BNL 917 (C-43)

80

10/4

OCT 7 1965

Conf-630805-1

ECOLOGICAL EFFECTS OF NUCLEAR WAR

G.M. WOODWELL, EDITOR

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
under contract with the
United States Atomic Energy Commission

DISCLAIMER

BNL 917 (C-43)
(Biology and Medicine;
Health and Safety - TID-4500, 41st Ed.)

*Proceedings of a Symposium**
Sponsored by

THE ECOLOGICAL SOCIETY OF AMERICA

at the
Thirteenth Meeting of

THE AMERICAN INSTITUTE OF BIOLOGICAL SCIENCES

Amherst, Massachusetts
August 1963

Biology Department
BROOKHAVEN NATIONAL LABORATORY
Upton, New York

***Original title,** *Some Approaches to the Effects of Nuclear Catastrophes on Ecological Systems.*

LEGAL NOTICE

PRINTED IN USA
PRICE $3.00

Available from the
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards
U.S. Department of Commerce
Springfield, Virginia

August 1965 2250 copies

PREFACE

Nuclear war between major powers would be a world-wide catastrophe of unprecedented proportions. Yet the threat of just such a war retains a dominating influence in international politics and raises the very difficult, almost unanswerable question, "If there were a war, how bad would it really be?"

The potential direct effects of war on humans have been discussed abundantly in many publications and are reasonably well known. The broader question of the effects of such a war on the living and nonliving systems upon which man superimposes his civilization is much more difficult and perplexing. To clarify the present status of knowledge on this subject, the Ecological Society of America sponsored a symposium entitled *Some Approaches to the Effects of Nuclear Catastrophes on Ecological Systems.* The papers published here were originally prepared for this symposium, which was held at Amherst, Massachusetts, in August 1963.

The major ecological effects of nuclear war hinge on two environmental factors: fire and ionizing radiation from fallout. Four papers deal primarily with these two subjects. One paper, a case history study of an insect outbreak in coniferous forests, provides an analogy useful in drawing general conclusions about the behavior of insect populations in natural ecosystems under various types of biological and physical stress.

It is hoped that this collection of papers will prove useful not only in clarifying the complex ecological problems involved in a nuclear holocaust, but also in defining for the generalist the normal patterns of structure, function, and development characteristic of natural ecosystems.

GEORGE M. WOODWELL

CONTENTS

Physical Damage From Nuclear Explosions

CARL F. MILLER
Stanford Research Institute, Menlo Park, California

The major hazards of nuclear explosions are well known: (1) the initial nuclear radiation, (2) thermal radiation, (3) blast and shock, and (4) residual ionizing radiation or fallout. The first three occur within a fraction of a second to minutes after an explosion, and their iso-intensity patterns on a horizontal surface are circular about the point of detonation. Local fallout occurs over a period of minutes to hours later and is concentrated downwind from the point of detonation.

The objective of this paper is to define the physical proportions of these hazards which, as the following papers will show, may have important ecological consequences as well as direct effects on man.

AREAS AFFECTED BY A NUCLEAR EXPLOSION

For a single nuclear explosion near the earth's surface, three characteristic areas may be identified. One area would receive gross physical damage from blast and heat, and a second, larger area would be affected only by fallout. The third area, outside these two zones, would sustain no blast damage and would receive less than some specified low level of fallout, which would permit free movement of people and vehicles immediately after the attack.

The area nearest the explosion, that receiving physical damage from the blast and thermal radiation, is called in this discussion the *damaged* area. Part of this area would receive fallout deposits from both low airbursts and land-surface explosions, at least from the detonations causing the blast damage. Areas receiving more than a certain level of fallout but no direct physical damage are termed *radep* (for "radioactive deposit") areas; all other areas are called *free* areas. The boundaries of these three zones may be defined in several ways. The *damaged* area is quite simply defined in terms of physical damage such as broken glass from the blast wave or fires started by thermal radiation from the explosion. The fires would probably provide the more spectacular evidence of the *damaged* area and would tend to set its boundary around larger areas for larger explosions. The boundary might also be defined by the 3-psi overpressure contour. Inside a *damaged* area thus defined, the above-ground water distribution systems and other services would be destroyed, and the streets covered with debris. In either case the *damaged* area in cities generally would be uninhabitable after an attack.

The *radep* areas include those which would receive sufficient local fallout to necessitate some level of shelter protection. It is not possible to define boundaries of *radep* areas in terms of the environment's being safe or hazardous. However, approximate methods for locating these boundaries can be devised in terms of exposure doses from ionizing radiation. The National Committee on Radiation Protection and Measurements' indicates that the largest dose that does not cause illness severe enough to require medical care in most people is about 200 r (roentgen units), i.e., the equivalent residual dose (ERD). Thus the location of the lowest fallout level resulting in an exposure dose of 200 r, ERD (maximum), could be used to define the outer perimeter of the *radep* area. Such an exposure dose is about 40 times the yearly maximal exposure dose currently permitted under controlled occupational radiological environments.

For an average fallout arrival time of 1 hr after detonation, the maximal ERD is about 80% of the infinity exposure dose.[2,3] However, for a fallout arrival time of 30 min, the maximal ERD increases to 100% of the infinity exposure dose. To allow a safety factor of at least two over the 200-r ERD, the criterion for determination of the initial boundary of the *radep* area must be an infinity exposure dose of 100 r or less. Figure 1 shows the decay rate of the radioactive component of fallout which is used to compute exposure doses.

In view of the spatial distribution of targets and the varying wind patterns that could occur during a nuclear war, *free* areas would include those receiving only world-wide or local fallout producing < 100 r. These *free* areas would be otherwise unaffected directly by the four major effects of the explosions. Movement of people and material within these areas would be unrestricted, and no protective measures would be required to assure immediate short-term survival of people.

An idealized fallout pattern' for a one-megaton (1-MT) 100%-fission surface detonation is shown in Figure *2*. The pattern shows a hot spot near ground zero and another farther downwind. In a real fallout pattern the iso-intensity contours would be much more irregular than the idealized ones shown in the figure. If it is assumed that the explosion was caused by a thermonuclear weapon in which half of the yield was due to fission reactions and half due to fusion reactions,[3] then the exposures on the iso-intensity contours of Figure *2* would be half the values shown.

The relationships of the position of the 100-r contour, the time of arrival of fallout, and the standard intensity of radiation, calculated for 1 hr after detonation, appear in Table 1. Applying the values of Table 1 directly to the contours of Figure 2 would give an outer boundary for the *radep* area which quite closely approximates the 30-r/hr contour at 1 hr.

The iso-intensity contours, however, are not very useful in determining rapidly or accurately whether a specific location would be within the *radep* areas (i.e., whether the infinity dose would be 100 r or more). Another method derived from calculated data[3] for a 5-MT land-surface explosion with a 50% fission yield utilizes an approximate relationship between the time of fallout arrival and the maximal observed ionization rate for the locations at which the infinity dose is 100 ± 20 r. This relationship is given by

$$I(\max) \simeq \frac{20}{t_a}, \qquad (1)$$

where $I(\max)$ is the maximal observed dose rate and t_a is the arrival time of the fallout in hours. Thus, if fallout starts arriving 1 hr after detonation, the distinction between *free* and *radep* areas would be a maximal observed intensity of 20 r/hr.

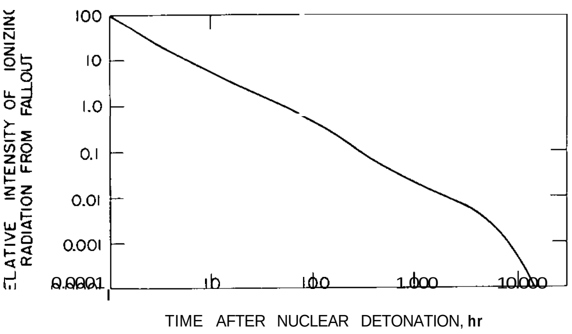


Figure 1. Decay rate of the radioactive component of fallout.’

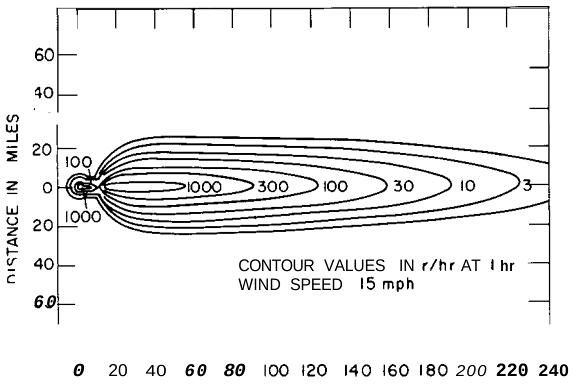


Figure 2. Idealized fallout pattern for a 1-MT-yield surface burst with 15-mph wind velocity and 100% fission.’

Table 1

Approximate Values of the Average Fallout Arrival Time, Standard Intensity, and Downwind Distance* for Which the Infinity Exposure Dose Is 100 Roentgens**

Average fallout arrival time after detonation, hr	Standard intensity, r/hr at 1 **hr** after detonation	Downwind distance to 100-r contour, miles
0.5	15	⩽ 10
1	19	15
2	22	30
5	28	75
10	32	150
15	36	225
20	39	300

*An effective wind velocity of 15 mph is assumed.

**These values include an instrument response factor of 0.75, as do the contour values of Figure 2.

When the fallout from more than one detonation is deposited at a location, the smallest t_a value would be used along with $I(\text{max})$; this application would be conservative for situations in which the various detonations contributing to the radiation levels are close enough together in location and in time to result in a more or less continuously rising intensity for 4 to 6 hr. If the detonations producing the fallout were spaced over several days, account would have to be taken of the doses in previous exposures, and the value of 20 should be decreased in proportion to the levels already received.

If the weapons had $<50\%$ fission, $I(\text{max})$ would be decreased proportionally for a given value oft,; in this case, the approximation would be a conservative guide. For a single detonation, the approximation appears to hold within the stated reliability for times of arrival from about 20 min (i.e., within the *damaged* area) to about 24 hr. For locations with arrival times >24 hr and weapon yield within the range of 5 to 25 MT with a 50% fission yield, the infinity dose will never exceed 100 r.

The approximation can be applied to determine whether a location is in the *radep* or ***free*** area only if the observer has a watch to measure the time between the flash or sound from the blast and the time of fallout arrival, and if he has a radiation detector to find the radiation rate after the fallout begins to arrive. For arrival times longer than several hours at an average wind velocity of about 20 mph, the peak radiation rate should occur about 2 hr after the fallout arrives.

The approximate dimensions of the various areas affected by a 5-MT 50%-fission land-surface detonation appear in Figure **3.** The outer perimeter of the *damaged* area in this figure is based on the distance within which kindling fuels are ignited inside houses on a clear day when visibility is 10 miles.

The *damaged* and *radep* areas will overlap for a single land-surface detonation, especially downwind from ground zero (Figure **3).** Thus, several distinct zones would occur within the *damaged* area. First, a region within the outer perimeter of the *damaged* area, here termed the Grey Belt, would exist in which physical damage to objects occurred with little or no local fallout. For large explosions and for some targets, fire might be the main cause of damage in the Grey Belt.

The inner boundary of the Grey Belt is defined by the 100-r infinity dose; however, in some instances this boundary could also be defined either by the initial boundary of the *damaged* area or by the periphery of a conflagration if large-scale fires developed. Any one of these definitions of the Grey Belt within the *damaged* area would have operational significance with respect to the conduct of Civil Defense countermeasure actions. To describe how the inner boundary of the Grey Belt could be defined and recognized according to the 100-r infinity dose criterion, it is necessary to summarize selected data describing in detail what might be seen at locations in the *damaged* area shortly after a nuclear detonation.

Local situations in the *damaged* area upwind from the point of detonation of a 5-MT-yield land-surface detonation would include the following'[3]: (1) upwind distance to the 100-r infinity exposure dose contour – 4.2 miles; (2) overpressure at 4.2 miles – 6 psi; **(3)** blast damage at 4.2 miles – frame houses flattened, brick houses and apartment buildings blown over, exterior walls of multistory wall-bearing monumental buildings and reinforced concrete buildings badly cracked, interior parti-

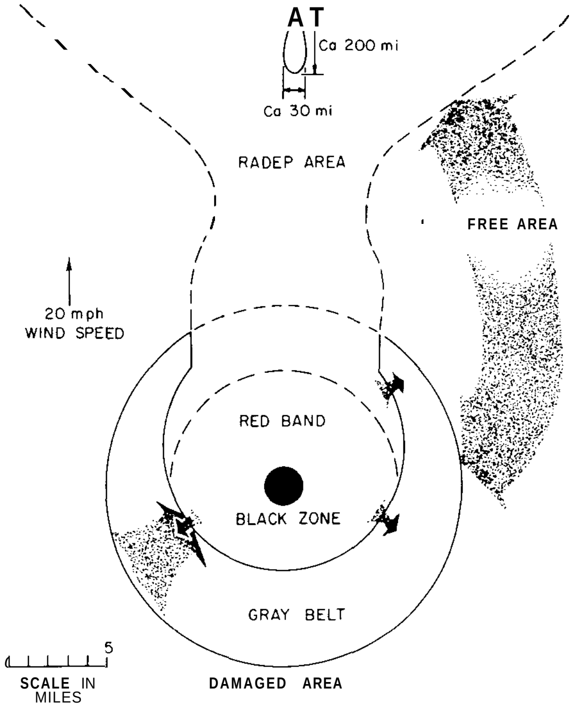


Figure 3. Approximate dimensions of the areas affected by a 5-MT-yield land-surface detonation (50% fission).

tions badly cracked or blown down, structural frame distorted, extensive spalling of concrete, heavy steel-frame industrial buildings (25 to 50-ton crane) sustaining some distortion to the frame with larger, heavier buildings showing smaller amounts of damage, cars and trucks turned over, displaced, badly dented, frames sprung – trees uprooted, telephone poles broken, railroad car doors demolished, frames distorted and debris in the streets in built-up areas; (4) distance to 2-psi overpressure – 8 miles; and (5) distance for thermal ignitions in houses (curtains, upholstery, etc.) – 9 miles.

The damage in the crosswind direction from ground zero for this detonation would include (1) crosswind distance to the 100-r infinity exposure dose contour – 5.8 miles; (2) overpressure at 5.8 miles – 4 psi; (3) blast damage at 5.8 miles – about the same as for the 6-psi distance, except that some frame houses will not be completely collapsed and some brick houses and apartment-type buildings may have exterior walls only badly cracked, with lesser damage to the larger buildings; and (4) time of fallout arrival – 20 min.

The general effects on people at the inner perimeter of the Grey Belt may be approximated from comparisons with data on survival rates of the people of Hiroshima and Nagasaki during World War II[4] "(Table 2). These survival rates include both the injured and uninjured. The over-all survival rates for both Hiroshima and Nagasaki at 4 to 6 psi were 60 to 80%; however, the thermal radiation within this

Table 2

Survival Rates at Hiroshima and Nagasaki

Exposure	Condition	% Survival
50-100 cal/cm^2	Outside	0
	Indoors or shielded	90-100
4-6 psi	Outside	0
	In frame building	85-90
	In concrete building	95-100
	In underground shelter	100

range of overpressure was less intense in these cities than it would be for a 5-MT detonation. A major factor influencing survival rates from the initial thermal radiation would be the extent to which people were shielded.

The total extent of the *damaged* area for a 5-MT detonation would be about 260 sq miles. The Grey Belt would be 130 sq miles, or about 50% of the *damaged* area.

In nuclear war, where multiple detonations would most likely occur, the Grey Belt of one detonation could be in a *radep* area from one or more detonations farther upwind. If the time difference of detonations was small, the situation would be similar to being downwind instead of cross- or upwind from the nearest detonation.

Another portion of the *damaged* area may also be defined. This portion, called the Black Zone, is the region in which complete destruction of all structures except the strongest of underground shelters would occur. This area could be defined for a surface detonation as the area enclosed by a radius about twice that of the crater radius (normally where the overpressure would be 300 to 400 psi). Another way of specifying the outer boundary of the Black Zone would be to set its radius equal to the maximal radius of the fireball, where the overpressure would be 100 to 200 psi. The 100-to-200 psi radius would probably best represent, in a rough way, the distance from ground zero at which no human beings in heavy buildings would survive. For a 5-MT land-surface detonation, this distance would be about one mile.

In the region between the Black Zone and the Grey Belt, there remains an area 2 to 4 miles in width upwind and crosswind from ground zero of a 5-MT-yield explosion. In this region unshielded travel of survivors or others entering the area would be restricted for some time by radiation from fallout and, especially in urban areas, by debris. The radiation intensities would increase rapidly with distance from the inner boundary of the Grey Belt in the direction of the Black Zone. This region of both extensive physical damage and high radiation intensities is here called the Red Band (Figure **3).**

FALLOUT CALCULATIONS FOR A VERY LARGE HYPOTHETICAL ATTACK

Fallout iso-intensity contours for a hypothetical 20,000-MT attack on continental United States appear in Figure 4. Calculations were made on the assumption that all weapons were detonated as land-surface explosions. The iso-intensity contours are given for 100%-fission weapons; thus, if 50%-fission weapons were assumed, the contour values would be decreased to half those shown. The points are assumed ground zeros for each of the weapons; the number of targets within each of the impact areas was arbitrarily adjusted to account for the programmed total attack weight. No strategic or other assumptions were made with respect to the delivery of the selected weight of attack.

The highest levels of fallout for the assumed attack occur in Montana, North Dakota, South Dakota, Minnesota, Missouri, and Illinois. Most of the *free* areas are in the Rocky Mountain states. The hot spots generally fall to the east of the impact sites and in the west center mainly on agricultural areas. Large deviations from the general east-west direction of the illustrated contours could occur depending on the direction and velocity of the high altitude winds. The computation was carried out for only one wind pattern observed in the past; it is not likely to occur again.

RADIOLOGICAL PROPERTIES OF FALLOUT

The two major hazards of fallout particles are (1) the "external" gamma radiation and (2) the "internal" hazards due to absorption or ingestion of radionuclides in fallout. The external gamma radiation is recognized as the major risk in the early aftermath of nuclear war. This hazard declines rapidly (Figure 1), leaving the long-lived gamma and beta emitters which have been absorbed into living systems as the principal, long-term hazard.

Figure **4.** Fallout contour map for hypothetical 20,000-MT attack on the United States. Contours are in r/hr at 1 hr, referenced to 100% fission yields. **All** weapons are assumed to be land-surface detonated. The white areas are the *free* areas.

The large particles contributing to local fallout consist mainly of fused and sintered grains of soil minerals. Fused particles are spherical, glassy beads and are usually the most highly radioactive. While in a fluid state in the fireball, these particles incorporate a large fraction of the least volatile fission products into a glassy matrix where such fission products are fixed. As the particles cool in the fireball and become viscous, the more volatile fission products (or their daughter products) collect on their surfaces. In this way, the larger of the fallout particles, those first ejected from the fireball, have radionuclide compositions enriched with the least volatile fission products, i.e., volatile element concentration is lowest. The smaller fallout particles, which remain in the rising cloud the longest, have radionuclide compositions enriched in the volatile elements.

Because of this fractionation, the gamma decay rates of radionuclides carried by the larger fallout particles differ from the decay rates of radionuclides carried by the smaller particles. The fact that the more volatile nuclides are concentrated in the smaller particles increases the number of contacts at aqueous interfaces, which allows more rapid dissolution of such a volatile nuclide–small particle system. This fractionation, occurring at the time of formation, may cause a reversal in the relationship between rapid dissolution and particle size of fallout from small-yield explosions and low airbursts where the particle temperature profile and exit times differ from those of larger land-surface detonations.

Table 3

Contamination Factor, a_L,* for Crops

Distance from ground zero, miles	Red clover	Alfalfa	Wheat	Mixed grasses
		Apple II Shot (Tower)		
7	5.6×10^{-5} (0.0011)**	–	5.3×10^{-5} (0.0020)	–
48	4.2×10^{-4} (0.0066)	–	6.0×10^{-4} (0.0240)	–
106	8.3×10^{-4} (0.0120)	–	18.0×10^{-4} (0.0580)	–
		Smoky Shot (Tower)		
132	–	2.6×10^{-3} (0.0490)	–	–
259	–	4.2×10^{-3} (0.1170)	–	3.2×10^{-3} (0.0530)

$$^{*}a_L=\frac{\text{gross activity collected per g dry weight of foliage}}{\text{gross activity collected per sq ft of soil area}}=\frac{\text{sq ft of soil area}}{\text{g dry foliage}}.$$

**Values in parentheses are the fractions retained; they are equal to $a_L w_L$ where w_L is the foliage surface density in grams of dry foliage per sq ft of soil area.

Table 4

Summary of a_L Values Obtained at Operation Buffalo for Contamination of Rye Grass

Approximate I(max) range, r/h at 1 hr	a_L(av), $\frac{\text{sq ft of soil area}}{\text{g foliage}}$	$a_L w_L$*
0.07–0.15	6.8	0.15
0.15–0.30	7.1	0.16
0.30–0.60	5.9	0.13
0.60–1.00	2.7	0.06
1.00–2.00	4.0	0.09
2.00–5.00	2.9	0.07
5.00–9.00	1.4	0.03

*Where $w_L = 22.3$ g foliage/sq ft of soil area (height of grass $= 0.33$ ft).

FOLIAR CONTAMINATION

Data on contamination of foliage by fallout particles such as those produced by land-surface detonations are few. Some field test data from weapons tests are summarized in Tables 3 and 4 in terms of a contamination factor designated as a_L. The foliar contamination factor is the average specific activity of the foliage (dry weight basis) divided by the surface density of the fallout deposited.

U.S. data' indicate that the contamination factor increases with decreasing particle size or with increasing distance from ground zero. United Kingdom data[8] also suggest that the foliar contamination factor varies with particle size, since higher values are obtained for the foliar contamination factor for the lower fallout intensity values.

Semitheoretical treatment of foliage collecting efficiencies" suggests the relationship between a,, and particle size by means of particle falling velocity, given by

$$a_L^0 = K[1+(v_w/v_f)^2]^{1/2}, \qquad (2)$$

in which v_w is the wind speed, v_f is the particle falling velocity, and K is an over-all foliage collecting efficiency parameter depending on the surface area of the foliage and, indirectly, on the particle size. Analysis of the U.S. data' of Table 3 gives an average value of $(7.6 \pm 2.5) \times 10^{-5}$ sq ft of soil area per gram of dry foliage for K, assuming it to be a constant for all the foliage types listed.

Other data on foliage contamination from various sources in both the U.S. and U.K. indicate that the value of a_L decreases with time because of such factors as wind and perhaps vegetational characteristics, having a half-life of about two weeks." Thus the suggested variation of a,. with time is

$$a_L = a_L^0 \exp[-0.05(t-\bar{t}_a)], \qquad (3)$$

where t is the time after detonation and $\bar{t}_a$ is the mean time of fallout arrival at a location. Equations (2) and **(3)** are both based on very scant experimental data.

SUMMARY

The hazards of nuclear explosions for man are described in terms of areas around the blast designated as *damaged, radep,* and *free*. The general effects of initial ionizing radiation, thermal radiation, blast and shock, and residual ionizing radiation are summarized with respect to the hazards that would result in case of nuclear war, and specific criteria are given for the definition of such areas. The 3-psi overpressure contour or the distance within which there is thermal ignition in houses, whichever gives the larger area, is used to define the *damaged* area; the outer perimeter of the *radep* area is defined by the 100-r infinity exposure dose contour. The area:; so defined are illustrated for a 5-MT-yield surface detonation. Calculations for the *radep* and *free* areas resulting from a 20,000-MT hypothetical attack on North America are summarized. Some of the available data on the radiological properties of fallout, such as its gamma decay rate, rate of nuclide dissolution, and rate of contamination of foliage, are presented and discussed.

REFERENCES

1. Glasstone, S. (Editor). 1962. *The Effects of Nuclear Weapons*. USAEC. 730 pp.
2. National Committee on Radiation Protection and Measurements. 1962. *Exposure to Radiation in an Emergency.* Report No. 29. 90 pp.
3. Miller, C.F. 1963. *Fallout and Radiological Countermeasures,* Vols. I and II. Stanford Research Institute, Menlo Park, California. Project IMU-4021. Vol. I, 405 pp. Vol. II, 309 pp.
4. Oughterson, A.W. and Warren, S. (Editors). 1956. *Medical Effects of the Atomic Bomb in Japan.* McGraw-Hill, New York. 477 pp.
5. White, C.S. 1961. *Biological Effects of Blast.* Technical Progress Report. Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico. DASA 1271. 121 pp.
6. Miller, C.F. 1963. *Fallout Nuclide Solubility, Foliage Contamination, and Plant Part Uptake Contour Ratios.* Stanford Research Institute, Menlo Park, California. Project IMU-4021.
7. Romney, E.M., Lindberg, R.G., Hawthorne, H.A., Bystrom, B.G., and Larson, K.H. 1963. Contamination of plant foliage with radioactive fallout. *Ecology* **44,** 343-9.
8. Russell, R.S. and Possingham, J.V. 1961. Physical characteristics of fallout and its retention on herbage. In *Progress in Nuclear Energy.* Series VI, Biological Sciences, Vol. 3, J.C. Bugher et al., Editors. Pergamon Press, New York. Pp. 2-26.

