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PLANT-GROWTH
REGULATORS
AS SELECTIVE HERBICIDES

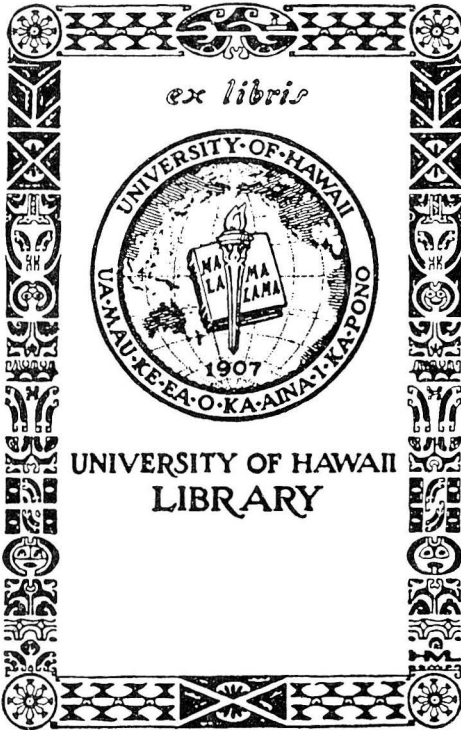
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PREFACE

Weed control has been a major problem in agriculture ever since man learned to distinguish the desirable from the undesirable products of the soil and to cultivate only the former. He soon discovered that for maximum production he had to prevent the undesirable plants (weeds) from competing with the desirable plants (crops) for the plant nutrients in the soil and for sunlight. By eradicating the weeds solely by hand or with the aid of simple implements, he was able to remove the source of competition. Thus was born the first method of weed control.

With the development of improved mechanical means of weed control and the use of chemicals, oils, and flame for eradicating weeds, the laborious job of hand weeding and the cost of weed control were materially reduced. It was later discovered that some of the chemicals and oils were selective in herbicidal activity, e.g., they were injurious to some species of plants only. Many of these chemicals, however, left in the soil deleterious residues which eventually made crop production impossible.

The latest advancement in weed control methods is the use of a group of synthetic organic compounds called plant-growth regulators. These compounds have three decided advantages over the other chemicals used for weed control: (1) they are more selective, (2) they require much lower concentrations for effective weed control, and (3) they do not leave toxic residues in the soil for any extended period.

Since the discovery of the herbicidal properties of plant-growth regulators in 1940, many investigators in England and in the United States have devoted much time and effort in research on this type of herbicide. The findings of these investigators are now appearing in many scientific and popular publications. This accelerated impetus is no doubt the result of the urgent need for increased food production which is seriously handicapped by the high cost and drastic shortage of farm labor.

The purpose of this paper is to present the historical development of the use of plant-growth regulators as selective herbicides. The author has attempted to present and summarize all available published reports known to him on this subject up to the time of the preparation of the manuscript.



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PLANT-GROWTH REGULATORS AS SELECTIVE HERBICIDES

BY ERNEST K. AKAMINE

DISCOVERY OF THE HERBICIDAL PROPERTIES OF PLANT-GROWTH REGULATORS

Although the work of Slade, Templeman, and Sexton of England did not appear until 1945 (132), these investigators claim that in August, 1940, at the Jealott's Hill Research Station, they discovered that *a*-naphthylacetic acid, when applied at the rate of 25 pounds per acre to oats weedy with yellow charlock (*Brassica sinapis visiani*), killed the charlock without injuring the oats to any great extent. This seems to be the first instance in which a plant-growth regulator was used as a selective weed killer (33).

In the United States credit for first suggesting the use of plant-growth regulators as herbicides is given to E. J. Kraus of the University of Chicago, who, it is claimed, suggested the idea as early as August, 1941 (61, 110, 150).

The discovery by Slade, Templeman, and Sexton (132) resulted in their search for plant-growth regulators more active than *a*-naphthylacetic acid. After testing numerous hormonelike compounds, they found that the substituted phenoxyacetic and naphthoxyacetic acids were outstanding from the standpoint of selective herbicidal activity. In November, 1941, these same workers concluded that 2-methyl-4-chlorophenoxyacetic acid (Na salt) was one of the two most active of the compounds tested. In November, 1942, knowledge of selective weed killers was offered to the Agricultural Research Council, and Slade, Templeman, and Sexton cooperated with this organization in the further testing of their findings. Field trials made in 1943 and 1944 confirmed the merits of 2-methyl-4-chlorophenoxyacetic acid as a selective herbicide.

2, 4-Dichlorophenoxyacetic acid (2, 4-D), the other most active compound tested by Slade, Templeman, and Sexton, was used by Nutman, Thornton, and Quastel (111) at the Rothamsted Experiment Station in 1942 in further experiments to test the merits of this compound as an herbicide. In 1943, Blackman (24) at the Imperial College of Science and Technology began experiments to compare 2-methyl-4-chlorophenoxyacetic acid with 2, 4-D and found the former to be more selective and less likely to injure crops than the latter when applied to control broadleaf annual weeds growing with cereals.

The initial findings of the English investigators on selective herbicides have been emphasized strongly and spread widely in subsequent English publications which refer to 2-methyl-4-chlorophenoxyacetic acid as "Methoxone" or "Agroxone" and 2, 4-D as "Chloroxone" (1, 2, 3, 4). Further research on 2-methyl-4-chlorophenoxyacetic acid has since been carried on (25, 156, 157a, 160), and in Great Britain this compound seems to be widely used to control broadleaf weeds in cereals.

In 1942, Zimmerman and Hitchcock (177) published the results of their work with plant-growth regulators, and they are generally given the credit for being the first investigators in the United States to demonstrate the physiological properties (cell elongation, morphogenesis, root development, and parthenocarpy) of substituted phenoxy acids, of which 2, 4-D is one. The work of Beal in 1944 (21) in which he showed abnormal physiological disturbances in all organs of the sweet pea plant resulting from application of 4-chlorophenoxyacetic acid to one portion of the plant suggested the possible use of this compound as an herbicide. In the same year, Mitchell and Hamner (103) as a result of their search for suitable carriers for growth-regulating compounds suggested the possibility of using 2, 4-D and other similar compounds with "Carbowax" (a polyethylene glycol carrier) as selective herbicides, since different species of plants exhibited wide variation in response to these chemicals. First actual experiments designed to test the potentiality of the growth regulators as herbicides were conducted by Hamner and Tukey (61) shortly thereafter in 1944. They successfully used 2, 4-D and 2, 4, 5-trichlorophenoxyacetic acid to kill bindweed (*Convolvulus arvensis* L.). Thereafter numerous investigators started using these and similar compounds to determine their herbicidal effects on other weeds.

