about 11,600 detonations without overlapping fallout fields; it suggests that about 5×10^6 km^2 would be exposed to 1000 R or more in downwind areas. About 85 percent of this total exposure would be received within 48 hours. Such an exposure is lethal to all exposed people and cause the death of sensitive plant species such as most conifers—trees that form extensive forests over most of the cooler parts of the Northern Hemisphere. If nuclear reactors, radioactive waste storage facilities, and fuel reprocessing plants are damaged during an exchange, the area affected and the levels of ionizing radiation could be even greater.

If we assume that approximately half of this area affected by fallout radiation in the range 1000 to 10,000 R is forested, there would be about 2.5×10^6 km^2 within which extensive mortality of trees and many other plants would occur (*15*). This would create the potential for extensive fires. Most conifers would die over an area amounting to about 2.5 percent of the entire land surface of the Northern Hemisphere.

The possibility that as much as 30 percent of the mid-latitude land area would be exposed to 500 R or more from gamma radiation emphasizes the scale and severity of the hazard (Table 1A). While 500 R of total exposure would have minor effects on most plant populations, it would cause widespread mortality among all mammals, including human beings. The unprotected survivors would be ill for weeks and more prone to cancer for the remainder of their lives. The total number of people afflicted would exceed 1 billion.

UV-B Radiation

In the weeks following the exchange, tropospheric and stratospheric dust and soot would absorb the UV-B flux that would otherwise be transmitted by the partially destroyed ozonosphere. But when the dust and soot cleared a few months later, the effects of O_3 depletion would be felt at the surface. In the Northern Hemisphere, the flux of UV-B would be enhanced for about a year by a factor of about 2 for the baseline TTAPS exchange and by a factor of 4 for the 10,000 MT war-treated in Table 1A. As is the case for an undepleted ozonosphere, the UV-B dose would be significantly greater at equatorial than at temperate latitudes.

Even much smaller O_3 depletions are considered dangerous to ecosystems and to people (*16*). If the entire UV-B band is enhanced by about 50 percent, the amount of UV-B at the higher energy end of the band, near 295 nm, would be increased by a factor of about 50. This region has particular biological significance because of the strong absorption of energy at these wavelengths by nucleic acids, aromatic amino acids, and the peptide bond. In large doses, UV-B is very destructive to plant leaves, weakening the plants and decreasing their productivity (*17*). Near-surface productivity of marine plankton is known to be depressed significantly by contemporary ambient UV-B levels; even small increases in UV-B could have "profound consequences" for the structure of marine food chains (*16*).

There are at least four additional ways in which increased levels of UV-B are known to be harmful to biological systems: (i) the immune systems of *Homo sapiens* and other mammals are known to be suppressed even by relatively low doses of UV-B (*18*). Especially under conditions of increased ionizing radiation and other physiological stress, such suppression of the immune systems leads to an increase in the incidence of disease. (ii) Plant leaves that reach maturity under low light intensities are two to three times more sensitive to UV-B than leaves that develop under high light intensities (*19*). (iii) Bacterial UV-B sensitivity is enhanced by low temperatures, which suppress the normal process of DNA repair, a process that is dependent on visible light (*16*). (iv) Protracted exposure to increased UV-B may induce corneal damage and cataracts, leading to blindness in human beings and terrestrial mammals (*20*). Thus the effects of increased UV-B may be among the most serious unanticipated consequences of nuclear war.

Atmospheric Effects

In a nuclear war, large quantities of air pollutants, including CO, O_3, NO_x, cyanides, vinyl chlorides, dioxins, and furans would be released near the surface (*4, 5, 21*). Smog and acid precipitation would be widespread in the aftermath of the nuclear exchange. These toxins might not have significant immediate effects on the vegetation that was already devastated, although, depending upon their persistence, they could certainly hinder its recovery. Their atmospheric transport by winds to more distant, initially unaffected ecosystems, on the other hand, might be an important additional effect. Large-scale fires coupled with an interruption of photosynthetic CO_2 uptake would produce a short-term increase in the atmospheric CO_2 concentration. The quantity of CO_2 now in the atmosphere is equivalent to that used by several years of photosynthesis and is further buffered by the inorganic carbon reserves of the ocean (*22*). Therefore, if the global climate and photosynthetic productivity of ecosystems recovered to near-normal levels within a few years, it is unlikely that any significant long-term change in the composition of the atmosphere would occur. It is not beyond the realm of possibility, however, that an event encompassing both hemispheres, with the ensuing damage to photosynthetic organisms, could cause a sudden increase in CO_2 concentration and thus long-term climatic changes. For comparison, the time scale for recycling of O_2 through the biosphere is about 2000 years (*23*).

