Effects of Ionizing Radiation on Terrestrial Ecosystems

Experiments show how ionizing radiation may alter normally stable patterns of ecosystem behavior.

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During the past two decades man has had the capacity to increase levels of ionizing radiation in the environment by almost any magnitude and on a global scale. No other environmental factor is yet subject to such manipulation, and no other factor appears to have quite the same potential for producing both genetic and somatic effects in living systems. Preoccupation with the potential effects on man has led to concentration of research in environmental biology on the possibility of contamination of man's food chain with radioactive isotopes and to neglect of the potential effects of radioactivity on ecological systems. The recent discovery that certain plants are damaged by total exposures in the same range as those which cause damage in mammals emphasizes the possibility that substantially higher levels of ionizing radiation in the environment would be not only a direct hazard to man but also would cause changes in the ecological systems of which man is but a part. The nature of the potential changes in terrestrial ecosystems and the exposure levels at which they occur is a topic of vital current interest, bearing not only on the possible aftermath of war but also on the feasibility of large-scale peaceful use of ionizing radiation.

Sensitivity of Primary Producers

Plants, the primary producers of all ecosystems, are subject to damage from ionizing radiation at lower levels than was previously thought to be the case (*1*). The gymnosperms include some of the most sensitive of plants; the algae and bacteria, some of the most resistant. Sensitivities within this range vary by a factor of the order of several thousand (*2*). For example, exposure of pitch pine (*Pinus rigida* Mill.) to average levels of less than 5 roentgens per day for several years has killed more than 90 percent of these trees, while exposures in the range of 1 to 3 roentgens per day inhibit growth in diameter (*3*) and needle growth (*4*). Recently Miksche *et al.* (*5*) demonstrated that a total exposure of 82.5 roentgens at a rate of 3.75 roentgens per day damages *Taxus* buds. Near the other extreme of sensitivity among the higher plants, *Arabidopsis* survives long-term exposures of several thousand roentgens per day. Bacteria, algae, and fungi are in many instances still more resistant. In general, the trend of research on both the somatic and the genetic effects in higher plants is toward recognition of effects at lower and lower exposures.

Differences in sensitivity are not restricted to differences between species; sensitivity varies during the life cycle of an organism. Sparrow and I have suggested (*6*) that reproductive stages in plants are generally more sensitive than vegetative stages and that lethal effects occur during flowering and seed set at approximately one-fourth the exposure necessary to cause 100-percent mortality in mature plants. In animals, especially in insects, variations in sensitivity at different stages have been recognized for many years (*7*).

The mechanisms which appear to account for the effects of ionizing radiation on the growth of plants, as well as the effects themselves, have been reviewed recently by Read (*8*), by Sparrow and Evans (*2, 9*), by Gunckel and Sparrow (*10*), and by Sparrow and me (*6*). The primary site of damage appears to be the chromosome, and the great differences in sensitivity among organisms are attributable to differences in chromosome number and size. Organisms with few, large chromosomes may lose a significant portion of their genome from one chromosome break, while organisms with many, small chromosomes may suffer only minor genetic damage from a single break. Sparrow and Miksche (*11*) have shown that this relationship between sensitivity and chromosome size and number holds for several plant species.

Effects on Organisms and Ecosystems

The effects of exposure of plants to ionizing radiation range from death, through varying degrees of growth inhibition, to effects on reproductive capacity and to even more subtle genetic effects recognizable only in subsequent generations. Numerous instances of stimulation of growth have been reported, especially in the Russian literature (*12*). Additional effects are recognizable in animals, including shortening of the life span (*13*).

In general, the research which has elaborated these effects in plants and which has yielded estimates of sensitivities has been carried out on small populations under conditions of cultivation in greenhouses or gamma-radiation fields—under conditions specifically designed to reduce the variability attributable to environmental stress. Introduction of the various forms of environmental stress characteristic of natural ecological systems can be expected to intensify the damage from exposure to ionizing radiation and to produce measurable effects at lower exposure levels (*6, 14*), possibly to produce additional effects not recognized previously.

