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THE STIMULATION OF PLANT GROWTH BY IONIZING RADIATION *

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Abstract--The stimulation of plant growth by exposing seeds or growing plants to low doses of ionizing radiation, or by the use of radioactive fertilizers, has been reported by many investigators during the past 65 years. There is critical evidence that ionizing radiation may stimulate plant growth at certain stages of development and may induce earlier flowering. It can also stimulate lateral bud development, presumably by auxin inactivation. These stimulating effects are usually of small magnitude and are often not reproducible, although in individual tests the differences may be statistically significant. The evidence for increased yields of crop plants is less conclusive. Large increases in yields of crop plants by irradiating seed, soaking seed in radioactive solutions, or by the use of radioactive fertilizers have been reported from the U. S. S. R. Similar tests in the U. S. have given only negative results.

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DISCLAIMER

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Only a few years after the discovery of X rays by Roentgen in 1895 reports of a stimulating effect on plant growth by X-irradiation began to appear. Since that time hundreds of papers have been published dealing with the stimulation of seed germination, induction of faster seedling growth, earlier flowering, and the production of larger plants and greater yields by exposing seeds or plants to low doses of ionizing radiation.

The early work has been well reviewed by Breslavets (4) in her book Plants and X Rays, published by the U.S.S.R. Academy of Science in 1946. An English edition, translated by Alena Elbl and edited by Arnold H. Sparrow, was published by the American Institute of Biological Sciences in 1960.

Accelerated germination of X-rayed seeds was first reported by Maldiney and Thouvenin in 1898. In 1906 Evler observed some cases of stimulated growth following irradiation of seeds of beans, radish, lettuce and squash, and in a few cases earlier flowering of the resulting plants. Schmidt in 1910 obtained larger plants following irradiation of soaked pea seeds. Koernicke in 1904-1915 found some stimulation of early

growth by irradiating Vicia and Brassica seeds with low doses of X rays, and observed that Brassica was much more resistant to the damaging effect of high doses of X rays than was Vicia. Ancel's negative results in France from 1924-1927 are given little attention by Breslavets.

This early work on radiation effects done in France and Germany was soon followed by work on X-ray stimulation of plant growth in other countries. Yamada in Japan in 1917 reported a 40 percent increase in yield of rice following irradiation of the seeds, and Komuro in 1919 reported that X-irradiation stimulated the germination of rice seed. Sakamura in 1920 was one of the first to describe the effects of X rays on the nucleus and chromosomes.

The early work in the United States is well reviewed. In a long series of experiments from 1926 to 1936 Edna Johnson reported positive stimulating effects in some cases and negative results in others. As early as 1929 Sprague and Lenz reported that irradiation of sprouting seed potato tubers produced plants with larger tubers, although there was no significant increase in yield of tubers. The experiments of Shull and Mitchell published in 1933 showed that low doses of X rays given to corn seeds resulted in a stimulation of early growth of the seedlings. Not mentioned by Breslavets is the fact that these very able plant physiologists were so convinced that their results had practical significance that they patented the process in 1932. Also included are the results obtained by Long and Kersten in

1936 showing that irradiation of soybean seeds produced a stimulating effect on early growth.

The early work in the U.S.S.R. is described in more detail, especially the work of Breslavets and her colleagues done in 1935-1937. Remarkable increases in the growth and yield of rye are reported to be induced by giving the seeds a dose of 250 r of X rays. Similar results are reported for peas and rye grass.

A total of 125 references are listed covering the early work on alleged stimulation of plant growth following seed irradiation at low doses. Chapters in Breslavets' book also include one on mutation effects with 77 literature references: one on the intracellular changes induced by radiation, with 197 references, and one on the quantity and quality of ionizing radiation on the "transformation" of plants, with 75 literature references. In this last chapter reference is made to Ancel's work done in 1928 showing that fractional dosage was less effective than an acute dose in producing radiation damage, and to the work of Alberti and Politzer, who in 1924 found that resting cells were more resistant to the damaging effect of X rays than were cells which were in the process of mitosis.

Although the early work on the stimulating effects of ionizing radiation was based upon inadequately controlled experiments, there is critical evidence that low levels of irradiation

do have a stimulating effect on certain stages of plant development. The older explanation of such effects, based upon the Arndt-Schultze Law that "Weak irritants stimulate activity; medium irritants depress it; strong ones halt it", has recently been replaced by a more rational physiological interpretation.