SELECTIVITY OF GROWTH REGULATORS WHEN APPLIED AS FOLIAGE TREATMENT

One of the most important properties of herbicides of the hormone type is their selectivity, e.g., their capacity to injure or kill only certain species of plants. Studies indicate that in general, when the aerial portions of the plants are treated with these herbicides, members of the grass family (Gramineae) are relatively little affected, whereas the so-called "broadleaf" plants show varying degrees of susceptibility. However, when these herbicides are applied to the soil, the difference in the degree of susceptibility of the species seems to be minimized, since the emergence of the seeds of most plants is either partially or entirely prevented.

Growth Regulators as Foliage Herbicides in Crops

It has been reported from England that when 2-methyl-4-chlorophenoxyacetic acid is sprayed on fields of cereal crops (oats, wheat, and barley) infested with broadleaf weeds, the crops are not damaged to any great extent, but the weeds are killed readily (1, 2, 3, 4, 24, 25, 132, 160).

From Puerto Rico, van Overbeek *et al.* (164, 165, 165a) report that 2, 4-D can be used to control effectively certain nongraminaceous weeds including nutgrass (*Cyperus rotundus* L.) in fields of sugarcane and coffee without injuring these crops. Alligator weed has been controlled with 2, 4-D in sugarcane fields of Louisiana (26), where this herbicide is also used to control weeds in rice fields (126, 127). For the control of Canada thistle and other perennial weeds in peas, 2, 4-D can be used only as a spot spray, since peas are injured by this herbicide (19). It seems that broadleaf weeds in Irish potato plantings can be controlled by

2, 4-D sprays without producing any serious adverse effects on the growth of the potato plant or on the yield or the quality of the tubers (41, 137). Whereas 2, 4-D has no herbicidal effect on Irish potatoes, related compounds with the 2, 4, 5-trichlorophenoxy- configuration (2, 4, 5-trichlorophenoxyacetic acid, etc.) have decided herbicidal action on this crop. 2, 4-D was found to be ineffective as a weedicide in carrots, since it failed to kill grass weeds and greatly reduced the stand and yield of carrots (112). According to Carlson (30), under certain conditions, 2, 4-D may safely be applied at a concentration of 1,000 p.p.m. to strawberry plantings to eliminate weeds. Because spraying with 2, 4-D causes deformed blossoms and fruits, such spraying should be done after harvest or when no strawberry crop is desired. Control of bindweed in apple orchards was obtained with 2, 4-D sprays, but apples were deformed by such treatment (28). It is believed that these malformations in apples may be caused by the translocation of the 2, 4-D stimulus from the roots to the fruit by the material drifting at the time of spraying, or by the volatile materials in the spray itself. Apparently in crops like cotton and most vegetables, 2, 4-D cannot be used for weed control, since these crops are too sensitive to this herbicide (80, 138, 171). Weaver *et al.* (171) studied the effect of 2, 4-D on vegetable crops at various stages of development. The effects of 2, 4-D on pines and other woody plants have also been studied (38, 76).

Repeated sprayings with 2, 4-D solutions controlled weed growth in Kentucky bluegrass lawns for 2 years (94). Applying dry mixtures of fertilizer and 2, 4-D to turf and lawn seems to be a good way to control weeds and to enrich the soil at the same time (93, 94, 95, 97). The potency of 2, 4-D in such mixtures does not seem to be affected, and the fertilizer, which acts as a carrier, seems to aid in the early recovery of the grass from the temporary growth-retarding effect of the herbicide.

Effect of Foliage Spray on Grasses

Although 2, 4-D has relatively no effect on most of the grasses when applied in herbicidal concentrations, it does have some effect on the growth and reproductive capacity of certain cereals and grasses. Klingman (79) found that if applied at or before jointing or after the heading stages of growth, 2, 4-D may be sprayed to control weeds in wheat and barley without seriously damaging the grain yield. Spraying in the boot stage caused many sterile heads and thus significantly depressed the yield. After spray application of 2, 4-D, timothy immediately became pale yellow and its growth was depressed, but recovery was evident after 44 days (96). Seed stalks and seed heads of the treated timothy plants were normal and the seeds harvested from such plants germinated normally. Seed harvested from 2, 4-D-treated Kentucky bluegrass sod also germinated normally (97). It has been found that the tolerance of bentgrass varies considerably among its various strains (12).

Weeds Sensitive to 2, 4-D

Marth and Mitchell (92) list the following weeds as relatively sensitive to 2, 4-D: dandelion, narrowleaf plantain, Dutch white clover, chickweed,

pigweed, woodsorrel, knotweed, broadleaf dock, bindweed, and shiny pennywort. The growth of dandelion, plantain (72, 78), and bindweed (28, 61) has been effectively controlled by 2, 4-D application. 2, 4-D has been used effectively to kill water-hyacinth, a serious menace to river navigation (69). Thimann (158, 158a) reported that 2, 4-D is an effective herbicide for some woody tropical weeds. Pollen production in ragweed, a curse to hay fever sufferers but a desirable plant for the prevention of soil erosion, can be controlled by proper application of 2, 4-D sprays without killing the plant (51, 52, 53, 133). Weeds are listed according to 2, 4-D susceptibility by Seely and Erickson (129), Lynch (88), and Orchard (114). Tam (149) conducted investigations on the comparative herbicidal value of 2, 4-D and 2, 4, 5-trichlorophenoxyacetic acid on some Hawaiian herbaceous weeds, shrubs, and trees and listed the species according to susceptibility to these compounds.

Inactivation of 2, 4-D on Plants

Weaver (168a) demonstrated that plants which are sensitive to the effects of 2, 4-D could be protected by dusting or by spraying (aqueous suspension) with an activated carbon preparation (Norit A) or with a cation exchanger (Zeo-Karb H) just prior to, or immediately after, dusting or spraying these plants with 2, 4-D preparations. The ion exchange material seemed to be less effective in this respect than the activated carbon; lamp black and bone black were only partially effective.

SELECTIVITY OF GROWTH REGULATORS WHEN APPLIED TO SOIL

Historical

The English workers, Slade *et al.* (132), were probably the first to use growth regulators to prevent the germination of weed seeds. They proved that the sodium salt of 2-methyl-4-chlorophenoxyacetic acid could be used to prevent seed germination of broadleaf weeds as well as to destroy established plants. Later Templeman (156) reported that an application of this compound to the soil at the rate of 2 pounds per acre in fields seeded to spring oats and barley resulted in no injury to these crops and gave a high degree of weed control.