Virtually all of the effects recognized at the organismal and cellular levels have implications at the population and ecosystem levels; combined, they present a bewildering array of possibilities at these higher levels. For simplicity I divide possible effects into short-term and long-term effects, assuming *short-term* to mean less than 2 years. In most terrestrial ecosystems the short-term effects are dominated by the consequences of differential sensitivities; the long-term effects, by these consequences plus effects on re-

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productive capacity and genetic effects. I dwell here principally on the short-term effects.

Two types of short-term effects would be expected from long-term irradiation of an ecosystem: (i) selective mortality of sensitive species, due to direct and immediate effects of exposure, and (ii) shifts in the relative importance of species populations through alteration of the biological interactions which normally contribute to a stable pattern of ecosystem behavior. These interactions include not only the many vaguely defined inter-organism relationships commonly lumped as "competition" but also parasite-host and predator-prey relationships. There are numerous models suggesting the potential consequences of such shifts in biological interactions. Some of these have been summarized by Elton (*15*) and Andrewartha (*16*).

Exposures Necessary To Produce Effects on Ecosystems

Research on the effects of ionizing radiation on organisms living in natural arrays is complicated by the variability of these arrays and the necessity for recognizing slight effects caused by exposure to the low-level radiation present. In addition, the effects of exposure are usually confounded with the factor of location, making clear separation of radiation effects from other environmental influences difficult. The lowest levels of long-term ionizing radiation at which nongenetic effects on higher plants had been observed, approximately 2 roentgens per day, were estimated by Sparrow and me (*6*) to be 8000 times greater than the highest exposure levels from fallout in New York City in 1958 (*17*). It is probable that effects on stem diameter and needle growth in pine could be observed at levels perhaps half those used in our calculations, and it is true that in some areas levels of fallout radioactivity are higher than they are in New York City; nevertheless, a large gap exists between present general radiation levels and the lowest level necessary to produce a measurable effect in a sensitive plant. There is, therefore, little reason to believe that radiation effects can be seen now in natural ecosystems other than ecosystems exposed to local fallout from experimental bomb bursts, as suggested by reports such as those of Fosberg (*18*), Palumbo (*19*), and Shields and Wells (*20*) and ecosystems such as that adjacent to the Lockheed reactor in Georgia (*21*). To produce observable effects even in ecosystems containing pines, which are among the most sensitive plants known, long-term exposures in the range of 1 to 5 roentgens per day would be necessary, while to produce parallel effects in oak, minimum exposures of 10 roentgens per day would be required. Much higher levels would be necessary to kill these plants within a short period and to produce presently recognizable morphological effects in other, more resistant species. Miller and I (*3*) and McCormick and Platt (*14*) have presented data indicating that environmental stress increases the damage in plants caused by exposure to ionizing radiation at any level, and Sparrow and I (*6*) have suggested one mechanism in explanation of this effect. We suggest that damage on a unit-cell basis is the principal factor governing response, and that any increase in the exposure of a cell prior to division increases damage. Cells which divide slowly are exposed to more radiation prior to division, and sustain greater damage, than those which divide rapidly. Any environmental factor which reduces the rate of cell division increases the exposure on a unit-cell basis and thereby increases the effects. In any case it seems possible that exposure to ionizing radiation reduces tolerance to environmental stress, and that ionizing radiation kills or damages plants at lower levels in irradiated ecosystems than under conditions of cultivation. We would, therefore, expect to find nongenetic effects in the most sensitive plants in natural arrays at long-term exposure rates of the order of 1 roentgen per day.

Table 1. Vegetation zones around the gamma-radiation source and the approximate exposures each zone received during the first 6 months of the experiment. The zones remained stable in general throughout the summer, but they are expected to recede during the second year of the experiment.

