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STUDIES ON THE USE OF ARSENICALS FOR CRABGRASS CONTROL IN TURF

R. J. Stadtherr, 1963

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STADTHERR, Richard James, n.d.
STUDIES ON THE USE OF ARSENICALS FOR CRABGRASS CONTROL IN TURF.

University of Minnesota, Ph.D., 1963
Agriculture, plant culture

University Microfilms, Inc., Ann Arbor, Michigan

21541851

STUDIES ON THE USE OF ARSENICALS FOR CRABGRASS CONTROL IN TURF

A Thesis

Submitted to the Faculty of the Graduate School

of the University of Minnesota

By

Richard James Stadtherr

In Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy

1963

ACKNOWLEDGMENTS

The author wishes to express sincere appreciation to his advisor, Dr. R. E. Nylund, Professor of Horticultural Science, for his advice during this study and in the preparation of the thesis.

Grateful acknowledgments are extended to Dr. D. B. White, Department of Horticultural Science and Drs. A. J. Linck and T. W. Sudia, Department of Plant Pathology and Physiology, members of the reading committee who offered helpful suggestions to improve this manuscript.

Financial assistance provided by the Golf Course Superintendents' Association of America and the PAX Company were greatly appreciated and helpful in finishing the experiments.

Finally, to the many true friends and close relatives whose assistance and encouragement made completion of this study a reality, I offer a hearty and sincere thank you.

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INTRODUCTION

Extensive investigations have been conducted on the use of lead and calcium arsenate to control crabgrass in bluegrass lawns. In the late fifties, PAX, a commercial crabgrass herbicide composed of various arsenicals, became popular. With the exception of experiments to compare it with other crabgrass herbicides, few basic investigations on the use of this pre-emergent crabgrass herbicide have been reported.

The present study was undertaken to determine the effectiveness of PAX in crabgrass control, its residual action, the tolerance levels of various seeded and established basic turf grasses and crabgrass to PAX, the influence of soil type on activity of PAX, its leachability in soil, and its site of action in crabgrass control.

LITERATURE REVIEW

Two species of crabgrass (Digitaria) are important lawn weeds. Common or hairy crabgrass [Digitaria sanguinalis (L.) Scop.] is the species most prevalent in Minnesota. Smooth crabgrass [Digitaria ischaemum (Schreb.) Muhl.] is also found but in relatively fewer numbers.

Common crabgrass has a semi-prostrate habit with decumbent culms which develop adventitious roots at nodes touching the ground. Tops develop from these rooted nodes giving rise to a complete new plant. Because of its aggressiveness, crabgrass can dominate weakened or poor Kentucky bluegrass (Poa pratensis L.) sod in a short time.

Abundant seed production aids crabgrass in crowding out turf grasses. Single crabgrass plants have produced up to 200,000 seeds. Toole and Toole (58) found that freshly harvested seed germinated poorly even under optimum environmental conditions. Year-old seed stored dry germinated promptly and completed germination within two weeks in a proper environment. Germination percentages ranged from 96 to 99%.

Early attempts to control crabgrass in lawns by chemical treatments utilized iron or ammonium sulfate or combinations of the two. Sprays of these sulfates killed tender crabgrass seedlings upon contact. Leach and Lipp (32) in 1927 reported the first crabgrass control by using lead arsenate at 35 lb/1000 sq ft in experiments to control soil-borne insects. Lead arsenate was applied to the soil surface and then incorporated to a depth of four inches. Perennial ryegrass, German mixed bentgrasses, Chewings fescue, and Kentucky bluegrass, seeded into arsenate-treated soils, showed no apparent inhibition to establishment and growth. Creeping bent stolons grew well too. Treated plots were almost free of weeds, whereas untreated control plots were heavily infested with crabgrass, chickweed, and dandelion.

Extensive crabgrass control studies with arsenates were conducted by Welton and Carroll (60, 61, 62) at the Ohio Agricultural Experiment Station from 1930 to 1947. Lead arsenate applied at 35 lb/1000 sq ft on July 25, 1930, gave no crabgrass reduction in that year; but in the succeeding six years, control was 94.6, 98.2, 97.1, 97.6, 95.8, and 97.1%, respectively (62). Investigations involving various rates showed that either 25 lb of lead arsenate or 15 lb of calcium arsenate per 1000 sq ft were the lowest amounts giving satisfactory control when arsenates were uniformly spread over the lawn surface. Application method, whether by mixing with soil, applying dry, or spraying in water, had little effect on subsequent crabgrass control. Turf grasses tolerated higher rates of lead arsenate than calcium arsenate. The persistence of a single lead arsenate application of 35 lb/1000 sq ft made in 1930 for crabgrass was still evident in 1940 (61).

Because of unpredictable and rather variable results with lead arsenate, its poison hazards, difficulty of application, and high cost ($5/1000 sq ft), interest in the late thirties shifted to post-emergence herbicides for crabgrass control. Nylund and Stadtherr (45) reviewed the post-emergence crabgrass control literature up to 1956. After sodium arsenite, phenyl mercuric acetate, and potassium cyanate had gained and declined in favor, methyl arsonates became popular. Since these herbicides required frequent and properly timed applications, poor results often occurred. Instances of moderate to heavy turf damage were common.

In the late fifties, interest was renewed in pre-emergence herbicides. Two non-arsenicals, dacthal (dimethyl 2, 3, 5, 6-tetrachloroterephthalate) and zytron [O-(2, 4-dichlorophenyl)-O-methyl isopropylphosphoramidothioate], were reported by many workers (14, 20, 21, 30, 47, 48, 52) as being very effective in crabgrass control. Calcium and lead arsenate formulations were reported also as being effective (9, 14, 15, 20, 30, 47, 48, 52). Good crabgrass control using PAX (9, 15, 36, 42, 47, 48, 53, 64) has been reported from many different areas of the United States. Only the arsenates exhibited control extending for several seasons from a single application.

A number of research workers (1, 14, 16, 22, 44, 47) have observed poor or variable results with the arsenates. Engel et al. (16) obtained poor crabgrass control with arsenates applied either in fall or spring. Engel and Meggitt (17) had poor results with lead arsenate but good results with calcium arsenate. From an April 8 application of tricalcium arsenate and PAX, Gallagher and Otten (23) in Pennsylvania rated crabgrass control better in June than in September.

Crafts (4) found that soluble arsenic in water cultures was extremely toxic to plants. Fergus (19) observed extensive arsenic damage to root hairs and rootlets in French beans. Liebig et al. (33) considered that lemon cuttings growing in culture solutions were stimulated in growth at 1 ppm arsenic but at 5 ppm arsenite arsenic or 10 ppm arsenate arsenic both root and top growth were reduced. Machlis (34) working with sudangrass and beans noted arsenic was absorbed from a nutrient solution in proportion to its concentration unless the concentration were sufficiently high to kill plants quickly.

Naylor (43) reported growth stimulation in Kentucky bluegrass seedlings from .6 and 1.5 lb/1000 sq ft arsenious acid in sand cultures. Applications were made at seeding time and to 1 1/2 and 3 1/2 month old plants. At the .6 lb rate, which was equivalent to applying 1 lb/1000 sq ft of sodium arsenite, Kentucky bluegrass seed grew a thicker and taller stand in a shorter time than the controls. Harmful effects of arsenic acid increased progressively with higher arsenic rates. Although older plants reacted more slowly to higher arsenic levels, death resulted at 3 and 6 lb/1000 sq ft rates.

Rumburg et al. (50) grew Clinton oats in nutrient cultures in which phosphorus levels were varied but which had 10 ppm arsenic added per culture. With 1 ppm phosphorus, plants were near death within four days. Some plants with 62 ppm phosphorus showed no visible arsenic poisoning symptoms. These plants had accumulated 2 micrograms arsenic in 72 hours after treatments were made. At 10 ppm phosphorus, plants had 6.4 mg arsenic, while in 1 ppm phosphorus, 15 mg arsenic.

Arsenate toxicity and accumulation in plants from nutrient solutions could differ considerably from those in soils. Mc Murtrey and Robinson (35) found no relationship between quantities of total and water-soluble arsenic in the soil. Amounts of water-soluble arsenic in soils, to which arsenates were added, depended upon soil reaction and quantity and nature of the clay or colloidal matter in the soil.

Vandecaveye et al. (59) measured soluble arsenic in Washington orchard soils and found soluble arsenic mainly within the top six inches of the soil. Soluble arsenic decreased in amount with depth. Five years after arsenates had been applied to the soil surface, Welton and Carroll (60) found no soluble arsenic below the four-inch depth. Most of the soluble arsenic was found in the upper two inches of the soil indicating a slow availability of soluble arsenic and great arsenic persistence. Crafts and Rosenfels (6) in leaching studies with columns containing soils of various textures observed that arsenic was retained mainly in the upper two inches in a clay soil while deeper penetration of the arsenic was observed in sandy soil. Depth of penetration depended upon the form and amount of arsenic applied, soil type and soluble salt content of the soil. Biological tests although limited by the sensitivity of the indicator plant gave a direct index to the arsenic availability and to the toxicity or crop-limiting power of arsenic.