Effect of 2, 4-D on Emergence of Plants

When 2, 4-D is applied to the soil, the emergence both of grasses and of broadleaf species is prevented. Thus Mitchell and Marth (105) found that if 2, 4-D were sprayed on the soil the emergence of redbud, fescue, and bluegrass was suppressed. 2, 4-D application to the soil reduced the stand of lawn grasses (119) and annual grasses (122). 2, 4-D applied to the soil at plowing time gave promise of eradicating quackgrass and other perennial weeds whose roots constitute a menace because of resprouting (121). Broadleaf weeds as well as grass weeds were controlled with the application of 2, 4-D to soil and manure (35, 57). In general, broadleaf species seem

to be more sensitive to 2, 4-D and 2-methyl-4-chlorophenoxyacetic acid than are grass species when planted in soils treated with these compounds (13, 77a, 106).

Pre-emergence¹ Control of Weeds in Crops

Economic crops differ in their degree of sensitivity to 2, 4-D in the soil. The yield of beans was reduced significantly only when 2, 4-D was applied at planting time (171), and the stimulation in the aerial growth of beans by very low concentrations of 2, 4-D salts in the soil was accompanied by chlorosis (32). Although 2, 4-D and 2-methyl-4-chlorophenoxyacetic acid have some use as selective herbicides in Irish potato fields, 2, 4, 5-trichlorophenoxyacetic acid and other compounds with the 2, 4, 5-trichlorophenoxy- configuration have decided herbicidal action on the crop even when applied to the soil (41). Normal plants of beans and corn grew only after the toxicity of the 2, 4-D in the soil had dissipated (67), but Anderson and Wolf (15) effectively controlled weeds with no detrimental effect on corn with an application of 2.7 pounds of 2, 4-D per acre applied 2 days before the corn emerged. Hamner *et al.* (64) also controlled weed growth in corn with soil application of 2, 4-D with little damage to the emergence and growth of the crop. They pointed out that the corn plants in 2, 4-D-treated fields were stimulated to produce an increased number of brace or "prop" roots from the second node above the soil surface thus preventing the lodging of the plants. As a result of an initial suggestion by H. F. Clements in 1946 on the experimental use of 2, 4-D dust as a means of controlling sugarcane weeds (predominantly grasses under Hawaiian conditions), many of the larger sugar plantations are now, at the start of the ratoon crop, using airplanes for dusting 2, 4-D (95 percent) at the rate of from 5 to 10 pounds per acre without any carrier (9, 75, 129a). This treatment effectively controls weed emergence, but it has no effect on the growth of the cane or on the quality and yield of sugar. As a pre-emergence treatment to control weeds in cotton, 2, 4-D is of no value because of the extreme sensitivity of this crop to this herbicide (84). For the control of weeds in gladiolus fields, 2, 4-D seems to have practical value as a pre-emergence herbicide. When applied as a foliage spray, 2, 4-D injures gladiolus plants, but when applied to the soil, it does not interfere with the growth of the plants to any great extent even when the corms are planted immediately prior to the treatment of the soil with the herbicide (82).

SELECTIVITY OF GROWTH REGULATORS IN NUTRIENT CULTURES

Taylor (150, 151, 152, 153) made observations on the growth of plants in nutrient cultures containing growth-regulating compounds. Cereals were more resistant to 2, 4-D than broadleaf crops (150, 151). Ammonium salt of 2-methyl-4-chlorophenoxyacetic acid was slightly less toxic to wheat

¹ As implied in the literature, the term "pre-emergence" as used here in connection with herbicides refers to crops rather than to weeds.

than 2, 4-D (152). With equivalent amounts of the growth regulator, about four to five times as much inhibition of growth resulted in solution cultures as in a light soil mixture (153). Audus and Quastel (15b), using water-culture solutions, found that 2, 4-D inhibited the growth of roots of cress (*Lepidium sativum*).

PERSISTENCE OF 2, 4-D TOXICITY IN SOIL

Period of Toxicity

The persistence of 2, 4-D toxicity in soils has been studied by many investigators and seems to vary considerably. Depending on many inter-related factors, it varies, according to reports, from 10 days to 13 weeks in cropped soils. In uncropped dry soils the toxicity may persist for as long as 18 months (106). Nutman *et al.* (111) were probably the first to report the residual effect of 2, 4-D in soils. They stated that small amounts of 2, 4-D in the soil lost their toxicity in 36 days. They also reported that leaching 2, 4-D-treated soil with great volumes of water did not completely remove this compound from the soil. Furthermore, these workers reported that when equivalent amounts of the growth regulator were applied to soils high and to soils low in organic matter, the growth of clover and wheat in these soils was much less arrested in the former than in the latter soils.

Cereals and grasses germinated and grew normally 54 and 58 days (60), and 5 weeks (105) after the soils had been treated with 2, 4-D. Four weeks after muck soil (high in organic matter content) was treated with 2, 4-D, seeds of bean and pea germinated and grew normally (56, 57). The toxic effect in the soil was assumed to have been dissipated through leaching or changing its form (56). According to van Overbeek (165), 2, 4-D was detectable in Puerto Rican soils for up to 3 weeks after 0.15 percent solution had been applied to the soil at the rate of 300 gallons per acre. It was detectable for up to 5 weeks after a 0.30 percent solution had been applied. The toxic effects of 2, 4-D persisted in the soil for 10 days (35), for 16 days (67), for 19 days (102), and for 7 weeks (155). Pridham (122) reported that in soil treated with 2, 4-D at the rate of 30 pounds or more per acre, a stand of oats was seriously reduced unless at least 6 weeks' time was allowed between spraying and planting. He also reported (121) that 2, 4-D applied in amounts up to 37½ pounds per acre remained sufficiently active to be detected for at least 2 months with red kidney beans but not with Victory oats. 2, 4, 5-trichlorophenoxyacetic acid seems to remain in an active state in the soil for a longer period than 2, 4-D or its various formulations (168a).

Leaching of 2, 4-D

By leaching experiments, DeRose (37) and Hanks (65) studied the persistence of 2, 4-D in soils. Their method consisted of treating soils with 2, 4-D, leaching them, then testing the leachate for the presence of 2, 4-D by applying it to plants or seeds sensitive to 2, 4-D (bio-assay method). DeRose (37) found that under greenhouse conditions

2, 4-D did not remain active in unleached soil for longer than 8 weeks, and in the field, it did not persist in the soil for more than 80 days. He stated that the reduction in herbicidal effectiveness can result from leaching, from hydrolysis or decomposition due to the action of soil micro-organisms, or from inactivation due to adsorption or fixation by soil colloids. Hanks (65) treated several soils representing a wide range in pH and physical properties with lime, 2, 4-D, and calcium salt of 2, 4-D. After treatment these soils were leached, and their leachates were tested for relative toxicities. Leachates from the peat soil were relatively nontoxic at the end of 2 weeks, and the leachates of all soils tested, except those of the naturally alkaline one, were relatively free of the herbicide at the end of 6 weeks. There was no significant difference in toxicity between the leachates from the limed and the unlimed soils; nor was there any significant difference in toxicity between leachates from the soil treated with 2, 4-D and from the soil treated with the calcium salt of 2, 4-D.

