Foreseeable Effects of Nuclear Detonations on a Local Environment: Boulder County, Colorado

by

JEFFREY O. BENNETT
Department of Astro-Geophysics,

PATRICIA S.C. JOHNSON,
JEFFREY R. KEY (M.A. Northern Michigan),
DOUGLAS C. PATTIE (M.S. Texas),

&

ALAN H. TAYLOR (M.S. Oregon State),
Department of Geography, University of Colorado, Boulder, Colorado 80309, USA.

In contemplating the catastrophic consequences of detonating some or all of the world's existing massive armament of nuclear weapons, recent studies have focused on possible direct effects on human populations and on changes in the global atmosphere (NAS, 1975; OTA, 1979; Barnaby *et al.*, 1982; WHO, 1984), while paying relatively little attention to the likely effects upon local environmental systems. In this paper we attempt to describe the effects which, in our opinion, a specified nuclear war would have on the local systems and life of Boulder County, Colorado.

REFERENCE SCENARIO

In order to assess the effects of nuclear detonations, it is necessary to choose a scenario describing the global magnitude of the hypothetical war under consideration. The reference scenario which we have used is taken directly from a special double issue of the Swedish journal *Ambio* (published as its Vol. **11**, Nos 2–3, 1982, and cited widely in the present paper). We assumed the *Ambio* scenario to be a realistic appraisal of a nuclear exchange, and less arbitrary than any we could have developed independently; however, it ought not to be considered a description of the most likely course of any possible nuclear war.

A total of the equivalent of 5,742 megatons of TNT is assumed to be detonated on the date of June 10. We assume that winds in Boulder on this date are from the south-east at 4 metres per second—a common pattern. The distribution of these hypothetical bombs near Boulder is shown in Fig. 1, along with the fallout plumes that affect Boulder. It is assumed that Boulder does not receive any direct hit, whereas Denver, Colorado, lying 40 km to the south-east of Boulder, receives three one-megaton (Mt) groundbursts. Under the wind conditions chosen, other nearby detonations, such as those at military installations to the north, are insignificant in their impact on Boulder County in comparison with the Denver blasts.

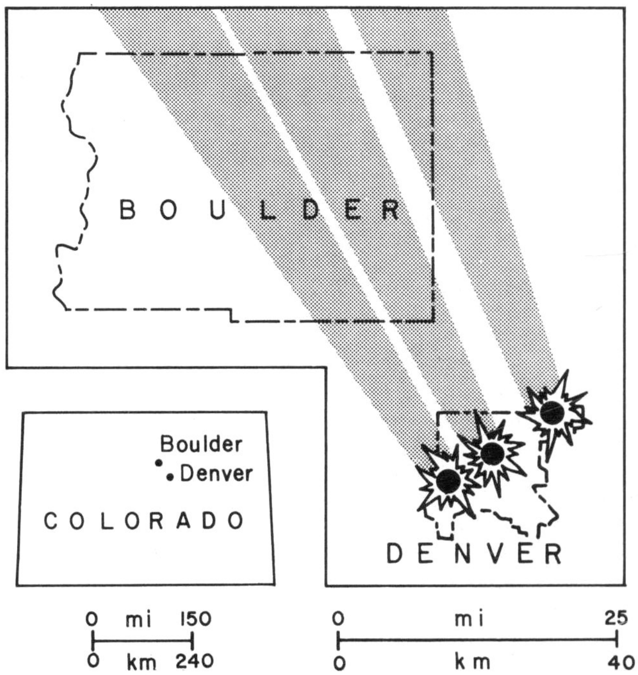

FIG. 1. *Boulder County, Colorado, with hypothetical wind-dispersal 'plumes' from imaginary detonations in Denver.*

RADIATION CALCULATIONS

We have calculated wind-dispersal plumes for radiation fallout based on the idealized fallout-pattern method presented in Glasstone & Dolan (1977). Plumes were mapped without overlap, and accumulated-dose contours were plotted. The whole-County radiation dose was calculated by taking the mean of the highest and lowest dose contours within the County. We consider this to be an underestimate of the actual dose, because of the uneven distribution of dose countours through the County. Whole-County radiation doses are presented in Table I for five different time-periods.

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TABLE I

Total Accumulated Radiation Doses for Boulder County.

Time Period (Days)	*Radiation Dose* (Rads)
1	650
7	1,095
30	1,238
180	1,370
365	1,374

To assess long-term impacts on the local environment, it was necessary to calculate the quantities of long-lived radioactive isotopes falling on Boulder County. This was done by assuming a total yield of three times that produced by a single 1 Mt bomb (Wetzel, 1982). We then assumed that this total quantity was evenly distributed throughout the plumes, and calculated the amounts in Boulder County on the basis of the fraction of the plumes' total area that was occupied by Boulder County. The results are shown in Table II.

TABLE II

Long-lived Radionuclides from Nuclear Fallout Which May Affect Consumability of Agricultural Products.

Isotope	*Half-life*	*Initial Accumulation from Fallout in Boulder County*
I^{131}	8 days	$2{,}080 \times 10^{-3}$ Ci/m^2
Sr^{90}	27.7 years	8.75×10^{-3} Ci/m^2
Cs^{137}	30 years	3.41×10^{-3} Ci/m^2
Sr^{89}	52 days	$1{,}214 \times 10^{-3}$ Ci/m^2

In addition to the local fallout from explosions in Denver, there would be global fallout from other detonations around the world. The effects of global fallout would, however, be negligible in comparison with that from the Denver explosions, though the possible consequences of temporary changes in global weather might be overriding. We note some of these global possibilities, but then concentrate on the local effects on living organisms as if there were to be no drastic alteration in weather-patterns.