Many research workers (3, 6, 23, 35, 49, 54, 55, 56, 62) have reported that soils high in colloids required larger amounts of arsenates to achieve phytotoxic levels than sandy soils. In some Western soils (35) arsenic had not leached below the depth of plowing in 20 years, whereas in a New Jersey podzol soil considerable leaching downward occurred in one year.

Gile (23) using foxtail millet (Setaria italica) demonstrated the effect of soil colloids in reducing arsenical toxicity. As the colloid percentage by weight in a soil increased, the amount of arsenic oxide needed to get a 50% reduction in millet growth increased sharply. In quartz sand having no colloids, 4 lb/acre arsenic oxide resulted in a 50% growth reduction in millet over plants grown in non-treated quartz sand. Adding 20% soil colloids to quartz sand, 192 lb/acre arsenic oxide was required to obtain a 50% reduction in growth. With 60% soil colloids in a quartz sand mixture, 2112 lb/acre arsenic oxide were needed to get a 50% growth reduction.

Greaves (26) analyzed over 50 orchard soils and found no correlation between water-soluble arsenic content and total soluble salts. He found a slight correlation between water-soluble arsenic and sodium carbonate and nitrate levels. High-calcium soils tended to have low levels of soluble arsenic. He theorized that arsenic toxicity depended upon chemical and biological properties of the soil.

Stewart and Smith (55) concluded that arsenic solubility was roughly proportional to the soluble salt content of the soil. Increases in carbonates, bicarbonates, and potassium ions were accompanied by increased soluble arsenic in the soil solution. According to Cooper et al. (3), large quantities of soluble arsenic were required on highly calcareous soil before injury occurred to many different crop plants.

Many research workers (7, 8, 15, 23, 49, 54, 56) have acknowledged the close relationship of phosphates and arsenates in soils. Daniel (10) concluded that since phosphorus and arsenic ions were similar in size, roots would absorb them in proportion to their concentration in the soil solution. Arsenic toxicity was basically phosphorus starvation within the plant. Phosphorus fertilization prevented the anticipated arsenic toxicity following an arsenate application, and crabgrass plants made normal growth. Steckel (54) stated that since arsenates and phosphates were absorbed similarly and behaved alike chemically, high phosphate-fixing soils would also be high arsenate-fixing soils. Larger arsenate levels would be needed to kill crabgrass in soils high in phosphates.

Working with peach trees growing in soils high in arsenic, Thompson and Batjer (57) were unable to alleviate arsenic toxicity symptoms by applications of superphosphate to the soil. However, by adding ferrous sulfate, the toxic effect of arsenic was overcome. Ferrous sulfate was less effective than zinc sulfate in reducing the arsenic content of the leaves. Batjer and Benson (2), working with young peach trees, concluded that applications of iron chelate to soils high in arsenic tended to increase the "shot-hole" and stunted appearance typical of a zinc deficiency. Additions of zinc chelate at 4 to 8 lb/acre overcame the arsenic toxicity.

Gile (23) believed that the effect of the soil colloids in arsenic fixation depended upon the quantity and reactivity of the iron present in the soil. Arsenic fixation wasn't affected by the amount of phosphates which were fixed. Crafts (4) and Crafts and Rosenfels (6) observed that reddish soils high in iron oxides and colloids had immense capacity to render phosphates and arsenates unavailable. Heavy arsenate levels were required to render such soils toxic to plants.

Welton and Carroll (60, 61) and Thompson and Batjer (57) found that higher nitrogen levels tended to overcome the toxic effect of arsenic to some plants. An established lawn treated with arsenate and later fertilized with nitrogen had more growth than the arsenical treatments alone (60). However, growth of bluegrass in the non-treated control after a nitrogen application was more than that on arsenic-treated areas with the same fertilization rate. However, Crafts (4) stated that nitrogen levels at time of application had little effect on arsenic toxicity.

Thomas (56) reviewed the literature and studied the chemistry of arsenic in the soil. He determined factors affecting the solubility, movement, and distribution of arsenic. His conclusions were that arsenic movement in the soil was related to the degree of base saturation and nature of the cations in the soil. Large amounts of arsenic were fixed in soils having a high base saturation. Arsenic penetration increased in the order $H < Ca < Na$. Fixation of arsenic was similar from arsenic acid, calcium arsenate, and lead arsenate. Lead arsenate was less soluble than arsenic acid or calcium arsenate. Residual arsenates existed apparently as iron or aluminum lead arsenate complexes. Breakdown of these residual arsenates into soluble forms depended on the acidity, nature of cations, and amount of soluble salts in the soil. Factors affecting retention and breakdown of arsenates and phosphates indicated similar reactions. Arsenates break down into soluble forms gradually and are available mainly as H_2AsO_4 ions.

Although high arsenic content in soils is considered more or less harmful to plants, reports (33, 43) indicated small amounts stimulated growth. Williams and Whetstone (63) obtained a 64% increase in rye growth on land which had calcium arsenate applications at 750 lb/acre prior to seeding. Montieth and Bengston (38) observed a stimulatory effect in bluegrass growing in soils treated with crude arsenic acid at 24 lb/1000 sq ft. Stewart and Smith (55) reported that many crops appeared to be stimulated by small amounts of arsenic added to the soil. Dry weight measurements of plants grown on the arsenic-treated soils were often less than those of plants on untreated soil. Crops differed in their resistance to arsenic applications. In wheat, they were unable to determine the arsenic absorbed and questioned if arsenic entered the plant roots. Radishes were very tolerant, but at higher levels root growth was greatly restricted.

Decreased yields caused by arsenic in soils have been reported by many research workers (3, 12, 13, 51, 59, 60). Morris (40) observed that green foxtail seed germinated but growth was 15% less than the controls. Roots in the upper three inches of the soil were yellowish to light brown. Yellow foxtail seeds did not germinate as well as green foxtail, and growth was reduced 30%. Barnyard grass germinated well and had 25% less growth. Kentucky bluegrass seed germinated normally, but growth was slow for about four weeks after emergence. Thereafter growth appeared normal. Leach and Lipp (31) reported a delay of three to six days in Kentucky bluegrass seed germination. After six to eight weeks no apparent differences were noted between turf on the arsenate-treated soil and the non-treated soil. Leach and Lipp (32) noted more vigor, greater density, and improved color in many seeded turf grasses types on arsenate-treated plots.

Engel and Meggitt (17) measured weight reductions of bluegrass clippings of 18% from calcium arsenate treatments of 12 lb/1000 sq ft and 25% at 16 lb/1000 sq ft. With lead arsenate at 20 lb/1000 sq ft, growth was as good or better than the controls. Arsenate applications were made March 25. Clippings were taken during October and November. Welton and Carroll (60) reported 26% average reduction of Kentucky bluegrass clippings from fall and winter applications of lead arsenate at 25 lb/1000 sq ft. Nylund (44) reported death to bluegrass wherever overlapping occurred in applying PAX. Accumulations of PAX in depressions in an irregular lawn surface caused dead spots in tests conducted by Mower and Cornman (41).

Daniel (9) rated the following weedy grasses in order of most to least susceptible to arsenic toxicity: crabgrass, yellow and green foxtail, witchgrass, barnyard grass, and annual bluegrass (Poa annua L.). Mature turf of creeping bentgrass and Kentucky bluegrass were listed as very tolerant. He hypothesized that seedings of these grasses would be successful.

Montieth and Bengston (39) made applications of arsenicals in late summer and early fall to lawns which were then fertilized and reseeded. Turf grasses became well established, affording little space for crabgrass to become established in the next year.

According to Juska (29) lead and calcium arsenate did not significantly reduce germination of Merion Kentucky bluegrass, annual bluegrass, or bentgrass, but calcium arsenate reduced stands considerably. Working with slightly acid soils, high in phosphate and potash, Juska (30) reported that treatment with PAX, while not affecting germination of Merion bluegrass and bentgrass, caused seedlings to become chlorotic and to die shortly after emergence. Gallagher and Otten (21) observed that the arsenates, dacthal, and zytron while being effective in crabgrass control had the serious disadvantage of preventing basic turf grass seeds from germinating and becoming established.

Arsenic toxicity symptoms vary among different plants. In apples, Headden (28) observed that high arsenic levels induced early leaf drop particularly of the older leaves and sloughing of the bark near the soil surface. He concluded that arsenic was a systemic poison and is translocated to all plant parts. Miller et al. (37) considered arsenic to be non-systemic since only those parts of orange trees which were sprayed with lead arsenate contained arsenic.

Stewart and Smith (35) believed arsenic poisoning of higher plants resulted in destruction of the chlorophyll followed by death of the affected leaves. Yellowing occurred first in the basal No leaves and progressed upward towards the tip. They concluded that if the main injury were to roots or stems, toxic symptoms should be seen first at the top of the plant or extreme leaf tips.