Effects of Fire on Major Ecosystems

A. Broido
Pacific Southwest Forest and Range Experiment Station,
U.S. Forest Service, Berkeley, California

The catastrophic impact that a nuclear war is expected to have upon major ecosystems can result from two sources: ionizing radiation, chiefly from fallout, and large fires started principally by thermal radiation emitted by the nuclear detonations. As yet no large land areas have ever been covered with high levels of radioactive fallout. Consequently there is little evidence on which to base conclusions about the ecological impact of fallout, and the subject is necessarily controversial. On the other hand, fire has long been recognized as a primary agent affecting major ecosystems.[13] Fires involving large areas have produced their impact frequently since prehistoric times, contributing in large part to the development of many of our present ecosystems. Many hundreds of studies have been conducted on the ecological effects of such fires, with greatly varied results.[2,33] Consequently, statements that can be made about the ecological impact of large-scale fires are, if possible, even more controversial than are those about fallout.

This paper describes the initial thermal radiation and fire effects of a nuclear detonation – a subject with which the author has had some experience. It will then discuss some ecological consequences of fire – a subject for which the author's primary qualification is a complete lack of prejudice due to no experience whatever. Since thermal and fire effects on the ecosystem of prime concern to man, the urban complex, have already received considerable attention, this paper deals primarily with ecosystems in which man's presence is secondary.

PRODUCTION OF FIRES IN A NUCLEAR ATTACK

It has been customary, although not necessarily correct, to assume that the gross fallout distribution pattern following a nuclear detonation may be completely specified once the characteristics of the detonation itself and the prevailing wind patterns have been determined. That is, the pattern is assumed to be independent of the characteristics of the target on which the fallout lands. Obviously the same cannot be said about fire effects. In addition to the characteristics of the detonation, effects of fire are highly dependent upon such factors as fuel, terrain, and weather. Thus, fallout patterns are often described without considering whether the fallout is landing on a city, a forest, a desert, or a lake, but fire effects cannot be so described – although fire effects on deserts and lakes do not require much discussion.

In an urban area, fires may be started both by blast (rupturing of gas lines, short-circuiting of wiring, etc.) and by thermal radiation (direct ignition of appropriate fuels by the visible and infrared radiation emanating from the fireball).[6,16]

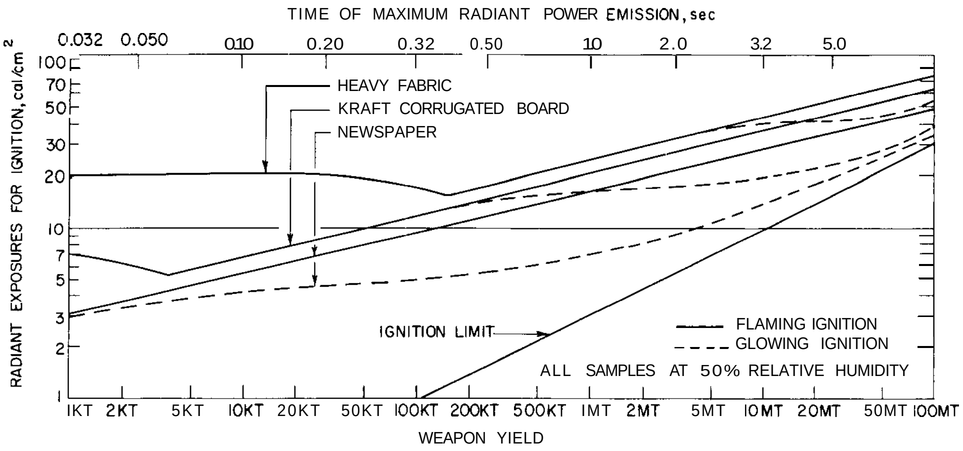


Figure 1. Radiant exposure levels for ignition by nuclear airbursts of 1-kT to 100-MT yields.[23] There curves are derived from laboratory exposure of materials in a plane, normal configuration using a small (maximum diameter, 0.75 in.), apertured spot of uniform irradiation. They therefore ignore any possible influence of sample geometry and area. Some of these data have been confirmed for larger area samples exposed to low-yield weapons during weapons tests. However, for the longer pulses of high-yield weapons, materials exposed under less ideal conditions exhibit an increased susceptibility to flaming ignition. For this and other reasons the curves for glowing ignition are believed to be of greater significance in estimating weapon effects.

The blast-caused ignitions are recognized as at first consisting of a number of small, individual fires. To produce a blaze over a large area, they must spread – merging some minutes later. Similarly, the thermal radiation ignitions occur as a number – perhaps a very large number – of separate small fires which subsequently must spread if there is to be an effect of consequence.

Not all fuels normally considered highly inflammable can be ignited by the short pulses of thermal radiation produced in a nuclear detonation.” For example, if thick, sound wood is exposed to a short pulse of radiant energy, its surface can char, perhaps badly. Flames may often be produced during the application of radiant energy. However, the temperature throughout the fuel will not be raised sufficiently to sustain ignition, and any flames which start die out immediately after the exposure. On the other hand, such thermal pulses easily ignite many kindling fuels. These include thin materials, such as dried leaves and newsprint, or materials like rotten wood which on the macroscale appear to be solid but which may be considered as an extended network of thin, porous, inflammable materials. Only as a result of the ignition of these fuels are adjacent thicker fuels ignited.

As a general rule, materials that can be ignited by the thermal flash of a nuclear detonation can be readily ignited by a single match. If the match will not affect them seriously (wherever they are exposed to its flame) or if they shrivel up or ablate without ignition, as is the case with much green vegetation, they will not be ignited by the thermal flash.

The radiant exposure required to ignite exposed kindling depends upon such factors as the yield and height of burst of the weapon (or more rigorously the time-

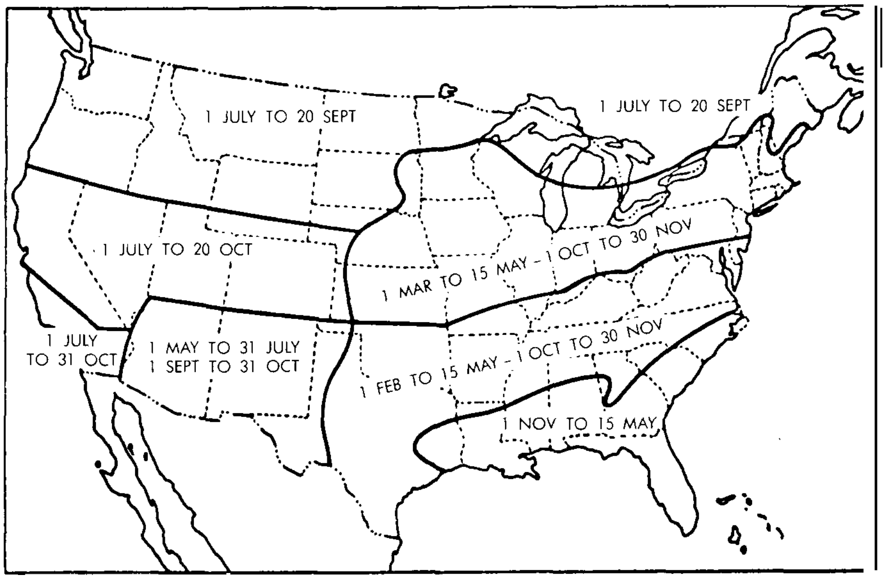


Figure 2. Fire seasons map of the United States.'"

irradiance characteristics of the thermal pulse), the chemical composition, color, thickness, and heat capacity of the fuel, and the relative humidity of the environment. To simplify the problem of estimating incendiary ranges, kindling fuels have been grouped into three categories. The most susceptible category is typified by newspaper, the commonest man-made kindling fuel; this category includes such natural fuels as dried deciduous leaves, fine grasses, duff, and rotted wood (punk). A less susceptible class is typified by Kraft corrugated paperboard; this class includes such materials as heavy paper products and light fabrics. The third category, typified by drapery-weight fabrics, includes awnings, upholstery fabrics, and wildland fuels of equivalent thickness. Typical curves of ignition exposure levels as a function of airburst weapon yield are given in Figure 1.

In urban areas, both blast and thermal radiation may cause fires indoors where the ignition and initial spread is largely independent of outdoor weather conditions. Once a fire is well established indoors, it can readily overcome the retarding effect of moisture in heavier exterior fuels. In fact, studies conducted during World War II indicate that even when rain was falling during conventional fire bomb attacks, the damage produced averaged only 20% less than that produced under favorable weather conditions.

Wildland areas contain very few of the items susceptible to ignition by blast effects. Therefore the possibility of a fire's starting is almost entirely a function of the availability of ignitable kindling fuels. Further, as thermal radiation travels in straight lines, only those kindling fuels which are not shaded, for example by the forest canopy, will be ignited. Pulse times are much too short to permit the successive removal of several layers of foliage and exposure of fuels below. Within a few seconds after a nuclear detonation, then, a wildland area would look much as if, say, millions of burning matches had just been scattered randomly over hundreds of square miles. Only under conditions such that one of these matches would cause an ignition could the thermal flash ignite exposed fuel.

Whether any ignitions that resulted would be of any consequence would depend upon their ability to spread and involve additional combustible material. Thus fire spread in wildlands will be influenced by just those characteristics of weather and fuel that influence wildland fires in peacetime. During hazardous fire periods in any location, a nuclear detonation can be expected to produce a large wildland fire; during safe periods, no such fires are to be expected. A map showing the usual fire seasons in various parts of the United States[32] is reproduced in Figure 2. However, it should be remembered that such fire seasons represent periods during which adverse weather may be expected, but only on relatively few days during such periods will the most hazardous conditions prevail.

Under conditions of weather and fuel availability which permit the formation of mass fires, it is also likely that the fires will spread beyond the radius of initial involvement and continue to burn until they run out of fuel or are extinguished by appropriate weather changes – aided, perhaps, by some heroic fire fighting efforts. Thus, fire effects may extend well beyond the radius of fire initiation given in the preceding paper, and, although it is unlikely that severe fire effects will extend in any one direction as far as the distances of severe fallout hazard, the over-all fire area may be as large or larger, since it is expected to be much more circular than the long, narrow fallout pattern.

ENVIRONMENT IN LARGE-SCALE FIRES

A recent article' summarizes our past experience on large-scale fires in the following two paragraphs.

"In seeking information about the environment in large-scale fires we find unfortunately all too much practical experience to draw upon. London in 1666, Moscow in 1812, Chicago in 1871 and San Francisco in 1906 are perhaps the best known examples. Not so well known are the large forest fires, single fires that have covered millions of acres. For example, on October 8, 1871, the date of the Chicago fire, fires in Wisconsin and Michigan burned almost four million acres with the loss of life many times greater than was experienced in Chicago.[18] In August, 1910 a fire in northern Idaho and northwestern Montana burned more than three million acres.'" As recently as 1950 fire destroyed almost two million acres east of Fort Yukon, Alaska.[22] Fires covering tens and hundreds of thousands of acres can be expected every year in parts of the United States, in Canada, in Australia, in South America – wherever the right combination of vast expanse of fuels and extreme weather is found.

"The bombing attacks of World War II, however, added a new dimension to the fire problem. Large areas could now be ignited more or less simultaneously, enveloping whole cities in fire and burning them to the ground in a matter of hours. The old city section of Hamburg took four days to burn in 1842.[27] In contrast, in the fire raid on Hamburg on July 27, 1943, two-thirds of all the buildings in a five square mile area were ablaze within 20 minutes.[5] Within a few hours the fire had begun to run out of fuel and die down, although hot rubble heaps made large areas unapproachable for several days."

There is good reason to believe that mass fires such as those at Hamburg and Hiroshima have been sufficiently large to preclude new factors that would significantly influence conditions within the fire zone.' The mass fires that may follow a thermonuclear catastrophe are thus expected to produce short-term conditions similar to those observed a number of times during World War II, and differing from those of large-scale peacetime fires of the past. However, this does not mean that long-term ecological effects may be expected to differ significantly from those already experienced. At first glance it would appear that the heat effects of a fire that burned slowly over a period of days and one that burned rapidly over a period of a few hours would be drastically different, particularly in such matters as heat transfer downward into the soil. However, when one of the large fires of the past burned for a period of several days, it was not burning everywhere in the entire area for the duration of the fire. In fact, in any one location its duration was probably not much different from that of an equivalent area in a mass fire. The difference between the two types is that in one, the fire burns the area piecemeal, and in the other, the burning periods everywhere in the fire zone coincide. Also, despite the awesome nature of such catastrophes as mass fires, the energy they release is trivial compared to energies we are exposed to in our day-to-day routine. Thus, the burning of about 20 tons of fuel per acre will release ≈ 2000 cal/cm^2. Of this, 200 to 400 cal/cm^2 will reach the ground as radiant energy – an amount somewhat less than that absorbed by a fire-blackened, exposed surface as a result of radiation from the sun during one moderately clear day.

All things considered, it seems reasonable to assume that the ecological consequences of a large mass fire will not differ significantly from similar consequences of a fire burning out the same area over a period of several days. To whatever extent we know the ecological consequences of fires in the past we can predict consequences of bomb-induced fires in the future.

ECOLOGICAL EFFECTS

As with most factors having a major effect on an ecosystem, the long-term good or harm caused by a large fire depends in large part upon point of view. For instance, it is universally agreed that the replacement of pine and spruce forests of the northern Lake States by aspen is entirely the result of past fires." Whether this is good or bad depends upon whether you want conifers or aspen. The brush forests of southern California have been expanding largely as the result of frequent fires,'" and for maintenance of the brush species prevalent there, fire is a very desirable thing. The fire that ravaged the Kenai Peninsula in Alaska in 1883[14] destroyed the lichens on which the caribou feed, and the caribou herds vanished. However, the fire resulted in abundant growth of willows, birches, and cottonwoods. The area is now known for its moose herds. In passing judgment on the effects of this fire, it is safe to assume that the moose and caribou would not vote on the same side. Even fires more directly affecting man, those in urban areas, are not without their advantages in slum clearance, rodent control, and general urban redevelopment. San Francisco today is a cleaner, more healthful, more beautiful, more modern place in which to live because of the 1906 fire. However, I do not advocate the routine burning of our cities, by nuclear war or other means, as an acceptable method of slum clearance.

Even if one can agree upon objectives, the advantages and disadvantages of a fire are not without controversy. Thus, to preserve a forest area, some conservationists make the apparently logical assumption that they should do everything possible to prevent the occurrence of fire. Others make a perhaps equally logical assumption, namely that the complete elimination of fire for all times is impossible, and that periodic burning of the light fuels and dead vegetation is necessary to reduce the risk of a disastrous fire if these materials are permitted to accumulate.

Without worrying about whether a given effect is good or bad, one can find logical but opposing descriptions ofjust about every consequence of a large fire. For example, Curtis” has concluded that under climatic conditions tolerable to both grasslands and forests, the existence of grassland is evidence of frequent burning. As John Muir[25] put it: “The uniformly rich soil of Illinois and Wisconsin prairies produced so close and tall a growth of grasses for fires that no trees could live on it. Had there been no fires, these fine prairies, so marked a feature of the country, would have been covered by the heaviest forest. As soon as the oak openings in our neighborhood were settled and the farmers had prevented running-fires, the grubs (sprouting oak roots) grew into trees and formed tall thickets so dense that it was difficult to walk through them and every trace of the sunny ‘openings’ vanished.”

On the other hand, longleaf pine, like the bur oak of Muir’s “prairies,” has a root system that favors recovery after fire. Chapman,’”Green[17] and others hold that the longleaf pine forests of the South are the result of many years of grass fires. As Wahlenberg[31] puts it, the longleaf pine forests are “so dependent upon fire that their normal life cycle cannot continue without its influence.” Thus in predicting consequences of fire in a new area, one can conclude either that fire will lead to grasslands or that fire will lead to forests.

Nor is the situation less controversial if one considers any of the other effects of fire. Smokey the Bear has brought tears to our eyes with scenes of Bambi and his friends running for their lives before a forest fire. Yet it is claimed” that fire stimulates the production of browse and results in an increase of the deer population. Some years after a fire – if there is no further burning – tree crowns close in and reduce browse supply, and the result is a starving deer population.

It is claimed that insect and disease infestations following a forest fire may be responsible for more tree damage than the original fire.[24] It is also claimed”>that fire is valuable in purging the forest of insect and fungus enemies and in restoring vigorous, fast-growing species. Even in such matters as the organic content of soil in a burned-over area there is disagreement as to whether a reduction in organic soil content can be expected, and even more controversy about whether such a reduction improves or hinders subsequent forest growth. It might be assumed that the effect on mineral content of the soil would be noncontroversial, but even here opposite results are reported. Burning has been found’ to increase available potassium in the soil; however, it has also been found” that the removal of vegetation leads to increased leaching by rain and thus to a net decrease in soil potassium.

The clearly physical consequences of a forest fire are perhaps less controversial than the other effects. It is generally agreed that extensive burning increases erosion, surface runoff, and the possibility of flood on many sites. However, claims have been made' and disputed[3] that on certain types of sites erosion and runoff do not seem to be affected by burning. Removal of the forest canopy affects the soil in many ways. It increases the force with which rainfall hits the ground, thereby accelerating erosion." It lets in more sunlight, and this, coupled with increased light absorption by the blackened surface, produces a considerable increase in soil temperature.[19] Higher temperatures and increased air circulation may also result in more rapid drying out of soil, although good evidence to the contrary is also available.[28] The effects of these physical changes on subsequent plant and animal life in the burnt-over region are as controversial as any of the other ecological effects discussed previously.

POSTATTACK FIRE VULNERABILITY

One last problem that should be considered is the increased potential for burning of ecosystems that have been damaged by nuclear radiation. Although we have no direct evidence of the increased fire hazard in fallout-damaged wildlands, the effects should not differ much from similar effects resulting from damage from other causes, e.g., earlier fires or chemical vapors. The destruction of vegetation by the toxic effluents of various chemical processes has occurred in many parts of the world. Typical are the blighted areas around the copper smelters at Ducktown, Tennessee; Anaconda, Montana; and Kennett, California.'' Damage in these areas begins with minor injury to the most vulnerable species, but results ultimately in totally denuded and eroded lands. Just as in the case of forest fires, the opening up of the forest canopy results in higher temperatures and lower fuel moistures in the lighter vegetation below. Thus, fire hazard can increase considerably. As the fume- or fallout-killed forests dry out, occasional fires may be expected which will hasten their disappearance. The probability of occurrence of such fires, as well as the ultimate consequences of this accelerated elimination of dead vegetation, is difficult to assess. The increase or decrease in fire hazard to radiation-damaged but not killed ecosystems is of course subject to all the uncertainties mentioned throughout this paper.

SUMMARY

In heavily built-up urban areas, mass fires are to be expected if nuclear attack should occur. In wildlands, thermal radiation from nuclear detonation can ignite exposed kindling fuels over large regions. Whether such ignitions spread and merge to form a catastrophic fire depends on the same factors that influence the spread of any wildland fire. Should a mass fire occur, its gross characteristics during the period of active burning are expected to differ considerably from those of large-scale peacetime fires. However, the greatly shortened burning time of the mass fire compared to a conventional large fire pertains to the over-all burning period. The conventional fire covers piecemeal an area in which, for the mass fire, the burning periods everywhere coincide. The duration of either fire at any given point should be much the same. Hence, the ecological consequences of the fires that may occur after a nuclear catastrophe are not expected to differ seriously from the consequences of holocausts of the past. Although large fires have been with us since prehistoric times, interpretations of their effects on major ecosystems are still quite controversial – whether one considers the effect on plant succession, on animal life, on plant diseases and pests, on the chemical composition of the soil, or on such physical factors as temperature and humidity.

REFERENCES

1. Adams, F., Ewing, P.A., and Huberty, M.R. 1947. *Hydraulic Aspects of Burning Brush and Woodland Grass Ranges in California.* California Division of Forestry, Sacramento. 84 pp.
2. Ahlgren, I.F. and Ahlgren, C.E. 1960. Ecological effects of forest fires. *Botan. Rev.* **26,** 483-533.
3. Anderson, H.W. 1949. Does burning increase surface runoff? *J. Forestry* **47,** 54-7.
4. Austin, R.C. and Baisinger, D.H. 1955. Some effects of burning on forest soils of Western Oregon and Washington. *J. Forestry* **53,** 275-80.
5. Bond, H. (Editor). 1946. *Fire and the Air War.* National Fire Protection Association, Boston, *262* pp.
6. Broido, A. and Trilling, C. 1955. *Thermal Vulnerability of Military Installations.* U.S. Naval Radiological Defense Laboratory Report. USNRDL-TR-101. 99 pp.
7. Broido, A. 1963. Surviving fire effects of nuclear detonations. *Bull. At. Sci.* 19, 20-3.
8. Broido, A. 1963. Fire effects of thermonuclear detonations. *Fire Res. Abstr. and Rev.* **5,** 1-11.
9. Buell, M.F. and Cantlon, J.E. 1953. Effects of prescribed burning on ground cover in the New Jersey pine region. *Ecology* **34,** 520-8.
10. Chapman, H.H. 1932. Is the longleaf type a climax? *Ecology* **13,** 328-34.
11. Curtis, John T. 1959. *The Vegetation of Wisconsin.* University of Wisconsin Press, Madison. 657 pp.
12. Davis, K.P. 1959. *Forest Fire.* McGraw-Hill, New York. 584 pp.
13. Daubenmire, R.F. 1947. *Plants and Environment.* Wiley, New York. 424 pp.
14. Dufresne. Frank. 1946. *Alaska's Animals and Fishes.* A.S. Barnes, New York. 297 pp.
15. Finn, R.F. 1943. The leaching of some plant nutrients following the burning of forest litter. *Black Rock Forest Papers* 1, 28-34.
16. Glasstone, S. (Editor). 1962. *The Effects of Nuclear Weapons.* USAEC. 730 pp.
17. Greene, S.W. 1931. The forest that fire made. *Am. Forests* **37,** 583-618.
18. Holbrook, S.H. 1943. *Burning an Empire.* Macmillan, New York. 229 pp.
19. Isaac, L.A. 1930. Seedling survival on burned and unburned surfaces. *J. Forestry* **28,** 569-71.
20. Kraebel, C.J. 1955. Conquering Kennett's gullies. *Am. Forests,* Dec.
21. Leopold, A., Sowls, L.K., and Spencer, D.L. 1947. A survey of overpopulated deer ranges in the United States. *J. Wildlife Management* 11, 162-77.
22. Lutz, H.J. 1956. *Ecological Effects of Forest Fires in the Interior of Alaska.* USDA Tech. Bull. 1133. 121 pp.
23. Martin, S. and Broido, A. 1963. *Thermal Radiation and Fire Effects of Nuclear Detonations.* U.S. Naval Radiological Defense Laboratory Report. USNRDLTR-652. 46 pp.
24. Miller, J.M. and Keen, F.P. 1960. *Biology and Control of the Western Pine Beetle.* USDA Misc. Publ. 800. 381 pp.
25. Muir, John. 1916. *The Writings of John Muir.* Vol. I. *The Story of My Boyhood and Youth and a Thousand-Mile Walk to the Gulf.* Manuscription Edition. Houghton-Mifflin, Boston. 428 pp.
26. Muller, K.M. 1929. *Augban, Wuchs, und Verjüngung der Südösteurepäischen Urwalder.* M. & H. Schaper, Hanover. 322 pp.
27. Rumpf, Hans. 1931. *Brandbomben.* E.S. Mittler & Sohn, Berlin. 224 pp.
28. Sampson, A.W. 1944. Effect of chaparral burning on soil erosion and on soil moisture relations. *Ecology* **25,** 191-5.

29. Shantz, H.L. 1941. *The Use of Fire as a Tool in the Management of the Brush Ranges of California.* California Division of Forestry. 156 pp.
30. Spencer, Betty G. 1956. *The Big Blowup.* Caxton Printers, Caldwell, Idaho. 286 pp.
31. Wahlenberg, W.G. 1946. *Longleaf Pine.* Charles Lathrop Pack Forestry Foundation, Washington, D.C. 429 pp.
32. U.S. Civil Defense. 1953. *Civil Defense Urban Analysis.* Federal Civil Defense Administration Publication TM-8-1. 85 pp.
33. U.S. Forestry Service. 1938. *Effects of Fire on Forests – A Bibliography.* Forest Service, USDA. 130 pp.