BOULDER COUNTY SETTING

Boulder County lies astride the boundary of two major physiographic provinces along the eastern flank of the Colorado Rockies in north-central Colorado. The western part of the County is within the front range section of the Southern Rocky Mountains physiographic province, and the eastern part is within the Colorado Piedmont section of the Great Plains physiographic province. The elevation of the County ranges from 1,490 m along the eastern edge to over 4,000 m in the southwestern part (Fig. 2).

The outstanding physiographic feature of Boulder County is the abrupt, wall-like mountain front forming

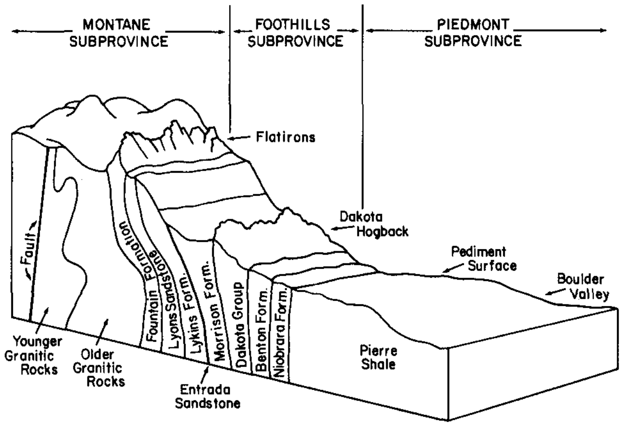

FIG. 2. *Geological cross-section of Boulder County, Colorado. Boulder County ranges in elevation from over 4,000 m in the south-west to 1,490 m in the east.*

the boundary between the Front Range and the Piedmont. The narrow foothills area along the western margins of the Piedmont is characterized by a series of folded and faulted sedimentary strata, the more resistant beds of which form prominent 'hogback' ridges that lie to the east of the igneous formations of the Rocky Mountains physiographic province.

The County is drained by tributaries of the South Platte River, the major ones being St Vrain Creek, Lefthand Creek, Boulder Creek, and Coal Creek. These streams originate in the mountainous western part of the County and flow in an easterly to northeasterly direction.

The County has a montane climate in the west and a high-plains, continental climate in the east. Annual precipitation ranges from 46–100 cm, increasing from east to west. A large proportion of the precipitation is in the form of snow, especially at the higher elevations. In the summer months of May to September, thunderstorm activity originating in or near the mountains is frequent.

Irrigated farmland in Boulder County supports a wide variety of crops, including corn (maize), alfalfa, sugar-beets, barley, oats, dry beans*, and pasture grasses. Cattle-grazing is common on rangeland, and considerable numbers of sheep, pigs, and turkeys, are raised by utilizing locally-available feed-crops (Table III).

ATMOSPHERIC EFFECTS

Effects of nuclear detonations on the atmosphere tend to be global in nature, owing to the rapid motions of air-masses, and it is clear that any such changes in the atmospheric environment would be of consequence to Boulder County. The effects of a nuclear war on the atmosphere can be broken down into two broad categories: (1) direct effects due to radiation and bomb-produced chemicals; and (2) indirect effects due to dust and smoke from bomb-induced fires.

* In response to our query about these, the first-named Author wrote (*in litt.* April 1984)) 'Dry beans refers to Navy Beans and Pinto Beans grown in Boulder; these are members of the genus *Phaseolus*. The term "dry beans" is used by the United States Census of Agriculture.'—Ed.

TABLE III

Estimated Populations of Selected Animal Species in Boulder County.

Domestic		*Non-domestic*	
Species	*Number*	*Species*	*Number*
Cattle	32,892	Golden Eagles (*Aquila chrysaetos*)	27
Pigs	3,695	Bald Eagles (*Haliaeetus leucocephalus*)	5
Sheep	3,100	Ptarmigan (*Lagopus leucurus*)	50
Horses	1,860	Mountain Lions (*Felis concolor*)	14
Chickens	625,928	Mule-deer (*Odocoileus hemionus*)	19,425
		Elk (*Cervus canadensis*)	1,615
		Black Bear (*Ursus americanus*)	75
		Beaver (*Castor canadensis*)	128

Sources: U.S. Census of Agriculture; Colorado Natural Resources, Division of Wildlife*.

Direct Effects

A primary concern resulting from direct effects is the possible destruction of the Earth's stratospheric ozone layer (Johnston, 1971, 1974; NAS, 1975). As this ozone 'shield' absorbs harmful solar ultraviolet radiation, a significant reduction in the layer would be of consequence. The key chemical constituents in this process of reduction are oxides of nitrogen, collectively known as NO_x.

NO_x are produced when air is heated to temperatures above 2000 K, as is the case in nuclear explosions (Crutzen & Birks, 1982). NO_x react differently with ozone in the troposphere and stratosphere. In the troposphere, NO_x are key factors in ozone production and the development of photochemical smog, whereas in the mid-stratosphere and above, NO_x act as catalysts for ozone destruction (Johnston, 1971, 1974; Crutzen & Birks, 1982). Thus, the effect of NO_x on the atmosphere depends crucially on whether the nuclear 'mushroom cloud' reaches the mid-stratosphere.