Working with bananas, Fergus (19) reported that leaves became chlorotic first along the margins. Chlorosis spread inwardly towards the midrib. Veins were dark green thus the leaf had a "striped" appearance. Necrotic areas developed from the leaf margins spreading inwardly until the entire leaf was dead. Gile (23) studying arsenic toxicity in millet, an annual grass, noted that older leaves became yellow and striated before withering and dying. Roberts and Pellett (47) observed that in Kentucky bluegrass arsenic caused wilting of the leaf blades, chlorosis, and tip burning.

Welton and Carroll (62) attributed the toxicity of lead arsenate to the anion. When lead arsenate was applied to crabgrass seedlings, they were not killed if they became established before the arsenate had time to break down in the soil. Seeds treated with lead arsenate at 20 lb/1000 sq ft showed no growth after 72 hours of treatment. They stated, "In order for lead arsenate to control crabgrass, it must lie in contact with the seed for a considerable time during which time it gradually breaks down and the poison penetrates the seed coat and eventually kills the seed."

Crafts and Robbins (5) concluded that arsenical compounds could kill by coming in contact with either foliage or roots. Daniel and Lee (11) stated, "When the soil surface has toxic concentrations of arsenic present, the susceptible crabgrass seedlings stop growing, turn yellow and die soon after young roots absorb the toxic arsenic. Meanwhile, the desired turfgrasses--bluegrass, bentgrass and, to a lesser extent, fescues and ryegrasses--are quite tolerant to arsenic and grow normally." However, in annual bluegrass, Daniel (8) showed that if an inch of topdressing of non-treated soil were placed over an arsenate-treated area, seedlings grew and became established in the topdressing layer. When an inch of arsenic-treated soil was placed over an untreated area, seed germinated but seedlings remained very weak for awhile until plants developed a tap root that grew into non-treated soil. Such plants grew normally and matured. Duich et al. (14) observed that annual bluegrass plants which grew in a calcium arsenate-treated soil were weakened and died during the first moisture stress period when temperatures were high.

Daniel (10) wrote, "Several of the compounds offered for weedy grass control in turf are carrying arsenic. There is one basic point in its successful performance--in some way sufficient arsenic must get into the plant to stop its normal carbohydrate transfer. Studies in plant physiology indicate that the Krebs cycle is affected. Visual observations show that arsenic accumulates, or affects first those cells which are dividing." Loss of chlorophyll and root growth curtailment preceded ultimate death of crabgrass seedlings.

Although many reports of arsenic accumulation in plants have been published (19, 33, 34, 35, 50, 55, 57, 59, 63), no reports were found which gave arsenic contents of crabgrass or Kentucky bluegrass on arsenate-treated soil.

MATERIALS AND METHODS

Eleven experiments were included in this study. Because they varied somewhat in objective and design, each one is more clearly discussed separately. However, certain materials and methods which were common to many of the experiments are given below.

Crabgrass throughout this study refers to Digitaria sanguinalis (L) Scop. It comprised about 90 to 95% of the total crabgrass population in field studies. In experiments in which crabgrass seed was planted, this species was used exclusively. Seeds were collected a year before they were used. They were stored dry at room temperatures before planting. Germination percentages were determined using the blotter technique prior to planting the seeds.

Established lawns or sod were mainly Kentucky bluegrass (Poa pratensis L.). The basic turf grass types included Kentucky bluegrass, creeping red fescue (Festuca rubra L.) and Highland bentgrass (Agrostis tenuis Sibth.). Commercial seed which had been recently tested was used in all seedings.

"Improved PAX with AR-76 and chlordane," a commercial lawn preparation supplying nitrogen and recommended for controlling crabgrass and soil insects, was used throughout this study.* Its composition is:

Standard lead arsenate ($PbHAsO_4$)[1]	8.25%
Arsenous oxide (As_2O_3)[1]	25.11%
Technical chlordane	0.35%
Inert ingredients[2]	66.29%

[1]Total arsenic as metallic was 20.80% (19.02% water soluble).

[2]Included 15% perlite, ammonium sulfate to provide 7% nitrogen and the remainder in fine siliceous rock.

*The term "PAX" is used in this paper when referring to this proprietary herbicide.

The manufacturer's recommendation for turf grass use was 25 lb/1000 sq ft, which gave 5.2 lb of total metallic arsenic and 1.75 lb total nitrogen.

Throughout this study various rates of PAX were used which were multiples of the rate suggested by the manufacturer. The 25 lb/1000 sq ft rate is designated as 1x PAX. The arsenical compounds (As), lead arsenate and arsenous oxide, and ammonium sulfate (N) were supplied at the same levels as found in a PAX rate. The numbers preceding "x" are equivalent to this number times the amount found in the recommended rate of PAX at 25 lb/1000 sq ft. The following rates of the chemicals were used in this study:

(1) PAX

0.03x PAX	rate of	0.8 lb/1000 sq ft
0.06x PAX	" "	1.6 " " "
0.12x PAX	" "	3.2 " " "
0.25x PAX	" "	6.3 " " "
0.5x PAX	" "	12.5 " " "
0.7x PAX	" "	17.5 " " "
1x PAX	" "	25 " " "
2x PAX	" "	50 " " "
4x PAX	" "	100 " " "
8x PAX	" "	200 " " "
16x PAX	" "	400 " " "

(2) Ammonium sulfate (N)

0.7x N	amount in	0.7x PAX rate	(N 1.23 lb)
1x N	" "	1x PAX "	(N 1.75 lb)
2x N	" "	2x PAX "	(N 3.50 lb)
4x N	" "	4x PAX "	(N 7.00 lb)
8x N	" "	8x PAX "	(N 14.00 lb)

(3) Arsenical compounds (As) are lead arsenate and arsenous oxide.

0.03x As	arsenic as in	0.03x PAX	0.06 lb	0.20 lb
0.06x "	" " "	0.06x PAX	0.13 lb	0.39 lb
0.12x "	" " "	0.12x PAX	0.26 lb	0.78 lb
0.25x "	" " "	0.25x PAX	0.52 lb	1.57 lb
0.5x "	" " "	0.5x PAX	1.03 lb	3.14 lb
1x "	" " "	1x PAX	2.06 lb	6.28 lb
2x "	" " "	2x PAX	4.12 lb	12.56 lb
4x "	" " "	4x PAX	8.25 lb	25.11 lb
8x "	" " "	8x PAX	16.50 lb	50.22 lb
16x "	" " "	16x PAX	33.00 lb	100.44 lb

In this study, soil tests as conducted for florists' soils were made by the Soil Testing Laboratory of the University of Minnesota (25, 26). Other technical information about the soils used in this study was obtained from the Department of Soil Science, University of Minnesota, St. Paul 1, Minnesota.

Plant stands were used to measure density or plant populations per unit area as described in the experiments. Dry weights were used as a measure of growth. Dry weight was determined by drying the fresh plant material at 158 F for at least 72 hours and cooling in a desiccator before weighing.

The data were subjected to analyses of variance. Significance of mean differences was determined by Duncan's multiple range tests as described by Federer (18), and tables calculated by Harter (27) were used. Generally randomized block designs were used in this study. Other designs which were used are explained in the results for each experiment.

The eleven experiments which were conducted can be grouped as follows:

(A) Two experiments were conducted to determine the effectiveness of PAX or crabgrass control and its residual properties.

(B) Three experiments were conducted to determine the effects of PAX applications prior to seeding turf grasses and crabgrass.

(C) Two experiments were run to determine the effects of PAX and its components on established turf.

(D) Two experiments were conducted to study the effects of leaching on movement of toxic substances from PAX and the arsenicals.

(E) Two experiments were conducted to determine the site of action of PAX in preventing crabgrass establishment.

EXPERIMENTAL RESULTS

Residual Crabgrass Control

To determine the residual crabgrass control over a four-year period of an application of PAX to an established Kentucky bluegrass lawn. PAX at 25 lb/1000 sq ft was applied April 16, 1958, to 100 sq ft plots replicated three times. The surface soil was a Lester sandy loam to a depth of several inches overlaying a sandy clay subsoil. The surface soil had a pH of 6.2 and tested low in nitrogen, phosphorus, and potassium.

Means of crabgrass counts from three separate 1 ft^2 areas selected at random within each plot were determined for four successive years. Counts were made annually in late September.

Results

The analysis of variance for crabgrass plants found under a PAX treatment compared with the untreated control over a four-year period is shown in Appendix Table A. Although differences between treatments each year were large (see Table 1), these differences were not statistically significant due to the great variability between replicate plots and insufficient replication. The crabgrass stands in each plot are shown in Appendix Table A-1. The large inter-plot variability can be readily seen.

Although the statistical analysis failed to show significant differences between treatments, crabgrass populations were nevertheless considerably lower in the PAX-treated plots in all four years as shown in Table 1. Almost complete control was obtained during the first season, and control was 90% or more in the

Table 1. Mean crabgrass stands and percent control in four consecutive years after a single application of PAX

	Crabgrass plants per square foot		
Year	PAX-treated	Untreated control	Percent control
1958	0.3	26.6	98
1959	0.8	7.4	90
1960	0.6	17.1	96
1961	1.6	21.3	92

succeeding three years. Counts and visual appearance of the treated plots in 1961 indicated increased crabgrass populations.