The more recent work on the stimulating effect of ionizing radiation will be considered under three general categories: 1. Effects on seeds, bulbs and scions, 2. Effects of chronic irradiation of growing plants, and 3. Effects of radioactive "fertilizers" applied to the seed or added to the soil.

Irradiation of Seeds, Bulbs and Scions

In 1955 Kuzin(21) reported a stimulation of root length of rye, pea and cucumber following irradiation of the seeds with 250-500 r of X rays, and increased yields of radish (20-30%), cabbage (20%) and peas (10-20%) following seed irradiation of 500-1000 r for radish, 1000-2000 r for cabbage and 350-500 r for peas. He admitted however that there was "considerable fluctuation in the degree of effect as manifested by experiments conducted under different soil and climatic conditions, and insufficient elaboration of the theory of stimulation."

In 1946 Timofeev-Resovsky and Poryadkova (52) reported increased growth of many crop plants following irradiation of dry or soaked seeds with low doses of X rays, or by soaking the seed in radioactive solutions. The effect is attributed to "weak poisoning". Breslavets(6) in 1960 reported that chronic irradiation

of rye seeds, giving a total dose of 1000 r over a period of 27 days, resulted in an increased yield of 20 percent. Tedoradze[50] in 1961 claimed that seed irradiation not only increased yields of legumes by as much as 20 to 30 percent, but also promoted or delayed the time of flowering.

In reporting on a "conference on seed irradiation prior to sowing", sponsored by the Institute of Biophysics of the U.S.S.R. in 1961, Patskevich[32] summarized the recent work of many Soviet scientists, including that of Kuzin, Savin, Breslavets, Barezina, Kryukova, Kedov and many others. All report stimulating effects on growth, yield and/or earlier ripening of the resulting crop following seed irradiation. The general conclusion was that "presowing irradiation of seeds holds great promise from the viewpoint of its practical application in our nation's agriculture and that further extensive and painstaking work is needed."

Reports of a stimulating effect of radiation of seeds continue to appear from other countries, but these are limited largely to the effects on early growth or earlier flowering. Marchi et al.[25] in Italy reported that irradiation of barley seed with 100-500 r of X rays "enhanced the ultimate luxuriance of the plants", but no critical yield tests were conducted. Saric et al.[36] in Italy also found some stimulation of the growth of wheat seedlings following irradiation of the seeds with 500-2000 r of X rays, but efforts to increase yields by

such treatment "have not given unequivocal results." Bhatt et al.(2) in India claim a stimulating effect of low doses of thermal neutrons given to seeds of Plantago, Setaria and Oriza, often accompanied by earlier flowering.

In the United States some of the more recent work has supported the early results of Shull and Mitchell(39) in 1933, Long and Kersten(23) in 1936 and Kersten, Miller and Smith(18) in 1943, but negative results have also been reported. In no case is there any critical evidence that crop yields are increased by irradiating seeds. Jones and Plummer(15) in 1960 reported a stimulating effect for Trifolium. Spencer and Cabanillas(48) found that seed irradiation with X rays and thermal neutrons did have an early stimulating effect on the growth of Indigofera seedlings, but that the ultimate size of the plants was not increased. Hough and Weaver(13) reported that apple seeds exposed to thermal neutrons promoted seedling vigor, but only in seedlings from weak seeds. Stein and Steffensen(49) found some increase in length of both roots and shoots of corn seedlings following seed irradiation with 500 r of X rays. Similar results were obtained by Smith et al.(43) who conclude that "microbeam irradiation of the shoot and leaf of the dry seed embryo will bring about a stimulation of growth as evidenced by greater elongation of the primary root during the second, third and fourth day after hydration" and with no retardation of coleoptile growth.

Few of the tests in the U. S. have been based upon field tests and none on total yields of crop plants. In 1962 McCormick(24) reported work done on a population of Arenaria. The plants were exposed to 8000-30,000 r of gamma rays from a Co^{60} source from March to August in 1959. Seeds of these plants produced the following year a denser population, larger plants and more prolific flowering. This stimulating effect is attributed to the irradiation of the seed in 1959. The seed produced in 1960 was not subjected to irradiation and the following year (1961) the plants were of normal size and vigor.