Effects of Ionizing Radiation on Ecological Systems"

G.M. WOODWELL AND A.H. SPARROW
Biology Department, Brookhaven National Laboratoy, Upton, N.Y.

The surface of the earth is characterized by patterns described by natural vegetations such as forest, grassland, desert, and tundra, which together form a matrix within which man carries on agriculture and builds cities. These natural units are called ecological systems or ecosystems to emphasize that each is a well-integrated biological and physical system whose structure and function are governed by certain fundamental biological and physical principles. The purpose of this paper is to appraise the changes that ionizing radiation from nuclear war or another catastrophe might make in such systems.

Natural ecosystems maintain themselves by using solar energy alone; cities and agricultural ecosystems are maintained by man through input of energy which he conti-01s. Discussion here is concentrated on major natural ecosystems.

Natural ecosystems develop continuously toward stability, or climax. This concept is basic to an understanding of the three patterns characteristic of ecosystems: (1) geographical patterns, defined by the regional climax vegetations, (2) successional patterns leading to these climax systems, and *(3)* patterns of internal structure and function.[35]

Detailed discussions of climax and of these three types of patterns are available in the works of Clements,[6] Oosting,[18] Braun-Blanquet,[3] Odum,[17] Braun,' and elsewhere. For the purposes of this discussion it is important to recognize that the principal elements of structure in terrestrial ecosystems can be classified conveniently on the basis of the species which dominate plant communities.

THE MAJOR ECOSYSTEMS OF NORTH AMERICA

Figure 1 is a map of the major vegetation types of North America: Tundra, Coniferous Forest, Deciduous Forest, Grassland, and Desert. The tundra and deserts contribute least to the welfare of man; coniferous and deciduous forests and grassland, on the other hand, form the major part of the matrix within which man, using energy from fossil fuels, controls his immediate environment with varying degrees of success.

Leading up to each of these stable vegetations is a regular sequence of developmental stages. Each stage is itself an ecosystem, having clearly defined structure and well-integrated function. Such successional patterns are complex and in most vegetations still poorly known except in very general terms. Woodwell[35] has illustrated

---

*Research carried out at Brookhaven National Laboratory under the auspices of the U.S. Atomic Energy Commission.

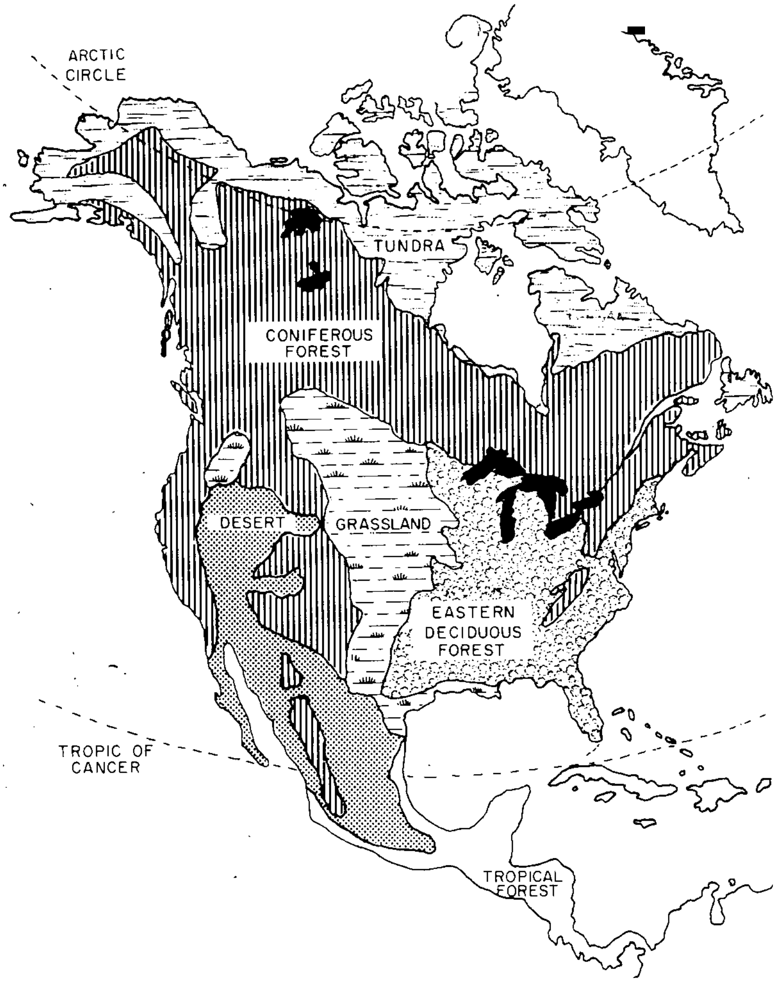


Figure 1. Major vegetation types of North America. Vegetation dominates the structure of terrestrial ecosystems and provides the basis for differentiating geographical patterns.

a successional sequence characteristic of the Eastern Deciduous Forest of North America by plotting approximate values for the accumulation of fixed energy against time. The graph for this vegetation is a sigmoid growth curve with the grand period spanning the first 50 years. Disturbance of a climax or lower stage sets the succession back along this curve, the speed and nature of the recovery depending on many factors, including climate, vegetation type, and season, as well as on the nature of the disturbance.

The patterns of internal structure can also be examined conveniently by using the distribution and flow of energy.[35] If only the energy fixed by the plants in a stable system is considered, energy losses in any year through export and respiration approximate the amount of energy fixed (Figure 2).

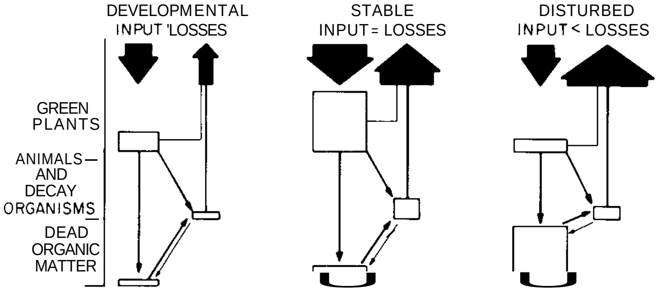


Figure 2. Energy flow through terrestrial ecosystems. In a stable or near-climax system, energy fixed approximates energy lost. In disturbed systems, losses may temporarily exceed fixation. In successional ecosystems, fixation usually exceeds losses.

Energy is retained within the system in three main categories: living green plants, dead organic matter, and the bodies of the consumers. Disturbance by fire, disease, or any other type of catastrophe such as high levels of ionizing radiation causes transfer of stored energy from the compartment representing green plants to the compartment representing dead organic matter. Following such a change a shift in consumer populations is expected to favor those feeding on dead organic matter as opposed to living green plants. Within a few years there is recovery of the plant populations, possibly augmented by invasion of species from outside the damaged area, and energy fixed in any year then exceeds energy lost. This is a developmental ecosystem, one of the stages leading to climax (Figure 2).

EFFECTS OF IONIZING RADIATION ON PLANTS

Classical descriptions of the effects of ionizing radiation on plants have usually recognized two types of effects: (1) genetic, and (2) somatic or physiological. A large body of recent research on plants has shown that both categories are probably due primarily to damage to the hereditary material. The importance of this relationship was shown recently by Sparrow, Cuany, Miksche, and Schairer[25] and by Sparrow and Miksche,[26] who demonstrated that plants with large nuclear volumes are generally more sensitive to radiation damage than plants with small nuclear volumes. These two categories of effects, then, are really differences in the manifestation of damage, the one involving mutations with minor immediate effects on growth or form, the other probably also involving mutations but showing immediate changes in function, including reduction in rate of growth, reduction in fertility, and possibly even an increase in mortality.

At the ecosystem level effects can be expected to parallel these and to involve (1) changes in the frequency of mutations and (2) changes in the vigor of the organisms irradiated.

It is well known that exposure to ionizing radiation produces an immediate increase in the frequencies of deleterious mutations.[30] Most of these mutants, however, are not new to the population; they also occur spontaneously in the natural population at some low rate, and any exposure to ionizing radiation can be expected to increase their frequencies. But if there is no long-term change in mutation rate, and if crossing is at random and selective forces within the ecosystem remain unchanged, then gene frequencies would become stabilized at the preirradiation levels within a few generations in accordance with the Hardy-Weinberg equilibrium. While there is real question as to whether all these conditions would hold following a nuclear catastrophe, it is probably true that any stimulus to evolution[13] would be of relatively minor importance.

It therefore appears that the principal immediate effects of fallout radiation would be those pertaining to the survival and vigor of the organisms irradiated. Selective elimination or inhibition of the most radiosensitive organisms would reduce the diversity of species in the ecosystem.[35] Such simplification, whatever the cause, starts a chain of secondary effects which include large immediate increases in the surviving populations that have the capacity for rapid growth or reproduction. These populations include both plants and animals, but include in particular small organisms such as the decay organisms and the insects because of their rapid reproduction, small size, genetic diversity, and mobility. Simultaneously, with the expansion of these populations invasion may occur from outside the area affected, and a new succession toward stability begins. This generalized pattern applies to a disturbance of any sort. The objective here is to define the radiation exposures that would trigger this well-recognized syndrome in major North American ecosystems.

BASIS FOR ANALYSIS OF RADIATION EFFECTS IN ECOSYSTEMS

Data available for such an analysis are of two types: data from radiobiological studies at the cellular and organismal levels, and data from field studies of irradiated ecosystems. A third possibility is the use of data from other major catastrophes not related to ionizing radiation as a basis for inference concerning recovery from radiation effects. We shall consider principally the first two of these.

CORRELATION BETWEEN CELL NUCLEAR CHARACTERISTICS AND RADIOSENSITIVITY

Of the data from radiobiological studies the most promising relationship for field application is the correlation shown by Sparrow and his colleagues between the volume of the nucleus or chromosome and radiosensitivity (Figure *3)*. Use of this correlation has made it possible to predict within broad limits the sensitivity of plants to damage from ionizing radiation.[23,24] Sparrow and Woodwell[29] predicted the effects of one year's radiation exposure on an oak-pine forest. Woodwell and Sparrow[37] reported that this prediction was substantially correct, although plants in this forest were generally more sensitive than anticipated. Precision in prediction apparently depends upon incorporation of additional information, such as data on the rate of cell division, stage in the life cycle exposed, the end point measured, and various environmental conditions as well. Despite these variables, estimates based upon nuclear or chromosome volume alone have frequently been,accurate within a factor of 2 to 5. Since the potential variability among higher plants spans a factor of several hundredfold, this type of estimate is of substantial advantage.

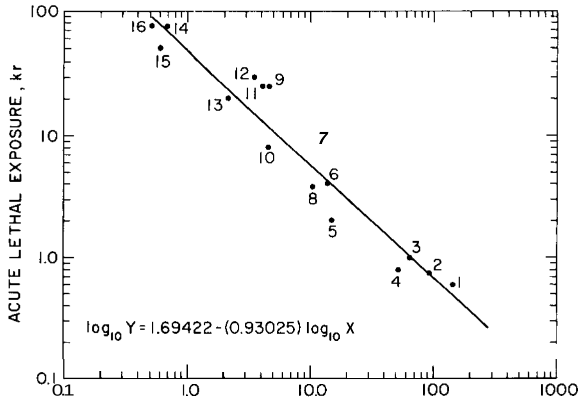


Figure 3. Relationship between calculated interphase chromosome volume (nuclear volume/ chromosome number) and acute lethal exposure for 16 species of plants: (1) *Trillium grandiflorum*; (2) *Podophyllum peltatum*; (3) *Hyacinthus orientalis* HV Innocence; (4) *Lilium longiflorum*; (5) *Chlorophytum elatum*; (6) *Zea mays*; (7) *Aphanostephus skirrobasis*; (8) *Crepis capillaris*; (9) *Sedum ternatum*; (10) *Lycopersicum esculentum*; (11) *Gladiolus* HV Friendship; (12) *Mentha spicata*; (13) *Sedum oryzifolium*; (14) *S. tricarpum*; (15) *S. alfredi* var. nagasakianum; and (16) *S. rupifragum*.[27]

FIELD STUDIES OF IRRADIATED ECOSYSTEMS

Data on radiation effects on ecosystems are limited to a relatively few field studies of ecosystems which have been irradiated experimentally. At the Pacific bomb test sites and at those in the North American desert, radiation effects have usually been confounded with the effects of blast and heat, and clear recognition of the influence of ionizing radiation has not been possible.[9,19,22,22a] The work of R.B. Platt[20] and his colleagues in the radiation-damaged areas around the Lockheed reactor in northern Georgia is discussed in the next paper. This series of studies is an important contribution to recognition of the potential effects of radiation on natural ecosystems.

At Brookhaven during the past two years a case-history study of an irradiated forest ecosystem has been under way.[34] The source of radiation is 9500 curies of Cs^{137} centrally located in an oak-pine forest which was selected because of its relative homogeneity. Exposure rates range from several thousand r per day within a few meters of the source to 1 to 2 r per day at 125 meters and on down to background levels. The forest has been irradiated for 20 hr daily since November 22, 1961

DESCRIPTION OF THE EFFECTS OF A SIX-MONTH EXPOSURE OF A FOREST

Vegetation

The condition of the irradiated forest after six months of exposure has been described by Woodwell.[33] The major change in structure occurred at exposures in

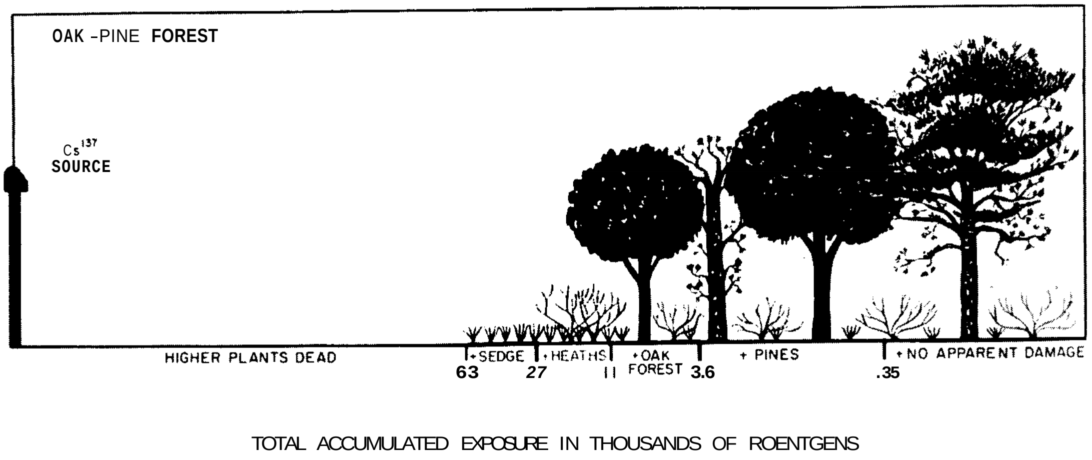


Figure 4. An oak-pine forest after six months' exposure to chronic gamma radiation.

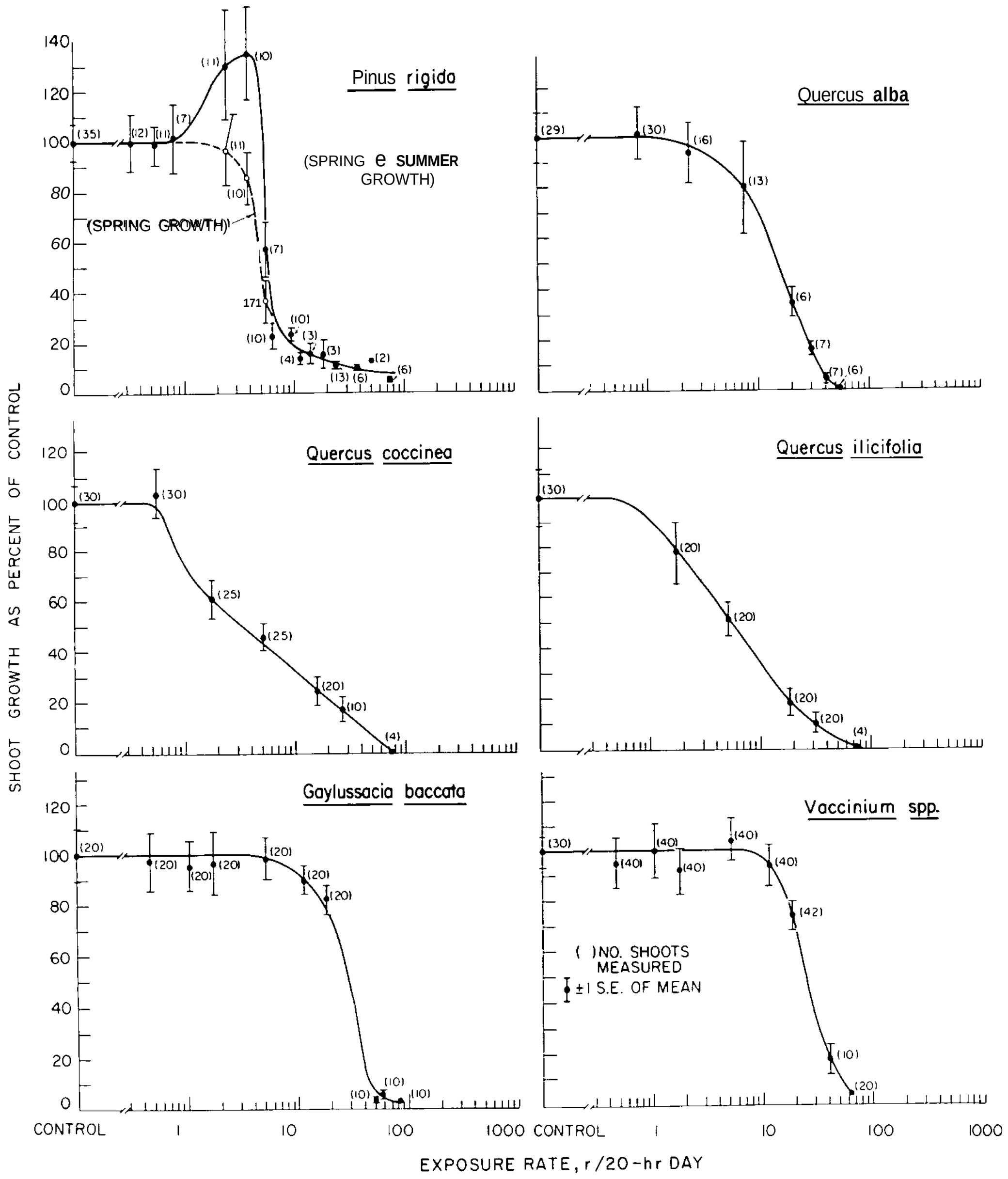


Figure 5. Growth of woody species in a chronically irradiated forest during the first year (1962) following installation of the radiation source.[37]

excess of about 60 r per day (11,000 r total), which killed the above-ground parts of most trees. Trees that appeared to have survived exposures in excess of 60 r per day had shielded buds which therefore were exposed to lower doses than average for that location."[34] These results are summarized in Figure 4.

At 23 r per day cumulative exposures of about 4000 r reduced foliage production of pine (*Pinus rigida*) (nomenclature follows Fernald[8]) to $<$10% of nonirradiated controls. Similar damage occurred in oaks (*Quercus alba, Q. coccinea*) at about 60 r per day (11,000 r total). The heath-shrub ground cover (*Vaccinium angustifolium*, *V. vacillans*, and *Gaylussacia baccata*) survived to about 150 r/day (27,000 r total) and the sedge (*Carex pensylvanica*) to $\approx$300 r/day (60,000 r total). Exposures in excess of about 63,000 r (350 r/day) killed all the higher plants of this forest, and the central area around the source supported only one or two individuals of *Baptisia tinctoria*, *Solidago*, and *Apocynum* during the summer of 1962.

As would be expected, shoot growth of the major species was inhibited by much lower exposures (Figure 5). Less than 10 r/day (1800 r total) reduced shoot growth of all tree species below that in a nearby unirradiated forest. Exposure of pine trees to 1 to 5 r/day (180 to 900 r total) caused a second flush of growth in midsummer, which resulted in greater shoot elongation for the year, but at higher exposures growth was inhibited (Figure 5).

The heath-shrub ground cover showed little damage at exposures $<$10 r/day (1800 r total). *Carex pensylvanica* was substantially more resistant. This plant reproduces rapidly vegetatively and within two years formed an irregular but extensive mat in the zone where other higher plants had died. Other evidence has shown that much smaller total exposures would produce equivalent effects if administered in a shorter period such as days or hours as opposed to months (see below).

Insect Populations

Insect populations in this experiment have been studied by Brower,[5] who made standardized sweep samplings of the shrub layer during 1961 prior to the establishment of the source and in 1962 and 1963 after irradiation was started. These samplings were supplemented by extensive systematic observations accompanied by limited sampling of other populations. The data have shown in general that the principal changes in insect populations have followed changes in abundance of food. The bark lice *(Psocoptera)*, for instance, which feed in part on fungi, and the bark beetles *(Ips)*, which inhabit dead and dying pine trees, increased in abundance in the zone of tree mortality. Populations of leaf hoppers (*Scaphytopius*), however, were depressed where the cover provided by blueberries and huckleberries was reduced by radiation damage.

In certain instances there was a clear increase in the amount of damage by herbivorous insects. Woodwell[33] reported an increase in the abundance of defoliators on radiation-damaged white oak trees during the summer of 1962. This increase was tentatively attributed to the concentration of endemic populations on the smaller total leaf-surface area of radiation-damaged trees. During the summer of 1963, the second summer following commencement of irradiation, exceptionally high populations of aphids occurred on leaves of radiation-damaged oaks.[5] These populations were more than 200 times as great as those in a similar nearby non-irradiated forest, which suggests that for some reason aphid populations were more successful on damaged trees. While the insect damage to surviving plants was conspicuous, the aphid populations declined later in the summer, and no evidence was found in this study that the biological interactions that are normally part of an orderly succession had been upset in any persistent or catastrophic way.

DESCRIPTION OF EFFECTS OF A SIX-MONTH EXPOSURE OF AN OLD FIELD

The effects of chronic gamma irradiation of an old field ecosystem at Brookhaven National Laboratory have been described elsewhere.[35,36] The results agree in general with those of McCormick and Platt[15] and Daniel.[7] Figure 6 is a summary of the results of the first year's observations of the old field, with total exposures covering the same period as for the forest (Nov. 22 - May 22). This treatment of exposure seems reasonable since the field contained only annuals whose seeds were probably distributed during the fall of the previous year[31,36] and were exposed on or near the surface of the soil during the winter. The exposure required to reduce diversity in the herbaceous plant community to 50% was $\approx$1000 r/day (total, 100,000r), or $>$5 times the exposure required to produce a similar effect in the forest. Clearly the plant populations of this old field ecosystem are substantially more resistant than those of the irradiated forest.

COMPARISON OF BROOKHAVEN FIELD EXPERIMENTS WITH POTENTIAL EFFECTS FROM FALLOUT

Dr. Miller has described in this symposium the nature of the radiation in fallout fields, which differs qualitatively and quantitatively from the radiation fields of the

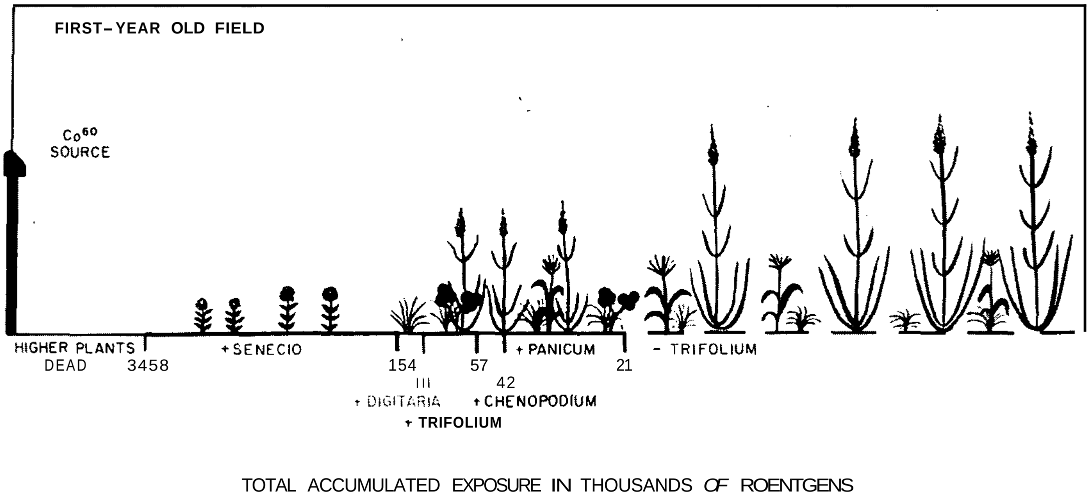


Figure 6. **A** first-year old field plant community which developed under daily gamma irradiation at levels that in six months gave total exposures shown.