In the control plots, crabgrass seedlings emerged in large numbers on June 20, 1958, June 5, 1959, June 15, 1960, and June 11, 1961. Germination followed several days of 70 F average temperature when soils were moist. The unusually low crabgrass population in the control plots in 1959 resulted from a severe drought following crabgrass emergence. This drought period was accompanied by 90 F temperatures, cloudless days, and drying winds.

The treated plots were surrounded by an area heavily infested with crabgrass. Possibilities of an annual reinfestation with crabgrass seeds were high. Regular mowing, animal traffic, raking, and rain or irrigating water could move seeds into the treated areas. No sharp increase in crabgrass stands was observed in the treated areas until the fourth year after PAX applications were made. Indirect evidence that a single PAX application gave residual action in crabgrass control for several growing seasons was shown in this experiment.

In the previous experiment, the residual crabgrass control over a four-year period from a single application of PAX was determined under field conditions. A second experiment to determine residual effects of PAX was conducted on established bluegrass sod in greenhouse flats.

Bluegrass sod growing on a Lester sandy loam was lifted in November 1957, and fitted into 2 sq ft greenhouse flats. Tests indicated the soil to be similar to that in the previous experiment except that the nitrogen level and organic matter content were higher.

The flats were kept outdoors in full sun until early December when they were moved to an unheated building. The grass was dormant and the soil remained frozen until the flats were placed in the greenhouse on March 24, 1958.

All flats were raked thoroughly to remove dead grass and seeded with two grams (about 3900 seeds) of crabgrass having 70% germination. Seeds were distributed evenly over the surface of the sod immediately before herbicides were applied on March 25.

The following treatments replicated twelve times were used:

(1) Untreated control

(2) 0.7x PAX

(3) 1x PAX

(4) 1x PAX plus 1 lb N/1000 sq ft from ammonium sulfate

Greenhouse temperatures averaged 75 F during the daytime and 62 F at night. The soil was kept moist and the grass was cut at a 2-inch height while the flats were in the greenhouse.

In early summer, the flats were moved outdoors where they received full sunlight daily until late afternoon when they were shaded for about 3 to 4 hours by large trees. Flats were placed on a 6-inch layer of washed calcareous sand and randomized within each replication. The grass was cut regularly to a 1-inch height which prevented reseeding of any crabgrass within the flats. All crabgrass plants were pulled and counted annually in late September.

In late November or in December, the flats of frozen sod were moved to an unheated warehouse which allowed sunlight to enter. The soil remained frozen during the winter. The flats were moved to their growing season location, as described above, each spring in the next three years and handled as in the first year.

Results

Crabgrass populations varied significantly for treatments, years, and treatment x year interactions (Appendix Table B).

The mean crabgrass counts in the untreated flats over the 4-year period were 229.0, 20.5, 30.8, and 21.4 per square foot, respectively, for 1958 through 1961. To obtain a better measure of differences among the PAX treatments the data were analyzed excluding the untreated controls (Appendix Table C). Treatments, years, and treatment x year variances were again statistically significant. Table 2 gives the crabgrass stands for 4 years after a single application of three different PAX treatments. Significantly more crabgrass grew in the PAX-treated flats at the 0.7x rate than in flats with the 1x rate. Additional nitrogen at this rate did not significantly reduce the crabgrass population. Since crabgrass stands in 1961 were significantly larger than in 1959 and 1960, the effect of the application of PAX was decreasing. Crabgrass stands in 1959 and 1960 were not significantly different but they were significantly less than those in 1958 and 1961.

Significantly larger crabgrass stands in flats treated at the 0.7x rate in 1958 and 1961 contributed towards making the mean of all PAX treatments for these years significantly larger than those of 1959 and 1960. No significant differences occurred among the means for each year from flats treated with the 1x PAX rate with or without additional nitrogen. Residual crabgrass control for four

Table 2. Stands of crabgrass over a four-year period following single applications of three PAX treatments to bluegrass sod in flats. Means are for 1 sq ft areas.

	Means[1] of crabgrass stands in indicated treatments				
Year	Untreated control	0.7x PAX	lx PAX	lx PAX 1 lb N	Year means[2]
1958	229.04	6.00 a	1.00 c	0.09 c	2.36 a
1959	20.54	3.50 b	0.96 c	0.04 c	1.50 b
1960	30.79	4.29 b	0.17 c	0.21 c	1.56 b
1961	21.42	7.21 a	0.25 c	0.71 c	2.72 a
Treatment means	75.47	5.25 a	0.60 b	0.26 b	

[1]In this and succeeding tables means within a particular variable not having a common letter are significantly different at the five percent level.

[2]Means do not include the untreated controls.

years resulted from a single application of PAX in this experiment. Additional nitrogen was not effective in further reducing the crabgrass population.

Preplanting Application of PAX

PAX applications to control crabgrass are often made to lawns having thin or bare spots. An experiment was conducted to determine the effects of preplanting applications of several rates of PAX on the establishment and subsequent growth of seeded turf grass.

A colluvial fine sandy loam was placed in 4-inch clay pots. Rates of 4, 2, 1, .5, .25, .12, .06, and .03 times the recommended rate of PAX were mixed with the weight of a half-inch of screened, air-dried soil. An inch of such PAX-treated soil was placed over untreated soil in each pot. Each treatment was replicated four times.

About 700 viable seeds of Kentucky bluegrass, creeping red fescue, and Highland bentgrass were planted in bands selected at random on the soil surface in each pot. The pots were kept in the greenhouse where daily temperature averaged 72 F. Soil moisture was kept near field capacity throughout the experimental period.

Clippings were taken 6, 10, and 13 weeks after seeding and dried to constant weight. Movement of seeds in watering made separate harvesting of the grass types impossible. Kentucky bluegrass predominated the pots, contributing 90% or more of the total clipping weights. Since no growth occurred in pots treated with PAX at the two highest rates until the twelfth week after planting, these treatments were not included in the analyses.

Results

Dry weights of the clippings taken on the three dates were analyzed for each date and as accumulated weights as shown in Appendix Table D. The means of clipping weights for all treatments are given in Table 3.

Incorporation of PAX into the surface soil at rates of .03x to 1x did not significantly reduce the growth of turf grasses subsequently seeded on such soils. At the 2x and 4x rates bluegrass and bentgrass were delayed in germination for 12 weeks, but seedlings later became established under these treatments.

Few red fescue seeds germinated in all treatments including the controls. No red fescue plants were found in the pots treated with 2x and 4x rates of PAX. Bluegrass and bentgrass grew equally well and predominated the pots. Bentgrass being more dwarf and less vigorous in growth contributed only a small part of the total dry weight of clippings per pot.

Although no significant differences in turf grass growth were apparent in pots treated with PAX at rates of 1x or less, as seen in Table 3, density of stands appeared to be reduced as PAX rates increased. However, these differences were not reflected in clipping weights since growth was more vigorous in pots with fewer plants.

Several investigators (32, 62) have reported the gradual break down of lead arsenate into soluble arsenic which was lethal to susceptible seedlings. Although turf grasses are considered resistant, the large amount of soluble arsenic (19%) in PAX could conceivably be toxic at certain intervals after application. An experiment was

Table 3. Effects of pre-planting treatments with PAX on dry weights of turf grass clipped at three intervals following seeding

Treatments	Dry weight means of clippings (grams) taken at indicated intervals after seeding			Treatment means
	6 wks.	10 wks.	13 wks.	
Controls	1.7	2.7	0.9	1.6
.03x PAX	1.8	2.7	0.7	1.7
.06x PAX	1.8	2.8	1.1	1.9
.12x PAX	1.6	2.6	0.7	1.6
.25x PAX	1.9	2.8	0.8	1.9
.50x PAX	1.6	2.6	0.7	1.7
1.00x PAX	1.2	2.2	0.4	1.5
2.00x PAX	0.0	0.0	0.0	0.0
4.00x PAX	0.0	0.0	0.0	0.0

conducted to determine the interval of time necessary between an application of PAX and successful reseeding of Kentucky bluegrass on three soil types.

The following soils were used to fill 4-inch clay pots for this greenhouse study:

Soil A was a black sandy loam greenhouse mixture composed of four parts composted sod on a Lester soil, three parts muck and two parts coarse washed calcareous sand. The soil mixture had a pH of 6.5 and a medium level of nitrogen. Phosphorus, potassium, and soluble salt content were very low. Organic matter was 9.5%.

Soil B was a tan sandy clay Keewatin till taken from about three feet below the soil surface. The pH was 7.4. Soil tests showed very low levels of nitrogen, phosphorus, potassium, and soluble salts. The calcium content was very high. No organic matter was present.

Soil C was a coarse, washed, buff calcareous sand having a pH of 8.0.