Negative results have also been reported. Kankis and Webster(17) in 1956 found no growth stimulation by irradiating Sorghum seeds with thermal neutrons at various doses. A very thorough test reported by Osborne and Bacon(31) in 1960 gave largely negative results. Tests of various species showed no stimulation of seedling growth following seed irradiation at doses of 500-100,000 r, except in one of the 18 tests. Similar results were obtained by Skok and Charney(41) at the Argonne Laboratory. Sunflower seeds were exposed to 50 r to 750 r. The authors concluded that "stimulating effects occurred with lower doses but were generally not reproducible". Similar inconsistant differences were found with buckwheat.

In a later and more extensive series of experiments Skok et al.[42] investigated the stimulating effect of X rays with seeds and plants of various genera. They found small but significant increases in growth in some cases, but these results were not always reproducible. They question the value of ionizing radiations to stimulate plant growth of field crops.

Negative results of seed irradiation have also been reported for pine and spruce by Gustafsson and Milan[11] in Sweden. Even in the U.S.S.R. negative results were reported by Vasilev[53] in 1959. Exposure of wheat seeds to 25-100 r of

X rays did induce fluctuating variations of growth at various periods of seedling development, but no increase in total growth. In 1957 Klechkovsky(19) cautioned his colleagues in accepting reports of increased yields following seed irradiation.

The irradiation of bulbs, corms or scions seems to have given more consistent results than has irradiation of seeds. In 1948 Johnston(14) reported increased vigor of plants of Kalanchöe following irradiation of plantlets with 2500 r of X rays. Matsumura and Fujii(26) in 1959 observed stimulation of sprouting of lemon cuttings following exposure to 5 kr of X rays. Cuany and Guardia(8) found that cuttings of Panicum exposed to chronic irradiation of 37 r/day produced twice as many shoots as the controls. Both Sax(37) and Spencer(47) found a significant induction of earlier flowering following irradiation of dormant bulbs or corms. The effect was not maintained the following year, and was attributed to changes in auxin level induced in the bulbs or corms by the X rays. Only negative effects were found by irradiation of potato tubers by Fischnick et al.(10) and for Crocus by Mitsukuri and Shinohara(29).

Stimulation of Plant Growth by Chronic Irradiation

Shortly after the gamma field was put in operation at the Brookhaven National Laboratory it was found that low doses of chronic irradiation sometimes stimulated plant growth. In 1953 Sparrow and Singleton(45) reported that chronic exposure

of tobacco plants to 100-350 r/day stimulated earlier flowering, and in the following year Sparrow[46] observed an increase in plant height of Antirrhinum when exposed to 230 r/day of gamma rays. Evans and Sparrow[9] in 1961 found an increase in net dry weight of shoots and roots of Vicia when exposed to 20 r/day for 20 days and of Lilium when exposed to 5 r/day for 35 days.

Mikaelsen and Aastveit[28] in Sweden also find that low doses of chronic irradiation stimulates growth. Oat plants exposed to 12.5 r/day of gamma irradiation for 108 days were taller than the control plants, but sterility of the irradiated plants greatly reduced grain production. Similar results were obtained with barley exposed to 27-50 r/day.

Breslavets[5] in 1958 reported rather fantastic effects of very low doses of chronic irradiation from a 1 curie Co^{60} source. The green weight of corn was increased 36 percent following an exposure of 1.6 r/day. Tests with buckwheat, repeated for three years, showed increased growth each year by an exposure of as little as 1 r/day, and a 60 percent increase in plant weight following exposures of 2 r/day. Honcariv[12] in 1959 reported a 70 percent increase in green weight of Trifolium with as little as 0.24 r/day of chronic gamma irradiation.

Equally striking were the results reported by Cervigni et al.[7] of Italy at the Radiation Conference at Harrogate,

England, in 1962. They reported that chronic gamma irradiation of wheat plants increased the number of culms up to as much as 25 times over the control plants, and a 6-fold increase in the mean weight of the mature plants. As early as 1949 Leopold and Thimann[22] had reported a four-fold increase in tillering of barley seedlings by exposure to 25 r of X rays each week. This response was attributed to the effect of the X rays on growth hormones. As Skoog[40] found long ago relatively small doses of X rays reduce or inactivate auxin production, and development of lateral buds are promoted by irradiating shoot tips.