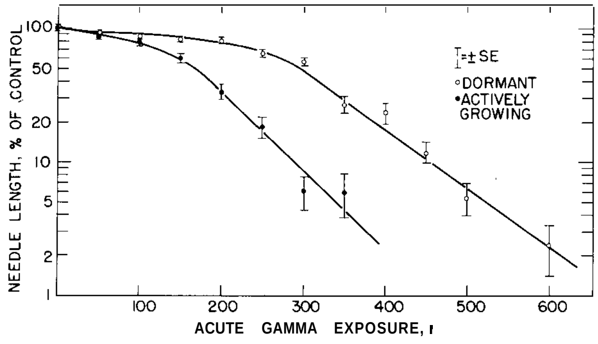


Figure 7. Needle growth of acutely exposed pine *(Pznus strobus)* during active growth and during dormancy.[28]

Brookhaven experiments. First, the exposure rate in a fallout field diminishes rapidly, dropping within 100 hr to <1% of the rate 1 hr after the blast. Dose rate is well known to be an important factor in radiobiology.[21] Second, the fallout field contains both gamma emitters and isotopes producing alpha and beta emissions. These latter emitters may have important effects not only after the radionuclides are incorporated into living material, but also when they are deposited on the surface of sensitive structures such as poorly protected buds or other meristems. Furthermore, while there would be local geographic variation in the amount of fallout, the general effect would be to blanket large areas with exposures relatively much more uniform than those of the experimental fields. These areas would be of the order of tens to hundreds or possibly even thousands of square miles.’” This is of particularly great significance to considerations of the reinvasion of the devastated area by plants and animals in the recovery period. By contrast, the radiation in the Brookhaven experiments is entirely gamma from a single source of approximately constant size, and the area devastated is small and subject to reinvasion from the less disturbed areas nearby. Despite these important differences, the first year’s results from the Brookhaven experiments, together with other data on radiosensitivity of species, provide a firm basis for appraising broadly the potential effects of fallout radiation from bombs on ecosystems. The experiment is particularly well suited for appraisal of effects on plant populations and on populations of sessile insects, less well suited for study of small mammals or motile insects.[34]

RELATIONSHIP BETWEEN SIX-MONTH **CHRONIC** EXPOSURE AND EXPOSURE **FROM** FALLOUT

The relationship between the exponential decay curve characteristic of fallout radiation and the chronic and acute exposures used in most experiments with radiation effects is difficult to resolve in a thoroughly satisfactory manner, since the degree of damage produced is a function not only of dose rate, but also of inherent characteristics of the organisms and of environmental conditions during and after exposure.[23,29,33,35] It is true, however, that the “acute” exposures of hours to a few days’ duration are better approximations of the fallout exposures than chronic exposures.

Furthermore, total exposures administered chronically exceed in general the acute exposure required to produce the same effect by factors which may be as high as 20 or more. Perhaps the best index of the difference between the chronic exposure of six months and an acute exposure required to produce the same effect is provided by data on pine. In the irradiated forest, for example, $>90\%$ of the pines were dead in September at exposure rates of >23 r/day[37] (Figure 4). Assuming that this damage occurred during the first six months of exposure, the total exposure required to kill them was about 4100 r. Laboratory experiments with seedlings have shown that $>90\%$ mortality occurs commonly in *Pinus rigida* at acute exposures in the range of 500 to 1000 r. Occasionally seedlings survive as much as 2000 r. Assuming that an acute exposure of 2000 r is the maximum that *P. rigida* will survive, there is then a ratio of about 2 between the total exposure administered chronically in the field over six months and the acute exposure needed to produce the same effects. The use of a factor of 2 therefore has been adopted for adjusting total six-month chronic exposures to the exposure from fallout.

EFFECT OF SEASON ON DAMAGE FROM FALLOUT EXPOSURES

The nature and severity of radiation effects are also influenced importantly by the phenological condition of the organisms irradiated. Dormant plants, for instance, are substantially more resistant to acute exposures and probably to fallout exposures than actively growing plants (Figure 7). This difference spans a factor of 2, possibly more. The variation in sensitivity during the entire life cycle in plants is even greater[29] and it is still greater in insects.'' From the standpoint of damage to the plant populations that dominate the structure of terrestrial ecosystems, the greatest sensitivity to fallout radiation would be in the spring or early summer, the least probably in late summer or fall, when there would be a maximum period for recovery before the next growing season. The range of variation in somatic effects introduced would span a factor of at least 2, possibly more. Where effects on sexual reproduction or seed set are important, as they would be in many agricultural or horticultural plants, the variability would be potentially much greater, with certain stages probably sensitive to as little as one-tenth the exposure necessary to affect vegetative growth adversely.

PATTERNS OF RADIOSENSITIVITY AMONG ECOSYSTEMS

It has been suggested by Woodwell[35] that there are patterns of radiosensitivity among ecosystems. He based this conclusion on several relationships. First, a striking difference has been observed between the exposure necessary to devastate the forest and that to aiter the old field. Second, there are sharp differences in sensitivity between such trees as pines and oaks, both of which are important dominants of different ecosystems. Third, the gymnosperms in general, which form the major component of certain ecosystems in both the Northern and Southern Hemispheres, have been shown in several studies to be more sensitive than the majority ofangiosperms to damage from ionizing radiation. This is particularly evident in Figure 8, which shows that gymnosperms in general have larger chromosome volumes than angiosperms

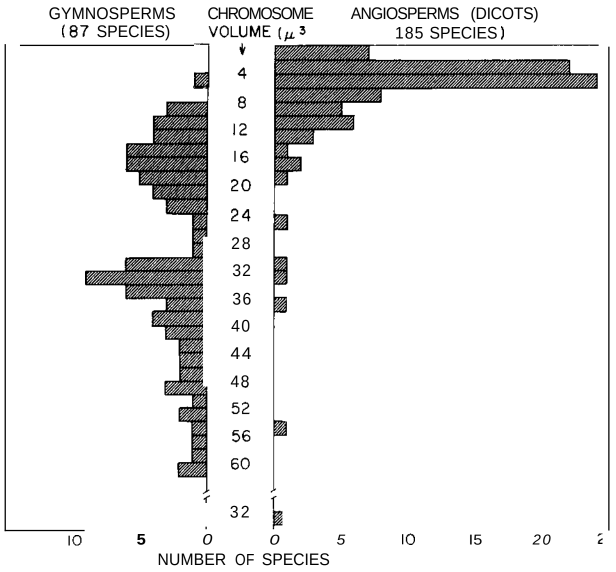


Figure 8. Comparison of the distribution of interphase chromosome volumes of 172 species of dicotyledonous and gymnospermous plants (adapted from Sparrow'").

and therefore are probably more sensitive to radiation. Fourth, certain adaptations such as the annual habit, asexual reproduction, and high degrees of polyploidy are characteristic of plants of certain types of ecosystems (see Sparrow and Woodwell" for further discussion). These adaptations contribute importantly to resistance to radiation damage as well as to ability to survive harsh environmental conditions. Among successional ecosystems, the early stages characterized by herbaceous annuals are substantially more resistant than the later forest stages, the difference spanning a factor of 5 to 10 in the Eastern Deciduous Forests (Figures 5 and 6).

DISCUSSION OF THE SEVERITY OF FALLOUT RADIATION EFFECTS ON NATURAL ECOSYSTEMS

Most natural ecosystems of temperate zones retain their capacity for regenerating the climax after a wide range of types and degrees of damage. Forests are usually self-regenerating units, even after clear cutting; abandoned fields revert to stable native vegetations through a series of developmental stages. It is axiomatic that these successions are not regressive but developmental, leading toward climax." The physical destruction initiating the succession causes the regression and, if the destructive influences are chronic, may maintain one of these developmental stages indefinitely as a Clementsian subclimax or disclimax. Destruction of the ecosystem, however, may reduce the potential of the site for supporting life for long periods, possibly for scores of years, at least in the diversity present previously. This would be true, for instance, if erosion occurred or if there were a loss of essential nutrients which had accumulated in the system through hundreds of years.

Three categories of damage to natural ecosystems which might be caused by ionizing radiation are discussed below. The first two include damage whose repair is well within the capacity of the system. The third category includes severe effects which might lead to a long-lasting reduction in the capacity of the habitat to support an ecosystem equivalent in complexity to the one destroyed.

Minor Effects

Low exposures may inhibit growth of sensitive species temporarily, possibly reducing reproductive capacity as well. Such minor effects are common in nature from various causes such as wind or frost or unfavorable seasons, and the impact of radiation-induced effects would be similar to these. Recovery from such damage occurs rapidly without changes in the species composition of the plant community and without conspicuous change in the direction or rate of succession. Damage of this nature would be considered "minor." The exposure required to produce this "minor" effect would vary in different ecosystems (see Table *2).*

Intermediate Effects

Selective inhibition or mortality of sensitive populations would initiate successions similar to those following catastrophic storms, grazing, or selective logging of forests. The generalized pattern would involve the immediate direct effects of the radiation followed by shifts in both the plant and animal populations to occupy the new resources available. These shifts are part of the homeostatic processes characteristic of natural ecosystems and usually, although certainly not always, proceed in orderly and grossly predictable fashion, without catastrophic insect or plant plagues. Included in this category is damage that is severe enough to change the populations of plants present and thereby initiate new successions.

The conditions under which the initial damage caused by the radiation would be amplified by biological interactions before the establishment of an orderly succession are largely unknown and highly speculative and probably depend primarily upon the severity of the radiation damage. The principal type of interaction possible would seem to involve secondary damage to plants from herbivorous insects which are capable of relatively rapid reproduction. Such interactions have been observed in the Irradiated Forest Experiment at Brookhaven, but effects have been short-lived and the damage has been minor. The possibility of rapid upsurges of plant pathogens cannot be disregarded, although evidence for it is so far lacking. These biological interactions might be expected within this category of effects, especially **at** higher exposures, but would not prevent the establishment within 2 to ***3*** years of an orderly succession leading toward an ecosystem basically similar in structure and function to the system destroyed.

Severe Effects

Very intense exposures of ecological systems to ionizing radiation might damage them sufficiently to reduce the capacity of the site for supporting life, slowing the succession greatly or diverting it toward a new, less complex climax. There are certain parallels for this type of destruction. The harvest or burning of certain tropical rain forests for instance is thought to lead to the removal by leaching of essential

Table 1

Estimated Acute Exposures Required To Affect Dominants of Major North American Vegetations

Estimates are based on correlations between radiosensitivity and interphase chromosome volume. Variability introduced into the estimates by the measurements of nuclear volumes alone is about ±30% of the means listed. Other uncontrolled intrinsic and environmental factors increase the potential errors greatly (see text). Data reported are those available in January 1964.

	Somatic chromosome number	Interphase chromosome volume (μ^3)±S.E.	Sensitivity range: slight inhibition of growth to mortality, r
		FORESTS	
Boreal			
Picea glauca	24	39.7±1.6	220- 590
Abies balsamea	24	33.4±2.2	270- 700
Subalpine (Rocky Mountains)			
Picea engelmannii	24	26.8±1.6	330- 880
Abies lasciocarpa	24*	33.5±1.7	270- 700
Montane (Rocky Mountains)			
Pseudotsuga menziesii	26	28.5±1.1	310- 820
Pinus ponderosa	24	36.7±2.8	240- 640
Montane (Sierra-Cascades)			
Abies concolor	24	23.3±0.9	380- 1010
Pinus lambertiana	24	57.8±3.1	150- 410
P. jeffreyi	24	48.1±1.9	190- 490
P. ponderosa	24	36.7±2.8	240- 640
Pseudotsuga menziesii	26	28.5±1.1	310- 820
Pacific Conifer			
Tsuga heterophylla	24*	23.7±0.9	377- 990
Thuja plicata	22	8.6±0.4	1040- 2730
Abies grandis	24	33.2±1.1	270- 710
Eastern Deciduous			
Mixed Mesophytic			
Fagus grandfolia	24	2.3±0.1	3810-10000
Magnolia acuminata	76	4.8±0.2	1850- 4840
Tilia americana	82	2.5±0.1	3520- 9230
Liriodendron tulipifera	38	6.4±0.5	1400- 3680
Acer saccharum	26	3.2±0.2	2800- 7360
Quercus alba	24	6.6±0.3	1350- 3550
Tsuga canadensis	24	21.350.8	420- 1100
Beech-Maple & Maple-Basswood			
Fagus grandifolia	24	2.3±0.1	3810-10000
Acer saccharum	26	3.2±0.2	2800- 7360
Tilia americana	82	2.5±0.1	3520- 9230
Hemlock-Hardwoods			
Tsuga canadensis	24	21.3±0.8	420- 1100
Betula lutea	84	2.2±0.1	3860-10120
Pinus strobus	24	46.5±2.8	190- 500
P. resinosa	24	43.2±3.5	210- 540
Acer saccharum	26	3.2±0.2	2800- 7360

Table 1 (continued)

Eastern Deciduous (continued)			
Oak-Chestnut			
Castanea dentata	24	4.7±0.3	1900- 5000
Quercus coccinea	24	3.6±0.3	2490- 6530
Q. prinus	24	6.1±0.3	1470- 3870
Pinus rigida	24	48.3±2.8	190- 490
Oak-Hickory			
Quercus alba	24	6.6±0.3	1350- 3550
Q. rubra	24	5.5±0.3	1620- 4250
Q. uelutina	24	3.2±0.2	2830- 7430
Q. stellata	24	4.4±0.2	2040- 5350
Q. marilandica	24	3.3±0.2	2690- 7060
Carya ovata	32	2.5±0.2	3560- 9340
C. cordiformis	32	1.81–0.1	5090-13370
C. tomentosa	64	1.8±0.5	5080-13350
C. laciniosa	32	2.6±0.1	3470- 9110
Pinus taeda	24	52.6±4.1	170- 450
GRASSLANDS			
Andropogon scoparius	40	6.4±0.4	2330- 9200
AGRICULTURE			
Zea mays HV Golden Bantam	20	14.0±0.6	1060- 4200
Tetraploid	40	10.8±0.6	1370- 5410
Triticum aestivum	42	14.6±1.1	1020- 4020

*Probable chromosome number.

nutrients normally held in the system and recycled. The loss of these nutrients following destruction of the forest limits the rate of succession and may delay indefinitely the re-establishment of the original vegetation. Erosion following logging or fires on steep slopes in temperate regions may have similar effects through loss of nutrients compounded by the presence of unstable soils. If destruction were severe over many square miles, seed sources might be remote from devastated areas, which would further slow rates of succession and possibly alter the potential of the site for developing the original climax. Climatic changes, which isolated seed sources, seem to have caused the grassland and heath-shrub areas called “balds” in the Southern Appalachians.[11,32]

It is possible at present to estimate in general terms the radiation exposures necessary to produce these broad categories of effects. Such a prediction can be based on (a) the correlation between radiosensitivity and interphase chromosome volume, and (b) the limited experience we have had with irradiated natural ecosystems. This correlation has been used to predict the potential effects of acute radiation exposure of major dominants of certain natural vegetations in North America (Table 1). Exposures listed are average exposures required to cause damage in plants ranging from slight inhibition of growth to mortality of all individuals. Variability in the measurements of chromosome volumes and in the data used in the regression equation introduces errors which place the 95% confidence limits $\approx$30% above and below the exposures listed. Other intrinsic and environmental factors influencing radiosensitivity of plants in nature have not been accounted for in these estimates and could introduce variability of as much as five times the means under field conditions.[37]

Estimates of radiosensitivity of species for which data were available in January 1964 are given in Table 1. Terminology of the vegetation follows Oosting.[18] Plant names follow Little[11] where Fernald[8] does not apply. Species that are dominant in more than one vegetation are repeated to simplify use of the table.

Average interphase chromosome volumes range from highs of about 50 μ^3 for certain of the pines to lows of about 2 μ^3 for some of the hickories. The gymnosperms in general have much higher chromosome volumes than the angiospermous trees, although *Thuja plicata* appears to be an exception, having an average chromosome volume of 8.6 μ^3, which is much closer to the 6.6 of white oak than to the 48.3 of pitch pine.

Estimated acute exposures to kill 100% of any population range from lows of about 500 r for certain pines through highs of 10,000 to 13,000 r for birch, beech, and the hickories. In general, the forests that contain gymnosperms as major dominants appear to be more sensitive than the deciduous forests of the East. Exposures of a few hundred to 2000 r are enough to kill most trees of the coniferous forests, while 5 times that exposure range would be required to do the same damage in hardwood forests.

Few data were available for native grasslands. *Andropogon scoparius*, the broom sedge, has an average interphase chromosome volume of 6.4 μ^3, which suggests that it would be killed by exposures of $<$10,000 r.

Corn and wheat have larger chromosome volumes, 14 and 14.6 μ^3, respectively. According to the correlation, exposures of $<$5,000 r would kill both plants.

Extension of such predictions as these to anticipation of effects on ecosystems is subject to large errors. There is no question, however, that radiation exposures in the range 10,000 to 100,000 r will kill all or most of the higher plants of certain ecosystems. The capacity of the systems for recovery depends on a host of factors including the availability, distribution, and vitality of seeds; the ability of surviving plants to sprout or produce seeds; the numbers of destructive insects which survive or which, living nearby, can infiltrate and multiply; the uniformity of the fallout distribution; the size of the area devastated and its condition (whether burned or not); and the environmental conditions during and after exposure.

Probably the most important single factor that might delay recovery indefinitely in North America would be unstable soils. Montane and piedmont areas would be particularly sensitive to erosion and to radiation damage, since the principal trees of many of these areas are the highly sensitive gymnosperms. Deciduous forests in lowlands would be substantially less sensitive, probably by as much as an order of magnitude, because the trees themselves are less sensitive to radiation damage, there is a greater diversity of species available to contribute to stabilization of the site and recovery of the system, and there is less possibility of severe erosion.

Destruction of vegetation over areas as large as tens or hundreds of square miles might slow recovery by isolating devastated areas by distance alone from sources

Table 2

Estimated Radiation Exposures Required To Damage Major Ecosystems

Major ecosystems	Level of Damage		
	Minor	Intermediate	Severe
City	200	200	—
Agriculture	200	200	—
Coniferous forest	200	200- 2000	>2000
Deciduous forest	200	200-10000	>10000
Grassland	2000	2000-20000	>20000
Herbaceous successional	4000	4000-70000	>70000

of recolonization. The probability that destruction could be that severe after a heavy attack is real enough.[16] Fire might follow such widespread devastation, slowing recovery further.[4]

Table *2* summarizes the radiation exposures estimated as necessary to produce the three levels of effects in North American ecosystems. Estimates are based on the field studies summarized in this paper, on data from the literature, and on the correlations reported between radiation tolerance and nuclear or chromosomal volumes. All such estimates are subject to large errors at present, but it is useful to make a broad appraisal of radiation exposures necessary to cause varying degrees of damage to major ecosystems.

In cities and most agricultural ecosystems the most sensitive dominant organism is man, and the severity of radiation effects on the system would be determined by his ability to survive and function normally. If radiation exposure is the only hazard, serious effects would be apparent in men at exposures >200 r.[30] Few, if any, people would survive whole-body exposures >1000 r of gamma radiation.

In ecosystems not dominated by man, the greatest changes in structure would follow damage to the plant populations. The sensitivities of these populations range from those of the gymnosperms, some of which may be killed by exposures in the same range that kills man (500 to 1000 r), to those of the highly resistant forms such as certain algae and fungi whose tolerances go above 100,000 r. In these ecosystems the net effect of the radiation would be simplification of the system by selective inhibition or mortality of sensitive species. Although mammals and even certain stages of insects''' might be substantially more sensitive than most of the plant populations, the major changes in the structure and function of natural ecosystems would probably be associated with the direct effects on the plants and with the plant successions initiated.

Table *2* shows that intermediate effects, including the initiation of new successions, would be expected in coniferous forests at exposures in the range of a few hundred to about 2000 r. The upper limit for such effects extends to about 10,000 r in deciduous forests and to 20,000 r and above in grasslands and communities of herbaceous plants. At exposures above these, radiation damage would be severe by our definition, probably beyond the limits of homeostasis for certain ecosystems, especially those in which erosion may occur. Although these estimates are tenuous, it would seem wise to bend future research efforts less toward refining their precision than toward eliminating the hazard of catastrophic irradiation.

SUMMARY

1. The purpose of this paper is to define broadly the potential effects of fallout radiation on the natural ecological systems forming the homeostatic matrix within which civilization exists.

2. Ecosystems have three basic patterns: geographic pattern, such as deserts, grasslands, forests, and tundras; temporal patterns which are successions; and patterns of internal structure and function. The latter can be defined in many ways. In this paper the distribution and flow of energy among the various populations is used.

3. Three sources of information are available for analysis of the potential effects of fallout radiation on these patterns: data from experimentally irradiated ecosystems, data from radiobiological studies of many organisms, and data from other parallel catastrophes in which ionizing radiation was not a factor. This discussion concentrates on the first two sources.

4. Experimentally irradiated ecosystems contributing data to this analysis include those around the Lockheed reactor in northern Georgia and recent experiments in an oak-pine forest and in old fields at Brookhaven National Laboratory.

5. Radiobiological data of particular use are the correlations recently developed at Brookhaven between the radiosensitivity of plants and chromosome volume.

6. These analyses show patterns of radiosensitivity among the plant populations of natural ecosystems; communities of herbaceous annuals, for instance, would probably withstand fallout radiation exposures up to 4000 r with minor effects, while most coniferous forests would be devastated by 2000 r or less.

, 7. Field experiments with small, open, irradiated ecosystems have shown no clear tendency for devastating population explosions of insects after radiation damage, but experience is limited. Changes in herbivorous insect populations have followed, in general, the abundance of food.

8. Three categories of radiation effects on ecosystems were established for predicting potential fallout effects: minor effects involving temporary inhibition of growth or reduction of reproductive capacity in plants, intermediate effects involving the initiation of new plant successions, and severe effects involving the potential alteration of the capacity of the site to support life. This latter range of effects might occur after erosion or loss of essential nutrients. Prediction of “severe effects” is subject to large uncertainties introduced by ecological factors in addition to irradiation.

ACKNOWLEDGMENTS

Various associates of the authors have contributed greatly in numerous ways to this publication. The authors wish to thank, in particular, J.K. Oosting, G.M. Courtin, L.A. Schairer, E. Klug, Virginia Pond, Anne F. Rogers, and Rhoda C. Sparrow. Valuable statistical advice and assistance was rendered by K. Thompson.

Dr. F.H. Bormann of the Department of Biological Sciences, Dartmouth College, has contributed freely of his time, efforts, and ideas through numerous discussions and through reading the manuscript.

REFERENCES

1. Blumberg, B.S. and Conard, R.A. 1960. A note on the vegetation of the Northern Islets of Rongelap Atoll, Marshall Islands. In *Medical Survey of Rongelap People Five and Six Years After Exposure to Fallout.* BNL 609 (T-179). Brookhaven National Laboratory, Upton, N.Y. Pp. 85-6.

2. Braun, E. Lucy. 1950. *Deciduous Forests of Eastern North America.* Blakiston, Philadelphia. 596 pp.

3. Braun-Blanquet, J. 1932. *Plant Sociology.* Translated and reviewed by G.D. Fuller and H.S. Conard. McGraw-Hill, New York. 439 pp.

4. Broido, **A.** See paper in this symposium.

5. Brower, J. 1963. Changes in insect populations in a natural forest community exposed to chronic gamma radiation stress. (Abstr.) *Bull. Ecol. Soc. Am.* **44,** 69.

6. Clements, F.E. 1928. *Plant Succession and Indicators.* H.W. Wilson, New York. 453 pp.

7. Daniel, C.P. 1963. A study of succession in fields irradiated with fast neutron and gamma radiation. In *Radioecology,* V. Schultz and A. Clement (Editors). Rheinhold, New York, and American Institute of Biological Sciences, Washington. Pp. 277-282.

8. Fernald, M.L. 1950. *Gray's Manual of Botany.* American Book, New York. 1632 pp.

9. Fosberg, F.R. 1959. Plants and fallout. *Nature* **183,** 1448.

10. International Atomic Energy Agency. 1963. *Radioisotopes and Ionizing Radiations in Entomology. Bibliographical Series No. 9.* IAEA, Vienna. 414 pp.

11. Johnson, N. and Woodwell, G.M. 1963. Field use of thermoluminescence for gamma dosimetry. (Abstr.) *Bull. Ecol. Soc. Am.* **44,** 68.