Sixty-four pots of each soil type were prepared. To one half of the pots of each soil type a 1x rate of PAX was applied to the soil surface. At intervals of 0, 2, 6, and 12 weeks following herbicide application, four treated and four untreated pots were planted with Kentucky bluegrass (100 seeds per pot). Similarly crabgrass seeds were planted in four other pairs of treated and untreated pots at the same intervals. Seeds were covered lightly with untreated soil of the same type as in each pot. All pots were watered at regular intervals before and after seeding.

Since this experiment was initiated in January, supplementary light was used to give a total of 16 hours per day. Four 150 watt incandescent bulbs were used which were 4 ft apart and 2 ft above the rim of the pots. Temperature in the greenhouse varied from 65 to 90 F during the day and 60 to 68 F during the night.

Surviving plants were counted 1 month after the last seeding date. Survival percentages were calculated as the ratio of stands on PAX-treated soil to stands on untreated soil in each pair. Paired pots were used because germination percentages in the controls showed large variations in bluegrass establishment. Since no crabgrass plants grew in PAX-treated soils, only the bluegrass data were analyzed statistically.

Results

Variances for Kentucky bluegrass stands were significant for dates, soils, and the date x soil interaction (Appendix Table E). Table 4 shows means for bluegrass stands as influenced by soil type and date of planting after PAX was applied.

The time interval necessary before bluegrass could be safely seeded following the application of PAX was influenced significantly by soil type. In loam soil (soil A), seeding immediately after PAX treatment did not result in reduced stands. In sand (soil C), stands were reduced only when bluegrass was seeded immediately following treatment. In clay soil (soil B), stands were significantly reduced on the first two seeding dates, but normal stands were obtained when seeding was delayed six weeks. In both the sand and clay soils, when bluegrass was seeded too soon after treatment, seedlings appeared but died while still very small.

Table 4. Mean percent stands of Kentucky bluegrass on three soil types seeded on four dates following herbicide application

Seeding dates after PAX treatment (weeks)	Bluegrass stand (%) on indicated soil type[1]			Date means
	A-Loam	B-Clay	C-Sand	
0	70 bc	0 a	1 a	23 a
2	135 c	15 a	69 bc	74 b
6	71 bc	58 bc	157 c	95 b
12	88 bc	112 bc	91 bc	97 b
Soil means	91 b	46 a	79 ab	

[1]Percent stand is the ratio of stand on PAX-treated soil to stand on untreated soil.

The above experiments on the effects of preplanting applications of PAX on the establishment of seeded turf grasses were conducted under greenhouse conditions. An experiment was also conducted to determine the effects of preplanting applications of PAX on turf grass establishment and weed control on a prepared lawn seedbed.

A seedbed on a Lester sandy loam low in nitrogen, phosphorus, and potassium and having a pH of 6.0 was prepared by rototilling and raking. Crabgrass seed was broadcast at the rate of 1 lb/1000 sq ft over the entire area and raked into the soil. The area was subdivided into four replications of 8 x 32 ft. Each of these replicates was then subdivided in one direction into four plots (8 x 8 ft) to which the following herbicide treatments were applied in random order:

(1) Untreated control

(2) 0.7x rate of PAX plus 1 lb N/1000 sq ft

(3) 1x rate of PAX

(4) 1x rate of PAX plus 1 lb N/1000 sq ft

In each replication, four plots each 2 x 32 ft were marked off across the above four herbicide plots and grass seed was planted in these plots at 0-, 2-, 6-, and 12-week intervals (June 19, July 3, July 30, and September 11) after herbicide applications. On each date three types of turf grass seed (bluegrass, creeping red fescue, and bent) were sown in randomized 2 x 2 2/3 ft subplots within each of the 2 x 8 ft date of seeding plots within each herbicide plot. Allowing for border areas, each of these subplots was 3 sq ft (2 x 1 1/2). The experimental design was a split split plot (treatment x seeding date) with seed type subplots within each of these. It was hoped that by the use of this design more precise information on the establishment of each turf grass type would be obtained.

Prior to seeding on each date, the soil in each plot to be seeded was reworked to a depth of one-half inch to provide a loose surface to receive the seeds. About 4000 viable seeds of each grass type were planted in each sub-subplot. Weeds were so large and abundant that they had to be removed before reworking and seeding the plots before the third and fourth seedings.

Overhead irrigation was used when necessary to keep the soil surface moist throughout this experiment. Water was applied at about 1 inch per unit area in numerous light sprinkles each rainless week.

Weeds were cut at the soil surface, counted, and identified on July 29 and September 10 in the year of application.

Results

Treatment variances for crabgrass stands and other weed populations using total counts for the two dates were highly significant (Appendix Table F). All other sources of variation were non-significant with the exception of seedings in the "other weeds" data. This latter variance could be expected to be significant since many weeds were removed by cultivation prior to the second seeding but were not removed in the 0-, 6-, and 12-week plots until time of seeding.

Table 5 shows the stands of crabgrass and other weeds as influenced by the three PAX treatments and the control. PAX

Table 5. Stands of crabgrass and other weeds in a prepared seedbed as influenced by three PAX treatments. Stands were based on total counts from two dates for each plot.

Treatments	Mean plants / sq ft	
	Crabgrass	Other weeds
Untreated control	45.8 b	213.5 b
0.7x PAX + 1 N	4.8 a	35.7 a
1.0x PAX	2.1 a	30.4 a
1.0x PAX + 1 N	4.0 a	31.5 a

treatments reduced the stands of crabgrass and other weeds significantly. No differences were shown among the PAX treatments. The control plots had roughly nine times more crabgrass and six times more other weeds than plots treated with the lower PAX rate.

Other than crabgrass the most prevalent weeds were witchgrass (Panicum capillare L.), tall pigweed (Amaranthus retroflexus L.), purslane (Portulaca oleracea L.), dandelion (Taraxacum officinale Weber), annual dropseed (Sporobolus neglectus Nash), and barnyard grass [Echinochloa crusgalli (L.) Beau]. On the average, PAX treatments reduced the populations of these weeds by 80, 84, 94, 81, 82, and 27%, respectively.

Observations of turf grass establishment made in the fall of the treatment year showed less turf grass growth on plots treated with PAX before seeding than on the control plots. In density of bluegrass stands, no differences were discerned.

Ratings of density of turf grass made in July of the next year showed no significant differences among treatments applied the previous year. All plots had a dense cover of turf grass. Plots which had been seeded to creeping red fescue were covered mainly with bluegrass and bentgrass. Evidently seeds of these grasses had moved into these areas by surface runoff water. Only an occasional crabgrass plant was seen in the treated plots while the controls had many plants. Crabgrass control was almost 99% in the treated plots. Other weeds were scarce in all plots. Regular mowing practices eliminated most of the large broad-leaved annual weeds. The dense cover of turf grass reduced populations of other weed types.

Effects of PAX and N on Established Turf

An experiment was conducted to determine the effectiveness of PAX alone, nitrogen alone, and PAX plus nitrogen in the control of crabgrass in an established bluegrass lawn.

The following treatments were applied on May 12, 1960, to 100 sq ft plots replicated four times:

(1) Untreated control

(2) 0.7x PAX

(3) 1x PAX

(4) 2x PAX

(5) 0.7x N

(6) 1x N

(7) 2x N

(8) 0.7x PAX + 1 lb N/1000 sq ft

(9) 1x PAX + 1 lb N/1000 sq ft

An old established bluegrass lawn on a Lester sandy loam was used. The soil tested low in all nutrients and had a pH of 6.2. This bluegrass lawn had been heavily infested with crabgrass the previous season. Since nitrogen levels were low, color differences and growth responses to nitrogen fertilizers were readily seen.

Crabgrass control ratings were made on September 15 using a scale of 1 to 10 with 1 = no crabgrass, 2 = less than one crabgrass plant per square foot to 10 = crabgrass population equal to or exceeding the control plots.

Results

Visual ratings of crabgrass control varied significantly (Appendix Table G). Table 6 shows the means of ratings for all treatments. Crabgrass control ratings among PAX treatments did not differ significantly. Crabgrass control in the PAX-treated plots was significantly better than in untreated plots or those receiving nitrogen only. One hundred percent crabgrass control was obtained by 1x or higher rates of PAX. PAX at the 2x rate showed considerable initial burning to the turf. The bluegrass recovered but appeared to be less dense than in plots receiving nitrogen only. During periods of drought, the grass in these plots showed a grayish color typical of wilted bluegrass. The bluegrass revived with ample moisture and grew well.

The nitrogen treatments did not give satisfactory control. Crabgrass control in plots receiving the 1x rate was significantly better than that in the untreated control and in the plots treated with the 2x rate. The higher population of crabgrass plants at the 2x rate probably resulted from initial bluegrass injury which weakened the turf and allowed more establishment of crabgrass.

A second experiment, conducted in the greenhouse, was carried out to determine the effects of the major PAX components, alone or combined as in PAX, applied at several rates on growth of bluegrass sod.