As a general rule, individual bombs must have yields of 1 Mt or more to inject material into the stratosphere (Glasstone & Dolan, 1977). Our reference scenario assumes that few bombs of this size would be used. Under this scenario, stratospheric ozone depletion does not appear to be a serious concern (Crutzen & Birks, 1982). Lower-yield bombs can, however, inject material into the stratosphere if detonated at high altitudes, or if clouds from multiple detonations merge.

In the troposphere, directly-produced NO_x will contribute to photochemical smog and ozone production. This would greatly increase the concentration of pollutants in Boulder County.

Indirect Effects

Large numbers of fires are expected to be ignited in a nuclear war—started either directly from thermal radiation in nuclear detonations, or indirectly from such events as broken gas-lines. Complicating this situation would be the fact that most fire-fighting capabilities would be incapacitated.

Thermal radiation is released during the first few seconds after detonation, and consists primarily of visible and infrared light. In a typical nuclear explosion, thermal radiation accounts for approximately 35% of the total energy-yield. Thermal radiation is attenuated by the atmosphere, and the distance over which fires can be ignited is strongly dependent on atmospheric conditions (Glasstone & Dolan, 1977). Under clear, dry conditions, a single 1-Mt burst can ignite fires up to 16 km away (Lewis, 1979).

It is unlikely that thermal radiation from the Denver blasts would ignite fires in Boulder. It is likely, however, that fires started near Denver would spread into Boulder County. Ash and dust from these fires might cause a local darkening of the atmosphere over Boulder County during the burning period, and emissions from fires distributed globally would greatly increase this effect.

Using the *Ambio* scenario, Crutzen & Birks (1982) conservatively estimated that, globally, 10^6 km^2 of forest would burn in the wake of that hypothetical nuclear war. This is roughly 20 times the average annual area of wildfires. A total production of 2–4 $\times$ 10^{14} g of particulate matter is estimated from these nuclear-engendered fires, with an average composition of 55% tar, 25% soot, and 20% ash. Assuming tropospheric residence times of from five to ten days, with fires lasting for two months, Crutzen & Birks (1982) calculate the average particle-loading in a vertical column to be 0.1–0.5 g per m^2 over half of the northern hemisphere. The resulting average sunlight penetration to the ground would be reduced to one-hundredth of its normal value for 1.5 months (Ayensu *et al.*, 1983; cf. Ehrlich *et al.*, 1983).

It should be noted that these estimates include only emissions from forest fires. Crutzen & Birks (1982) suggest that a similar total urban area could be expected to burn. In addition, it is conceivable that gas- and/or oil-wells might be targeted. Such occurrences would greatly increase the total amount of matter injected into the atmosphere.

Crutzen & Birks (1982) also point out that fire emissions contribute to air pollution through the mechanism of photochemical smog. Dust in the atmosphere exacerbates pollution problems by creating a temperature inversion. Those Authors estimate that tropospheric ozone concentrations could reach from three to five times the normal background levels for several months following a nuclear war. Ozone has been shown to produce numerous public-health effects, and inhibits plant growth (Taylor, 1980; Treshow, 1984). Crutzen & Birks (1982) would expect additional heavy pollution from ethers, NO_x, PAN (peroxyacetyl nitrate),

* A referee points out that 'The sources provided for Table III are incomplete to the point that precludes their being tracked down; this prevents one from checking the correctness, and determining the precise date, of when Boulder County, Colorado, contained exactly 625,928 chickens.'—Ed. [Later correspondence with the Authors elicited further sources as follows, 'for domestic count: US Dept of Commerce, Bureau of the Census, 1980; for non-domestic: Schrupp, Donald, Colorado Natural Resources, Division of Wildlife, pers. comm.—Ed.]

and other compounds. Turco *et al.* (1983) suggest that nitrite compounds, burned in urban fires, might decompose into cyanide vapours which could prove lethal if inhaled. Certain synthetic organics also release extremely stable and toxic dioxins and dibenzofurans in combustion, which might prove even more lethal than cyanide (*Ibid.*).

There has been some speculation that these effects on the atmosphere might lead to global ecological changes. If land-surface sunlight levels were reduced by a factor of 100 for even a few days, most of the phytoplankton and herbivorous zooplankton in the oceans of the northern hemisphere would die (Milne & McKay, 1982). This occurrence could lead to major changes in ocean environments and biotic populations.

Turco *et al.* (1983) have attempted to quantify the effects of atmospheric particles injected by fires, using detailed models involving the various optical absorption parameters of the injected particles. They estimate that surface temperatures over continents in the northern hemisphere would drop by 40°C initially and remain below freezing-point for six months. The model predicts that surface temperatures would recover to ambient levels only after two years. At the same time, they estimate a warming of 80°C in the lower stratosphere, producing a strong inversion.

The global consequences of such an extreme surface cooling event are difficult to predict, and we do not consider this impact in our discussion of Boulder County. It is reasonable to assume that a six-months' period of sub-freezing temperatures would prove lethal to many local organisms. However, long-term climatic changes are not anticipated from the model presented by Turco *et al.* (1983).