Effects of Moisture, Organic Matter, Temperature, and Lime on Retention of Toxicity

From their studies on the relationship between moisture content and the persistence of 2, 4-D in soils, Mitchell and Marth (106) found that the toxic effect of 2, 4-D was reduced more rapidly in moist than in dry soil. In warm, moist soil the toxicity of 2, 4-D lasted for only 2 weeks, while in dry soil it persisted for as long as 18 months. They postulated that since 2, 4-D was inactivated in moist soil in the absence of leaching, the compound might be decomposed or rendered inactive by some soil micro-organisms or the acid might be chemically inactivated by some soil component. These investigators concluded that "it is apparent that the effectiveness of the acid in killing weed seeds and seedlings in soil will depend in part upon the organic and moisture content of the soil, upon the temperature to which it is subjected, and upon the soil flora and fauna present." The findings of DeFrance *et al.* (36), Jorgensen and Hamner (77a), and Brown and Mitchell (27a) also seemed to indicate that increase in moisture content tends to hasten the dissipation of the 2, 4-D effect in the soil. High temperatures were more favorable to the disappearance of 2, 4-D (Na salt) than freezing or subfreezing temperatures, the compound being equally effective as a weed seed killer under all these temperatures (77a). Brown and Mitchell (27a) showed that with soils treated with 2, 4-D and stored, the higher the storage temperature, the greater was the rate of inactivation of the compound. According to Krone and Hamner (82), 2, 4-D had a more lasting effect in mineral soils (sandy and sandy loam) than in muck soil. The relation of moisture content, organic matter content, and lime to the persistence of 2, 4-D toxicity in the soil has been studied by Kries (81), and her work likewise indicates that the residual effect of 2, 4-D persists for a long period in dry soil. By planting indicator crops, she found that the toxicity of the herbicide in the limed soil lasted for a longer period than in the unlimed soil. It may be recalled that according to Hanks (65) the leachates from limed and unlimed soils showed no significant difference in toxicity. In view of the long persistence of 2, 4-D toxicity in limed soil, Kries suggested

caution in the use of this herbicide in calcareous or newly limed soils. By adding large amounts of leaf mold to the limed soil, she was able to cause a striking reduction in the degree and persistence of the 2, 4-D. In contrast to the findings of Kries, Jorgensen and Hamner (77a) found that the difference in soil pH (4.5, 6.0, 7.5) had no effect on the rate of loss of 2, 4-D toxicity.

Effect of Soil Micro-Organisms on 2, 4-D Persistence

The relationship between soil organic matter and soil micro-organisms is well known, but the relationship between the latter and the retention of 2, 4-D toxicity is little known. Since micro-organisms thrive on organic matter and since 2, 4-D is an organic compound, it is assumed that the higher the organic matter content, the greater will be the number of micro-organisms to decompose the 2, 4-D. A light application of manure to soil low in organic matter hastened the inactivation of 2, 4-D, but for some unknown reason a heavy application retarded the inactivation (27a). Autoclaving the soil, which destroyed the soil micro-organisms, reduced the rate of inactivation of the herbicide (27a). It has been demonstrated that some fungi and bacteria grow readily on agar media containing as much as 1,000 p.p.m. 2, 4-D (139). Martin (98) found that "the 2, 4-D was more toxic to soil microbes under acid than under alkaline conditions" and that "at neutral reaction common soil fungi were unaffected by 2, 4-D while in acid medium growth was inhibited by the same concentrations (0.1 and 1.0 percent) of the hormone." Concentrations of 1 to 100 p.p.m. of 2, 4-D in silt loam and 500 p.p.m. in sandy soil "had no significant effect on the total plate counts, actinomyces, fungi, and protozoa" (136). The growth of some 10 micro-organisms was not inhibited by 1,000 p.p.m. 2, 4-D solutions (85). 2, 4-D either reduced or prevented nodulation in legumes (32, 49, 115).

Effect of Method of Application and Culture on 2, 4-D Persistence

2, 4-D mixed into the soil was more rapidly inactivated than that applied on the soil surface (27a). "Spading (plowing) resulted in a great decrease in toxicity in a field soil contaminated with 2, 4-D" (168a).

Inactivation of 2, 4-D

From studies made on the inactivation of 2, 4-D by adsorption phenomena, some light is thrown on the mechanism of the inactivation of 2, 4-D in soils. Lucas and Hamner (86) inactivated 2, 4-D by adsorption on charcoal, and Weaver (167, 168) employed various ion exchangers to inactivate 2, 4-D. When roots of sweetpotato slips were treated with activated carbon prior to planting in 2, 4-D-treated soil, the 2, 4-D injury to sprouts was minimized (15a). The addition of Norit A (activated carbon) to soil previously treated with 2, 4-D decreased the toxic effects of the herbicide; Zeo-Karb H (cation exchanger) was less effective than Norit A in inactivating the 2, 4-D in the soil (168a). These studies may offer an explanation for the different periods of toxicity of 2, 4-D in soils—some

soils may have higher or lower adsorptive and ion-exchange capacity than others. It seems that acid soils may have higher adsorptive capacities for 2, 4-D than basic soils (167, 168).

Summary

From the above studies made on 2, 4-D toxicity in soils, it is seen that its persistence depends on a number of factors present in the soil. These factors include leaching, moisture content, temperature, chemical composition including organic matter content, physical properties, pH, and micro-organisms. If the factor of leaching is eliminated, as is the case in most agricultural practice, it seems that in order to cause the 2, 4-D residue to dissipate rapidly from the soil, such soil must be high in moisture, organic matter content, and temperature. It can be assumed that high organic matter content in soil will be associated with increased population of soil micro-organisms. Reports on the effect of soil pH on the retention of the toxic residue are contradictory. Finally, soils may differ in their physical and chemical capacity as adsorbing agents and as ion exchangers of 2, 4-D, and this difference may modify their capacity to retain 2, 4-D in active form.

METHODS OF APPLYING 2, 4-D

Dusts and Sprays

2, 4-D may be applied as a dust or as a spray. Dusts are usually applied to the soil as a pre-emergence treatment (9, 56, 75, 122) and sprays are used as a foliage herbicide (40, 73, 135, 170) as well as a pre-emergence treatment (56, 105, 121, 122). Modifications of the ordinary spray method are the use of the atomizer (63) and the fog gun (140) for foliage treatment. Another modification of the spray method is the use of aerosol (58, 59, 178), which was originally developed to spray insecticides and which has more recently been used to spray plant-growth regulators to control blossoming and fruiting and to induce parthenocarp in greenhouse-grown tomatoes. This method can probably be developed for the application of 2, 4-D in herbicidal treatments. Dusts may be applied with (91) or without carriers and hygroscopic agents.