12. Little, E.L. jr. 1953. *Check List of Native and Naturalized Trees of the United States. Agriculture Handbook No. 41.* Forest Service: USDA, Washington. 472 pp.

13. Margalef, R. 1963. On certain unifying principles in ecology. *Ann. Naturalist* **97,** 357-74.

14. Mark, A.F. 1958. The ecology of southern Appalachian grass balds. *Ecol. Monographs* **29,** 293-336.

15. McCormick, F.J. and Platt, R.B. 1962. Effects of ionizing radiation on a natural plant community. *Radiation Botany* 2, 161-204.

16. Miller, C.F. *See* paper **in** this symposium.

17. Odum, E.P. 1959. *Fundamentals of Ecology.* Saunders, Philadelphia. 546 pp.

18. Oosting, H.J. 1956. *The Study of Plant Communities.* W.H. Freeman, San Francisco. 440 pp.

19. Palumbo, R.F. 1961. Recovery of the land plants at Eniwetok Atoll following a nuclear detonation. *Radiation Botany* I, 182-9.

20. Platt, R. See paper in this symposium.

21. Read, J. 1959. *Radiation Biology of* Vicia faba *in Relation to the General Problem.* Blackwell, Oxford. 270 pp.

22. Shields, L.M. and Rickard, **W.H.** 1961. **A** preliminary evaluation of radiation effects at the Nevada Test Site. In *Recent Advances in Botany.* University of Toronto, Toronto. Pp. 1387-90.

22a. Shields, L.M. and Wells, P.V. 1962. Effects of nuclear testing on desert vegetation. *Science* **135,** 38-40.

23. Sparrow, **A.H.** 1962. *The Role of the Cell Nucleus in Determining Radiosensitivity. Brookhaven Lecture Series No. 17.* BNL 766 (T-287). Brookhaven National Laboratory, Upton, **N.Y.** 29 pp.

24. Sparrow, **A.H.** 1965. The tolerance of plants to ionizing radiation: variations, modifications and predictions. In *Thermonuclear War: Some Effects on People and Nature,* T. Stonier (Editor). Blaisdell. To be published.

25. Sparrow, A.H., Cuany, R.L., Miksche, J.P., and Schairer, L.A. 1961. Some factors affecting the responses of plants to acute and chronic radiation exposures. *Radiation Botany* I, 10-34.

26. SPARROW, A.H. AND MIKSCHE, J.P. 1961. Correlation of nuclear volume and DNA content with higher plant tolerance to chronic radiation. *Science* **134,** 282-3.
27. SPARROW, A.H., SCHAIRER, L.A., AND SPARROW, R.C. 1963. Relationship between nuclear volumes, chromosome numbers and relative radiosensitivities. *Science* **141,** 163-6.
28. SPARROW, A.H., SCHAIRER, L.A., SPARROW, R.C., AND CAMPBELL, W.F. 1963. The radiosensitivity of gymnosperms. I. The effect of dormancy on the response of *Pinus strobus* seedlings to acute gamma irradiation. *Radiation Botany* **3,** 169-74.
29. SPARROW, A.H. AND WOODWELL, G.M. 1962. Prediction of the sensitivity of plants to chronic gamma irradiation. *Radiation Botany* **2,** 9-26.
30. UNSCEAR. 1962. *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. General Assembly. Official Records: 17th Session, Supplement No. 16.* United Nations, New York. 442 pp.
31. WAGNER, R.H. 1965. The autumnal seed rain in an irradiated forest. *Ecology.* In press.
32. WHITTAKER, R.H. 1956. Vegetation of the Great Smoky Mountains. *Ecol. Monographs* **26,** 1-80.
33. WOODWELL, G.M. 1962. Effects of ionizing radiation on terrestrial ecosystems. *Science* **138,** 572-7.
34. WOODWELL, G.M. 1963. Design of the Brookhaven experiment on the effects of ionizing radiation on a terrestrial ecosystem. *Radiation Botany* **3,** 125-33.
35. WOODWELL, G.M. 1963. Ecological effects of radiation. *Sci. Am.* **208,** 40-9.
36. WOODWELL, G.M. AND OOSTING, J.K. 1965. Effects of chronic gamma irradiation on the development of old field plant communities. *Radiation Botany* (in press).
37. WOODWELL, G.M. AND SPARROW, A.H. 1963. Predicted and observed effects of chronic gamma irradiation on a near-climax forest. *Radiation Botany* **3,** 231-8.

Ionizing Radiation and Homeostasis of Ecosystems

ROBERT B. PLATT
Emoy University, Atlanta, Georgia

This paper is a review of the concept of homeostasis as applied to ecosystems. It emphasizes the fundamental distinctions among various methods for the study of radiation effects on homeostatic mechanisms within ecosystems, presents one line of evidence for evaluation of these effects, and reviews the fundamental bases necessary for predicting effects of radiation stress on homeostatic mechanisms in other kinds of ecosystems. The paper is restricted to radiation effects *per se* with particular reference to nuclear war, and does not pertain to the distribution and fate of radionuclides in the natural environment.

A historical perspective is essential to understanding current concepts of homeostasis within irradiated ecosystems. Although most studies in the early days of the Atomic Age were medically or economically oriented, the significance of ionizing radiation as an ecological factor in man's natural environment did attract the interest of many biologists. Some of the first research programs were initiated in the 1940's at the Pacific Atoll test site," and later at the Nevada test site.[16] The first major step in the development of radiation ecology, however, was the establishment in the mid-1950's of an Environmental Sciences Branch within the Division of Biology and Medicine, U.S. Atomic Energy Commission, to study direct effects of radiation and the fate of radionuclides in man's natural environment.

Among the first papers to attract widespread scientific and political interest was one of Wolfe's[18] on the ecological effects of nuclear war. Mitchell[8] presented perhaps the first Civil Defense analysis of ecological problems relating to postnuclear war recuperation. Studies were begun in 1956 at Emory University on radiation effects on ecosystems using primarily short-term exposures from point sources,'' and in 1960 at Brookhaven National Laboratory using primarily continuous irradiation from point sources.[19] Many other programs, too numerous to review here, have been initiated in recent years. The First National Symposium on Radioecology was held in September 1961 under the auspices of the Environmental Sciences Branch of the USAEC and the American Institute of Biological Sciences.

This brief review shows that most of our concepts have been developed within the past ten years and that most publications on radiation ecology have appeared within the last five years. Today research on radiation effects on ecosystems, which involves homeostasis, is in a vigorous and actively expanding condition. With the broad outlines developed, the trend is toward research in greater depth, with increasing emphasis on physiological as well as ecosystem ecology.

HOMEOSTATIC MECHANISMS

The term homeostasis is used to emphasize the concept that ecosystems have regulatory mechanisms paralleling those of organisms, and that ecosystems react to radiation stress in the same manner as to other environmental stresses. Utilizing these regulatory mechanisms, they adjust to continuously changing environmental conditions, including diurnal and other cycles, and react and adjust to various catastrophes.

Physical mechanisms affecting homeostasis include conditions of the physical environment such as temperature, moisture, light and ionizing radiation, nonliving materials, and energy flow. Structure refers to the spatial relationships of the various species, such as the trees and shrubs which form a closed canopy in deciduous forests, or the widely spaced plants of the desert, which form an open or interrupted canopy.

Species composition includes the diversity of species, the abundance and distribution of the component species, and the function of these species within the community in performing autotrophic or heterotrophic activities. In general, the greater the diversity, the greater the resources of the ecosystem in adjusting to stress. If certain species are removed by insect injury, extreme drought, ionizing radiation, or other stresses, the availability of replacement species becomes significant. Most ecosystems contain an ample supply of replacement organisms in the form of seeds and underground perennating organs. The removal or alteration of the overstory or other parts of the community changes conditions and presents opportunities for replacement organisms to establish themselves. These immediately available replacement organisms could have been left by prior successional stages or carried in by wind, birds, and other means. When an eastern deciduous forest is cut over, weed seeds that have been carried in by wind and other sources can germinate because of the changing conditions and within a matter of weeks and months re-establish a ground cover.

Tolerances to physical conditions, including ionizing radiation, temperature, moisture, and light, provide other homeostatic mechanisms unique to each species.

Still another ecosystem characteristic is productivity, which refers to the amount of energy fixed per unit of time. Earlier stages of succession are generally thought to be more productive than later stages because of the rapid change in species composition with time.

One of the most difficult homeostaticmechanisms to evaluate involves the biological interactions within and among populations. These include, for example, growth rate, growth form, age distribution, physiological state, competition, predation, and parasitism. Such interactions can vary widely and are constantly compensating so that over a long period of time there is a leveling off of species activities, even though fluctuations are essential to maintain the flow of energy, ample food supply, and other conditions within the ecosystem.

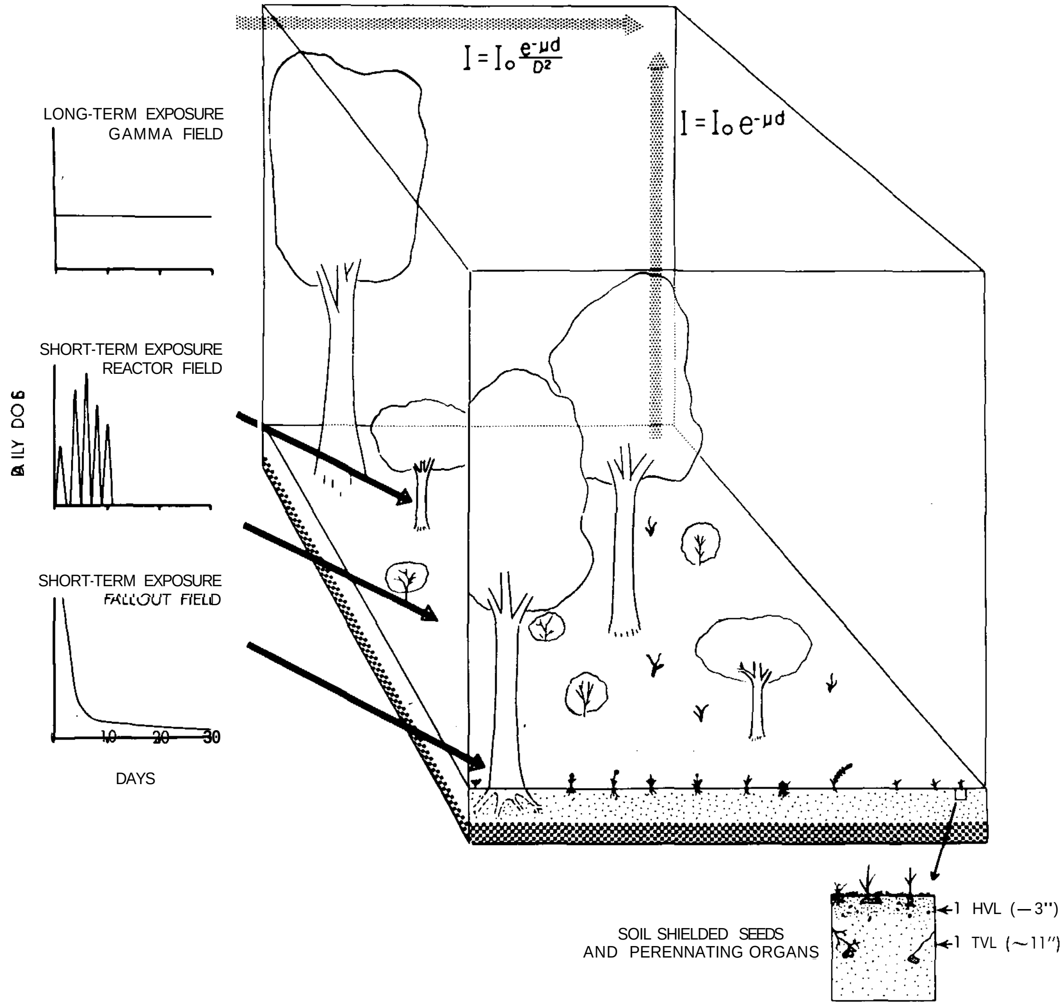
The important point in this brief discussion of homeostatic mechanisms is that ionizing radiation is an environmental stress on organisms and ecosystems, and as such must be considered as another environmental factor. This concept has been developed by Platt et al.,[12,13,15] Woodwell,''"" and others.

METHODS FOR IRRADIATING ECOSYSTEMS

Four basic methods, with many intermediate combinations, may be used for irradiating ecosystems. **A** three-dimensional model of an ecosystem, presented in terms of duration, dose rate, total dose, and dose distribution, is used in discussing these methods (Figure 1).

The methods are (1) short-term exposure from a uniform radiation field, followed by recovery; (2) short-term exposure from a point source, followed by recovery; (3) long-term or chronic exposure from a point source with concomitant adjustment to the continued stress; and **(4)**direct radiation from a nuclear explosion, accompanied by heat and blast, followed by recovery. In this paper, *acute* means exposure up to several hours; *short term,* exposure from several hours *to* several weeks;

Figure 1. A comparison of the radiation distribution from a point source and a fallout field. This three-dimensional model of an ecosystem demonstrates dose characteristics for two sources of radiation, one a uniform blanket of fallout, and the other a point source located away from the area studied. The lower right insert demonstrates environmental shielding of soil organisms, ½ of the radiation being attenuated by about **3** in. of soil, and ⁹⁄₁₀ths by about 11 in. The inserts on the left show 3 kinds of dose rates over a 30-day period.



long term or *chronic,* exposures of several months or more; *low-level* dose refers to doses in tens and hundreds of rads, and *high-level dose* to doses of tens of thousands of rads.

Short-Term Exposures From Uniform Radiation Fields

Fallout received as a uniform blanket on the surface of the ground would provide **a** "short-term exposure" (Miller, this symposium). The inverse-square law does not apply to such a uniform radiation field, and radiation dispersion is a function of the coefficient of absorption of the medium through which the radiation travels. Upward distribution of exposure is limited only by absorption by air and any vegetation that may be present. Distribution downward would be limited by absorption by the leaf litter and soil. Since the attenuation of upward distribution is relatively slight, dose distribution above ground from gamma irradiation is relatively uniform. Attenuation downward through the soil would be abrupt, however, the half-value layer for gamma radiation through soil being $\approx$3 in., and the $1/10$ value layer $\approx$11 in.

The distribution of beta radiation would be negligible, because of its high attenuation by air as well as soil. In the event of interception of fallout particles by leaves and twigs, the beta activity could be of some significance, because of its proximity to sensitive tissues in meristems.

Exposure rates and period of exposure are of particular significance. **As** shown on the left side of the diagram in Figure 1, the decay of fallout radioactivity is very rapid, two-thirds of the dose to infinity coming in two weeks. The exposure from fallout, then, is a short-term exposure by the definition used here. Recovery of the ecosystem would begin as the stress was relieved. None of our data suggests that the continued low-level radiation received from the decay of fallout particles after the first two weeks would have any significant effects on an ecosystem, although it may have some effect on certain species within the ecosystem. One example of this type of exposure is reported by Conard[2] at Rongelap. No serious effects were found in natural vegetation after exposures from fallout as high as 3000 r.

Short-Term Exposure From a Point Source

In certain experiments it has been convenient to use a single, centrally located source of radiation. Dose distribution in this case follows the inverse-square law, so that the attenuation falls off inversely with the square of the distance; there is also attenuation by the medium through which the radiation passes. If the distance from the radiation source were large in comparison with the distance across the area of interest, the change, according to the inverse-square law, would be relatively small, and dose distribution would approximate that received from a uniform fallout field, as in the case above.

Attenuation by the leaf litter and soil would follow the same general rule, since penetration into the soil is not greatly affected by the angle of incidence at which the radiation arrives. In the case of rough terrain, however, dose distribution below the soil may vary widely. Because of the buildup factor, as well as scattering by vegetation above the surface of the ground, it is possible that in some cases the dose will exceed that received above ground. (This is illustrated in Figure **3,** where the dose distribution over the brow of a hill from the source increases along the surface of the ground relative to the line-of-sight dose because of scatter and buildup.)

If the duration of exposure is limited to a short term of a few hours or days, this system of radiation very closely approximates that received from fallout.

The Lockheed air-shielded reactor with its several hundred acres of irradiated ecosystems is the only large-scale example of this method.

Long-Term or Chronic Exposure From a Point Source

This method is similar to the one immediately above, with one exception. The stress here is continuous rather than temporary, and the effects are correspondingly quite different, since there is no opportunity for recovery as long as the stress is applied. An applicable expression would be "adjustment to the continued stress," with the ultimate consequence being that of a changed situation, with no chance at all of the area's returning to its original condition as long as the stress persists.

An ecological analogue of chronic exposures would be a hot spring, in which the ecosystem by adjustment to the continuously high temperature is quite different from other spring ecosystems. The continued exposure of an oak-hickory forest around a copper smelter at Copper Hill, Tennessee, ultimately resulted, after many years of continued stress, in a denuded landscape, including the top soil. In contrast, forests nearby that are occasionally subjected to intense fires still retain, following such a fire, essential elements of the ecosystem such as soil, and therefore retain the capacity to restore themselves to their original condition within a few years or decades. In another comparison, a deciduous forest climax under 35 in. annual rainfall would probably readjust to a prairie if the rainfall were reduce to 20 in. Likewise, a forest could survive a chronic irradiation stress of 300 r/day, but probably would readjust to a herbaceous ecosystem if the stress were greatly increased.'"The irradiated forest at Brookhaven is the only example of this method. Radiation, started in November 1961, has been continuous and could be continued until a new equilibrium is reached. Results obtained after a few weeks or months exposure would be short-term data, but of course there would be no recovery.

Direct Radiation From Nuclear Explosions

Effects from this kind of radiation are very difficult to evaluate. The effects from the accompanying blast and heat have been in most instances more severe than that from radiation. Effects from these three stresses often are difficult to separate, and the radiation, coming in a flash, is a mixture of gamma, beta, and neutron doses. Subsequent irradiation of these highly disturbed ecosystems from the radioactive decay of materials in the area apparently produces minor effects in comparison to those above. However, in this case, as in the first two, recovery occurs as the stress is relieved. Atomic test sites provide many examples.[9]

FACILITIES AND EXPERIMENTAL DESIGNS FOR EMORY UNIVERSITY STUDIES

Facilities for the series of studies at Emory University consist of an outdoor gamma irradiation facility on the campus and the 10,000-acre reservation surrounding an air-shielded nuclear reactor operated by the Lockheed Aircraft Corporation. The radiation released into the environment around the air-shielded reactor has provided a unique situation. It is the only instance in which an ecosystem covering several hundred acres has been irradiated at exposures ranging from above-lethal to background levels over a period very closely approximating that which would result from fallout. It has the added advantage for our purposes of having received radiation of the order of tens of thousands of rads of accumulated exposure without the effects of heat and blast associated with bomb tests.

The Lockheed 10-MW reactor is in the center of a 10,000-acre reservation in the foothills of northern Georgia, an area of great ecological diversity.'" The principal vegetation is mixed evergreen-deciduous forest on both moist and dry sites, flood plain forests, and old fields on both upland and flood plain sites.

The irradiated area within which definitive biological studies have been made extends 1000 to 3000 ft from the reactor, depending upon the terrain. The irradiated area is roughly equivalent to that contained within a circle 2000 ft in radius, or almost 300 acres.

This large area has provided a broad numerical base for statistical analyses. For example, the irradiated forest contained an average of 150 trees/acre. Since at least 250 acres of land were wooded, the number of trees >3 in. in diameter in the total experimental sample could be estimated at 37,500. Figures for shrubs and herbs are even more impressive. Sample numbers, therefore, of hundreds and

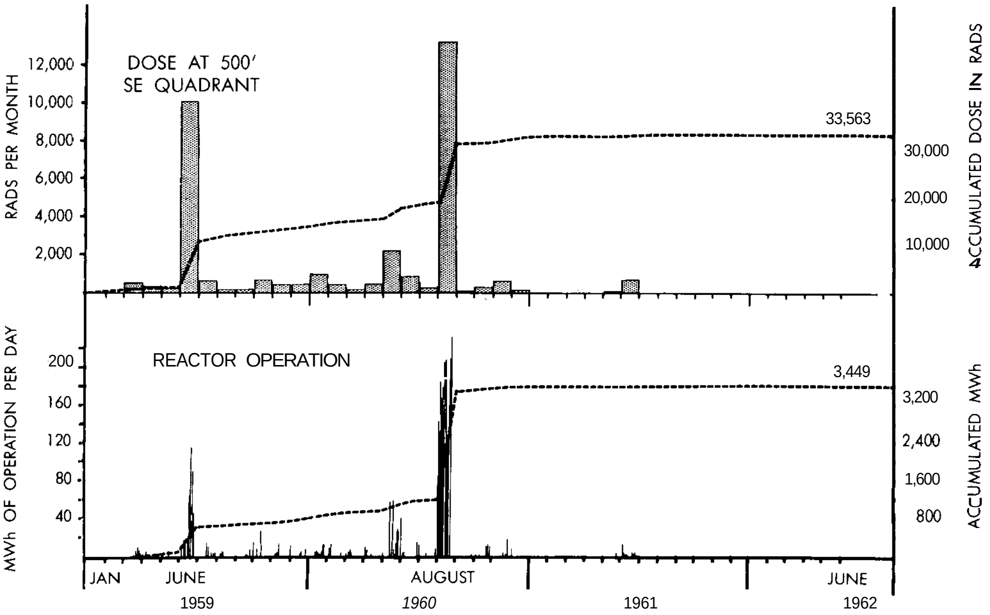


Figure 2. Lockheed reactor operation data beginning with the initial run. The schedule from June 1962 to the present has been approximately the same as that for 1961. Note that >80% of the radiation was released at two times, and that each time it approximated irradiation from fallout in both duration and total dose. At 500 ft, the dose each time was about that of the maximum expected over 2 to 5% of the United States from a 20,000-MT attack.

thousands per experimental plot have made it possible to distinguish between effects of ionizing radiation and those of other adverse environmental factors with which they may easily be confused, such as drought, killing frosts, insect damage, and disease. **As** these effects also occur in natural ecosystems, such distinctions are of extreme importance.

This large area provided radiation dosage gradients ranging all the way from accumulated doses over several months of 100,000 rads to background levels.

The distances at which biologically effective dosages were received were great enough that the decline in exposure with increasing distance from the source was relatively low. This means that exposure gradients across the crowns of large trees as well as across sizable experimental plots were very slight.

The irradiation pattern followed that of the second method above, short-term exposure followed by recovery.

By good fortune, >80% of the radiation released came in 2 short-term exposures of 2 and 3 weeks respectively, one in June 1959 and the other in August 1960 (Figure 2). The intensity and duration of each of these exposures were by chance similar to those expected from fallout following a nuclear catastrophe. The other 20% was delivered intermittently over a 3-year period at low intensities which had little or no effect at distances >500 ft from the reactor, except on selected species. Thus, the second exposure followed the first by 14 months, and 4 years have elapsed since then. This combination of exposures has provided unparalleled opportunities for observation of recovery over a 14-month period following the first exposure, and over a total of 5 years since radiation was first released.

Two years' study of the area was possible prior to the initial reactor operation, so that experimental plots, control areas, inventories of plants and animals, and other necessary preirradiation procedures could be carried out.

In order to test the observations made around the reactor site, a gamma radiation field was established on the Emory University campus as a control facility for the duplication of critical experiments under controlled conditions.

ECOLOGICAL DOSIMETRY

The expression *ecological dosimetry* is used to emphasize the unique nature of the dosimetry program developed in the rough terrain surrounding the nuclear reactor.' To sample adequately the distribution of radiation exposure throughout the 300 acres, over hills and across valleys, at various distances above ground as well as below ground, and at various positions within arboreal vegetation, detection stations were placed at 68 locations, each station consisting of a series of neutron and gamma-ray detectors. Twenty-three were in the reactor "line-of-sight," while the others were arranged to measure various types of shielding by vegetation and terrain.

Neutron activation detectors were used for the field measurements of neutron flux. Thermal and resonance neutron distributions were measured by reactions with cobalt, sodium, manganese, and gold detectors, while the fast neutron distribution was measured by using sulfur, thorium, and nickel threshold detectors. By using a series of these detectors at each field location, a neutron energy spectrum was constructed. The primary gamma-ray measurements were made with film badges used for the radiation monitoring of personnel, and with chemical dosimeters. These measurements were augmented with a selected number of silver-activated phosphate glass dosimeters. The film badges were used primarily for measuring low doses, while the other two types of dosimeter were useful for high doses. The accuracy of the chemical dosimeters for the dose rates and ranges encountered was within ±10%, while the accuracy of the film and glass dosimeters was within ±20% All dose measurements were expressed in rads (1 rad = 100 ergs/g).