Hydrologic Effects

The scenario assumes an even dispersal of about 8,750 Ci/km² of strontium-90 over Boulder County, as precipitation infiltrates the land surface and becomes available for plant transpiration or ground-water recharge. The radioactive strontium-90 might then be immobilized by base exchange, by sorption reactions with the soil or aquifer matrix, or with stream-bed materials. The nuclides might react with stream-borne sediment and remain mobile, with the greater part of the delayed fallout residing near its point of fall until moved as water-borne sediment. Following the *Ambio* scenario, the rate of leaching of strontium-90 from the soil would be of the order of 1.5% (2.4×10^5 Ci/year), and about 2,000 Ci/km² would be exchanged or absorbed and prevented from being taken into solution by ephemeral rivulets or perennial streams. The direct fallout on the surface of the water area (40 km²) is expected to have only a minimal effect on the concentration levels.

Snow is a major vector for removing radioactive particles from the atmosphere. The amount of atmosphere washed free of radioactive fallout per unit volume of water is greater *via* snow than *via* rainfall (Stead, 1965; Osborn, 1966). Snow distribution in Boulder County is extremely uneven, and is largely dictated by altitude, general topography, temperature, wind force and direction, and vegetation type (Madole, 1965). Approximately two-thirds of the annual precipitation in Boulder County is in the form of snow, whose depth ranges from zero cm on the foothills to an average of 345 cm at Wild Basin and 660 cm at the Boulder water reservation station. Radioactive snow falling in June would accumulate in the hollows and other areas where the wind velocity is reduced.

During June the melt-rate from the glaciers exceeds the accumulation rate, and as water percolates into the snowfield, accumulated debris particles would serve as sorption surfaces for filtration of radioactive particles from the water. The snowfields of the Arapahoe and Arikaree Glaciers would retain all of the gross beta radioactivity until the snow-depth became reduced to only a few centimetres. Rocky substrates (gneiss, schist, monzonite, segenite, and granite) in the upper mountain zone, where large amounts of snow are deposited, filter great quantities of water. The gross beta activity on the rock surfaces might thus reach high levels.

By late summer the alpine lakes of Boulder County would contain much more radioactivity than the low-altitude reservoirs (such as Barker, Gross, and Boulder), though, over time, the large-capacity, long-residence-time reservoirs would begin to accumulate high concentrations. Radioactivity is reduced sharply within a few centimetres of a snow-accumulation site. The upper-alpine soil may easily contain some centimetres of water that is capable of nullifying the penetration of beta particles (strontium-90) (Martinelli, 1976; Schultz, 1982).

By late June, 95% of the stream-flow is supplied by late-lying snowfields and the filtration process of the first-order streams has become very important. Research indicates that stream-flow radioactivity is a function of stream branching, and influences the amount of radioactive particles to be filtered from the stream system (Allen, 1961; Iman, 1980). Steepness of the radioactive reduction gradient would depend on the type of substrate and the distance from the snowfield to the lake.

By July, one month after the detonation, gradients of radioactive water within Boulder County's drainage basins would be characterized by a sharp down-valley decrease, with each of the summer lakes and tundra ponds steadily increasing in radioactivity. Throughout much of the mountain environment, runoff would be increased as forest fires ignited by the detonations on Denver denuded the slopes. As a result, the lack of tree-cover would lead to an increase, by from by 13 to 15%, in the amount of precipitation impacting the ground surface (Claassen, 1981). In addition, the increased solar radiation in the treeless areas would produce a more rapid melt than formerly during the summer, which would increase at the expense of infiltration while simultaneously promoting increased erosion and incidence of mudslides.

However, one year after the detonations on Denver, the major tributaries of Boulder County would have strontium-90 levels lower than their maximum permissible concentration in drinking-water under the assumed scenario conditions (Table IV).

The effects of the supposed detonations at Denver on the ground-water systems of Boulder County would be influenced by the lithological, mineralogical, and physical, properties of the land surface and the aquifers; by the

TABLE IV

Estimated Concentrations in Streamflow One Year After Postulated Nuclear Detonations on Denver.

Boulder County Streams	*Strontium-90 Concentrations uCi/ml*
Boulder Creek	$.014 \times 10^{-7}$
South Boulder Creek	$.004 \times 10^{-7}$
St Vrain Creek	$.006 \times 10^{-7}$
Lefthand Creek	$.005 \times 10^{-7}$

Maximum permissible concentation in drinking-water (National Bureau of Standards) = 1×10^{-7} uCi/ml.

local porosity and the transmissibility, hydraulic head, gradient, direction, and velocity, of water-flows; by the chemical character of the water in each aquifer; by each aquifer's location and value of discharge; and by the 'working' distribution-coefficients for strontium-90 in equilibrium with the rock matrix of each aquifer (Hvinden, 1960; Stead, 1965; Waddell, 1981).

Both the granitic formations that underlie the mountainous western portion of the County and the sedimentary stratigraphy beginning at the slope-break, are important to the ground-water hydrology in Boulder County. The very deep sedimentary formations (known as the Pierre Shale, Dakota, Benton, Foxhill, Lamarie, and Araphoe, formations) are recharged by seepage from the overlying alluvial deposits. The rate of nuclide dispersal within the aquifers would depend largely on their reaction with materials by base-exchange and sorption which can be predicted from the flow-rate and chemical composition of the ground-water, together with the porosity and permeability of the substrate (Hvinden, 1960).

As soluble strontium-90 percolated into the aquifers of the Arapahoe formation and reacted with successive sandstone segments, the nuclides would be transported down the hydraulic gradient, while hydrodynamic dispersion would spread nuclide-bearing water both longitudinally and laterally, thereby diluting the initial concentration of strontium-90 by possibly one or more orders of magnitude.