Smith (135) made some studies on the quantitative aspects (effects of concentration, volume, and droplet size) of herbicidal sprays, 2, 4-D and concluded that sprays of relatively large droplet size were more effective than sprays of smaller droplet size. Solutions of 2, 4-D were found to be more effective than dust in treating soils for the pre-emergence control of weeds (56).

Carriers and Solvents

2, 4-D is only slightly soluble in water; it is insoluble in inexpensive mineral oils such as kerosene and fuel oil (42). Because the various salts of 2, 4-D are soluble in water, their use has been recommended in some cases in place of the acid (40). Laboratory studies have indicated that the addition of glycerin to various water-soluble herbicidal sprays, including

sodium trichlorophenoxyacetate and sodium pentachlorophenoxyacetate, improves the effectiveness of such sprays (73). In an aqueous spray the potency of the 2, 4-D can be enhanced by the addition of polyethylene glycols ("Carbowaxes"), which disperse the acid more evenly in the water (40, 103, 124a, 158a).

Oil is a better carrier of 2, 4-D preparations than water under certain conditions, as in rainy areas where the oil is less likely than water to be washed off the plant (170). Of some 50 organic solvents tested by Ennis *et al.* (42), only tributyl phosphate proved satisfactory as a solvent for preparing oil-miscible solutions of 2, 4-D. 2, 4-D readily dissolves in this compound, which in turn readily dissolves in mineral oils. Tributyl phosphate causes local burning of plant tissues at points of direct contact; such an effect may be desirable for herbicidal purposes. This solvent is also capable of dissolving large amounts of 2, 4, 5-trichlorophenoxyacetic acid, parachlorophenoxyacetic acid, 2-methyl-4-chlorophenoxyacetic acid, and other substituted phenoxyacetic acids.

Commercial Preparations

Commercial preparations of 2, 4-D consist of acid dust, acid in liquid carrier, acid plus sodium carbonate or sodium bicarbonate, salts and amine of 2, 4-D, and esters of 2, 4-D (66). The liquid preparations may contain solvents, emulsifying agents, stickers, and spreaders.

Cleaning Equipment

It is very difficult to remove the toxic residue of 2, 4-D in spray equipment. Therefore, if possible, one should not use the same sprayer for fungicides or insecticides, since very small amounts of the toxic residue in the equipment may be sufficient to injure sensitive plants (77). However, if the same equipment is to be used for other sprays, it must be thoroughly washed with soap and water (for aqueous preparations) or with some solvent (for oil preparations) before it is used again (66, 77, 172).

MORPHOLOGICAL AND HISTOLOGICAL RESPONSES

Since the appearance of the work of Zimmerman and Hitchcock (177), which demonstrated the physiological activities of the substituted phenoxy acids, these investigators (147, 148, 175, 176, 179) and others have studied the morphological and histological effects of these compounds on various plants (20, 21, 22, 23, 29, 48, 109, 120, 144, 150, 159, 162). Morphological response of 2, 4-D treatment on a fern was studied by Strickler (141).

Zimmerman and his coworkers (176, 177, 179) stated that the activities of phenoxy compounds on plants cannot safely be predicted from the appearance of the structural formulae of these compounds. They concluded that "it is necessary to make a biological assay to determine whether or not a substance is active" (179). Later, however, it was discovered that only those members (acids or amides) which possess an even number of carbon atoms in the aliphatic acid portions of *w*-(2, 4-dichlorophenoxy) aliphatic acid molecules are active as growth regulators (2, 4-D, 2, 4-di-

chlorophenoxybutyric acid, etc.) (148). The findings of this investigation also suggested a possible mechanism by which the members of the series higher than 2, 4-D might be made active by oxidation to the acetic acid homolog.

The term "telemorphic" response was used by Beal (20, 21) to mean morphological response induced or incited in a plant even at a point considerably distant from the point of application of a substance. He observed the telemorphic effects of the application of substituted phenoxy compounds on sweet pea, marigold, and bean plants. These effects were manifested by abnormal growth responses of the different organs of the plant treated with growth regulators.

Histological reactions of normal (22) and decapitated (23) bean plants to certain of the substituted phenoxy compounds were studied by Beal. Tukey *et al.* (162), in their investigation on the morphological and histological changes due to 2, 4-D treatment in bindweed and sowthistle, proposed four possible mechanisms contributing to the herbicidal action of 2, 4-D: (1) chlorophyll depletion reducing food synthesis in leaves, (2) translocation of food interfered with by phloem proliferation, (3) food reserves depleted by increased respiratory activity, and (4) invasion of soil organisms due to disorganization and rupture of rhizome and root cortex. Swanson (144) states that meristematic tissues and those capable of reverting to the meristematic state are most readily affected by 2, 4-D and that the effect of this compound is systemic in nature. Morphological changes induced by 2, 4-D in plants grown in nutrient cultures were studied by Taylor (150). Murray and Whiting (109), in their study of the comparative effectiveness of 2, 4-D and its salts in inducing histological responses in decapitated bean plants, concluded that "despite certain variations in the reactions of bean plants to 2, 4-D and its salts, the responses resulting from any one treatment appeared to fall within the range of effects distinctive for 2, 4-D." The growth-regulating properties of numerous chemicals have been studied by Thompson *et al.* (159) and by Fults and Payne (48), using biological assay methods. Seedlings of beans from parent plants sprayed with 2, 4-D during ripening of pods developed 2, 4-D symptoms (viruslike crisp foliage, dwarfing of growth, and serration and fusion of leaflets) in juvenile and mature leaves (120). Studies on the formative effects of certain substituted chlorophenoxy compounds on bean leaves were conducted by Burton (29).

DETERMINATION OF GROWTH REGULATORS

Bio-assay Methods

Bio-assay methods of determining growth regulators are used rather than chemical analyses for these compounds in plants, because, with the exception of auxin a, auxin b, indole acetic acid, and indole acetaldehyde (identified but not isolated), the synthetic growth regulators have not been identified in, nor isolated from, plants. English scientists (111) were probably the first to employ the root-length of plants as a measure of the toxic effects

of growth regulators. This method was one of the three tests used by Thompson *et al.* (159) to test the growth-inhibiting activities of some organic compounds. Swanson's bio-assay method (143) of 2, 4-D determination in aqueous solutions consists of determining the effect of 2, 4-D on the elongation of primary seedling roots of corn. A modification of this method was used by Hanks (65) to test leachates for the presence of 2, 4-D toxicity. Another bio-assay method (124), which is considered to be an improvement over Swanson's method, involves the use of cucumber seeds instead of corn; the elongation of both primary shoot and primary root is taken as the criterion of 2, 4-D injury instead of the root elongation only. Audus and Quastel (15b) used root-length as the measure of the effect of the interaction between growth regulators and other chemicals.