Vegetation zone	Daily exposure rates (r)	Approximate total accumulated exposure (r)
Oak-pine forest	Background*	
Oak forest	20– 60	3,600–11,000
Gaylussacia-Vaccinium heath	60–150	11,000–27,000
Carex zone	150–350	27,000–63,000
Zone in which all higher plants died	>350	>63,000

* Tree growth was inhibited in this zone at exposures as low as 2 r/day (Fig. 3).

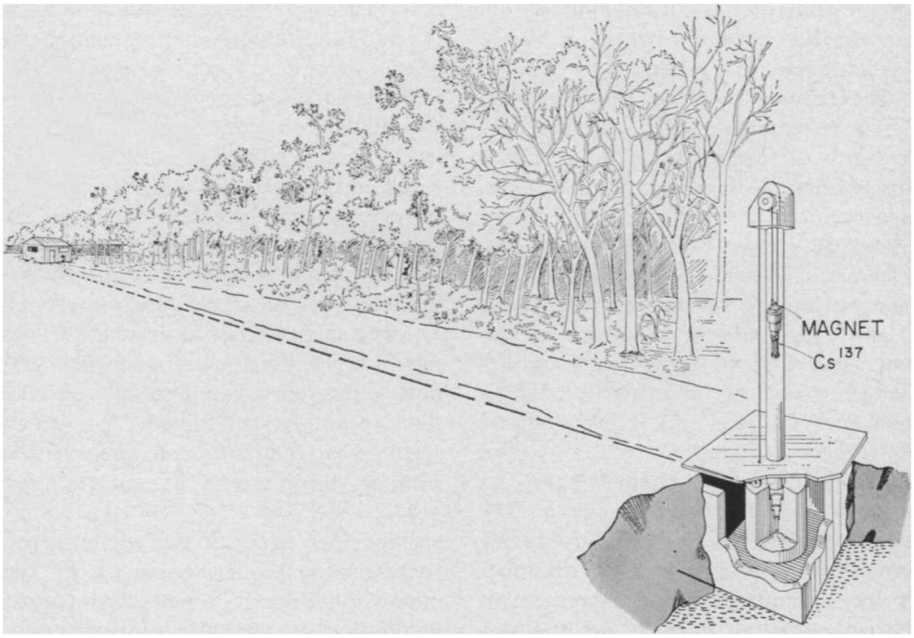


Fig 1. Mechanism for controlling the gamma-radiation source used in irradiating a forest ecosystem at Brookhaven National Laboratory. The source can be raised or lowered into a lead-shielded container through operation of a winch in the building a safe distance away.

Experimental Approach

These difficulties dictate an experimental approach to the quantitative study of effects at community and ecosystem levels. For such an experiment the radiation levels used must vary from levels lethal to most organisms through low levels approximating background. Gamma radiation from a central point seems most appropriate for experimental purposes because, with a relatively small quantity of radioactive material, an intense radiation source can be conveniently provided. In addition, there is no activation problem as there is with neutrons.

Such a radiation facility has been established at Brookhaven National Laboratory, specifically to provide opportunity for systematic study of the effects of ionizing radiation on a terrestrial ecosystem and its components. The ecosystem chosen for this experiment supports a stand of the Long Island oak-pine forest, with *Quercus alba, Q. coccinea*, and *Pinus rigida* the principal tree species.

The source of radiation is cesium-137 (9500 curies), a gamma emitter, centrally located; it can be shielded, when shielding is desired, through operation of a winch (Fig. 1). Rates of exposure around this source vary from several thousand roentgens per day within a few meters to about 2 roentgens per day at 130 meters. The source is exposed 20 hours per day, and has been exposed on this schedule since 22 November 1961.