BIOLOGICAL EFFECTS: VEGETATION

The effect of ionizing radiation on plants varies significantly among species. The radiosensitivity of a particular species has been linked to the chromosome number: species with high chromosome numbers are more radiosensitive than those with low ones (Woodwell & Whittaker, 1968). Species-sensitivity is also related to the type of radiation, total exposure, rate of exposure, and the plant's developmental stage (Bensen & Sparrow, 1971).

Forests

Extensive coniferous forests are found between the elevations of 1,830 and 3,470 m (Marr, 1961). These forests cover approximately 835 km²—45% of Boulder County. Radiosensitivity ranges for dominant coniferous species that are found in the region, are presented in Table V. Accumulated radiation doses (Table I) for Boulder County fall within the lethal range for all dominant coniferous species. Thus it is anticipated that extensive tree mortality would be caused by early fallout.

Lethal doses for understorey shrubs and herbaceous species exposed to chronic irradiation in Long Island, New York, are greater than those expected from early fallout (Woodwell, 1982). We assume that Rocky Mountain understorey and herbaceous species would exhibit a similar response. Life-forms with an erect stature have been found to be more radiosensitive than other life-forms in a chronically irradiated forest (Woodwell & Whittaker, 1968).

TABLE V

Estimated Acute Exposures for Coniferous Species Found in Boulder County, Colorado: Low Values Represent Thresholds for Sensitivity, High Values a Fatal Dose. (Adapted from Woodwell, 1982.)

Species	*Exposure Range* (rads)
Picea engelmannii	330–880
Abies lasiocarpa	270–700
Pinus ponderosa	240–640
Pseudotsuga menziesii	310–820

There are three distinct characteristics which separate the disturbance associated with anticipated early fallout and other disturbances of a catastrophic nature. There are: (1) the extent of disturbance; (2) the continued influence of ionizing radiation on physiological processes; and (3) possible synergistic effects associated with the radioresistance of organisms such as Bacteria, Fungi, and insects. The resultant impact from early fallout on ecosystem structure and function may be greater in magnitude and of longer duration than those associated with other familiar natural and human-induced perturbations such as cutting and fire.

Substantial nutrient losses from ecosystems can be anticipated with the loss of the forest canopy (Likens *et al.*, 1978; Bormann & Likens, 1979). The rate of nutrient loss would depend on the sequence of disturbance events following the nuclear exchange, and on the rate of revegetation. Rapid nutrient-loss by solution and volatilization could be expected in the event of forest fires. The accumulation of large amounts of fuel associated with canopy mortality, would favour major conflagrations following any nuclear explosions.

The recovery of forest ecosystems through successional processes would be expected following nuclear detonations, but at a slower rate than following natural disturbances. Several factors might inhibit short-term productivity, slowing the successional process. Ionizing radiation has been found to decrease net photosynthesis and increase respiration in some species (Woodwell & Whittaker, 1968). Atmospheric changes associated with the net global effects of nuclear war would also tend to decrease productivity. For example, increased UV-B radiation resulting from expected stratospheric ozone depletion might impair plant production.

Depressed photosynthetic rates have been measured in exprimental studies of exposing species to high values of UV-B radiation (Pfahler *et al.*, 1981), and exposure-rates would probably be much greater than expected in the aftermath of a nuclear war; consequently the magnitude of this effect is indeterminable. Decrease in incident solar radiation, caused by dust and smoke and to be expected globally, would depress the rates of photosynthesis (Westing, 1981; Crutzen & Birks, 1982). Radioresistant insects might also play a role in retarding ecosystem productivity (Bensen & Sparrow, 1971; Westing, 1981). Dead and dying timber would provide additional host materials and breeding grounds for many insects, leading to possible outbreaks of bark beetles and defoliating insects (Sharpe *et al.*, 1976).

An additional characteristic of ionizing radiation as an agent of disturbance could further impede successional processes: ionizing radiation has been found, in experimental studies on cultivars, to decrease seed production, seed viability, and the biomass of second-generation individuals. Chromosome aberrations also tend to be more frequent in irradiated specimens than in others (Fautrier, 1976; Fraley, 1980; Igbal & Aziz, 1981). Similar experiments using UV-B radiation indicated increases in partially-aborted seeds (Pfahler *et al.*, 1981). Although the total doses of ionizing and UV-B radiation used in these experiments on *Zea mays* were greater than was expected from fallout and ozone depletion, this does not rule out more subdued responses from native plants for which experimental data are lacking. If such responses were indeed manifested, species regeneration would be expected to be impaired.

A conservative estimate of the forested area which would be destroyed in Boulder County is 590 km^2—more than half of the total forest cover. Ecosystem structure and function would be severely altered. The most critical change would be the loss of nutrients associated with the regional devastation of the forest cover, from which recovery would be expected to be extremely slow.

Agriculture

Numerous crops are grown on the piedmont surface area of Boulder County (Fig. 2). The fact that lethal doses for many of those cultivars are higher than the fallout to be expected, does not negate the possibility of substantial crop mortality or yield reduction from external radiation doses. Significant yield-reductions have been found in wheat, sorghum, and corn (maize), irradiated during anthesis with doses of between 500 and 1,500 rads (Bensen & Sparrow, 1971; Igbal & Aziz, 1981).

A concern of comparable seriousness to that of decreased agricultural productivity, is whether crops would be consumable by people and their livestock. Radioactive fallout includes many radionuclides which can move through the soil–plant–animal system. The uptake of radionuclides in this system depends on a number of factors, including the solubility, concentration, and physiochemical properties, of the radionuclide; the manner of absorption; the plant species involved; and the type of soil (USDA, 1962; USDC, 1964; Annenkov *et al.*, 1973; Glasstone & Dolan, 1977). Radionuclides with long half-lives, or with characteristics that allow them to be absorbed quickly by plant tissues, are of the greatest concern (Table II).