In naturally shielded areas neutrons were attenuated proportionally more than gamma rays by vegetation. Conversely, the soil attenuated gamma rays proportionally more than neutrons. The terrain, however, always produced more total-dose attenuation than did the vegetation. This behavior is in accordance with what could have been anticipated on the basis of the scattering and absorption cross sections of soil and plant atoms for gamma rays and neutrons. In particular, it is believed that the large hydrogen content of plants is responsible for the proportionally large attenuation of neutrons in areas shielded by vegetation.

One of the most significant results of this study was the observation that large dosages result in locations that are partially or completely obscured from the direct beam of the reactor (Figure *3*). This can be attributed to initial air scattering and subsequent scattering by terrain and vegetation. Predominant scattering of the radiation in the direction of the incident beams was also observed in shielded areas. Maximum radiation protection in shielded areas was afforded at locations adjacent to the ground level or on the back sides of trees, away from the reactor, and is at-

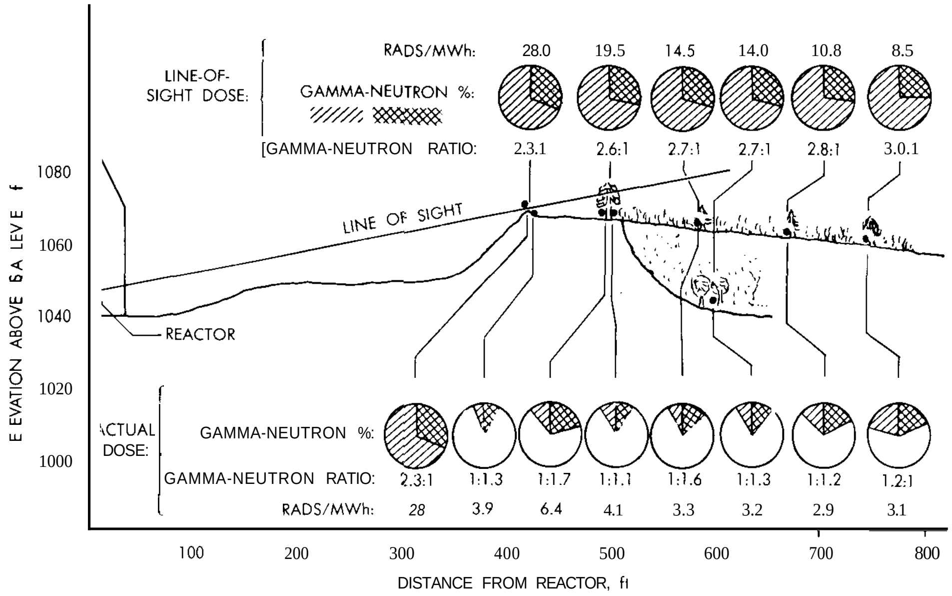


Figure *3*. The effects of terrain and vegetation shielding on total dose for a line of stations ESE of the Lockheed reactor, located in **a** mature oak-hickory stand. The upper circles give the expected line-of-sight dose, while the lower circles give the actual dose, as reduced by terrain and vegetation shielding. Note exaggeration of vertical scale.

tributed to absorption by the ground and vegetation of a large part of the scattered radiation which would otherwise have contributed to the dose.

From the data of this study, it is possible to reconstruct the radiation history at practically any location in the radiation field and for any given period of reactor operation.

CHRONOLOGY OF EVENTS FOLLOWING IRRADIATION

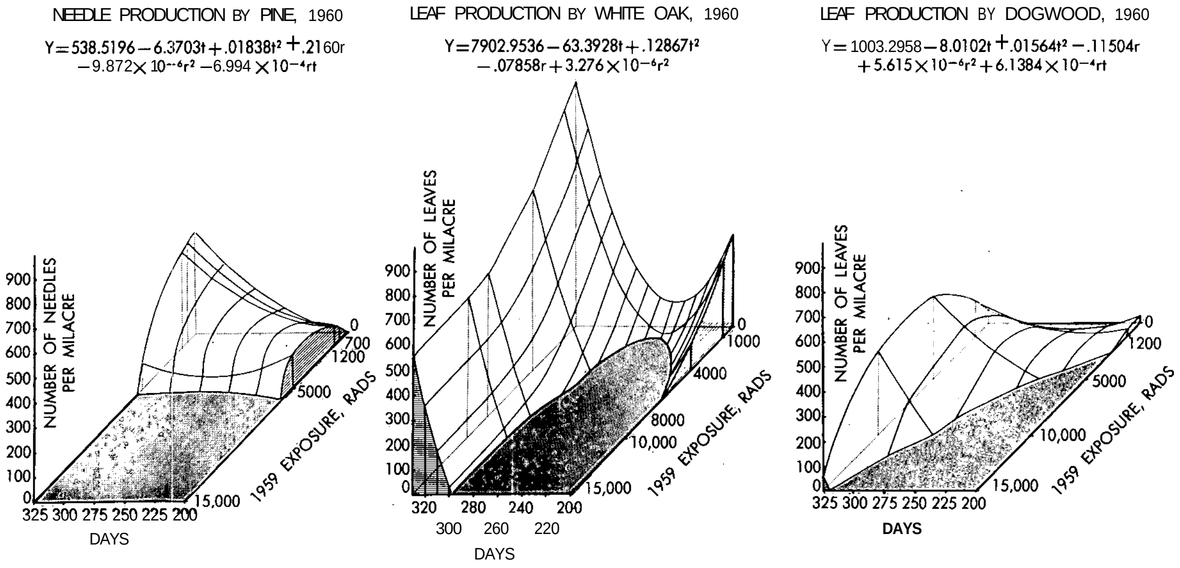
A hypothetical example based on studies around the Lockheed reactor seems appropriate for this discussion of the potential effects of war. People leaving their fallout shelters in much of the temperate portion of the world in the last part of June 1959, following a nuclear attack from which fallout had delivered as much as 15,000 to 20,000 r of radiation, would be "pleasantly" surprised to find that the familiar surroundings of field and woodland looked as they did before the explosion. The one marked exception would be the areas in which pine trees were evident, for pines receiving 8000 to 10,000 rads or more would have begun to turn brown,

Figure 4. View toward the Lockheed reactor in July 1960, 13 months following the June 1959 exposure. These loblolly pines were dead 8 to 10 months following an exposure of >4000 rads. Removal of the pine overstory released the hardwoods underneath, which accelerated succession.

and in a few days would be a brilliant red-brown all over. If these were scattered through hardwood stands, they would stand out as bright flags in an otherwise apparently unchanged landscape. In fact, with the exception of damage to gymnosperms, there would be little change through the summer until August, when an unusually early leaf fall would be experienced. **At** least this is what happened in the several hundred acres around the Lockheed reactor. Obviously, these effects would vary as ecological conditions and physiological states within the ecosystem varied.

The relatively high sensitivity of pines *(Pinus taeda* and ***P.** rigida*) in contrast to the other woody plants was one of the most surprising of all observations, for this was the first time that pines had been irradiated. Within one week after the June irradiation, pine trees receiving doses of 7500 rads or more began to turn a brilliant orange-red and died within **a** few weeks. Those receiving about 4000 rads took much longer to die. In two years, most of those within 1500 to 2000 ft of the reactor were dead (Figure 4). Discoloration, death of terminal buds, and inhibition of reproduction by seed began with exposures $>$1000 rads. Apical meristems of pines were much more sensitive than lateral, and at certain doses when apical growth had stopped, radial growth seemed to be accelerated. Photosynthetic rates and tolerance to heat and drought were lowered by exposures of several hundred to several thousand rads.''

The second set of obvious effects on these ecosystems occurred in September when oak-hickory stands receiving 12,000 to 15,000 rads had a 7-week-early initiation of litter fall, followed by almost complete inhibition of leaf production the following year.[7] Oaks and hickories receiving 4000 rads had an early leaf fall of only



NEEDLE PRODUCTION BY PINE, 1960

$$Y = 538.5196 - 6.3703t + .01838t^2 + .2160r - 9.872 \times 10^{-6}r^2 - 6.994 \times 10^{-4}rt$$

LEAF PRODUCTION BY WHITE OAK, 1960

$$Y = 7902.9536 - 63.3928t + .12867t^2 - .07858r + 3.276 \times 10^{-6}r^2$$

LEAF PRODUCTION BY DOGWOOD, 1960

$$Y = 1003.2958 - 8.0102t + .01564t^2 - .11504r + 5.615 \times 10^{-6}r^2 + 6.1384 \times 10^{-4}rt$$

Figure 5. Three-dimensional response surface composed of regression lines for leaf production for three tree species as affected by the June 1959 exposure. Note relationships between time and dose along a transect 500 to1500 ft from the reactor. Reduction of the overhead oak-hickory leaf canopy released the more resistant understory dogwood, so that production for this species increased at the intermediate radiation doses. (From J.T. McGinnis, unpublished data.)

Figure 6. Photograph taken in July 1960, showing the effects of the June 1959 exposure. The white oak on the left received about 12,000 rads and the hickory on the right about 15,000 rads.

one week, as compared to nonirradiated stands, but leaf production was reduced to 39% the following year (Figure 5). Trees receiving 12,000 to 15,000 rads did not go through normal autumnal coloration, having lost their leaves early, while those receiving 4000 rads did go through a normal coloration.

The third set of effects was noted the following spring. In early April, when the hills of northern Georgia were bright with many hues of green due to the half-developed leaves of forest trees, an area up to one mile in diameter around the reactor was still in a state of winter dormancy. The prolongation of dormancy was proportional to the dose received, bud expansion being delayed from 1 to 2 weeks at doses of 10,000 to 15,000 rads. These effects were ascribed directly to the fact that the primordia of the estivating buds were already laid down in June of the preceding summer, but the radiation damage was not apparent until the buds expanded the following spring.

A fourth set of effects also appeared in the spring. On hardwoods receiving 3000 to 4000 rads, almost all the terminal buds were killed, and branches receiving

2 or **3** times this dose were killed back several inches. Almost all of these trees did develop lateral buds, but there was a very pronounced relationship between the severity of the dose and the position on the tree at which lateral buds appeared. Those receiving 3000 to 4000 rads had lateral buds developed on the same twigs on which the terminals had occurred, and, as irradiation increased, the buds developed on larger limbs so that those receiving 15,000 rads had only a few buds along the main trunk (Figure 6). In contrast, the lateral meristems in every case, including

Figure 7. Photograph of a southern red oak branch taken in July 1960, showing typical hardwood response to the June 1959 irradiation. Note aberrant growth.

trees having the highest doses, were bright green and remained so through the spring and summer.

Another obvious manifestation was that almost every leaf produced from a tree on which the terminals had been killed was highly aberrant (Figure 7). Species differences for the most part were slight, but some trees, such as buckeye and sourwood, were markedly different in their responses.

In July of 1960, 13 months following the irradiation, pines that had received >4000 to 5000 rads were dead, and those that had received >2000 rads were markedly affected. Hardwoods receiving 10,000 to 15,000 rads had been devastated (Figure 8) and had only a few flags of leaves, whereas hardwoods receiving 4000 to 5000 rads had leaf production cut to ¼ or ⅓, but nevertheless produced growth adequate for survival. Hardwoods receiving less than this dose were little affected.

Effects on the vegetation of abandoned agricultural fields within the irradiation area may be grouped into three types of response.[4] First, species became arranged along the radiation gradient in successive dominance bands, according to their interacting tolerances for radiation, light, moisture, and other factors. Second, within a uniform radiation zone, elimination of a radiation-sensitive species occurred when that species aborted by tissue breakdown or was unable to complete its

Figure 8. Photograph taken in July 1960, showing effects of the June 1959 irradiation on a mature oak-hickory stand. Doses ranged from 12,000 rads in the part closest to the reactor to about 8000 rads in the foreground. See Figure 12 for another view of this stand 3 years later.

life cycle. The resultant opening in the community was invaded by more radiation-resistant species which were able to complete their life cycles.

Third, perennials often held their position in the community by vegetative growth of perennating organs, although inviable seeds were being produced. Figure 9 shows a normal vegetational pattern for these fields over the first 5 years of succession. The over-all effect of severe irradiation was to throw the field back into an earlier stage of succession. **As** pointed out above, this was brought about by differential sensitivity of species and the concomitant change in the community structure. Although several experimentally established successional communities received 25,000 to 30,000 rads exposure, being fairly close to the reactor, at no time were these communities denuded. In fact a casual look would reveal no obvious effects, since these changes took place slowly over several months.

The second radiation exposure occurred over a 3-week period in August, 14 months after the first one. The same general kinds of effects occurred. This additional irradiation killed certain pine trees which had been damaged previously. Again, there was an early leaf fall which was roughly comparable to that of the preceding fall, and the following spring there was a comparable prolongation of winter dormancy, with killing of terminal buds and development of laterals.

This series of observations following the second exposure reveals one of the most interesting effects of the entire chronology. The effects of the second exposure were about the same as those of the first, which demonstrated that substantial recovery of

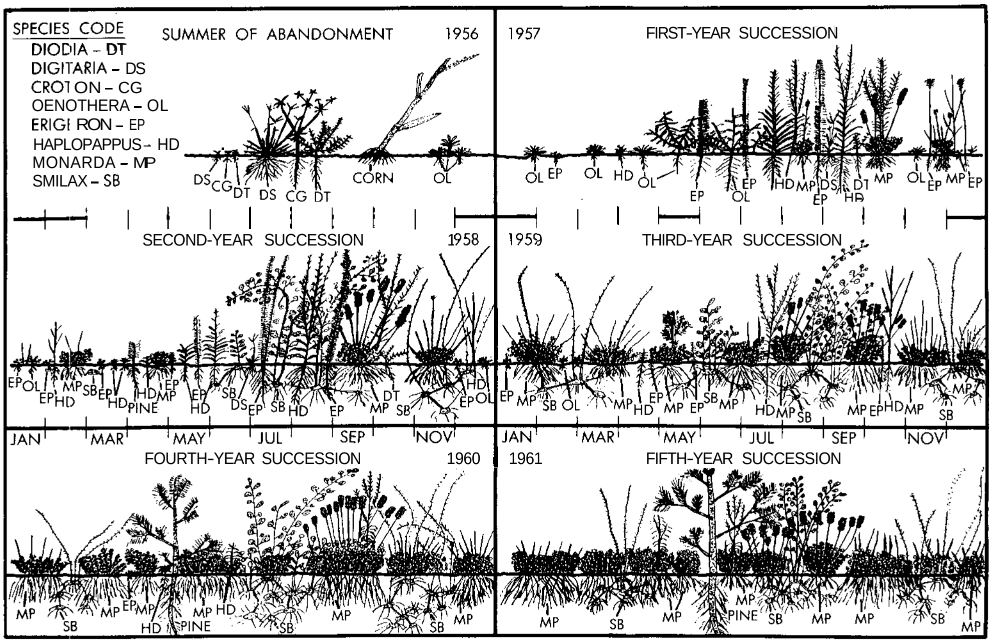


Figure 9. Diagrammatic representation of normal vegetation in the field adjacent to the Lockheed reactor. Radiation (up to 25,000 rads short-term dose) causes changes and reduction in species composition, with a corresponding shift to an earlier stage of succession. (From C.P. Daniel, unpublished data.)

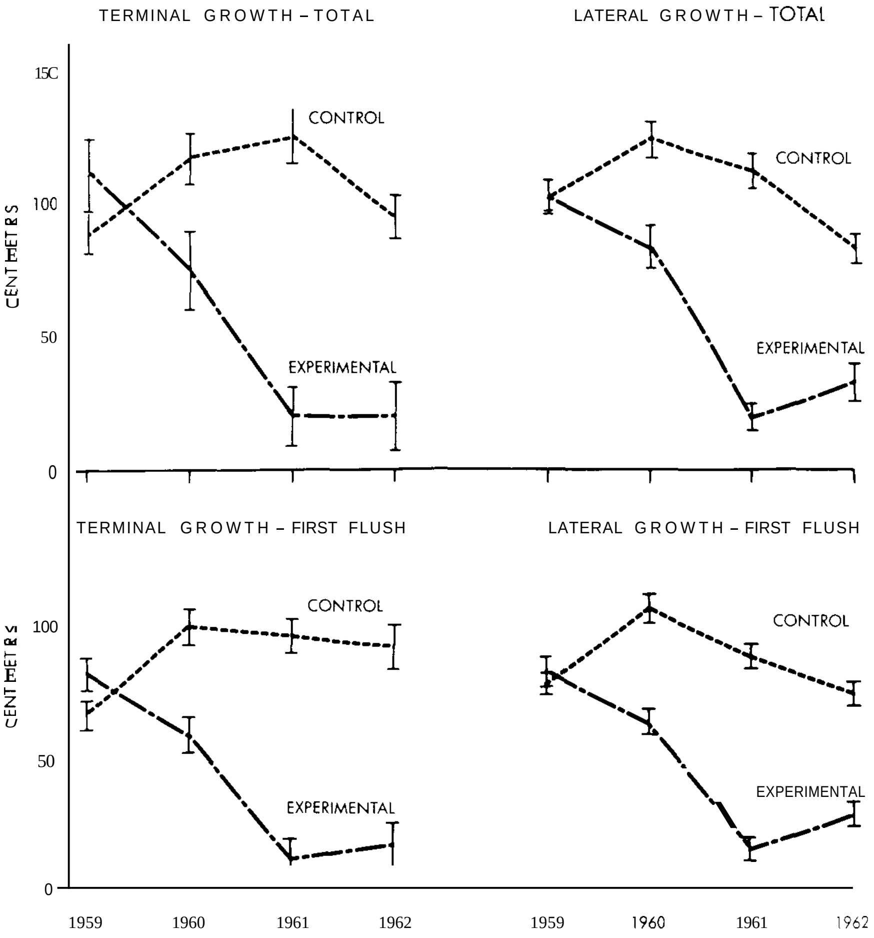


Figure 10. Graphs showing the effects of radiation on a pine stand receiving about 300 rads in June 1959 and 700 in August 1960. There was no visible evidence of damage. The crowns of 20 trees (10 from an experimental stand and 10 from an ecologically comparable control stand) were removed for study in August 1963. Of the 10,000 measurements obtained, those pertaining to four aspects of growth are analyzed. Vertical lines represent twice the standard error. Note that the June 1959 effects did not appear until 1960, and the August 1960 effects until 1961. With no irradiation in 1961, growth was normal in 1962.

damaged plants had occurred. Thus, the effects of the second exposure were not additive, except in those instances in which the trees were already close to dying, and this additional stress killed them, as a bad drought might. The delayed response in tree growth from summer to the following spring was widespread. Figure 10 graphically demonstrates this effect in pines receiving about 300 and 700 rads for the two irradiation periods.

Conditions during the summer following the second exposure were comparable to those of the first, with the exception of those areas in which the overstory had been killed and ground canopy removed (Figure 11). During the first summer this

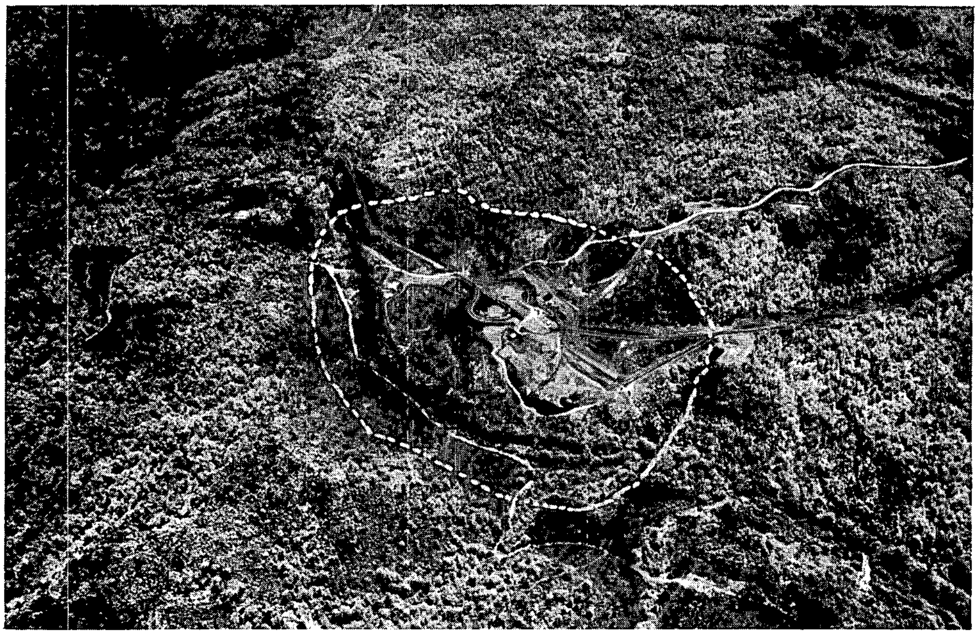


Figure 11. Infrared aerial view of the Lockheed 10-MW nuclear reactor located in the center of a 10,000-acre reservation. This photograph, taken in June 1961, shows the effects of radiation of the two preceding summers. The dotted line encloses the area of visible radiation effects, 800 to 1500 ft from the reactor.

floor under the opened canopy had demonstrated some sprouting from protected root crowns along with the growth of weeds whose seeds had probably lain dormant for many years on the forest floor pending a time at which conditions would favor germination and growth.

The weed flora was greatly increased the second summer because of the additional seed source from the first summer; at some points the weeds were 8 or 10 ft tall and almost too dense to walk through. The condition at that time seemed to indicate that these forests had been thrown back into an old-field stage and that normal old-field succession would now follow. However, in the third summer, root sprouts which had shown rather poor growth during the first two summers now began to develop rapidly and shaded out the weed flora before it had a chance to get well established. By the end of the third summer, hardwood sprouts began to dominate, and by the end of the fourth summer they had formed a closed canopy under which very few weeds were able to develop. This past summer, the fifth following the first irradiation, there was every indication that these sprouts would continue to develop and that the hardwoods would be restored (Figure 12).

. In forested areas in which leaf production was reduced up to 50%, there was no great change in the forest community, with the exception of an increased number of ground-cover plants in the first two summers. Three summers following the first irradiation, the leaf canopy was increasing and leaf aberrations were minor, and by the fourth and fifth summers the trees had returned to a fairly normal appearance.

In the old fields, the areas that had been thrown back to earlier stages of succession moved forward without further interruption, and there was no continued evidence of irradiation damage. The extensive aberrations in leaves and the effects of suppression of reproduction, as in *Smilax,* disappeared and plants were growing normally.'

DISCUSSION AND CONCLUSIONS

Information gained over the past 9 years from experimental irradiation of small, manipulatable ecosystems, along with that from 7 years of study at the Lockheed reactor site, is now sufficiently complete to demonstrate some fairly clear-cut cause and effect relationships for short-term exposures, similar to those that would arise from fallout following a nuclear attack.

1. The patterns of effects and recovery in plant populations seem now well established; they are shown graphically in Figure 13. The dose in rads is given in the left-hand column for exposures of 15 to 90 days. The year of development of various

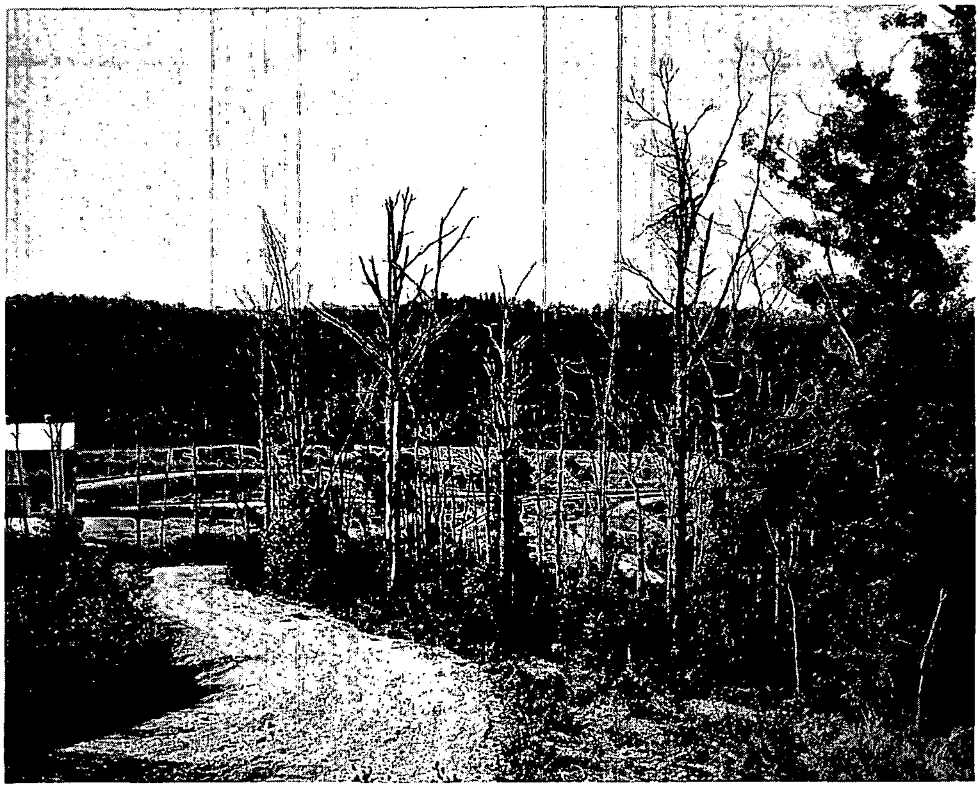


Figure 12. Photograph taken in August 1963 of the same area shown in Figure 8, three years after the second exposure. By this time trees have either died or begun recovery, intermediate stages disappearing. A flourishing growth of root sprouts seems to be returning the area directly to an oak-hickory forest.