Herbicidal properties of growth regulators are also studied by direct application to the aerial portion of the plant; the resulting stem curvature, epinasty, and formative effects (leaves) are then observed. The herbicide in either an oil or an aqueous medium may be sprayed on the foliage or a drop of it may be placed on a leaf (145, 159, 174). The toxicity of leachates of soils treated with 2, 4-D was determined by this method (37).

The emergence and growth of certain test plants (usually some very sensitive species) have been used as criteria of the degree and persistence of toxic residues of 2, 4-D and other similar herbicides in soils previously given pre-emergence treatments (35, 36, 37, 56, 57, 60, 67, 81, 82, 102, 105, 106, 111, 121, 122, 155, 165).

Felber (43) described a more direct method of introducing chemicals into plants. This "thread method" consists essentially of inserting into any part of the plant with a needle a piece of thread saturated with the chemical solution. The thread may be used as a wick if a continuous supply of the solution is to be introduced into the plant. It is suggested that this method may be a good way of introducing growth regulators directly into the plant. Later Felber and Lucas (44) used this method on bean plants in their investigation on the evaluation of growth responses resulting from 2, 4-D treatment and concluded that this method gave better results with regard to uniformity and specificity of growth responses than did surface application of the compound by means of a drop.

Offord (113) used the aquatic plant *Lemna minor* L. as a test plant for determining the phytocidal action of organic compounds including 2, 4-D.

A biometric evaluation of the herbicidal properties of some organic compounds was made with a modification of Went's split-pea test, using the reaction of 2, 4-D as the standard, followed by a study of herbicidal action on the castor-bean plant (48).

Use of Radioactive Compounds

Wood *et al.* (174) used a radioactive plant-growth regulator to trace its movement in the plant. (Discussed later under "Absorption and Translocation of Growth Substances.")

Chemical Methods

2, 4-D in soil leachates was identified by determining the melting point of the crystallized product of the leachate (37). Analytical methods for the determination of 2, 4-D and its compounds in commercial herbicides are described by Rooney (125). Bandurski (18) describes the spectrophotometric method for the determination of 2, 4-D in aqueous and ether solutions. Freed (46) developed a qualitative color test which is said to be applicable for 2, 4-D identification even when it is extracted from plant material.

SYNTHESIS AND CHEMICAL PROPERTIES OF GROWTH REGULATORS

The synthesis and chemical properties (melting point, molecular weight, dissociation constants, solubility, etc.) of the phenoxy compounds have been reported by various investigators (68, 118, 128, 147, 148, 179).

PHYSIOLOGICAL STUDIES OF HERBICIDES

Effect of 2, 4-D on Growth

Weaver (166) studied the effects of 2, 4-D application on the elongation and weight changes in parts of bean and soybean plants. Weight changes in bean plants due to 2, 4-D application were also studied by Felber and Lucas (44). Carlyle and Thorpe (32) reported that the aerial growth of beans was stimulated by very low concentrations of salts of 2, 4-D, but that this stimulation was accompanied by chlorosis. It has also been reported that seedlings in some instances grew more vigorously in soil treated with 2, 4-D than in untreated soil (81). According to Mitchell and Marth (105) the foliage of grass seedlings growing in soil treated with 2, 4-D turned green although their growth was inhibited. Stromme and Hamner (142) reported delayed maturity of bean plants sprayed with 2, 4-D solutions of unherbicidal concentrations.

Effect of Temperature on Herbicidal Activity

Marth and Davis (90) found that plants are killed more readily by 2, 4-D under temperature conditions favorable for growth than under temperature conditions unfavorable for growth. Applications of 2, 4-D as a foliage spray resulted in better kill of several shrubs, vines, and trees at time of leaf emergence during a warm period (80°-85° F.) in early April than during a cool period (below 50° F.) in late April (62). Klingman (78) obtained better kill of dandelion with July and August 2, 4-D applications than with June applications. Hitchcock and Zimmerman (72) found that 2, 4-D treatments applied in July were as effective or more so for killing dandelions and also for minimizing recovery, as were sprays applied in May, June, or September. This discovery, according to these investigators, is not in agreement with the prevalent concept that dandelions are more effectively eradicated in spring and fall than in midsummer. These conflicting results

may have been caused by different climatic conditions under which the various investigations were conducted.

Effects of Plant Extracts, pH, and Addition of Other Herbicides on Herbicidal Activity of 2, 4-D

The addition of onion extracts to 2, 4-D solution (sodium salt) enhanced the activity of the herbicide according to studies made by Lucas and Hamner (87). These studies also indicated that water extracts of garlic (closely related botanically and chemically to onion) were less effective than onion extracts in increasing the activity of 2, 4-D, that tomato extracts had no effect, and that red beet extracts actually inactivated it. Since the addition of 2, 4-D to onion extract and vice versa changes the pH of the resulting mixture very little, change of pH is not believed to be the cause of activation of 2, 4-D by onion extracts.

The herbicidal action of the sodium salt of 2, 4-D was greatly increased by applying it in an acid solution (55, 87). It seems that in alkaline solutions, the herbicidal effect of 2, 4-D partly disappears. "The titratable acid (within its non-injurious range) rather than the pH value of a solution accounts for the increased effect of the herbicide" (55).

The addition of 2, 4-D to a mixture of nonhormonal herbicides enhanced the herbicidal action of the latter or the latter enhanced the activity of the former (34, 89).

Effect of Light on Herbicidal Activity

Mitchell and Brown (101) and Weaver and DeRose (169) found that bean plants responded more to 2, 4-D in the light than in the dark or shade, but later Penfound and Minyard (117) found that the effect of 2, 4-D on bean plants was the same whether they were placed in the dark, in diffused light, or in direct sunlight. Difference in the 2, 4-D carriers used was suggested as the source of the discrepancy in these investigations—kerosene was the carrier used by Penfound and Minyard and water was used by the other workers. 2, 4-D-treated water-hyacinth plants produced greater epinasty and necrosis when placed in the shade than when placed in the full sunlight (117). Woody tropical plants in partial shade were slightly less affected by 2, 4-D than those in the full sunlight (158a).

Payne and Fults (116) activated 2, 4-D, the sodium salt and butyl ester of 2, 4-D, and 2-methyl-4-chlorophenoxyacetic acid with ultraviolet light in the laboratory. In view of their findings and because ultraviolet light quality and intensity vary with changes in atmospheric conditions, altitude, and season of year, these investigators suggested that comparative tests of the herbicidal effects of these activated and nonactivated chemicals be conducted to unearth a possible explanation of the variable results secured from uniform trials with 2, 4-D and other similar compounds at different places and times.