Radionuclides can enter plant tissue by two pathways: *via* soil through normal sorption processes, or aerially by fallout deposited directly on living tissue (USDC, 1964; Annenkov *et al.*, 1973; Glasstone & Dolan, 1977). Foliar intake of radionuclides is high initially but declines as fallout material is removed by wind and water into the soil sorption complex. The aerial pathway has been shown to produce the highest concentrations of radionuclides in crop plants (Annenkov *et al.*, 1973). Certain radionuclides penetrate plant tissues much more rapidly than others: thus caesium-137 moves quickly into plant tissues and accumulates in the grain, tubers, and roots, while strontium-90 and iodine-131 are only absorbed in small quantities (Annenkov *et al.*, 1973).

The amount of radionuclides absorbed *via* the aerial pathway also varies between species and cultivar. The intake through foliage depends on species characteristics such as leaf area, and on the density of plants in the field. Experimental results on crops typically grown in Boulder County indicate that absorption of radionuclides would be highest in corn (maize), followed in decreasing order by alfalfa, beets, hay, and oats (Annenkov *et al.*, 1973).

Accumulations of radionuclides by plant roots through the soil solution is many orders of magnitude less than that *via* direct foliar intake shortly after fallout deposition. However, as time since deposition increases, the soil pathway for radionuclide accumulation in plants becomes a major concern. This is particularly true for caesium-137 and strontium-90, which have long half-lives (Table II). Strontium-90 and caesium-137 are absorbed by plant roots in a manner similar to that of the nutrients calcium and potassium, respectively. The uptake of these radionuclides is significantly influenced by the amount of calcium and potassium in the soil. Calcium uptake by plants is slightly favoured over that of strontium-90 (USDC, 1964; Annenkov *et al.*, 1973; Glasstone & Dolan, 1977). Uptake of caesium-137 appears to be proportional to the total amount deposited on the ground (USDC, 1964; Glasstone & Dolan, 1977). Uptake of barium-140 by plants would be similar to that of strontium-90, but its shorter half-life diminishes its potential as a long-term health hazard.

Annenkov *et al.* (1973) expressed the differential accumulation of radionuclides in cultivars as a percentage of an introduced quantity. Corn (maize) and barley grains were found to have accumulated, *via* the soil pathway, only 0.34 and 0.02%, respectively, of the applied strontium-90. If we assume that the percentage uptake for these two crops in Boulder County is similar, the expected amount of strontium-90 in their grains can be estimated. Based on the assumptions in Table II, corn would accumulate 2.975×10^{-5}Ci, and barley grain 1.75×10^{-6}Ci, of strontium-90 *via* the soil pathway. Most other crops would accumulate concentrations of strontium-90 between these two values, with the exception of pasture species. Pasture species accumulated the largest amount of strontium-90 from soils of any type of crop plant tested by Annenkov *et al.* (1973). Pasture species are expected to accumulate 2.07×10^{-04} Ci of strontium-90.

Glasstone & Dolan (1977) indicate that only 1×10^{-6}Ci of strontium-90 needs to accumulate in the human body for the incidence of bone cancer to increase in human populations. With the scenario we have adopted, expected concentrations of strontium-90 in crops could reach 100 times this amount, which would expose the people and livestock of Boulder County to an extreme long-term health-hazard.

Biological Effects: Animal Life

While thermal radiation, the blast wave, and initial nuclear radiation, can cause serious direct injury to animal life, these factors are important only when the animal is within a few kilometres of the point of detonation. Boulder County, at its nearest point, is 24 km away from this epicentre (Fig. 1), and therefore no significant impact can be expected as a result of these components. Residual nuclear radiation, however, would have a serious impact on the animal life in Boulder County. While the data presented here have been generated from experiments with laboratory animals and, in some cases, farm animals, it is assumed that non-domestic species such as Mule-deer and Elk would exhibit responses similar to those of domestic animals.

The adverse effects of gamma radiation on the biotic environment appear to be caused by the ionization and excitation produced in the cells of living tissues. Cell constituents that are essential to normal functioning may be altered or destroyed—e.g. breakage of chromosomes, swelling of the nucleus, increase in viscosity of the cell-fluid, and increased permeability of the cell membrane. Irradiation of tissues and organs can result in ulcerations of the intestinal lining, epilation, haemorrhage with subsequent infection, and damage to lymphoid tissue and bone-marrow (Glasstone & Dolan, 1977).

In animals receiving whole-body irradiation, there is a symptomatic relationship between the total dose and the rate of administration. Animals receiving lethal doses at a slow rate (less than 25 rads per day) may survive for several weeks, even if the total dose is quite high (Glasstone & Dolan, 1977). On the other hand, if the same total dose is delivered in a period of a few hours, as is the case in our scenario, deaths occur more rapidly.

In addition to external whole-body exposure to gamma radiation, injury to the animals of Boulder County could be expected to result from inhalation and ingestion of fission-products. If the amount of consumed fission-products were great enough and the retention-time long enough, nuclides in the body could produce symptoms and injury resembling those from whole-body irradiation. The fission-products that present a long-term hazard from inhalation and/or ingestion are the isotopes caesium-137 and strontium-90. In general, internal exposures result in a concentration of radiostrontium in the bone-marrow, of radiocaesium in the muscle, and of radioiodine in the blood and thyroid. While ingestion, and to a lesser degree inhalation, would contribute to tissue damage, in most cases the animals of Boulder County would have received a fatal exposure from ambient fallout radiation long before the internal dose would reach critical limits (NAS, 1963).