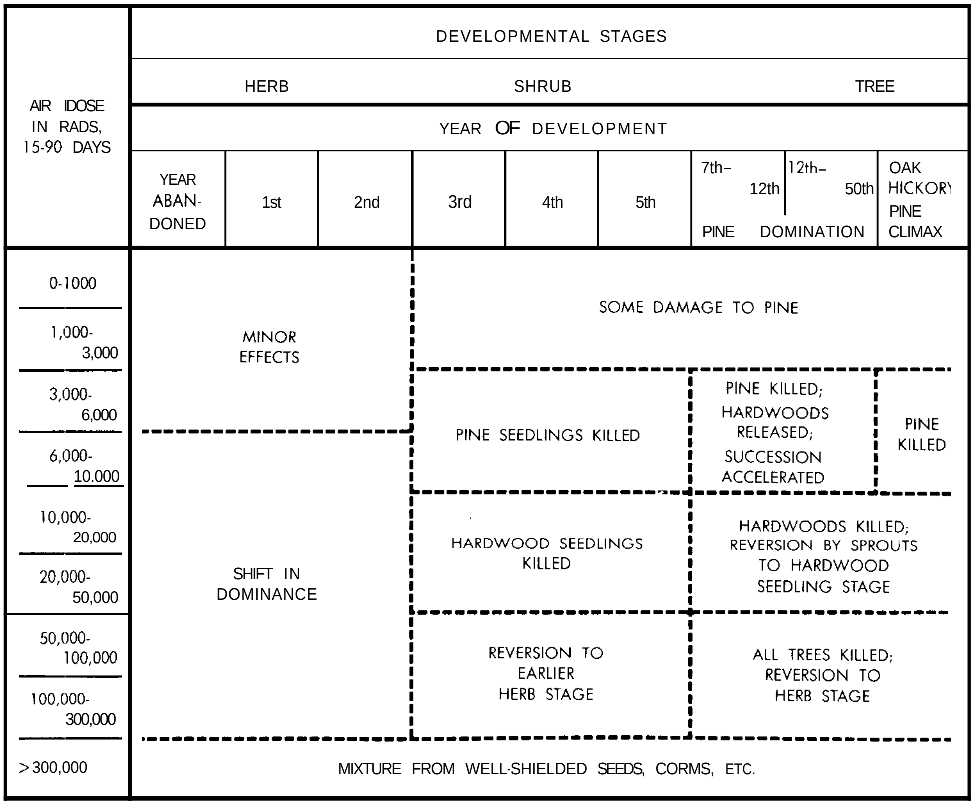


Figure 13. Ecological effects of short-term radiation exposure on temperate ecosystems, based on data from Emory University studies. Doses up to 300,000 rads are plotted against developmental stages from abandoned agricultural fields to climax forests.

ecosystems from the time of abandonment of agricultural fields to mature oak-hickory-pine climax forests is shown across the top. The results indicated would vary somewhat with the severity of other environmental stresses, the time of year of exposure, and other conditions.

Three ecologically significant community types have been studied: herbs, shrubs, and trees (Figure **13).** Herb communities can withstand radiation up to >100,000 rads exposure without elimination of the ground cover. Data on effects from the higher doses were obtained in the campus radiation field. For the shrub communities, i.e., the third, fourth, and fifth years of succession, during which the pine seedlings become established, the pine seedlings would be killed by doses >3000 rads and hardwood seedlings by >10,000 rads. If the dose exceeded 25,000 to 50,000 rads, the remaining herb stage would revert to an earlier year of development.

In ecosystems dominated by pine trees, as they would be from the seventh year on, pines would be eliminated first, hardwoods next, and a reversion to a herbaceous stage probably would not occur until 50,000 rads had been received, the latter due to elimination of root sprouts. The extensive work of McCormick and Platt' on granite outcrop ecosystems supports these conclusions.

2. The application of the experimental results to larger geographic regions is difficult, because the irradiated area is an island in the midst of normally developed ecosystems. What would happen if these conditions extended over several hundred square miles, so that most of the areas would have limited access to recolonization by higher forms of life, such as mammals and birds, or by seeds which might be brought in by various agents? **A** second factor involved in interpretation is that the exposures reported occurred only during the summer. Had the irradiations come at other periods, would the sequence of events have been comparable?

There is a good probability that neither situation would significantly alter the course of recovery as reflected in these studies. The single best argument for this is that recovery of vegetation is not dependent only upon the transport of organisms from other areas. Around the reactor site, replacement of killed or severely damaged plants was accomplished by the growth of seeds and underground perennating organs which were there before irradiation.

With respect to the larger animals, it is reasonable to suppose that extreme injury would be limited to areas of tens or hundreds of miles across, and there would be large numbers of refugia receiving less than lethal doses, from which repopulation of seriously damaged areas could begin. While this might require some time, repcpulation could occur.

The invertebrates for the most part have radiation-resistant or environment-shielded stages so that populations would become re-established in the same sense that plants would recolonize the area.

The question of wildly fluctuating populations of insects and other pests which would seriously affect the balance of nature following irradiation has been raised on many occasions. Our observations within these ecosystems suggest that great caution must be used in making such predictions. The effects from a forest fire might well be much more severe than the killing of hardwood trees in a comparable area by ionizing radiation. Yet from such ecological analogues as fires, population fluctuations usually have not been of the kind that would seriously affect man's ability to survive. Every time a tree dies in the forest, or a hurricane causes a severe windthrow and the canopy is changed, comparable wildly fluctuating populations of the microinsect fauna occur, but the ecosystem conipensates for this in many ways.

3. Irradiation in itself does not eliminate ground cover or leaf litter. In fact radiation which would kill the overstory of hardwood forests would probably leave the underground portion of the ecosystem relatively undisturbed because of shielding from the soil, although there would be changes in the microenvironment in terms of light, moisture, wind, and relative humidity.'

Unless an accompanying fire removed the ground cover, erosion would not be a factor. In the event that fires swept through the area following irradiation, there would probably be the same kind of recovery that has been observed many times before as a result of fires which have sometimes covered several hundred square miles at one time.

4. Radiation stress, like other stresses, tends to throw the ecosystem back to an earlier stage of development. Furthermore, the time of year of irradiation is of great

importance, and some of the most significant effects may be delayed for many months.

5. Sufficient information is on hand from many sources to make general predictions for the effects of radiation on other ecosystems. There seems to be general agreement that a rough correlation exists between the ecosystem's structural complexity on one hand, and resistance to radiation on the other, sensitivity of individual organisms to radiation being the principal exception.

One probable ranking of ecosystems in increasing order of resistance to radiation :stress would be: coniferous forests, rain forests, deciduous forests, grasslands, tundra, and desert. However, for predictions of greater reliability and depth, much more information is needed. Figure 14 gives the kind of information that ideally is required for each of the functionally significant species as well as for the ecosystem. Nuclear characteristics are applicable in determining the probable lethal dose. For lethal or sublethal doses, the effects are those determined in addition by hormone and other metabolic systems, physiological states, and interactions with other environmental factors. The latter involve the functional relationship of the organism to its ecosystem, and this in turn is related to the ecosystem's own characteristics.

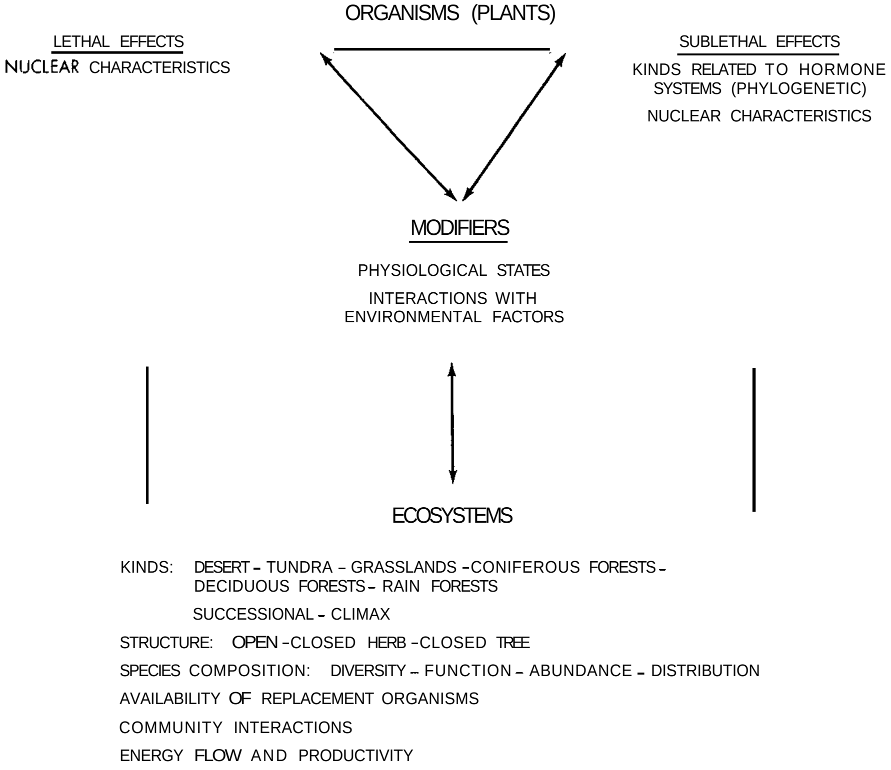


Figure 14. **A** scheme for homeostatic mechanisms that control radiation stress effects, the upper part relating to organisms (plants) and the lower to ecosystems. Conversely, an evaluation of these factors is revelant to the prediction of radiation effects.

EPILOGUE

Radiation effects and subsequent recovery in ecosystems near the air-shielded Lockheed nuclear reactor constitute the closest approximation of short-term radiation effects without heat and blast on vegetation. The two periods of high-level irradiation, 14 months apart, closely resembled fallout exposures, both in intensity and in duration. The course of recovery apparently has been well established in the five years since the first exposure and the four years since the second. Thus, it has been possible to establish ecological effects on vegetation for doses up to 300,000 rads, plotted against developmental stages from abandoned agricultural fields to climax forests. Since the pine-dominated stage is highly sensitive to radiation, the hardwood stage intermediately sensitive, and the herbaceous stage among the least sensitive, results from these three developmental stages have wide applicability to similar areas throughout the world.

In the event of a 20,000-MT attack on the United States with 100% fission, it has been estimated that 2 to 5% of the country would receive 15,000 r or more within 2 weeks, and 10% would receive 5000 to 10,000 r. The remaining 85 to 88% would receive <5000 r, the greatest percentage on the order of 1000 to 2000 r.

In view of these data, a broad generalization may be made for radiation effects from a nuclear war on this country's vegetation. From 5 to 20% of the forest ecosystems may have the tree overstory seriously damaged or killed. Another 20% may be visibly affected, but without the loss of the overstory; recovery for this percentage would be relatively fast. The damage may not be fully evident for several months to a year. If fire occurred, the damage would be increased. For the rest of the country (grasslands, deserts, and tundra), temporary changes may occur in the species composition in 2 to 10% of the area, the remainder being relatively little affected.

Therefore, direct radiation effects from nuclear war on vegetation are not likely to seriously limit man's reconstruction of his renewable resources. Other ecological effects may be far more limiting, such as radioactive contamination or effects on animals and food resources.

ACKNOWLEDGMENTS

This study was supported in part by Research Contracts AT-(40-1)-2412 and AT-(40-1)-2089 from the Atomic Energy Commission, by Contract AF-31845 of the U.S. Air Force with Lockheed Aircraft Corporation, and by several grants from the Research Committee of Emory University.

REFERENCES

1. Chappell, H.G. 1963. The effects of ionizing radiation on *Smilax* spp., with special reference to the protection afforded by its production of underground vegetative structures. In *Proceedings of the First National Symposium on Radioecology.* V. Schultz and A.W. Klement, Jr. (Editors). Reinhold, New York, Pp. 289-94.
2. Conard, R.A. et al. 1963. *Medical Survey of Rongelap People Eight Years After Exposure to Fallout.* Brookhaven National Laboratory, Upton, N.Y. BNL 780 (T-296). 74 pp.

3. Cowan, J.J. and Platt, R.B. 1963. Radiation dosages in the vicinity of an unshielded nuclear reactor. In *Proceedings of the First National Symposium on Radioecology.* V. Schultz and A.W. Klement, Jr. (Editors). Reinhold, New York. Pp. 311-18.
4. Daniel, C.P. 1963. A study of succession in fields irradiated with fast neutron and gamma radiation. *Ibid.,* pp. 277-82.
5. McCormick, J.F. and Platt, R.B. 1962. Effects of ionizing radiation on a natural plant community. *Radiation Botany* 2, 161-8.
6. McGinnis, J.T. 1963. Some environmental changes in forest stands following exposure to radiation. *Bull. Assoc. Southern Botanists* **10**, 33.
7. McGinnis, J.T. 1963. Effccts of radiation from an air-shielded reactor on forest litter production. In *Proceedings of the First National Symposium on Radioecology.* V. Schultz and A.W. Klement, Jr. (Editors). Reinhold, New York. Pp. 283-7.
8. Mitchell, H.H. 1961. *Ecological Problems and Post- War Recuperation: A Preliminary Survey From the Civil Defense Viewpoint.* The Rand Corporation, Santa Monica. RM-2801. **37** pp.
9. Palumbo, R.F. 1962. Recovery of the land plants at Eniwetok Atoll following a nuclear detonation. *Radiation Botany* **1**, 182-9.
10. Pedigo, R.A. and Platt, R.B. 1960. Studies in radiation ecology II: Plant communities of a 10,000-acre experimental area in North Georgia. *Bull. Georgia Acad. Sci.* **27**, 44-60.
11. Pedigo, R.A. 1963. Effects of ionizing radiation on *Pinus taeda* (L). In *Proceedings of the First National Symposium on Radioecology.* V. Schultz and A.W. Klement, Jr. (Editors). Reinhold, New York. Pp. 295-9.
12. Platt, R.B. and Witherspoon, J.P. 1958. Ecological effects of x-irradiation on plant communities of granite outcrops in the Southeastern States. *Bull. Ecol. Soc. Am.* **39,** 3.
13. Platt, R.B. 1959. Chronic radiation ecology studies at Emory University. *Proc. IX Intern. Botan. Congr., Montreal.* Univ. of Toronto Press. Vol. 2A, p. 28.
14. Platt, R.B. and Mohrbacher, J.A. 1960. Studies in radiation ecology I: The program of study. *Bull. Georgia Acad. Sci.* 27, 1-30.
15. Platt, R.B. 1962. Radiation and plant life. *Discovery* **23**, 42-7.
16. Shields, Lora and Wells, P.V. 1962. Effects of nuclear testing on desert vegetation. *Science* **135**, 38-40.
17. Sparrow, A.H. and Woodwell, G.M. 1962. Prediction of the sensitivity of plants to chronic gamma irradiation. *Radiation Botany* 2, 9-26.
18. Wolfe, J.N. 1959. *Long- Time Ecological Effects of Nuclear War.* Technical Information Service, USAEC. TID-5561. 5 pp.
19. Woodwell, G.M. 1962. Effects of ionizing radiation on terrestrial ecosystems. *Science* **138,** 572-7.
20. Hines, N.O. 1962. *Proving Ground. An Account of the Radiobiological Studies in the Pacific, 1946-1961.* Univ. of Washington Press. 366 pp.

Biological Interactions Associated With Spruce Budworm Infestations*

D.R. MACDONALD
Forest Entomology and Pathology Laboratory, Fredericton, N.B., Canada

One approach to studying the possible ecological effects of nuclear catastrophes lies in study of analogous natural catastrophes. The outbreaks of the spruce budworm, *Choristoneura fumiferana* (Clem.) in the spruce-fir forests of eastern Canada provide one such analogy.

This native insect periodically undergoes population explosions defoliating the new shoots of its favored hosts, balsam fir [*Abies balsamea* (L.) Mill] and some spruces [*Picea glauca* (Moench) Voss; *P. rubens* Sarg.]. It has probably always played an important role in the natural cycling of the climax boreal forest because the outbreaks are associated with the maturing of extensive areas of balsam fir and with climatic variation. Blais[3–5] has found evidence of a series of outbreaks in Ontario and Quebec, dating in one case as far back as 1670. There is also evidence'! in some parts of New Brunswick that outbreaks commenced about 1770, 1806, 1878, and 1912; the most recent infestation started in 1949. A recent example from Ontario illustrates the magnitude of this type of catastrophe when it is left unchecked.[8] Two essentially concurrent infestations between 1943 and 1955 extended over a gross area of 76,000 square miles and serious tree mortality occurred on over 12,000 square miles. The losses were estimated at 17,000,000 cords of pulpwood, representing 58% of the merchantable volume and roughly equivalent to the newsprint requirements of *The New York Times* for the next 400 years.

The outbreak which started in 1949 in New Brunswick also occurred in adjacent areas of Maine and eastern Quebec. A cartographic history of the outbreak by Webb, Blais, and Nash[28] showed that it reached its maximal extension in 1956 when approximately 61,700 square miles were infested, with about half of the area classed as suffering "moderate to severe attack." This outbreak collapsed in 1958, but a secondary outbreak developed in parts of central New Brunswick and northeastern Maine between 1959 and 1963. Tree mortality was forestalled throughout most of these areas by an extensive aerial spraying program started in 1952. The 1959 outbreak was studied more intensively than any other in Canada, and many of the results of the studies of population dynamics and chemical control have already been published.[6,23] These studies will be reviewed as examples of the interactions that follow environmental stresses such as insect defoliation and the addition of a poison, DDT, to the ecosystem.

---

*Contribution No. 1031, Forest Entomology and Pathology Branch, Department of Forestry, Ottawa, Canada.

INTERACTIONS FOLLOWING THE BUDWORM ATTACK

Among the first effects of severe budworm defoliation is the cessation of host-tree flower and seed production, causing a decline in the cone insect and small-mammal populations. Small-mammal census data in the Green River, New Brunswick, study area showed that the peaks in the cycles of both the red-backed vole and the deer mouse may have been associated with the abundance of tree seed. The rock vole, a relatively rare species in New Brunswick, increased markedly, possibly because of relief from interspecific competition with the red-backed vole.[24]

Increasing defoliation decreases survival of small budworm larvae by reducing the number of needles available to the young larvae for mining in the early spring.[25] Defoliation also reduces the attack rate of certain budworm parasites.'" High densities of budworms and the resultant defoliation have undoubtedly affected the abundance of associated insects." In an infestation of white spruce in British Columbia, environmental changes brought about by defoliation promoted the buildup of ordinarily innocuous fungi to the point where they became destructive to trees.[21]

An annual census of bird populations on a series of permanent plots in the Green River study area showed striking changes following increases in budworm populations. The Blackburnian, bay-breasted, and Tennessee warblers all increased, while the magnolia, myrtle, and black-throated green warblers all declined, presumably because of interspecific competition with those species responding directly to the budworm populations.[24]

Although the spruce budworm attacks both firs and spruces, balsam fir suffers by far the greatest damage. Tree mortality usually commences in the fifth year after the first severe defoliation, and by the eighth year most of the firs are dead.'[2] Light-tolerant shrubs such as raspberry, red elder, hazel, and mountain maple respond to the increased light coming through the defoliated canopy and quickly invade the stand, forming a dense shrub layer within a few years. The woodpeckers increase in response to the increasing beetle population and the white-throated sparrow increases as the open-nesting territory expands. Tennessee, black-pole, magnolia, and myrtle warbler populations remained static at Green River in this phase of the outbreak, but the Blackburnian and bay-breasted warblers declined with the decreasing budworm populations, and the winter wren became quite rare.[17] We have also observed that the white-tailed deer populations increase in these devastated areas, presumably in response to better food and cover available in the dense reproduction and shrub growth.

The new forest that develops under the shrub canopy is usually fir and spruce. It arises from the abundant supply of seedlings that survive the defoliation, from dormant seeds, and from seed produced by the surviving mature trees. Development of the forest is usually not appreciably restricted by competition with the shrub layer, although on very good sites dense mountain maple cover may slow succession temporarily. The exact composition of the new forest in terms of fir and spruce varies greatly from place to place.''

The mature spruce-fir forest is also subject to two other catastrophes that have biological interactions similar to those following budworm attack. These disasters are clear-cutting by man, and blowdown. The latter is probably more common in

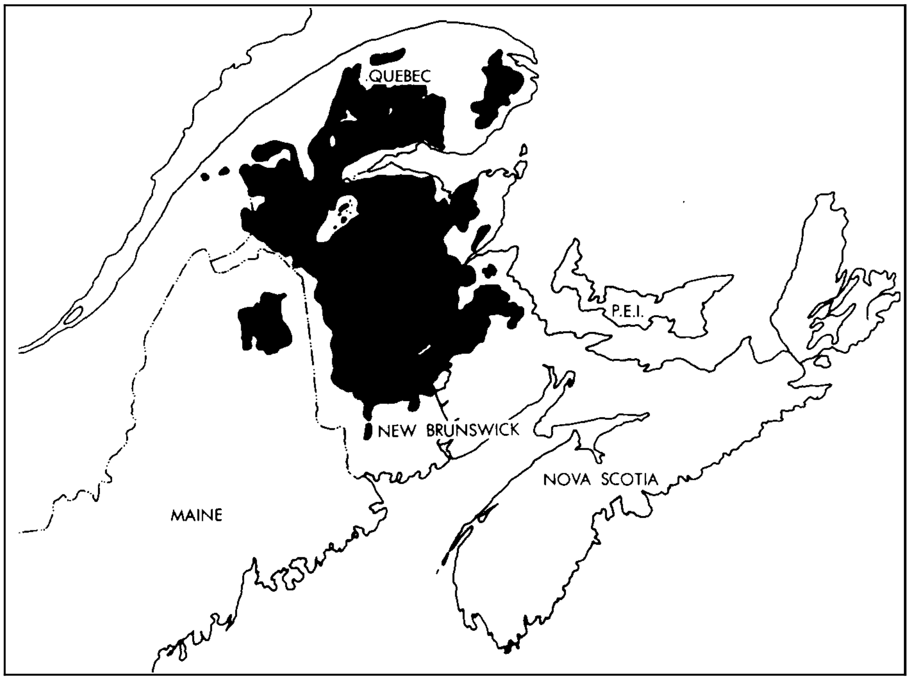


Figure 1. Areas sprayed with DDT against the spruce budworm in Maine, New Brunswick, and Quebec, 1952-63.

the Maritime Region of eastern Canada than in the inland continental area because the hurricane path is up the east coast. Many spruce-fir stands in New Brunswick date back to the Saxby gale of 1869, a hurricane that swept diagonally across the province from the southwest. Budworm infestations, blowdown, and, to a lesser extent, clear-cutting, all leave an accumulation of broken tops and trunks over large areas. Flieger[9] has suggested that practically all the very large forest fires in this area have started and spread through these extensive piles of dry fuel left by the budworm. These fires burn very intensely, and the litter of dead trees makes them extremely difficult to combat. They often gain unbelievable momentum and spread rapidly to previously undamaged stands. The succession of the new forest will depend largely on the type of burn and the amount of damage to the organic layer of the soil. Thus, a light fire burning only the surface of the humus layer usually favors the development of a predominantly white spruce forest. Moderate damage to humus favors a birch-aspen forest, while very intense fires or repeated fires burn deeply into the humus and result in a prolonged shrub growth. The end result, however, even though fire may temporarily alter the succession, is that fir and spruce seed in, eventually gain a dominant position, and restore the climax forest.

INTERACTIONS FOLLOWING THE ADDITION OF DDT

The development of the spruce budworm outbreak in the Maritimes prompted a series of aerial spraying operations that eventually covered a net area of 9,635,000 acres in northern New Brunswick, Quebec, and Maine between 1952 and 1958.[28] **A** resurgence and buildup of populations in central New Brunswick resulted in another 1,980,000 acres being sprayed between 1960 and 1963 (Figure 1). The average dosage on these operations in Canada was % lb DDT per ½ U.S. gal solvent oil per acre from 1953 to 1958. It was reduced to ¼ lb in ½ gal per acre in part of the 1960 operation and throughout the 1961, 1962, and 1963 operations, although in the latter years two applications were required in some areas to achieve satisfactory control of red spruce infestations. These operations have been conducted to prevent serious tree mortality, rather than to attempt to control or eradicate the budworm infestation, and have been very successful from this point of view.