Agricultural Systems

There is little storage of staple foods in human population centers, and most meat and fresh produce are supplied directly from farms. Only cereal grains are stored in significant quantities, but the sites at which they are stored often are located in areas remote from population centers. Following a spring or early summer war, the current year's crops would almost certainly be lost. Cereal crops would be harvested before a fall or winter war, but since the climate would remain unusually cold for many months, the following growing season would also be unfavorable for crop growth.

After a nuclear war, in short, the available potential supplies of food in the Northern Hemisphere would be destroyed or contaminated, located in inaccessible areas, or rapidly depleted. For nations experiencing the nuclear war di-

Table 3. Potential ecological consequences of the reference nuclear war, other than those induced by temperature and light reductions.

Stress	Intensity or extent	Mechanisms of effects	Ecosystem consequences
Local, global radioactive fallout from nuclear detonation*	≥ 100 rem average background; ≥ 200 rem over large area in Northern Hemisphere*	Direct health effects; immune system depression; differential radiosensitivities of species; genetic effects	Alteration in trophic structures; pest outbreaks; replacement by opportunistic species; genetic and ontogenetic anomalies
Enhanced UV-B	Fourfold increase over Northern Hemisphere*	Suppression of photosynthesis; direct health effects; differential sensitivities of species; damage to vision systems; immune system depression	Reduction in primary productivity; alterations in marine trophic structures; blindness in terrestrial animals; behavioral effects in insects including essential pollinators
Fire	Secondary fires widespread over Northern Hemisphere; ≥ 5 percent of terrestrial ecosystems affected	Direct loss of plants; damage to seed stores; changes in albedo; habitat destruction	Deforestation and desertification, which continues through positive feedback (*39*); local climatic changes; large-scale erosion and siltation; nutrient dumping; species extinction
Chemical pollution of surface waters	Pyrotoxins; release from chemical storage areas	Direct health effects; differential sensitivities of species; bioconcentration	Loss of organisms; continued contamination of surface and ground water systems; loss of water for human consumption
Chemical pollution of atmospheres	Major releases of NO, O_3 and pyrogenic pollutants from detonations; major releases of toxic organics from secondary fires in urban areas and chemical storage facilities	Direct health effects; differential sensitivities of species; acid precipitation	Widespread smog; freshwater acidification; nutrient dumping

*See Table 1A.

rectly, food resources would become scarce in a very short time. Further, nations that now require large imports of foods, including those untouched by nuclear detonations, would suffer an immediate interruption of the flow of food, forcing them to rely solely on their local agricultural and natural ecosystems. This would be very serious for many less-developed countries, especially those in the tropics.

Most major crops are annuals that are highly dependent on substantial energy and nutrient subsidies from human societies. Further, the fraction of their yields available for human consumption requires excess energy fixation beyond the respiratory needs of the plants, depending on full sunlight, on minimization of environmental stresses from pests, water insufficiency, particulates, and air pollution, and so on. Providing these conditions would be far more difficult, if not impossible, over much, if not all, of the Earth following a nuclear exchange. Agriculture as we know it would then, for all practical purposes, have come to an end.

Since the seeds for most North American, European, and Soviet crops are harvested and stored not on individual farms but predominantly in or near target areas, seed stocks for subsequent years would almost certainly be depleted severely, and the already limited genetic variability of those crops (*24*) would probably be reduced drastically. Furthermore, the potential crop-growing areas would experience local climatic changes, high levels of radioactive contamination, and impoverished or eroded soils. Recovery of agricultural production would have to occur in the absence of the massive energy subsidies (especially in the form of tractor fuel and fertilizers) to which agriculture in developed countries has become adapted (*25*).

Except along the coasts, continental precipitation would be reduced substantially for some time after a nuclear exchange (*4, 5*). Even now, rainfall is the major factor limiting crop growth in many areas, and irrigation, with requirements for energy and human support systems for pumping ground water, would not be available after a war. Moreover, in the months after the war, most of the available water would be frozen, and temperatures would recover slowly to normal values (*26*).

Temperate Terrestrial Ecosystems

The 2 billion to 3 billion survivors of the immediate effects of the war would be forced to turn to natural ecosystems as organized agriculture failed. Just at the time when these natural ecosystems would be asked to support a human population well beyond their carrying capacities, the normal functioning of the ecosystems themselves would be severely curtailed by the effects of nuclear war.