Another type of injury related to radioactive fallout that can be expected to occur is the beta burn. Beta burns are largely superficial and would rarely, if ever, have lethal physiological effects. As with internal exposures, levels of beta radiation high enough to cause serious injury would most likely be accompanied by gamma radiation of sufficient magnitude to deliver lethal whole-body exposure. However, this does not discount the possible additive effects of whole-body external, internal, and surface, irradiation. Table VI presents the estimated lethality from fallout to 50% of the animals within 60 days (LD 50/60), where sheltered animals (in barn or dense forest) are assumed to receive only external gamma radiation, those outside but not feeding (in pen or corral) would in addition receive beta burns, and those feeding outside (in pasture or field) would also be subject to intestinal exposure.

Table VI

Lethal Response (rads) *of Mammals and Poultry to Fallout* (LD 50/60).
(Adapted from Glasstone & Dolan, 1977.)

Species	*Barn*	*Pen or Corral*	*Pasture*
Horses	670	600	350
Pigs (swine, hogs)	640	600	550
Sheep	400	350	240
Cattle	500	450	180
Poultry	900	850	800

The total accumulated dose for Boulder County (Table I) would exceed the LD 50/60 doses listed above for mammals, and therefore extensive mortality would be anticipated. The amounts and patterns of mortality would depend on the effectiveness of shelter, the degree of feed contamination, and the physiological state of the individual. Those secondary and tertiary consumers that survived external whole-body irradiation would have the greatest chance of continued survival. Primary consumers (i.e. herbivores) would serve as a hazard-reducing step in the food-chain of higher-level consumers, as an animal's filtering capacity will prevent most contamination from reaching its edible tissues or food products (NAS, 1963).

The possibility of radiation-induced mutation has generated widespread public interest. Laboratory experiments have shown that the probability of mutation in offspring of insects, specifically fruit-flies, depends on the total dose received by the gonads, while for mammals the mutation rate depends on both the total dose and the dose-rate (Glasstone & Dolan, 1977). Expected dose-rates in our scenario for Boulder County are such that the probability of mutation in offspring of mammals is low.

While the data related to the effects of radiation on aquatic organisms are limited, it appears that the fallout would be far less significant to aquatic life than to terrestrial animal and plant life (Polikarpov, 1966). The most radio-resistant forms of aquatic organisms are unicellular organisms and macrophytes, followed (in order of increasing sensitivity) by invertebrate animals, fishes, and amphibians. Iodine-131 would be of concern on a short-term basis; radioactive strontium and caesium are generally diluted sufficiently to remove them as a problem to adult fishes. However, fishes and amphibians are most radio-sensitive in early developmental stages (Polikarpov, 1966) and, in this respect, a nuclear explosion at the time of a hatch would have a serious impact on the fry.

In summary, mammals would be the most severely impacted phylum of animal life, and we consider an estimate of 50% mortality of mammal populations to be conservative. No data are currently available on the sensitivity of non-domestic bird species, but if the relatively high radio-resistance of poultry is any indication of the radio-resistance of other birds, their survival rate would be expected to be reasonably high. Fish populations would suffer the loss of a significant portion of the young-of-the-year, but the population as a whole should become stable within a few years. These conclusions consider only the 'direct' effects of nuclear radiation on animal life. Additionally, the changes in vegetation, air, and water quality, would further impact animal life.

In all cases, survivors could be expected to exhibit low rates of productivity (e.g. milk or egg production, susceptibility to infection, etc.) for a number of years (Bensen & Sparrow, 1971). This could be attributed both to the physiological damage produced by early fallout and to the damage incurred from prolonged internal and external exposure to residual fallout. Low rates of productivity could also be expected for at least the first-generation offspring in most mammals as a result of continued exposure (up to 20–30 years) to the radioisotopes of caesium and strontium that would be present in the soil and plants as described above.

Landform Effects

The geomorphic effects accompanying nuclear explosions are threefold: (1) ground-shaking from surface seismic-wave generation, (2) displacement along faults, and (3) hillslope instability and the secondary effects of changes in plant cover resulting from blast wave generation.

The generation of seismic waves by underground nuclear detonations is well documented (Hamilton & Healy, 1969; McKeown & Dickey, 1969; Basham & Hormer, 1972; McKeown, 1975), and seismographs are routinely used as detectors of nuclear weapons testing. Seismic waves generated by these tests have been measured with amplitudes equivalent to earthquake magnitudes of 7 on the Richter scale (Bolt, 1976). The underground tests at the Nevada Testing Site during the late 1960s triggered ground-shaking in Las Vegas 50 kilometres away, although no structural damage was reported (*Ibid.*).

Underground explosions produce surface seismic-waves (Love waves) similar to those produced by shallow-focus earthquakes. Love waves move the ground from side to side in a horizontal plane parallel to the Earth's surface but at right-angles to the direction of propagation. The damaging effects are a result of horizontal shaking when applied to structural foundations in the vicinity.