A good pasture bluegrass sod was cut to a depth of 2 inches in late November, rolled and moistened when necessary until frozen. The sod was kept outdoors in a shaded area until early January when it was moved into the greenhouse and fitted into

Table 6. Crabgrass control ratings in established bluegrass for the indicated treatments four months after application.

Treatments	Rates lb/1000 sq ft	Rating[1] means
Control	-----------	10.0 a
0.7x PAX	17.50	1.8 c
1.0x PAX	25.00	1.0 c
2.0x PAX	50.00	1.0 c
0.7x N[2]	1.23	8.5 ab
1.0x N	1.75	6.5 b
2.0x N	3.50	9.5 a
0.7x PAX + N	17.50 + 1.00	1.2 c
1.0x PAX + N	25.00 + 1.00	1.0 c

[1]Rating of 10 = no control, crabgrass population as large or larger than the untreated control. 2 = satisfactory control with not over 1 crabgrass plant/sq ft. 1 = no crabgrass present.

[2]N = nitrogen from ammonium sulfate.

13 x 15 x 3 inch flats on top of a one-half inch of a sandy loam soil. The flats were placed on greenhouse benches and watered daily. All broad-leaved weeds were then removed by hand. On the same day, the sod was overseeded with bluegrass at the rate of 1 lb/1000 sq ft to assure a full coverage of bluegrass. Weeds were removed again on March 3, one day prior to the application of the treatments. The following treatments were applied to each of 4 flats: PAX at 1, 2, 4, and 8x rates; N at 1, 2, 4, and 8x rates; As at 1, 2, 4, 8, and 16x rates; and the untreated control.

At the time treatments were applied, the soil was moist but the grass blades were dry. All flats were watered thoroughly after treatment to prevent contact injury to the grass blades. Thereafter, the soil moisture was maintained near field capacity throughout the experimental period. Temperatures which averaged 65 F during the first month of the experiment gradually increased into June when they averaged 85 F.

Results

Visual injury ratings taken 3 days after chemicals were applied varied significantly between treatments (Appendix Table H). Treatment means are shown in Table 7. Severity of injury to the bluegrass increased with increasing rates of PAX. The 8x PAX treatment, eight times the rate needed for crabgrass control, caused severe bluegrass injury. The major components in PAX, ammonium sulfate and the arsenical compounds, also caused blue grass injury as the rates increased. Injury due to the PAX treatments, which was more severe than that caused by either component alone, was therefore a combination of injury from these components.

Table 7. Visual ratings[1] of bluegrass injury taken three days after treatments as indicated

Treatments	Mean ratings
Control	10.0 a
1x PAX	9.0 b
2x PAX	8.0 c
4x PAX	4.2 e
8x PAX	2.0 f
1x N	10.0 a
2x N	10.0 a
4x N	9.2 ab
8x N	8.0 c
1x As	10.0 a
2x As	10.0 a
4x As	7.0 d
8x As	6.2 d
16x As	4.2 e

[1]Rating range used: 10=no injury to 1= injury with plants apparently dead.

No apparent injury was caused by the two lowest rates of ammonium sulfate or arsenicals. Slight injury occurred in the 4x N treatment with more injury at the 8x N rate. In the arsenical plots, moderate bluegrass injury was caused by the 4x As and 8x As treatments while the 16x As treatment caused severe damage.

To obtain data on the effects of the treatments on bluegrass growth, the grass was clipped to 1 1/2 inches about every 15 days during March, April, May, and June and dry weights were recorded. Dry weights of clippings collected on each of the eight dates and the total weights were analyzed statistically (Appendix Table I). Differences among treatments were highly significant for each clipping date and for the total weights. The means for all treatments for each harvest are shown in Table 8. For easier comparisons, these data were converted to percentages of the untreated control as shown in Table 9.

Bluegrass growth following application of 1x or 2x rates of PAX was as good as or better than that in the controls as long as nitrogen was present. Heavy initial injury by the 4x rate of PAX necessitated a longer period of recovery before gains in growth occurred. However, the 8x rate of PAX caused such severe injury that recovery did not occur during the experimental period. When the nitrogen contained in the PAX was gone, the grass responded to the toxic effects of the arsenic by significant reductions in growth.

Nitrogen at high rates (4x and 8x) caused some initial injury which was rapidly overcome. After the first month, bluegrass growth under all nitrogen treatments was significantly better than

Table 8. Dry weights of bluegrass clippings for fourteen herbicide treatments on each of eight dates and the eight-date totals

Treatments	Mean weights of clippings (grams) on indicated dates								Total of 8 dates
	3/15	3/30	4/15	5/2	5/18	6/2	6/17	7/4	
Control	1.7 de[1]	3.4 def	3.2 c	4.9 ef	4.0 ef	6.1 cd	9.4 b	10.8 bc	44.1 c
1x PAX	2.6 bc	6.1 bc	5.5 b	5.0 def	3.6 fg	4.0 efg	7.4 c	8.3 d	42.5 c
2x PAX	2.0 cd	4.9 cde	5.9 b	7.4 bc	6.7 cd	5.7 cde	6.4 cd	6.0 de	44.9 c
4x PAX	1.3 def	3.0 efg	3.7 c	6.8 cd	7.6 bc	7.2 c	5.3 de	5.4 e	40.2 c
8x PAX	0.4 g	1.0 g	1.5 d	1.1 g	2.8 gh	3.2 gh	3.3 f	4.4 e	18.6 e
1x N	4.1 a	7.7 a	5.3 b	5.3 de	4.5 ef	6.0 cde	8.9 b	10.6 bc	52.4 b
2x N	3.4 ab	9.1 a	7.3 a	8.3 abc	6.0 de	5.2 de	7.1 c	9.6 bc	57.0 b
4x N	2.0 cd	5.4 bcd	8.4 a	9.5 a	9.1 ab	10.4 b	9.7 b	10.9 b	65.4 a
8x N	1.0 efg	4.0 cde	5.8 b	8.9 ab	10.0 a	12.9 a	14.2 a	18.8 a	75.6 a
1x As	1.4 def	3.0 efg	2.6 cd	3.3 fg	3.1 fgh	5.1 def	5.5 cd	9.5 c	34.6 c
2x As	1.8 de	2.4 fg	1.9 d	2.6 g	2.3 gh	3.5 fg	6.0 cde	6.4 de	26.8 d
4x As	1.1 efg	2.5 fg	2.0 d	2.3 g	2.4 gh	3.4 gh	4.5 ef	5.7 e	24.0 de
8x As	1.2 def	1.0 fg	1.8 d	2.5 g	2.5 gh	3.1 gh	3.7 f	4.1 e	20.8 de
16x As	0.7 fg	1.1 g	1.5 d	1.6 g	1.7 h	1.7 h	1.2 g	0.7 f	10.1 f

[1]Letters indicate significance of differences between means within each column.

Table 9. Bluegrass growth expressed as a percentage of the control for each of eight bimonthly clippings and for the total weight of clippings

Treatments	Clipping weights as percent of the control on indicated dates[1]								
	3/15	3/30	4/15	5/2	5/18	6/2	6/17	7/4	Total
Control	100	100	100	100	100	100	100	100	100
1x PAX	153*	179*	172*	102	78	66*	79*	77*	96
2x PAX	118	144	184*	151*	146*	93	68*	56*	102
4x PAX	76	88	116	139*	165*	118	56*	50*	91
8x PAX	24*	29*	47*	43*	61*	52*	35*	44*	42*
1x N	241*	226*	166*	108	98	98	95	98	119*
2x N	200*	268*	259*	169*	130	85	76*	89	129*
4x N	118	159	263*	194*	198*	170*	103	103	148*
8x N	59	118	181*	182*	217*	211*	151*	174*	171*
1x As	82	88	81	67	67	84	70*	88	79
2x As	106	71	59*	53*	50*	57*	64*	59*	61*
4x As	64	74	73*	47*	52*	56*	48*	53*	54*
8x As	71	59	56*	51*	54*	51*	39*	38*	47*
16x As	41*	32*	47*	33*	37*	28*	13*	6*	23*

[1]Comparisons can be made only within each column.

*Significantly different from the control.

in the control. The duration of the stimulation due to nitrogen was for 1 1/2 months at the 1x rate, 2 months at the 2x rate, 3 months at the 4x rate, and more than 4 months at the 8x rate. Growth in the nitrogen-treated flats after the nitrogen was exhausted did not usually differ significantly from the control.

Generally, in flats treated with arsenical compounds alone, bluegrass growth decreased with increasing rate of arsenic. Bluegrass growth under the lowest rate was not significantly different from the control except on the seventh date. The fact that growth during the first month was not significantly less under the 2x, 4x, and 8x rates than in the controls indicated that arsenical toxicity was gradual. On the last clipping date on July 4, flats which had initially received similar amounts of the arsenicals either alone or with ammonium sulfate as in PAX had approximately equal growth. An exception was in the 1x As treatment which had significantly more growth than that in the 1x PAX treatment (Table 8).