Absorption and Translocation of Growth Substances

Beal (20) stated that it is not known how or in what form the growth regulators that he used (substituted phenoxy compounds) entered the plant,

but Wood *et al.* (174) stated that the growth regulator that they used (radioactive 2-iodo-3-nitrobenzoic acid) appeared to enter the plant in molecular form and to be translocated as such. 2, 4-D and other growth substances were used by Ferri (45) to cause rooting of plants in such a way as to support the view of upward translocation of solutes in the xylem. In one of his experiments, Ferri removed the wood from the butts of *Hibiscus* cuttings leaving the bark intact, and dipped the butts in solutions containing growth regulators. The cuttings were then placed in a rooting medium and were found not to root easily. However, when the bark was removed and the wood was left intact before treating the cuttings with the growth regulators, the cuttings rooted readily. Weaver and DeRose (169) demonstrated that 2, 4-D passed upward but not downward through dead segments of stems. They also showed—as did Thimann (158a)—that the stomata did not appear to be important portals of entry of the compound and that when applied to the aerial portions of plants, the compound moved downward whenever translocation of synthesized materials occurred. Mitchell and Brown (101) also found that when 2, 4-D was applied to the leaves of bean plants, “the translocation of the resulting stimulus was closely associated with the translocation of organic food materials.” They concluded that the “movement of the acid stimulus from leaves of bean plants apparently occurred as a continual flow under conditions favorable for carbohydrate translocation, and was confined to living cells, probably those of the phloem or parenchyma.” They further stated that “when the acid was applied to the root system, however, the resulting stimulus was translocated through non-living cells of the stem, which indicates that it probably traveled in the transpiration stream of the xylem.”

Wood *et al.* (174) in their studies on the relative effects of a radioactive plant-growth regulator (2-iodo-3-nitrobenzoic acid) on bean and barley plants, concluded that since this compound seems to be absorbed by both of these plants, “it must be inferred that the growth-inhibiting effects of INBA (2-iodo-3-nitrobenzoic acid) in the bean plant and its failure to produce significant inhibition in the barley plant must be due to differences either in INBA concentrations in the two plant types or in the manner in which INBA reacts with the plant constituents in each case.” With the same amount of the chemical applied to the leaves, the bean plant analyzed more than double the amount of the chemical found in the barley plant. Later, however, these investigators (108), working with the same growth regulator on bean and oat plants, concluded that “the difference in the sensitivity of bean and oat plants to INBA cannot be accounted for on the basis of differences in the ability of the plants to absorb and translocate the compound or on the basis of a difference in the extent to which INBA accumulates in the rapidly growing parts of the plants, since with equal concentrations in the young leaves of each type of plant the growth of bean was greatly reduced but that of oat was not affected.”

Rice (124a) found that the addition of 0.5 percent Carbowax 1500 to an aqueous solution of ammonium salt of 2, 4-D resulted in an increased absorption of the herbicide by the leaves of bean plants; the carrier employed retained the moisture in the solution longer than did the wholly aqueous

solution and thus facilitated the entry of the chemical into the plant. The amount of the salt absorbed was positively correlated with temperature, but the effects of temperature on the translocation rate of the salt from the leaf were inconclusive. At the same air temperature, the amount of the salt absorbed was greater in the dark than in the light. The rate of translocation of the salt, however, was positively correlated with light intensity.

Effect of Herbicides on Chemical Composition

The effect of 2, 4-D on the chemical composition of plants has been studied by several investigators. The depletion of food reserves of the treated plants has been observed in these studies (100, 123, 134) with most of the loss being accounted for by increased respiration (27, 123, 134). Mitchell and Brown (100) showed that the readily available carbohydrates (sugars, starch, and dextrin) were depleted within 3 weeks after annual morning-glory plants were treated with 2, 4-D in herbicidal concentrations. Smith *et al.* (134) and Rasmussen (123), however, did not attribute the herbicidal effects of 2, 4-D wholly to the depletion of food reserves. The former stated that the herbicidal effects of this compound on bindweed tissues are largely the result of other physiological disturbances, and the latter postulated that the herbicidal effects of this chemical on dandelion are "symptoms of direct, specific, protoplasmic toxicity rather than causes of injury."

Skoog (131) suggested the possibility that the release of the native-bound auxins in 2, 4-D-treated plants may result in a preponderance of free auxins which cause the physiological and morphological disturbances. Van Overbeek (163) suggested a possible biochemical explanation of the herbicidal action of 2, 4-D. He stated that 2, 4-D, after combining with suitable proteins, may stimulate the liberation of inorganic phosphate from phosphorylated compounds with a resulting release of energy greater in quantity than that produced by natural auxins (combined with proteins). These auxins are constantly being inactivated in the organism, whereas synthetic hormones are not. This exaggerated energy release may hamper the oxidative processes of synthesis which cannot compete with the available hydrogen acceptors and are, therefore, inhibited. This theory may possibly explain why the toxic action of 2, 4-D is slow and why this compound increases respiration, starch hydrolysis, and depletion of food reserves, while at the same time, the growth process is inhibited.

Bean plants treated with herbicidal concentrations of 2, 4-D had higher moisture percentage, lower solid matter content, and higher respiration rate than untreated plants (27). As a result of his studies on the effect of 2, 4-D on the respiratory metabolism of bean stem tissues, Smith (132a) concluded that "while these experiments have shown certain characteristic respiratory differences between bean stem tissues with and without 2, 4-D stimulation under specific conditions, adequate proof that 2, 4-D does act on respiratory mechanisms is still lacking." Applications of sodium 2, 4-dichlorophenoxyacetate to potato plants caused no reduction in the sugar content of tubers, and the petioles of treated plants contained higher amounts of nitrate nitrogen and potassium than the petioles of the untreated plants

(137). 2, 4-D caused reduction in rates of CO₂ evolution and O₂ uptake by wheat and mustard seedlings at all ages tested (154).

Hildebrandt and Riker (71) in their studies on the influence of growth regulators including substituted phenoxy compounds on cultured tissues of sunflower and tobacco observed that the general effect of these compounds was increased wet weight at certain low concentrations and decreased wet weight at higher concentrations.

In reference to differential herbicidal properties of 2, 4-D, Gilbert (50) stated that the "broadleaved plants are stimulated to proliferate themselves to death." Also (123), "The resistance of the grasses and of some other plants to these differential sprays suggests that the toxicity of these substances may be directed toward certain cytoplasmic compounds, probably proteins, which vary between families and to a lesser extent between genera and species."