The bedrock in Boulder County is extensively faulted (Chase & McConaghy, 1972). Scott (1970) observed the displacement along the Quaternary-age Valmont fault to be 1.5 metres, but no other evidence of recent fault displacement has been cited in the County—which suggests that there has been little or no recent movement along the currently-mapped faults. It is generally believed that the fault systems within Boulder County are quite old and, consequently, inactive. Therefore, fault movement resulting from nuclear detonations under our scenario is assumed to be negligible.

Geomorphic hazards in Boulder County resulting from seismic-wave generation and/or fault displacement can be regarded as secondary in importance to those posed by hillslope instability and giving-way resulting from blast-wave propagation. This wave is a high-pressure system travelling near the surface of the land. The high topographic relief and the resulting high-energy environment of Boulder County makes the potential for mass-movement great. Slopes in excess of 20% are common in the foothills subprovince, and the active erosional setting of the County is such that some of these natural slopes are constantly on the verge of giving-way. The possibility of such slope failure, and also of surface erosion (which is more important in the long run), would be greatly increased with the removal of stabilizing vegetation that is expected after detonation of the suggested nuclear devices. Modification of a natural slope can result in disequilibrium, precipitating slope failure. Shock waves of any sort—from seismic tremour, thunder, mechanical equipment, or expose of slope material to oscillatory acceleration—can provide the slight increase in force which triggers a slide (Embleton & Thornes, 1979).

Slightly-cemented materials, loose sands, and steep, jointed rock-faces—all common in Boulder County—are particularly vulnerable to mass-movements caused by earthquakes and explosions. Shock vibrations tend to disturb intergranular bonds and cements, hence decreasing cohesion and internal friction. Rotational movement is caused by the increased horizontal forces acting on a slope; if the strength or stability of a slope which is already close to failure is reduced, a landslide will result (Embleton & Thornes, 1979).

Roughly 40% of Boulder County is underlain by the Pierre Shale (Crosby, 1978). Hummocky terrain throughout the eastern portion of the County is an indication of ancient landslide activity on weathered portions of this geologic unit. The Lykins Formation west of the Piedmont physiographic province and within the Foothills area, is also subject to mass-movement due to its high montmorillonite clay content. Therefore, mass-movement would be an important hazard to consider over the long term as well as being a likely short-term effect of detonation.

Recent evidence for mass-movement initiated by shock waves in Boulder County is common. Sonic vibrations caused by an early-morning thunderstorm in July 1972 apparently triggered a landslide in the Redrocks City

Park (Pendleton, 1978). The surface of the rupture occurred between the weathered Lykins Shale bedrock and colluvium*, after soils in the area had reached a near-critical saturated condition. Such occurrences are not unusual for the County. Areas as large as 195 acres (79 ha) had undergone extensive slope-failure prior to settlement of the Boulder urban area (Pendleton, 1978). Evidence of past landslide activity and areas susceptible to recurrence have been mapped. Many of these slopes could be expected to fail immediately following detonation of any nuclear devices in Denver, and additional hillslope failure could be anticipated with the removal of forest cover from such slopes. This condition could be expected to persist until new equilibrium conditions were established for each slope.

Clearly, increased landslide activity and mass-movement on slopes would increase sediment loads for adjacent stream channels. The tributaries of the South Platte River, which originate in the mountainous western half of the County, might be expected to receive higher-than-normal volumes of material from landslides originating within their areas of drainage. The primary effect of increased sediment loads in the streams would be flooding of urban settlements and adjacent cropland and rangeland. St Vrain Creek and Boulder Creek are mapped by the USGS as flood-prone, with adjacent property damage expected if debris accumulation within the stream channel occurs (McCain & Hotchkiss, 1975). Both of these drainages pass through rangeland and irrigated cropland of Boulder County and, as such, these areas could be expected to be impacted.

Failure of dams can result from skaking, fault displacement, overtopping from seiches (fluctuating levels of lakes), or massive landslides into the reservoir. The majority of mass-movements which might be expected to occur within Boulder County as a result of nuclear detonations and initial blast-wave propagation, would be along the mountain fronts and to the east, with very little in the way of direct effects likely to be felt farther up the mountain canyons. Therefore, Barker Dam and Reservoir, located approximately 11 km from the mouth of Boulder Canyon, are too far removed to be threatened by either surface waves or blast waves. However, indirect long-term effects on the structure, resulting from mass-movements precipitated by the loss of forest cover and subsequent erosional processes, cannot be discounted.

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* A 'heterogeneous mass of rock detritus or soil material emplaced primarily by gravitational processes on or at the foot' of a slope.—Ed.

SUMMARY

The effects on Boulder County, Colorado, of a major nuclear war are predicted. Although many of the effects of such a horrific event would be global in nature, the direct ones on Boulder County were considered in terms of being primarily due to three one-megaton blasts in Denver, situated 40 km to the south-east. Under assumed wind conditions, agricultural crops would be contaminated with radionuclides for prolonged periods, rendering them dangerous for human consumption. Loss of animal life, flooding, increased sedimentation, and extensive soil-erosion, should also be expected. Recovery times for environmental systems are difficult to predict. Indeed, unknown synergistic effects and global changes in atmospheric conditons might preclude eventual recovery.

Although numerous assumptions were made in these predictions, and the impacts described are scenario-dependent, the implications are clear: even if Boulder County received no direct hit, a nuclear war would have a devastating impact on the environmental systems that were considered.

The prognosis from this study and others for human societies and involved ecosystems in the event of nuclear war is grim. We hope that continued research and dignified publicity of results on the effects of nuclear war will increase the urgency with which solutions to the nuclear dilemma are sought.

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