'The outbreak of the budworm and the efforts to control it provide a series of studies useful in anticipating some of the interactions that might occur in natural ecosystems following a nuclear attack. Studies have been concentrated on the effects of DDT on budworm populations, although limited observations of other effects have also been made.

DDT spraying appears to have caused certain effects on budworm populations aside from the very high immediate mortality. In the first generation after spraying, survival of the small larvae was reduced by the residual poison. Then the effects of reduced population density, preservation of the habitat and the food supply promoted a high survival in the later larval stages. The net result was that survival was usually higher than normal in the first postspray generation. The high survival rate continued in the second postspray generation, but the increased density of the population and the concomitant increased defoliation usually became limiting and survival declined in the third postspray generation. Thus, although the poison effectively reduced the population to a very low level, it also tended to favor the recovery of the population. This effect continued until natural factors brought about a general population decline.[17]

The effect of DDT spraying on the parasite complex of the budworm has been reported by Macdonald'' and by Macdonald and Webb.'' One of the major small larval parasites tended to increase the year following spraying, and there was also an increase immediately after spraying in abundance of the parasite that attacks the late larvae and pupae. Only one parasite species declined consistently following treatment, and it usually increased in subsequent years. Spraying appeared generally to increases mortality from parasites in the low postspray populations, particularly during the declining years of the outbreak. Among the invertebrate predators on balsam fir the Coccinellidae invariably occurred at higher densities in sprayed areas than in unsprayed areas. However, abundance of Syrphidae, Pentatomidae and Chrysopidae usually declined immediately following spraying but recovered subsequently. There has been no evidence of a release of other pests, such as the outbreak of spruce spider mites on Douglas fir after budworm spraying in Montana.'[3]

The time of application of the spray may govern the susceptibility of many insect:;. In 1956 a small-scale experimental spraying 3 to 4 weeks earlier than normal for budworm control, annihilated the resident population of bumblebees and wasps. The experimental area was invaded by these forms the same season and supported normal populations the following spring. In nearby areas sprayed at the usual time, populations of bees and wasps were not seriously affected.'"

Limited studies of bird populations have indicated that they were not directly affected by the poison. There was evidence, however, that certain species moved from sprayed areas into adjacent unsprayed areas where higher budworm populations were still available.[18]

High dosages of DDT are known to affect the reproductive rates of a number of organisms. The dosage of poison used in eastern Canada, however, has been comparatively light: and any observed changes in fecundity in the budworm could be attributed primarily to changes in population density and food quantity and quality.'' Woodwell'" was unable to find any effect of operational dosages on cone production, germination, or seedling populations of balsam fir and red and white spruce. There is some evidence, however, suggesting that the reproductive rate of the woodcock population has been affected by a combination of DDT spraying in New Brunswick and the application of heptachlor for fire ant eradication on its overwintering territories in the southeastern United States.[30]

The genetic effects of DDT spraying on the budworm populations are not well defined. Watt'' has postulated that increases in the survival of large larvae in the year following severe stress, such as the application of DDT, may be due to selection's favoring resistant populations. Campbell' has suggested further that residual DDT might select against small male larvae carrying a type of chromosome known to be associated with large body size, slow development, high basal metabolism, and small eggs. Other influences, however, such as the improvement in foliage production and resultant changes in the micrometeorological conditions, also have important effects on survival.'' To make the problem more complex, sprayed areas are subject to recurrent moth invasions which tend to obscure any changes in genetic composition caused by DDT. It is possible too that only genetically superior stock participate in such invasions. Moth invasions have been infrequent since 1956, and a small but significant proportion of the budworm population is known to have developed resistance to DDT in areas sprayed 3 to 5 times since then.[26] Clearly these problems are complex and can be resolved only by detailed investigation of the genetic structure of the various populations involved.

The most serious adverse effects of DDT spraying in New Brunswick have occurred in the streams and lakes. Dosages of ½ lb DDT per acre caused serious reduction in young Atlantic salmon'" and in aquatic insect populations.'' Our limited studies of aquatic insects in streams that have had a relatively long and continuous spraying history in the northern part of the province have shown that all insect populations were severely reduced immediately following spraying. Trichoptera were the most severely affected, followed by Plecoptera, Diptera, Megaloptera, and Ephemeroptera. Certain forms, such as species of Chironomidae and Ephemeroptera, repopulated the streams rapidly, often in the same season. The noninsect invertebrate fauna, such as worms, snails, and water mites, appeared relatively resistant. In one stream sprayed annually for eight years, the oligochaetes and snails were more abundant in the eighth year than in any other stream. The recovery of insect populations *3* to 4 years after the last spraying in 2 major streams and *2* headwater streams appears in Figure 2 and may be compared to the number of genera found in a nearby unsprayed stream. The data suggest that the lower reaches of major streams are repopulated more quickly by insect drift from upstream than are

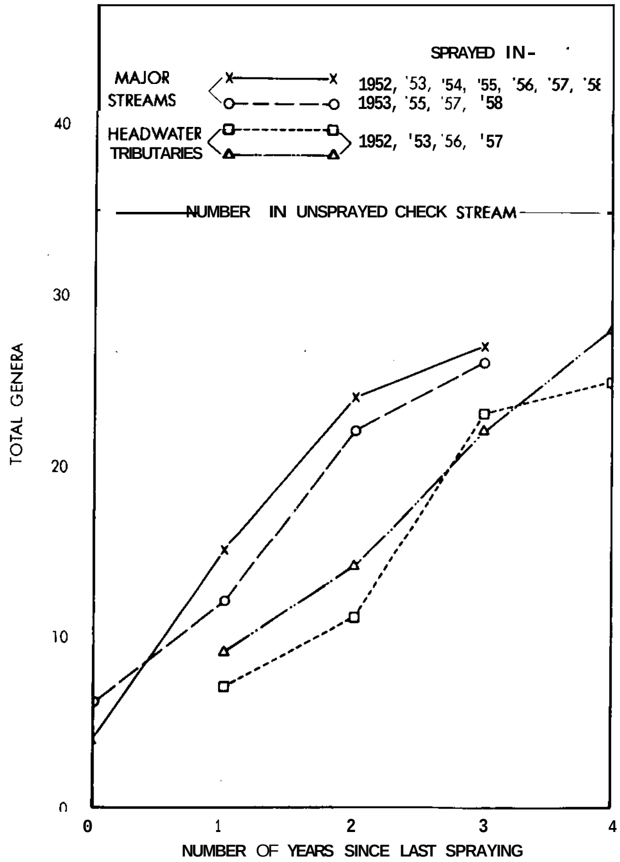


Figure 2. Qualitative recovery of aquatic fauna after DDT spraying against spruce budworm in northern New Brunswick.

the headwater tributaries. In either case ≈⅔ of the fauna recovered within **3** to 4 years after cessation of spraying. Similar recovery is now evident in salmon populations returning from the sea.

CONCLUDING REMARKS

Both the spruce budworm and DDT are very severe stresses to the plant and animal communities of the boreal forest. It is interesting to note, however, that in both cases when the stress is removed there is a very rapid trend toward recovery. In fact, the spruce-fir community maintains its own built-in mechanism for repair in the form of an abundant supply of advanced tree reproduction which largely escapes destruction and forms the new forest. It is actually a self-perpetuating system, alternating between mature and immature stages, and has been called both a "catastrophic climax"" and, perhaps more appropriately, a "dynamic climax".[3] Even when wildfire disrupts the system, succession is only temporarily delayed unless the site is burned repeatedly and the humus layer destroyed.

DDT poisoning is an unnatural stress on the animal community, but this community has also exhibited an amazing resiliency. Although an incredible number of budworms were killed each year, there is no reason to believe that the spraying operations have altered the course of the outbreak. Budworm populations collapsed simultaneously in sprayed and unsprayed areas in northern New Brunswick. Analysis of life-table data indicated that the decline was correlated with the same natural factors in both areas, which suggests that factors other than the poison regulated the population.

In 1963, five years after the collapse of the outbreak in northern New Brunswick, the budworm is present in endemic numbers in that area. We believe that it is fully capable of responding at any time in the future to the factors that promote population buildup. The associated defoliating insects and the parasites are also present and do not appear to have been seriously affected by the outbreak or by the poison. The severely affected aquatic insect and salmon populations are also recovering and approaching prespray densities.

It is clear that both the natural stress of the spruce budworm outbreak and the artificial stress of DDT poisoning have been followed quickly by compensatory reactions that have repaired this very resilient system and will direct it towards its highest attainable successional climax. Undoubtedly, the stresses of ionizing radiation will cause a different series of interactions, and certainly these interactions will vary with the magnitude of the catastrophe. Our experience in the boreal forest suggests, however, that the resiliency of the biological community and its wonderful capacitv to adapt to and recover from very severe stresses should not be overlooked.

ACKNOWLEDGMENTS

The author wishes to thank Dr. R.M. Belyea, Officer-in-Charge, and Dr. R.F. Morris, both of the Forest Entomology and Pathology Laboratory, Fredericton, for helpful suggestions and for critical review of the manuscript.

REFERENCES

1. **Basham**, J.T. **and Belyea,** R.M. 1960. Death and deterioration of balsam fir weakened by spruce budworm defoliation in Ontario. Part III. The deterioration of dead trees. *Forest Sci.* **6,** 78-96.
2. **Belyea,** R.M. 1952. Death and deterioration of balsm fir weakened by spruce budworm defoliation in Ontario. Part II. An assessment of the role of associated insect species in the death of severely weakened trees. *J. Forestry* **50,** 729-38.
3. **Blais,** J.R. 1954. The recurrence of spruce budworm infestations in the past century in the Lac Seul area of northwestern Ontario. *Ecology* **35,** 62-71.
4. **Blais**, J.R. 1961. Spruce budworm outbreaks in the Lower St. Lawrence and Gaspé regions. *Forestry Chron.* **37,** 192-202.
5. **Blais**, J.R. 1962. Collection and analysis of radial-growth data from trees for evidence of past spruce budworm outbreaks. *Ibid.* **38,** 474-84.
6. **Blais,** J.R. **and Martineau,** R. 1960. A recent spruce budworm outbreak in the Lower St. Lawrence and Gaspé Peninsula with reference to aerial spraying operations. *Ibid.* **36,** 209-24.
7. **Campbell,** I.M. 1962. Reproductive capacity in the genus *Choristoneura* Led. (Lepidoptera: Tortricidae). I. Quantitative inheritance and genes as controllers of rates. *Can. J. Genet. Cytol.* **4**, 272-88.

8. Elliott, K.R. 1960. A history of recent infestations of the spruce budworm in northwestern Ontario, and an estimate of resultant timber losses. *Forestry Chron.* 36, 61-82.

9. Flieger, B.W. 1953. Forest protection from the spruce budworm in New Brunswick. *Ann. Rept. Entomol. Soc. Ontario* **84,** 9-16.

10. Ghent, A.W., Fraser, D.A., and Thomas, J.B. 1957. Studies ofregeneration in forest stands devastated by the spruce budworm. *Forest Sci.* **3,** 184-208.

11. Ghent, A.W. 1958. Studies of regeneration in forest stands devastated by the spruce budworm. II. Age, height, growth, and related studies of balsam fir seedlings. *Forest Sci.* **4,** 135-46.

12. Ide, F.P. 1956. Effects of forest spraying with DDT on aquatic insects of salmon streams. *Trans. Am. Fish Soc.* 86, 208-19.

13. Johnson, P.C. 1958. *Spruce Spider Mite Infestations in Northern Rocky Mountain Douglas Fir Forests.* Intermountain Forest and Range Expt. Station, USDA, Ogden, Utah. Research Paper 55.

14. Kerswill, C.J., Elson, P.F., Keenleyside, M.H.A., and Sprague, J.B. 1.360. *Effectson Young Salmon of Forest Spraying With DDT.* USPHS. Technical Report W 60.3.

15. Macdonald, D.R., 1959. Biological assessment of aerial forest spraying against spruce budworm in New Brunswick. III. Effects on two overwintering parasites. *Can. Entomologist* 91, 330-6.

16. Macdonald, D.R. 1959. *Studies of Aerial Spraying Against Spruce Budworm in New Brunswick. XV. General Insect Abundance Assessed by Glass-Barrier Flight Traps, 1956, 1957.* Can. Dept. Agric. Forest Biol. Lab., Fredericton, N.B. Interim Report 1959-2.

17. Macdonald, D.R. 1963. The analysis ofsurvival and reproduction in the sprayed area (area 2). In *The Dynamics of Epidemic Spruce Budworm Populations,* R.F. Morris, Editor. *Mern. Entomol. Soc. Can.* 31, 288-310.

18. Macdonald, D.R. and Webb, F.E. 1963. Insecticides and the spruce budworm. *Ibid.*

13. McLeod, J.M. and Blais, J.R. 1961. Defoliating insects on field spruce in Quebec. Can. Dept. Forestry, Forest Entomol. Pathol. Branch. *Bimonthly Progr. Rept.* 17(1), 3.

20. Miller, C.A. 1960. The interaction of the spruce budworm, *Choristoneura fumiferana* (Clem.), and the parasite *Glypta fumiferanae* (Vier.). *Can. Entomol.* 92, 839-50.

21. Moinar, A.C. and Silver, G.T. 1959. Build-up of *Pullularia pullulans* (de Bary) Berkhout within a severe budworm infestation at Babine Lake, British Columbia. *Forestry Chron.* 35, 227-31.

22. Morris, R.F. 1958. A review of the important insects affecting the spruce-fir forest in the Maritime Provinces. *Ibid.* **34,** 159-89.

23. Morris, R.F. (Editor). 1963. *The Dynamics of Epidemic Spruce Budworm Populations. Mem. Entomol. Soc. Can.* **31.** 332 pp.

24. Morris, R.F., Chesire, W.F., Miller, C.A., and Mott, D.G. 1958. The numerical response of avian and mammalian predators during a gradation of the spruce budworm. *Ecology* 39,487-94.

25. Mott, D.G. 1963. The analysis of the survival of small larvae in the unsprayed area. In *The Dynamics Of Epidemic Spruce Budworm Populations,* R.F. Morris, Editor. *Mern. Entomol. Soc. Can.* 31, 42-52.

26. Randall, A.P. 1963. Evidence of DDT-resistance in spruce budworm from forest populations subjected to repeated large-scale DDT sprays. Can. Dept. Forestry, Forest Entomol. Pathol. Branch. *Bimonthly Progr. Rept.* 19(4), 1.

27. Watt, K.E.F. 1963. The analysis of the survival of large larvae in the unsprayed area. In *The Dynamics of Epidemic Spruce Budworm Populations,* R.F. Morris, Editor. *Mem. Entomol. Soc. Con.* **31,** 52-63.

28. Webb, F.E., Blais, J.R., and Nash, R.W. 1961. A cartographic history ofspruce budworm outbreaks and aerial forest spraying in the Atlantic region of North America, 1949-1959. *Can. Entomologist* 93, 360-79.

29. Woodwell, G.M. 1962. Effect of DDT on cone production, germination, and seedling survival in the boreal forest. *Ecology* **43,** 396-403.

30. Wright, B.S. 1960. Woodcock reproduction in DDT-sprayed areas of New Brunswick. *J. Wildlife Management* **24,** 429-20.

Summary

EUGENE P. ODUM
University of Georgia, Athens, Georgia

The kinds of effects described and discussed here are not individually unique to nuclear catastrophes; most can and do result from a variety of nonnuclear forces commonplace in our biosphere. What would be unique about a large-scale nuclear catastrophe stems from (1) the interaction of several severe limiting factors, with total effect not simply the sum of component effects, and (2) the great size of the stressed area, a quantity probably influencing the rate of recovery more than the severity of the acute forces themselves.

As the writers of this symposium so ably documented their specific topics I jotted down some of the ecological sequelae of storms, forest fires, pest irruptions, gamma irradiations, and other natural, accidental, or experimental stresses that mimic, in one way or another, nuclear war. From the standpoint of the ecosystem as a whole any acute limiting force, whether nuclear or not, might have some or all of the following consequences.

1. *Reduction in biological structure* (standing crop biomass). Storms, fire, and bulldozers, as well as the blast component of nuclear explosions, remove protective living matter from the landscape. As a consequence, temperature and moisture fluctuations may increase and nutrient loss may accompany the erosion of substrate. The damage that results from the sudden removal of protective vegetation varies greatly in different ecosystems depending on how well the physical structure of the environment is able to resist weathering in the temporary absence of, or reduction in, biological structure. Man should have plenty of information to predict the outcome of biomass removal because he has had centuries of experience in doing so!

2. *Growth inhibition* and reduction in productivity. These can be the result of frost, drought, etc., as well as ionizing radiation. Observations in Dr. Platt's irradiated forest indicate that an acute dose of ionizing radiation differs from an acute dose of frost chiefly in that growth inhibition continues for a longer period of time after the former stress. Despite the dramatic observations that have been made, quantitative data on (1) the actual reduction in rates of primary production (in terms of calories per unit time per unit area) and on (2) the recovery time to be expected at different dose levels in different ecosystems are almost completely lacking for the kind of single acute doses to be expected in nuclear catastrophes.

3. *Differential kill.* Since living components of ecosystems differ widely in sensitivity and vulnerability to different limiting factors, selective kill is a common result of weather extremes, herbicides, and insecticides? as well as ionizing radiation and other components of nuclear weapons. Principles for predicting the effects of radiation on higher plants, and on whole vegetations, are emerging as a result of the pioneer work at Brookhaven as reported by Woodwell and Sparrow. Experimental data are still needed on effects of differential kill at the ecosystem level, especially in

aquatic, tropical, and grassland communities. The effects of different dose rates and the differences between acute and chronic doses, contingencies now being understood at the organism level, are virtual unknowns at the ecosystem level of organization. The thinking here, of course, should not be confined to ionizing radiation, since man is now intent on creating a kind of chemical "fallout" throughout the biosphere for which there is as yet no "test ban."

4. *Food chain disruption* (disturbance or failure of biological regulation). Periodic failure of biological control mechanisms is a "normal" characteristic of some ecosystems, as exemplified by budworm irruptions in northern spruce forests as described in Macdonald's paper. In general, such periodic breakdowns seem to be characteristic of ecosystems which, for one reason or another, lack diversity in their biological structure and function. Since any severe stress will not only reduce diversity but will also reduce growth and hamper plant and animal defense mechanisms, we can confidently expect insect or other "pest" irruptions to follow catastrophes, in at least some cases. As was well pointed out by Macdonald, the time in the seasonal cycle that stresses or countermeasures are applied is extremely important. Man should be better prepared to assist ecosystems in regaining homeostatic control, since nature is wonderfully resilient if not stripped of the self-regulating mechanisms inherent in the natural diversity of predators and parasites. Thus, a healthy, diversified landscape can be expected to recover from severe stress better than a landscape that is already "sick" and overstressed by man. Unfortunately, the success of insecticides in agriculture has given man a sense of false security in regard to pest control in all environments. The net result has been that the study of life histories and food chains, once respectable research areas for the naturalist-oriented ecologist, is considered passé by the laboratory-oriented biologists of today. In the meanwhile wholesale destruction without understanding replaces scientific research in the field. The threat of a nuclear war should shock us out of the "one-track'' approach, since the spray gun probably will not be so available after a catastrophe (or, in the opinion of many, the unrestricted use of the spray gun will eventually lead to a biological catastrophe, war or no war!).

5. *Succession setback.* Long and complex ecological successions are especially characteristic of terrestrial ecosystems, a fact often overlooked by the physical scientist because succession is strictly a biological phenomenon (that is, while the physical environment determines the pattern of successional stages it does not cause succession to take place). Any severe stress has the tendency to set back succession to an earlier or "younger" stage. Such setbacks are, of course, not necessarily bad. Man uses fire to revert succession from a less productive to a more productive stage (from man's standpoint). Practically all agriculture involves maintaining "youthful" types of communities which yield large, harvestable net productions. What might be critical in a nuclear catastrophe, aside from the contamination of food supplies, is a sudden and widespread succession setback in mature vegetation that functions to protect or stabilize the landscape, for example, forests on steep slopes. Since the early stages of succession are less stable than the mature stages, the stability of the whole landscape would be reduced as the proportion of young vegetation increased, which would increase the probability of both physical and biological breakdowns as described in the preceding paragraphs.

6. *Changes in nutrient cycling rates.* The impact of severe stresses on nutrient cycles vital to the maintenance of productivity is but little understood at present. Sometimes disturbances make nutrients more available (as is the case, for example, in disking a sod-bound pasture or upwelling the bottom waters of a lake) and are followed by "blooms" in productivity; in other cases nutrients are lost from the biologically available pool. Radionuclide tracers inadvertently introduced into the biosphere via fallout from weapons tests offer an overlooked opportunity for experiment. As the movement of these tracers becomes known in a given ecosystem, one could subject the system to severe stress (fire, for example) and observe the resultant effect on the movement of tracers. Experiments such as the "cesium-137 forest" at Oak Ridge represent another approach that should provide answers.

7. *Evolutionary changes.* The past history of the biosphere indicates that catastrophes often result in marked changes in flora and fauna as a result of increased mutation rates, extinctions and invasions, removal of barriers, changes in competitive relationships, and the other evolutionary processes that are accelerated by mass destruction. A "postclimax" forest, for example, if destroyed or badly stressed would almost certainly be replaced by a different forest. The presence of mutagenic agents in the fallout accompanying a nuclear catastrophe might increase the mutation rate, change the selective pressure and, therefore, increase the probability that the recovered ecosystem would not be in exactly the same state as before the catastrophe.

Now that several broad *consequentiae* have been listed, let us return to the generalization in the first paragraph of this summary. My major point is that we already have considerable experience with, and some understanding of, the consequences of most of the individual factors that would result from a nuclear catastrophe. For example, a great deal is known about fire in the environment as documented in Dr. Broido's excellent summation. Thus, we can predict fairly well what will burn at a given time and place as a result of the "million-lighted-match" effect of thermal radiation from a nuclear explosion. While we should push ahead in the study of these individual factors, the greatest unknown stems from our almost complete lack of experience and understanding of *the interaction of factors that would be unique in a nuclear catastrophe.* Furthermore, radioactive fallout adds an additional dimension that is new to the biosphere; it is the one factor unique to nuclear force, and one that we have had but 15 years to study in a scientific manner!

The interaction of fallout and fire can be taken as an example. Since all nuclear tests have been conducted in essentially incombustible environments, there are no experimental data to indicate how these factors would interact. They could very well cancel rather than augment one another, in terms of total effect on man's environment. It is now well known that fallout nuclides enter the food chain of man and animals much more readily as a result of direct foliar contamination of vegetation than as a result of uptake from the soil. Consequently, the hazard would actually be reduced if the vegetation were burned just after or during fallout, because the fallout nuclides would end up in the soil rather than on the leaves. New plant growth would be far less contaminated than the original vegetation. The shielding capacity of mineral soil could also reduce dose. It might even be desirable to burn badly contaminated vegetation or crops as a recovery measure.

The interaction of fallout and fire could easily be subjected to experimental test. In fact, I am tempted to design such an experiment in connection with the ecological studies at the AEC's Savannah River Plant! A bit of artificial fallout could be laid down on one of the well-studied old-field or grassland ecosystems, and the vegetation then burned off on part of the area so as to provide a direct comparison. Experiments of this sort might also settle some of the questions that have been raised concerning the effect of fire on nutrient cycling.

The other great unknown hinges on what might be called the "mass effect." As the number of acres destroyed or stressed increased, the recovery time for any one acre would likely increase greatly. **A** small area, even if severely affected, remains protected by, and can be quickly repopulated from, the surrounding unaffected or less affected areas. Experience with the unshielded reactor at Dawsonville, Georgia, provides a good example. After one of the high-energy runs the entire population of marked cotton rats living in the adjacent small field was exterminated, but repopulation by unmarked migrants occurred rapidly. Small birds entering the radiation field were also undoubtedly killed, but repopulation was so rapid that "before and after" censuses revealed no clear-cut total effect. If a radiation field of exactly the same intensity had extended over thousands of acres the situation would be quite different; "before and after" censuses would show marked differences, and recovery would require much more time. Unless man was able to provide seeds and animal stocks to devastated areas of the size pictured by Dr. Miller in the opening paper, years might be required for repopulation. It is even possible that species with restricted geographic ranges would be completely exterminated. Small-scale experiments are not of much help in evaluating "mass effect." Comparison of recovery following the very large forest fires as mentioned by Dr. Broido and recovery following small, local fires of equal intensity might provide a basis for determining what power function should be used in relating recovery time to size of affected area.