Two broad research programs designed to elucidate effects at the ecosystem level are being carried out with this radiation facility. One involves measurement of changes in the populations of species which form the ecosystem; the other, measurement of the rates of energy fixation and the paths of energy movement through the system. The first of these programs includes study of short-term changes induced by direct and indirect effects on present populations and long-term effects of genetic changes and of changes in reproductive capacity. The second program is designed to provide a more nearly precise measure of effects on the system through measurement of the energy-fixing capacity of the system and of its components. Although use of this facility is by no means restricted to studies involved in these two programs, the programs form the core around which research on the behavior of the overall system is organized.

Prior to installation of the source, detailed information on the species composition of the vegetation and on the size and vigor of individual plants within the vegetation were obtained through the technique of Woodwell and Hammond (*22*). Less detailed data on insect, bird, and mammal populations were also obtained. These, plus data from other, similar stands remote from the source, are the control data for the experiment.

The required size of the gamma source was estimated from the correlation between radiosensitivity and chromosome number and size shown by Sparrow and his associates (*1, 6, 9*). A source size was selected which was estimated to be large enough to produce effects in the first year, through an area of approximately ½ hectare, ranging from mortality through inhibition of growth of most species in the vegetation.

Early Effects of Exposure

At the time of budbreak in the spring, approximately 6 months after irradiation was started, effects were obvious as far as 40 meters from the source (Fig. 2), where exposure rates were approximately 40 roentgens per day. Differences in sensitivity among plant species produced a zonation of vegetation, five zones being clearly defined (Table 1): a zone of total kill of all higher plants; a sedge zone; a heath-shrub zone; an oak zone; and, at lower levels of radiation, the oak-pine forest.

The striking differences in sensitivity of primary producers is indicated by the growth curves of Fig. 3 for white oak and pitch pine, which show severe inhibition of shoot elongation in oak at exposures above 35 roentgens per day and in pine at 15 roentgens per day. These curves approximate closely the responses predicted for these species by Sparrow and me on the basis of chromosome size and number (*6*).

A further effect of differential sensitivity among species is shown by the curves of Fig. 4, which show insect defoliation, expressed as a percentage of the leaves present on white oak, plotted against exposure rate. Defoliation by insects was approximately 10 times more severe on trees damaged by radiation than in the nonirradiated forest. This increase in damage was probably due not to an increase in the abundance of insects but, rather, to a decrease in the number of leaves available to the endemic populations. The populations of leaftiers (*Psilocorsis* spp.) leaf rollers (primarily *Argyrotoxa semipurpurana*), leaf beetles (Chrysomelidae), and loopers (Geometridae) which caused most of the damage shown (Fig. 5) were aparently more resistant to damage than their host trees.

These early observations illustrate the types of short-term changes which exposure to high levels of radiation in the general environment can be expected to produce in a forest ecosystem. While such high levels are above present levels of radiation from worldwide contaminants by many orders of magnitude, they are well within the range of exposures associated with local fallout from bombs (*23*). From Table 1 and Fig. 3 it is clear that contamination-producing exposures in excess of 1000 roentgens delivered over any period of less than 6 months would cause severe damage to pitch-pine forests and probably to other gymnosperm forests as well, while parallel damage would occur in oak forests at exposures in excess of 10,000 roentgens.

Furthermore, it is clear that ionizing radiation may alter such host-parasite relationships as those existing between a plant and its insect defoliators, and that radiation-damaged plants will suffer greater insect damage than plants not damaged by radiation. While the assumption that all host-parasite relationships will be affected in this direction is not justified, the hypothesis seems tenable that small organisms with wide ecological amplitudes and high rates of reproduction—in short, weeds and other organisms frequently considered pestiferous because of their persistence under persecution—have survival advantage under conditions of long-term exposure to ionizing radiation over large organisms with longer life cycles.