Effect of 2, 4-D on Seed Germination

From their studies on the effect of 2, 4-D on seed germination, Hsueh and Lou (74) found that 2, 4-D at low concentrations (0.01 percent) promoted germination, but that at high concentrations (0.1 percent), it inhibited aerobic respiration and checked germination of barley seed. Germination of rice seed, on the other hand, was not hindered by the inhibition of aerobic respiration caused by the high concentrations of 2, 4-D. It was concluded that the rice seed relies on fermentation as in anaerobic condition for energy, since the mode of germination of rice under anaerobic condition and in 2, 4-D is very similar. Mitchell and Brown (102) found clover and mustard seeds to be relatively resistant to 2, 4-D while in the dormant stage, but extremely sensitive to the acid in the germinating stage. Seeds harvested from weedy plants (*Brassica campestris* and *Barbarea vulgaris*) which had been previously sprayed with 2, 4-D at late flower or early pod stage germinated, but produced only a few healthy plants (138a).

EFFECT OF 2, 4-D ON ANIMALS AND MAN

Since weed control is important to the welfare of both man and domestic animals, it is well to determine the effect of the hormone herbicides on these two groups. Mitchell *et al.* (104) grazed cows and sheep in pastures treated with liberal applications of 2, 4-D and fed the chemical in rations without producing any detrimental effects on the health and performance of the animals. According to these investigators, E. J. Kraus is supposed to have reported that a human adult male had taken daily by mouth 500 mg. of pure 2, 4-D during a period of 21 days without experiencing any ill effects. Other investigators have also stated that 2, 4-D, when administered through the mouth, is relatively nontoxic to small experimental mammals (104a) and man (70). When injected subcutaneously, however, the lethal dosage of 2, 4-D was approximately 280 mg. per kg. of body weight for mice (28a).

ISOPROPYLPHENYLCARBAMATE

Historical

Isopropylphenylcarbamate (IPC) is another selective herbicide of the hormone type which is used only to a limited extent. Its effect is just the opposite of the effects of 2, 4-D—the grasses are sensitive to it but the broadleaf plants are relatively insensitive. The first-known reference to experimentation upon plants with the compounds of the urethane series (of which IPC is a member) is that of Friesen (47), who reported retardation in germination and abnormal growth of oat and wheat seedlings following treatment with dilute solutions of phenylurethane. In later years other investigators reported the effects of various urethanes upon plants (54, 83, 130, 146).

Templeman and Sexton (157) of England were the first to apply IPC to plants. In 1940 these researchers discovered at the Jealott's Hill Research Station that ethylphenylcarbamate killed oats but did not affect charlock (broadleaf weed)—low concentrations eventually killed oat seedlings and high concentrations prevented germination when applied to the soil at planting time. This discovery resulted in the testing of 50 related arylcarbamic esters and thiocarbamates. Of these, IPC was found to be the most active (three times more active than ethylphenylcarbamate).

Soil Applications of IPC and Its Persistence

IPC when applied to the soil in aqueous solutions severely stunted or killed seedling oats, wheat, corn, barley, and nonflooded rice, but it had no effect on soybean, kidney bean, cowpea, sunflower, radish, turnip, and sugar beet crops (14). When applied at rates which had no effect upon broadleaf species (buckwheat, a dicotyledonous species, responded like a cereal), IPC prevented the establishment of cereals; mixtures of IPC and chlorophenoxyacetic acids inhibited the development of seedlings of both cereal and broadleaf species, but no complementary action of the two types of compounds was evidenced (13). Mitchell and Marth (107) found that the sensitivity of grass seeds to IPC varies with different species. Seeds of Bermuda grass, Amber sorghum, Sudan grass, and millet were found to be relatively resistant to IPC when planted in soil treated with this chemical; but seeds of bluegrass, barley, fescue, ryegrass, redtop, timothy, orchard grass, and quackgrass were found to be very sensitive to this herbicide. Wolcott and Carlson (173), in a preliminary report, showed some promise of the control of quackgrass in an established sod by the application of this compound in the field.

The toxic effect of IPC persisted in cropped soils for 5 weeks (155), 30 to 60 days (173), and about 2 months (37, 107); it persisted for 12 days in soil stored moist (168a). This persistence of IPC is said to depend on the rate of application and the degree of aeration in the soil (173), and this compound is believed to be rendered inactive in the soil through the action of soil micro-organisms (107).

Foliage Application

Spraying IPC on aerial plant portions of oats and barley was found to be ineffective in reducing the yield of grains, but applying the compound to

the soil did reduce the yield (39). A concentration of 1,000 p.p.m. (normal herbicidal strength) of IPC sprayed on the leaves of growing plants of quackgrass failed to do much damage, but when the rhizomes of this grass were treated with concentrations above 500 p.p.m., new shoots failed to regenerate (31).

IPC in Solution Cultures

Taylor (152) grew plants in solution cultures containing plant-growth regulators and concluded that there were no marked differences in the toxicity of IPC and 2, 4-D to the growth of young cereals.

Solvents for IPC

IPC has low solubility in water and is insoluble in oil. It may be dissolved in twice its weight of tributyl phosphate, and the resulting solution is oil-miscible in all proportions (14). Acetone with water seems to be a better cosolvent than tributyl phosphate with #2 fuel oil, and isopropyl alcohol-water solutions can be used as a cosolvent also (39).

OTHER HISTORICAL REVIEWS OF WEED CONTROL

Up-to-date developments on weed control, including the use of plant-growth regulators, are given in various reports of weed control organizations (6, 7, 10, 17, 99). Reports of various experiment stations are also sources of latest information on the use of 2, 4-D and other chemicals as herbicides (8, 161).

The history of the use of chemicals including plant-growth regulators, oils, flame, and mechanical means for controlling and eradicating weeds is given in chronological order by Hildebrand (70). Gilbert (50), Avery and Thomson (16), Avery *et al.* (15c), and Mitchell and Marth (107a) have reviewed the uses of plant-growth regulators including use as herbicides. A summary of the investigations on hormone herbicides conducted by the armed forces of the United States during World War II has been published (5). Types of herbicides, including plant-growth regulators, have been listed and described (11). The use of synthetic hormones as weed killers in Puerto Rico has been reviewed by van Overbeek (163).

POPULAR PUBLICATIONS ON HORMONE TYPE HERBICIDES

Popular publications dealing with hormone weed killers have been produced by university experiment stations, university extension services, and state departments of agriculture (180). Articles dealing with these herbicides have also appeared in various popular magazines (181). Abstracts of scientific papers on herbicides of hormonal type and other information on herbicides have appeared in semipopular style of writing (182). Commercial dealers in these herbicides have published articles of practical interest in their own publications (183).

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