Acute exposure of growing plants to low doses of irradiation are also reported to result in stimulation of growth. Kreybig and Schagen[20] obtained a 10 percent increase in summer growth of Sinapsis following irradiation of 12-day old seedlings with 0.5 kr. Scully[38] reported that acute doses of 50 to 500 r of X rays frequently, but not invariably, stimulated stem length and dry weight of Xanthium plants. Sparrow[44] reported earlier flowering in Nicotiana after acute irradiation with 1800 r of X rays.

Radioactive Fertilizers

An excellent review of recent work on radioactive fertilizers was published by Kaindl and Linser[16] of the Austrian Nitrogen Company. Some experiments had been conducted early in this century, but interest in radioactive fertilizers was revived with the advent of the Atomic Age. In France and

the United States commercial types of radioactive fertilizers appeared following World War II. Tests of such fertilizers in the U. S. and Europe gave negative results, but in more recent years interest in radioactive fertilizers has been revived, especially in the U.S.S.R.

Kaindl and Linser have reported in some detail the work of Sheshell and Kuzin in the U.S.S.R. In a series of experiments covering 8 years (1947-1954) Sheshell applied radioactive fertilizers to potted plants of potatoes, cabbage, oats, clover, wheat, beets and sunflowers. Average increased yields ranged from 16 to 33 percent above the controls. Field tests made with tobacco in 1957 give increased yields of 33 percent with uranium, 20 percent with radium and 21 percent with shale fertilizers. Kuzin claimed similar results by pre-soaking seeds of peas, beans, vetch and lucerne in radioactive solutions. As Kaindl pointed out in 1951 the practical use of radioactive fertilizers for crop plants is "contra-indicated by health hazards of man" in using such plant products for food, unless the half-life of the radioactive fertilizer is limited to only a few days.

Vlasyup(54) and Timofeev-Resovsky and Porysdkova(52) in the U.S.S.R. also claim that seeds of various crop plants soaked in solutions of S^{35}, P^{32}, Ca^{45} or Zn^{65} before planting stimulates plant growth and increased dry weight. Similar

results were reported from the Latvian Science Institute by Miller[27].

According to Niemann[30] Sr^{90} added to the soil hastened flowering and increased plant size of Arabidopsis. Thaung[51] at the Burma Atomic Energy laboratory also claims that P^{32} used as a fertilizer increased yields of rice as much as 45 percent. He, too, points out the hazards of radioactive fertilizers used to promote growth of food plants.

Tests of radioactive fertilizers in the United States have given only negative results. In tests made during the years 1947 and 1948 at 38 field stations by the U.S.D.A. the results were negative (Alexander[1]). The radioactive fertilizers tested were "Alphatron", a commercial product, at the rate of 5-20 lbs. per acre, radium bromide at the rate of 300 micrograms per acre, and uranyl nitrate at the rate of 13.4 lbs. per acre. Blume[3] in 1952 found no effect of P^{32} used as a fertilizer for oat and barley plants grown in pots in the greenhouse. In 1961 Romney[34] found that "yield of wheat was not affected by solutions of mixed fission products incorporated with potted soil when the activity levels ranged from 0.01 to 1.5 mc per gram of soil."

Plummer[33] gave sunflower plants 160 microcuries of Ca^{45} and found that a brief period of inhibition was followed by elongation of the shoots so that the radioactive plants were eventually taller than the controls.

Conclusions

There is critical evidence that low doses of ionizing radiation can stimulate plant growth at certain stages of development and may promote earlier flowering. Such results could be attributed to the effects of irradiation on auxin balance. But claims that the irradiation of seeds, or the use of radioactive fertilizers, results in greater yields of crop plants still lacks critical confirmation. The situation in this respect has changed little since 1915, when E. J. Russell[35], in discussing the early work of Fabre in France, Molish in Germany, and Baker in the United States, concluded that, - "The results open up the prospect of an interesting discussion, but it also shows the danger of arguing from a simple physiological observation to a complex phenomenon like the growth of a plant in soil."

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