Discussion

If we consider from a very fundamental and practical standpoint the general problem of contamination of the environment with radioactive debris, it is clear that two types of con-

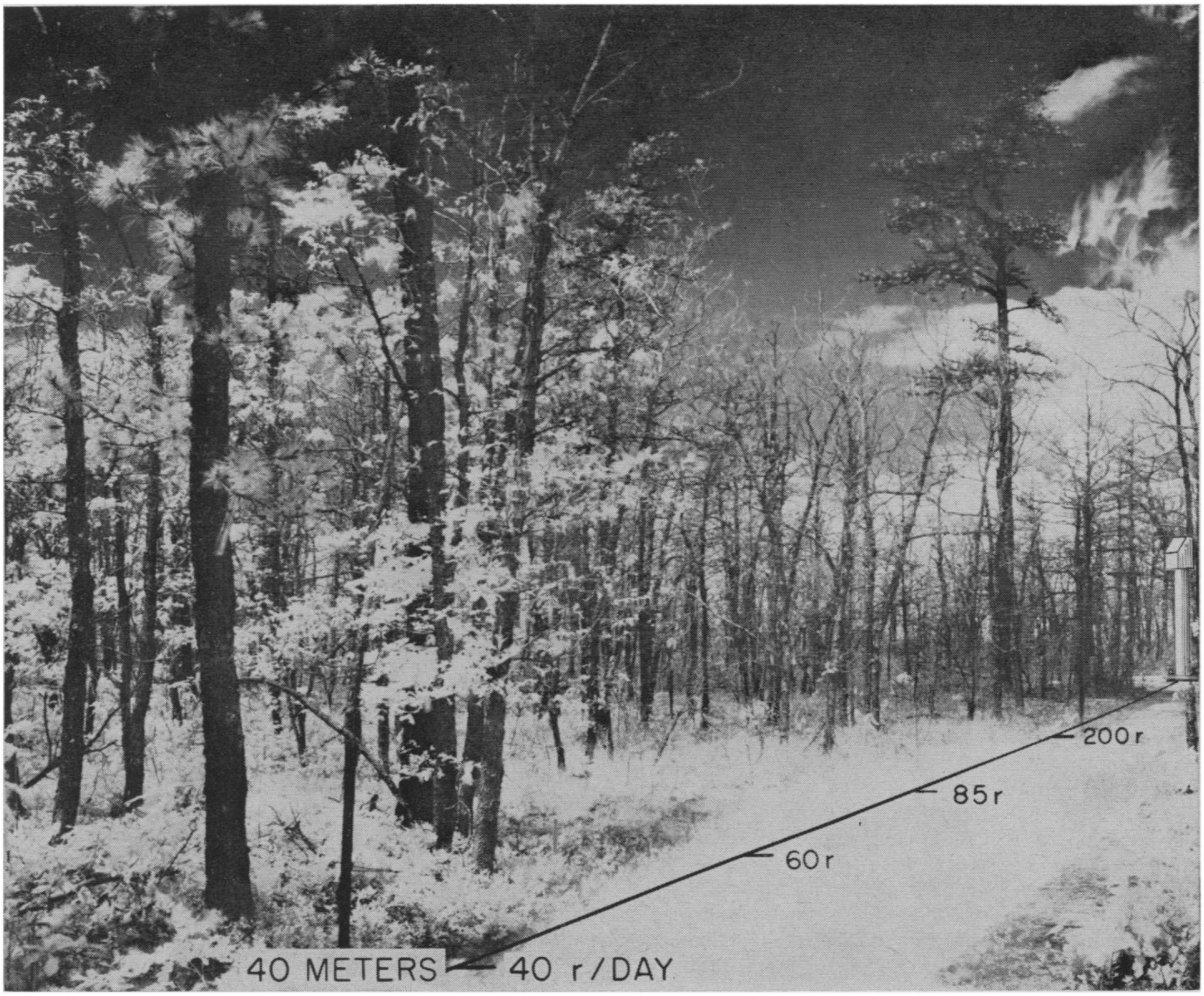
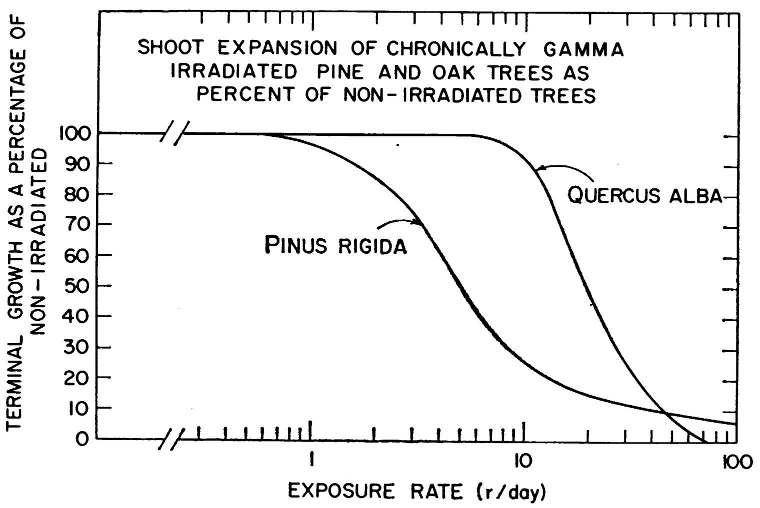