Subjecting these ecosystems to low temperature, fire, radiation, storm, and other physical stresses (many occurring simultaneously) would result in their increased vulnerability to disease and pest outbreaks, which might be prolonged. Primary productivity would be dramatically reduced at the prevailing low light levels; and, because of UV-B, smog, insects, radiation, and other damage to plants, it is unlikely that it would recover quickly to normal levels, even after light and temperature values had recovered. At the same time that their plant foods were being limited severely, most, if not all, of the vertebrates not killed outright by blast and ionizing radiation would either freeze or face a dark world where they would starve or die of thirst because surface waters would be frozen and thus unavailable. Many of the survivors would be widely scattered and often sick, leading to the slightly delayed extinction of many additional species.

Natural ecosystems provide civilization with a variety of crucial services in addition to food and shelter. These include regulation of atmospheric composition, moderation of climate and weather, regulation of the hydrologic cycle, generation and preservation of soils, degradation of wastes, and recycling of nutrients. From the human perspective, among the most important roles of ecosystems are their direct role in providing food and their maintenance of a vast library of species from which *Homo sapiens* has already drawn the basis of civilization (*27*). Accelerated loss of these genetic resources through extinction would be one of the most serious potential consequences of nuclear war.

Wildfires would be an important effect in north temperate ecosystems, their scale and distribution depending on such factors as the nuclear war scenario and the season. Another major uncertainty is the extent of fire storms, which might heat the lower levels of the soil enough to damage or destroy seed banks, especially in vegetation types not adapted to periodic fires. Multiple airbursts over seasonally dry areas such as California in the late summer or early fall could burn off much of the state's forest and brush areas, leading to catastrophic flooding and erosion during the next rainy season. Silting, toxic runoff, and rainout of radionuclides could kill much of the fauna of fresh and coastal waters, and concentrated radioactivity levels in surviving filter-feeding shellfish populations could make them dangerous to consume for long periods of time.

Other major consequences for terrestrial ecosystems resulting from nuclear war would include: (i) slower detoxification of air and water as a secondary result of damage to plants that now are important metabolic sinks for toxins; (ii) reduced evapotranspiration by plants contributing to a lower rate of entry of water into the atmosphere, especially over continental regions, and therefore a more sluggish hydrologic cycle; and (iii) great disturbance of the soil surface, leading to accelerated erosion and, probably, major dust storms (*28*).

Revegetation might superficially resemble that which follows local fires. Stresses from radiation, smog, erosion, fugitive dust, and toxic rains, however, would be superimposed on those of cold and darkness, thus delaying and modifying postwar succession in ways that would retard the restoration of ecosystem services (*29*). It is likely that most ecosystem changes would be short term. Some structural and functional changes, however, could be longer term, and perhaps irreversible, as ecosystems undergo qualitative changes to alternative stable states (*30*). Soil losses from erosion would be serious in areas experiencing widespread fires, plant death, and extremes of climate. Much would depend on the wind and precipitation patterns that would develop during the first postwar year (*4, 5*). The diversity of many natural communities would almost certainly be substantially reduced, and numerous species of plants, animals, and microorganisms would become extinct.

Tropical Terrestrial Ecosystems

The degree to which the tropics would be subjected to the sorts of conditions described above depends on factors such as the targeting pattern (*1, 6*), the prevalence of fire storms, the breakdown of the distinction between troposphere and stratosphere, and the rate of interhemispheric mixing as a function of altitude (*4, 5*). The spread of dense clouds of dust and soot and subfreezing temperatures to the northern tropics is highly likely, and to the Southern Hemisphere at least possible, so that it is appropriate to discuss the probable consequences of such a spread (*4, 5*) (Table 1B).

For example, the seeds of trees in tropical forests tend to be much more short-lived than those of temperate zones. If darkness or cold temperatures, or both, were to become widespread in the tropics, the tropical forests could largely disappear. This would lead to extinction of most of the species of plants, animals, and microorganisms on the Earth (*31, 32*), with long-term consequences of the greatest importance for the adaptability of human populations.

If darkness were widespread in the tropics, vast areas of tropical vegetation, which are considered very near the compensation point (*33*), would begin to respire away. In addition, many plants in tropical and subtropical regions do not have dormancy mechanisms that enable them to tolerate cold seasons, even at temperatures well above freezing. Even if the darkness and cold were confined mainly to temperate regions, pulses of cold air and soot could carry quick freezes well into the tropics. This would amount to an enhanced case of the phenomenon known as "friagem," which is used to describe the effects of cool temperatures spreading from temperate South America and entering the equatorial Amazon Basin, where they kill large numbers of birds and fish (*34*). One can predict from existing evidence on cooling effects during the Pleistocene and their consequences (*35*) that continental low-latitude areas would be severely affected by low air temperatures and decreased precipitation.