In total growth over the experimental period, no significant differences occurred among means of the untreated control, 1x PAX, 2x PAX, 4x PAX, and 1x As treatments. However, growth under the 2x and 4x As treatments was less than that under the 2x and 4x PAX treatments. Since the 2x and 4x As treatments were comparable to the 2x and 4x rates of PAX in arsenic levels, the nitrogen in the latter treatments was effective in overcoming the toxic effect of the arsenic at these levels. However, the grass in the 8x PAX, and 8x and 16x As treated flats grew significantly less throughout the experimental period than did that in the control, indicating that excessive bluegrass injury had occurred under these treatments. The initial injury caused by the large amount of nitrogen present in 8x PAX (14 lb N/1000 sq ft) together with the arsenic itself prevented the grass from benefitting from the presence of nitrogen later in the season.

The growth of Kentucky bluegrass over a 4-month period following PAX, arsenical, or ammonium sulfate treatments is shown graphically in Figure 1. Nitrogen alone resulted in better growth, and arsenicals alone resulted in poorer growth of bluegrass than that in the controls. These two components, when combined in PAX, resulted in growth similar to that in the control with the exception that when PAX was applied at the 8x rate, growth of the bluegrass was greatly reduced (Figure 1d). As previously discussed, the depressing effects of growth by the 8x PAX treatment was probably due to the combination of the immediate injury caused by the high nitrogen rate together with the slower acting toxicity of the high rate of the arsenicals.

Visual evidence of the reduction in bluegrass stands caused by the arsenicals is shown in Figure 2. As the rates increased, injury to the bluegrass increased. Only a few living plants are seen in the 16x As treatment. Figure 3 shows the growth in the 1x rates of PAX, N, and As. The reduced weed populations in the treatments receiving arsenical compounds (PAX and As) are apparent. Figure 4 shows the effects of the 8x rates of PAX, arsenicals, and nitrogen. The flat with the 8x nitrogen treatment shows fewer weeds than the control. The reductions in growth are apparent in the 8x As treatment and reductions in stands are seen in the 8x PAX treatment.

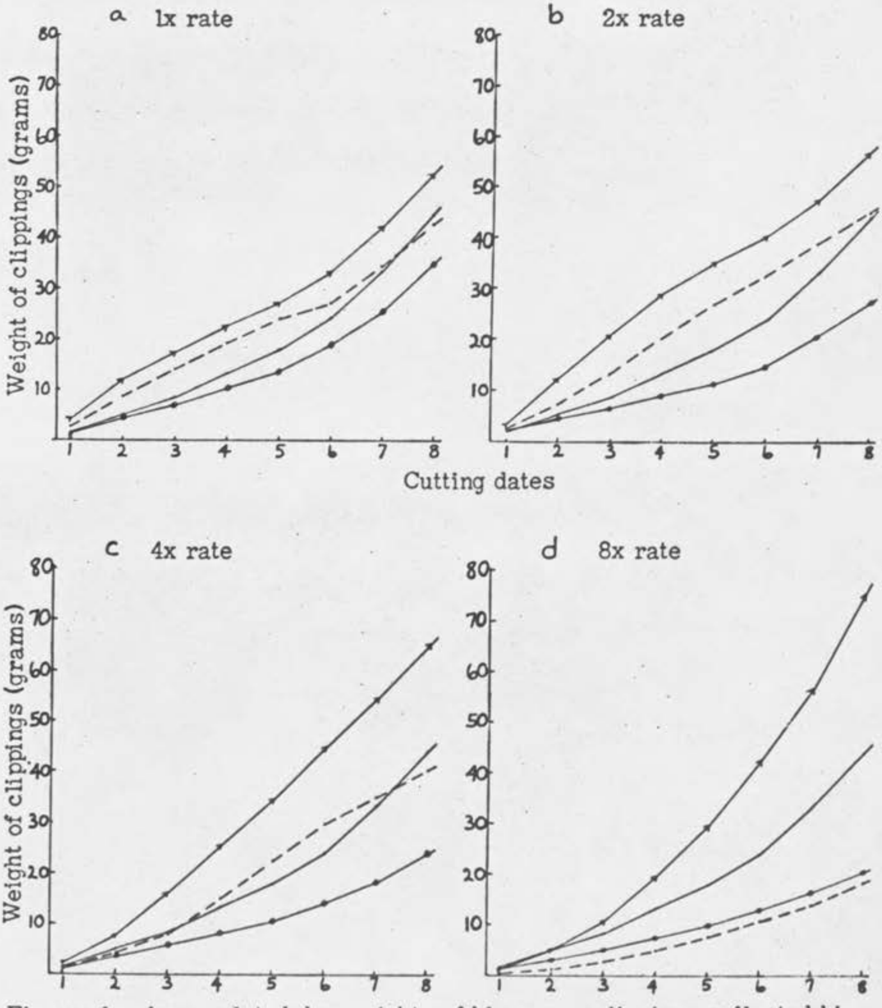

Figure 1. Accumulated dry weights of bluegrass clippings collected bi-monthly over a four-month period following treatment with four rates of PAX (- - - -), ammonium sulfate (→——→), or arsenical compounds (—⊖—⊖—). The untreated control (————) is included.

Figure 2. Kentucky bluegrass sod treated with arsenical compounds at rates listed below. (Photo taken four months after treatments.)

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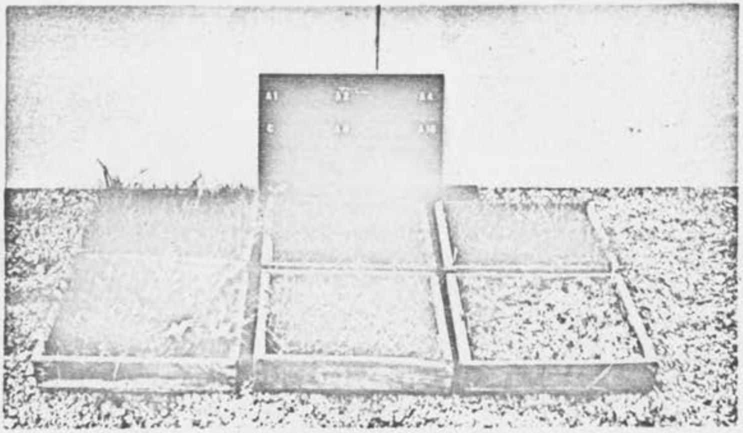
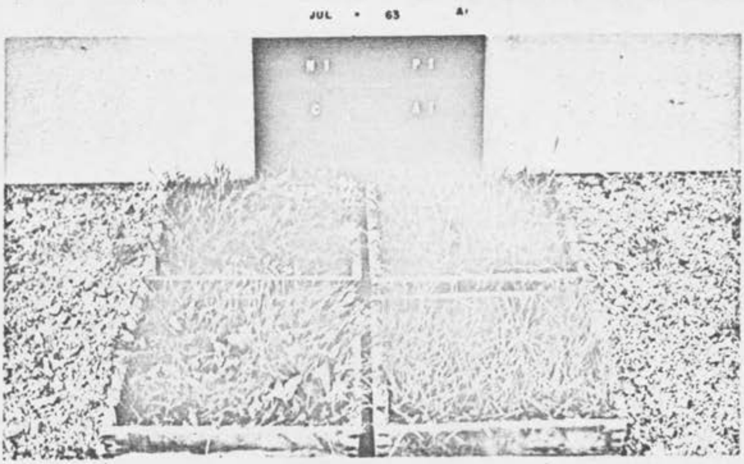


Top row: A1 = 1x As, A2 = 2x As, A4 = 4x As

Bottom row: C = untreated control, A8 = 8x As, A16 = 16x As

Figure 3. Kentucky bluegrass sod four months after treatment with PAX, N*, and As each at the 1x rate

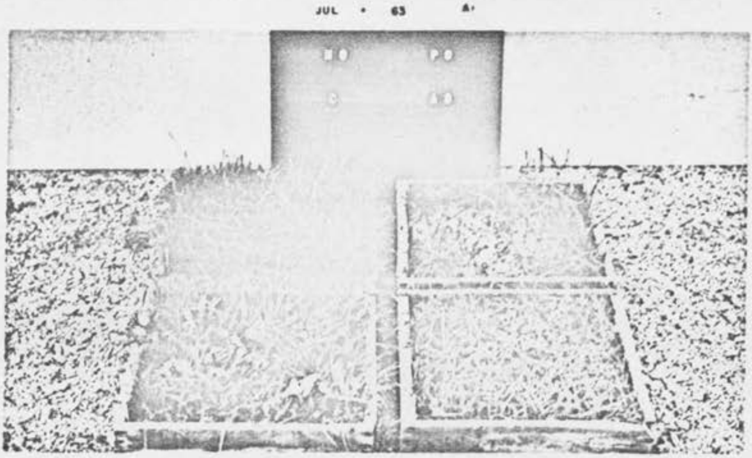


Top row: N1 = 1x N, P1 = 1x PAX

Bottom row: C = untreated control, A1 = 1x As

*Nitrogen is from ammonium sulfate.