Fig. 2. The forest within 40 meters of the source after 6 months' exposure to ionizing radiation. The source is cesium-137 (9500 curies), suspended in the tower at right. The numbers indicate approximate daily exposure in roentgens, at the point indicated.



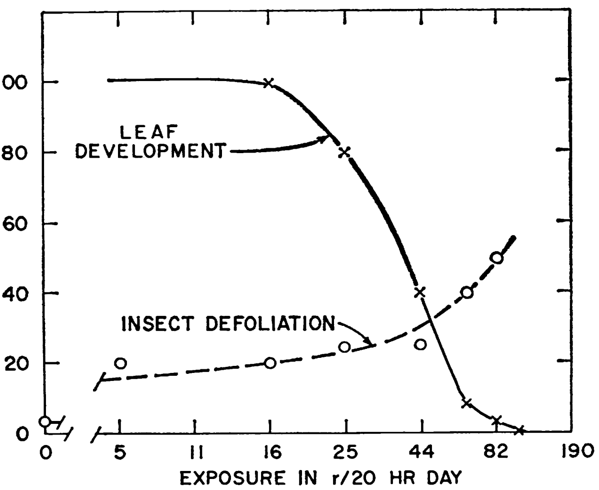


Fig. 3 (left). Growth of white oak and pitch pine in an irradiated forest, at various rates of exposure. Fig. 4 (right). Variation in the intensity of insect defoliation among white oaks damaged by ionizing radiation.