The dependence of tropical peoples on imported food and fertilizer would lead to severe effects, even if the tropics were not affected directly by the war. Large numbers of people would be forced to leave the cities and attempt to cultivate the remaining areas of forest, accelerating their destruction and the consequent rate of extinction. These activities would also greatly increase the amount of soot in the atmosphere, owing to improvised slash-and-burn agriculture on a vast scale. Regardless of the exact distribution of the immediate effects of the war, everyone on the Earth would ultimately be affected profoundly.

Aquatic Ecosystems

Aquatic organisms tend to be buffered against dramatic fluctuations in air temperature by the thermal inertia of water. Nevertheless, many freshwater systems would freeze to considerable depths or completely because of the climatic changes after a nuclear war. The effect of prolonged darkness on marine organisms has been estimated (*36*). Primary producers at the base of the marine food chain are particularly sensitive to prolonged low light levels; higher trophic levels are subject to lesser, delayed propagated effects. Moreover, the near-surface productivity of marine plankton is depressed significantly by present UV-B levels; even small increases in UV-B could have profound consequences for the structure of marine food chains (*16, 37*). It is often thought that the ocean margins would be a major source of sustenance of survivors of a nuclear war; the combined effects of darkness, UV-B, coastal storms, destruction of ships in the war, and concentration of radionuclides in shallow marine systems, however, cast strong doubt on this.

Conclusions

The predictions of climatic changes are quite robust (*4, 5*), so that qualitatively the same types of stresses would ensue from a limited war of 500 MT or less in which cities were targeted (*38*) as from a larger scale nuclear war of 10,000 MT. Essentially, all ecosystem support services would be severely impaired (Tables 2 and 3). We emphasize that survivors, at least in the Northern Hemisphere, would face extreme cold, water shortages, lack of food and fuel, heavy burdens of radiation and pollutants, disease, and severe psychological stress—all in twilight or darkness.

The possibility exists that the darkened skies and low temperatures would spread over the entire planet (*4, 5*). Should this occur, a severe extinction event could ensue, leaving a highly modified and biologically depauperate Earth. Species extinction could be expected for most tropical plants and animals, and for most terrestrial vertebrates of north temperate regions, a large number of plants, and numerous freshwater and some marine organisms.

It seems unlikely, however, that even in these circumstances *Homo sapiens* would be forced to extinction immediately. Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects *alone* resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of over 1 billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere. Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future (*4, 5*). In any large-scale nuclear exchange between the superpowers, global environmental changes sufficient to cause the extinction of a major fraction of the plant and animal species on the Earth are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

References and Notes

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Theodore von Kármán and Applied Mathematics in America

John L. Greenberg and Judith R. Goodstein

Applied mathematics is generally regarded as having become a distinct discipline in the United States during World War II. Brown University, under Roland G. D. Richardson, formally instituted a program in applied mathematics, the nation's first, in 1941. New York University, under Richard Courant, later established its own program (*1*). By that time, Theodore von Kármán (1881–1963), Hungarian-born engineer and applied scientist and the first director of the Daniel Guggenheim Graduate School of Aeronautics at the California Institute of Technology, had already spent more than 10 years struggling to make applied mathematics respectable in his adopted country. To him, the measures taken during the war represented the first concerted, nationwide effort to resolve a long-standing scientific gap in the United States.

Von Kármán figured prominently in the rise of Caltech's school of aeronautics in the 1930's, and his experience in America in the 1930's helped define the issues that would lead to the organized development of applied mathematics in the next decade. Frequently pressed for his opinions on how to mobilize mathematicians for the war, von Kármán contributed the lead article "Tooling up mathematics for engineering," to the first issue of the *Quarterly of Applied Mathematics*, published in 1943 (*2*) under the auspices of Brown's program. Using the form of a dialogue, he eloquently stated the case for the applied mathematician in the service of science. He did not, however, wholeheartedly approve of the proposals for new applied mathematics institutes drafted just before Pearl Harbor, especially the "exaggerated" appeal to an "emergency" created by the war. In his review of one such proposal, he noted that the problem of applied mathematics could not be solved "through the ordinary process of supply and demand" (*3*, *4*). Indeed, an entirely different set of imperatives guided von Kármán in the 1930's.

Mathematicians and Engineers

Shortly after he had completed his first tour of the United States in 1926, which included a visit to Caltech, von Kármán

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