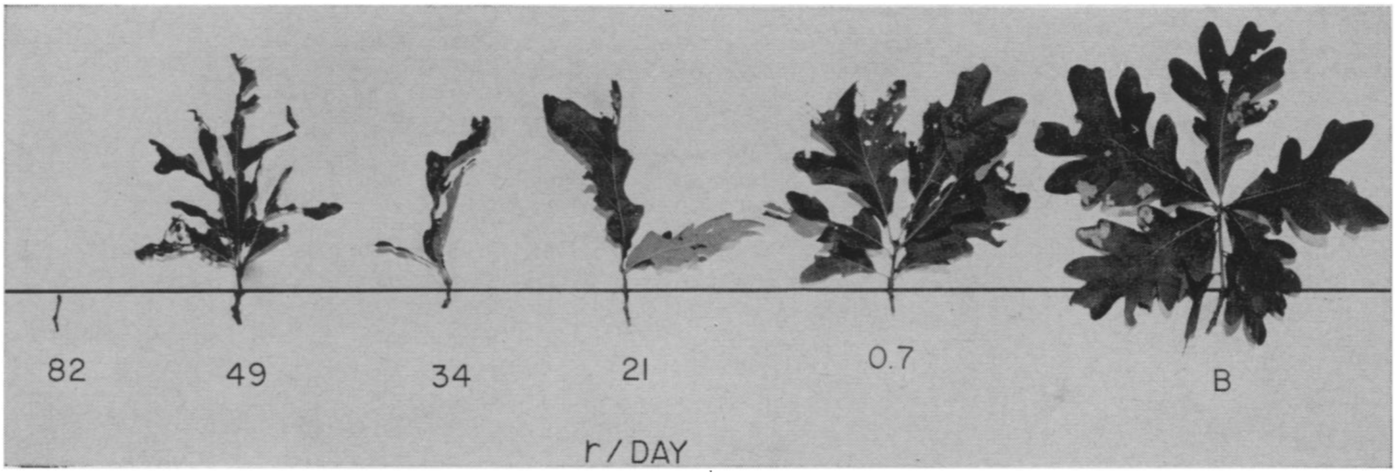


Fig. 5. Insect defoliation and damage from ionizing radiation in white oak. 30 July 1962.

tamination are possible; first, the severe contamination from heavy local fallout associated with bomb bursts; second, the much less intense long-term and world-wide contamination from sporadic bomb testing, from accidents, and from wastes originating from peaceful uses of atomic energy. These two situations are fundamentally different, the one involving large, short-term effects principally from external emitters, the other, long-term effects from both internal and external emitters. Both situations present problems which are difficult, and many of their finer points may be susceptible of only limited, empirical solution. Nonetheless, certain principles seem to bear on the general problem, and certain questions seem answerable within broad limits.

Numerous radiobiological studies emphasize that the principal damage incurred by an organism exposed to ionizing radiation occurs in the nucleus (*8*), and more recent work shows that the sensitivity of an organism is related to the size and number of chromosomes present (*2*). This relationship is now well enough established to be used as a basis for predicting the sensitivity of organisms to radiation of any level (*6, 24*). Although the technique lacks precision, it is useful; for instance, through this technique accuracy in predicting the range of sensitivity for a higher plant is increased to a point where predicted values deviate from experimental values by a factor of 4 or less instead of a factor of about 500. Further refinement of this technique should increase its precision greatly. At present it is obviously useful in predicting not only effects on individual plants but also the gross, short-term effects of heavy fallout on the plants of any ecosystem.

Long term effects of chronic exposures on organisms living in natural arrays are dependent to a higher degree on the nature of the contamination and on an additional set of biological factors. Such long-term effects are necessarily the result of exposure from both internal and external emitters, and it is clear that to predict effects of exposure for any type of intensity of contamination, the mineral cycles and periods of residence of isotopes in various organisms must be known. Great progress is being made in defining these cycles and their biological implications (*25*).

Less progress has been made in defining the biological considerations which are important in determining potential long-term effects. These considerations seem to be three.

1) Ionizing radiation is generally deleterious to living systems, and exposure can be expected to reduce physiological tolerances to environmental stress. Although there are notable exceptions to this generality (*12*), especially as a result of clever genetic manipulations by man (*26*), evidence from animals (*27*) and an increasing body of evidence from plants indicate strong interactions between stress and radiation exposure (*3, 14*). Sparrow and I have suggested (*6*) that relative sensitivity among species to this type of radiation damage probably parallels radiosensitivity shown by morphological characteristics. The extent to which this is true remains to be seen.

2) Variation in sensitivity to damage during the life cycle of an organism may be extreme, the population as a whole thus being much more sensitive than the mature stages of single organisms. In general, reproductive processes are most sensitive to damage, vegetative or mature stages least sensitive. On the other hand, there is no threshold exposure for the production of mutations.

3) Selective removal or differential inhibition of species will alter biological interactions, potentially upsetting the usual patterns of species abundance and ecosystem stability. This type of distrubance can have several forms including alteration of intra- and interspecific interactions among plants, shifts in the host-parasite balance, and shifts in predator-prey relationships. There are abundant models for disturbances of these types, ranging from the removal of chestnut from the extensive oak-chestnut forests of eastern North America by the fungus *Endothia parasitica* (*28*) to disturbances shown in numerous animal-population studies (*16*).

All of these changes produce potential instabilities in ecosystems, ranging from the initiation of a new successional sequence only slightly different from the old one to violent oscillations in population density which can result in extinction or in population explosions.

The research needed for elaboration of these large and complex problems is itself large and complex, involving the delineation of model systems and the analyses of these systems from numerous standpoints. Perhaps the most successful ecological study of this type is the series of studies of the spruce budworm in eastern Canada, carried out over more than two decades and involving many scientists (*29*). Although ionizing radiation presents a set of problems different from those posed by the budworm, the work in Canada emphasizes the need for long-term, integrated approaches to such large-scale and fundamental biological problems. One technique for analyzing certain aspects of the potential effects of ionizing radiation is outlined here. Installations such as that at Brookhaven, established within major vegetation types, with their control ecosystems, provide one type of model. A second type of model has been provided by chance at Rongelap Atoll and on neighboring atolls in the Pacific, and at the White Oak Lake Bed at Oak Ridge, Tennessee. Similar models must now exist in the Russian Arctic. The partially shielded Lockheed reactor in Georgia has provided a most useful model of an irradiated ecosystem. Use of these models as they become available, in conjunction with experiments involving mineral cycling and the effects of internal emitters not only on organisms but on populations and ecological systems as well, will provide at least an understanding of what is happening to the environment, if not the wisdom to control it (*30*).

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30. The research described is being carried out at Brookhaven National Laboratory under the auspices of the U.S. Atomic Energy Commission. Many of my associates have contributed to this work in various ways. I particularly want to thank Dr. A. H. Sparrow, whose continued and vigorous interest made the project possible.

News and Comment

Administration Sees No Ground for Jubilation as Missile Episode Is Brought to a Calm Conclusion

The administration is not encouraging any cheering over its success in thwarting the Soviet missile gambit in Cuba.

For one thing, the strong medicine that the United States employed in Cuba could have distant and unforeseen side effects, and jubilation is therefore considered to be premature. No matter how Khrushchev may euphemize the incredible events of the past two weeks, he, in effect, dismantled some of his own political and military prestige when he agreed to dismantle his Cuban missile launchers; it is not unreasonable to assume that he is looking to recoup his losses, and the administration is eager to refrain from any words that may irritate him toward accomplishing that quest.

Furthermore, the administration desires to make it clear, especially to American audiences, that it successfully responded to the Soviet threat, not with a bludgeon, but with carefully measured words and a minimum application of force. Thus it was no accident that the Navy employed binoculars, rather than a boarding party, to inspect the first Soviet-owned vessel—a tanker—that crossed the quarantine line. A Defense Department spokesman explained that an external examination had satisfied the Navy that the vessel was not carrying prohibited material. It would seem that this was more of an educated guess than a substantiated conclusion, but it had the merit of keeping armed American naval personnel from forcing their way onto to what is legally the equivalent of Soviet soil. When an actual boarding did take place, it was on a Lebanese vessel under charter to the Soviets. In this fashion, the highly provocative fact of the quarantine was tempered through judicious execution, and the Soviets cooperated by reversing the course of those vessels whose cargoes fell under the ban.

Although "hard-liners" are now praising the administration for taking the advice they were giving all along, the response employed in Cuba was quite different from what the jingoists were recommending. From the onset of the crisis, the administration set a course aimed at *convincing* the Soviets that the U.S. would use force to achieve the removal of the missile launchers if the Soviets did not remove them first. To get this idea across, it had to come perilously close to employing