Figure 4. Kentucky bluegrass sod four months after treatment with PAX, N*, and As each at the 8x rate



Top row: N8 = 8x N, P8 = 8x PAX

Bottom row: C = untreated control, A8 = 8x As

*Nitrogen is from ammonium sulfate.

At the conclusion of this experiment, the number of bluegrass plants in each flat and their root weights were estimated. In flats having dense growth, plant populations and root weights were based on a representative one-fourth sample of the total area. In sparsely covered flats, all plants were counted and root weights recorded. The total number of plants and dry weights of the roots per flat for each treatment were analyzed statistically (Appendix Table J). Treatment variances were highly significant for plant number and root weights. Comparisons between means are shown in Table 10 which also gives the plant number and root weight percentages based on the control at 100%.

Significantly fewer plants were found in the PAX treatments than in the control. The number of plants decreased with increasing rates of PAX. No significant differences in plant numbers occurred among the N treatments nor did they differ significantly from the untreated control. Plant numbers under the 1x As and 2x As treatments were similar to that in the control. However, at rates of arsenicals above the 2x As level, bluegrass stands were reduced, the smallest populations resulting from the highest rate (16x As). Each PAX treatment had significantly fewer plants than its corresponding arsenical treatment. A possible explanation of the apparent synergistic effect of the nitrogen plus arsenic combination on stand reductions is that the nitrogen stimulated root development thus allowing more roots to come in contact with the arsenic present.

Root weights were reduced as the rates of PAX or arsenicals were increased (Table 10). A close similarity between root weights

Table 10. Number of bluegrass plants and dry weights of roots per flat taken four months after treatments listed below. Percentages based on the control are given also.

Treatments	Mean stands		Mean dry weights of roots	
	Number of plants	Percent of control	Grams	Percent of control
Control	320 a	100	35.6 bc	100
1x PAX	230 b	75	23.2 cdef	65
2x PAX	131 c	41	16.4 efgh	46
4x PAX	133 c	42	13.3 efgh	37
8x PAX	60 d	19	7.3 gh	21
1x N	310 a	97	33.8 bcd	95
2x N	331 a	103	43.3 ab	122
4x N	332 a	104	42.3 ab	119
8x N	343 a	107	55.1 a	155
1x As	348 a	109	27.2 cde	76
2x As	331 a	103	20.4 defg	57
4x As	196 b	61	13.3 efgh	37
8x As	134 c	42	9.1 fgh	26
16x As	24 d	7	2.3 h	7

under treatments receiving comparable levels of PAX or As is apparent. Nitrogen applications tended to increase root weights but only the 8x rate, which probably was the only one to supply adequate nitrogen throughout the experimental period, produced significantly more root weight than the control.

Weeds per flat were counted and identified at the conclusion of the experiment. Weed percentages were determined, using the number of weeds as the numerator and the total plant population as the denominator. The analysis of variance for the weed populations taken at the end of the experiment are shown in Appendix Table K. The 4x PAX, 8x PAX, 8x As, and 16x As treatments had no weeds and thus were not included in the analysis. Differences among treatments were highly significant.

Table 11 shows the mean weed percentages for each treatment. The weed population was significantly larger in the control than in the treated flats. Weed control among the treatments containing arsenicals was excellent. Each increase in the level of nitrogen also reduced the weed population significantly.

White clover (Trifolium repens L.) was the most common weed found in the control flats. Other weeds present were dandelion (Taraxacum officinale Weber), common plantain (Plantago major L.), black medic (Medicago lupilina L.), mouse-ear chickweed (Cerastium vulgatum L.) common mullein (Verbascum thapsus L.), hoary vervain (Verbena stricta Vent.), prostrate spurge (Euphorbia supina L.), shepherd's purse [Capsella bursa-pastoris (L.) Medic], aborted buttercup (Ranunculus abortivus L.), and yellow sorrel (Oxalis stricta L.). Similar kinds of weeds were

Table 11. Weed percentages in bluegrass sod growing in flats taken four months after treatment

Treatments	Mean weed percentages
Control	10.2 a
1x PAX	1.2 e
2x PAX	0.2 e
4x PAX*	0.0
8x PAX*	0.0
1x N	7.8 b
2x N	4.8 c
4x N	2.8 d
8x N	0.4 e
1x As	0.9 e
2x As	0.2 e
4x As	0.4 e
8x As*	0.0
16x As*	0.0

*These treatments were not included in the analysis of variance.

found in the flats receiving the ammonium sulfate treatments except that the white clover was greatly reduced as the rates were increased. In the treatments containing arsenicals, a higher percentage of the weed population consisted of dandelions, prostrate spurge, yellow sorrel, black medic, and hoary vervain.

Leaching Studies

Since increasing rates of PAX resulted in progressively more bluegrass injury in the previous experiment, an experiment was conducted to determine if toxic arsenic levels could be reduced by heavy leaching.

Cultured bluegrass sod grown on a peat soil with high nutrient levels was brought into the greenhouse in December and fitted into 13 x 15 x 3 inch flats. The following day, PAX was applied at 1x, 2x, 4x, 8x, and 16x rates. Each rate was applied to eight flats. Eight untreated control flats received an ammonium sulfate application at the same rate as in the 1x PAX rate. Immediately after treatment, the flats were watered thoroughly to remove the herbicide from the foliage to prevent contact injury to the non-dormant grass. Visual ratings of injury were made 4 days after the herbicide applications.

Flats were placed in the greenhouse where temperatures averaged 65 F during the experimental period. Four weeks later, the grass in each flat was cut and overseeded with bluegrass seed at the rate of 3 lb/1000 sq ft. The surface of the soil was scratched vigorously to assure that seeds were in contact with the soil. Beginning a week after the seeding, about one surface inch of tap water was added to four of the flats of each treatment every

2 days for the first 2 weeks. Thereafter two leachings with 1 inch of water were made weekly until the experiment was ended. The remaining four replicates were watered so as to avoid leaching.

Clippings were weighed 7 and 14 weeks after the herbicide treatments were applied. Cuttings made between these intervals were left in the flats. Weights of grass clippings represented growth over a 2-week period. Grass clippings to be weighed were dried to constant weights.

The five treatments and the controls for the two watering practices were completely randomized within each of the four replications. Dry weights of clippings were analyzed statistically.

Results

Injury to established bluegrass sod in flats treated with 1x, 2x, 4x, 8x, and 16x rates of PAX increased with rates (Table 12). PAX at the 1x rate caused little initial injury to the bluegrass. The degree of injury ranged from slight at the 2x rate to complete kill of all vegetation at the 16x rate.

The analyses of variance of the dry weights of clippings taken 7 and 14 weeks after herbicide applications (2 and 7 weeks after leaching was begun) are shown in Appendix Table L. On the first date differences among treatments were statistically significant. Clipping weights for the herbicide treatments, as an average of the two watering methods, are shown in Table 13. PAX at the 1x and 2x rates did not reduce bluegrass growth significantly but higher rates did. All bluegrass was killed at the 16x rate.

Weights of clippings taken 14 weeks after the herbicide treatments differed significantly among treatments, waterings, and

Table 12. Visual ratings[1] of injury to bluegrass taken four days after herbicides were applied

Treatments	Mean visual ratings
Control	10.0
1x PAX	9.8
2x PAX	8.4
4x PAX	6.4
8x PAX	3.6
16x PAX	1.0

[1]Rating range used: 10 = no apparent injury to 1 = complete kill of all vegetation.

Table 13. Dry weights of bluegrass clippings over a two-week growing period, taken seven weeks after herbicide applications

Treatments	Mean weight per flat (grams)
Control	3.34 a
1x PAX	3.26 a
2x PAX	2.81 a
4x PAX	1.49 b
8x PAX	0.59 c
16x PAX[1]	0.00

[1]All vegetation was killed by this treatment and thus it was not included in the analysis.

treatments x watering interactions (Appendix Table L). Dry weights of clippings for this date are given in Table 14. Combining the data from both watering methods, no significant differences were observed among the 1x, 2x, and 4x rates of PAX and the control in bluegrass growth. Plants had recovered from the injury apparent under the 4x rate 7 weeks after treatment (Table 13), but the severe injury to the bluegrass caused by the 8x rate of PAX was still reflected in significantly reduced growth after 14 weeks (Table 14). Many bluegrass plants were also killed by this rate of PAX.

The effects of various rates of PAX on growth of bluegrass varied under the two watering regimes. Under regular watering, growth in the plots treated with the 2x rate of PAX was significantly greater than that in untreated flats or in those treated with the 1x or 8x rates of PAX. On the other hand, under heavy watering, growth of bluegrass did not differ significantly within the 0 to 8x range of rates. Apparently the high levels of nitrogen supplied in the 2x rate of PAX stimulated bluegrass growth under regular watering practices. While higher levels of PAX supplied even more nitrogen, the excessive initial injury caused by the high rates of herbicide reduced bluegrass stands and total growth. Under heavy watering, nitrates were probably leached out of the soil and thus did not stimulate bluegrass growth.

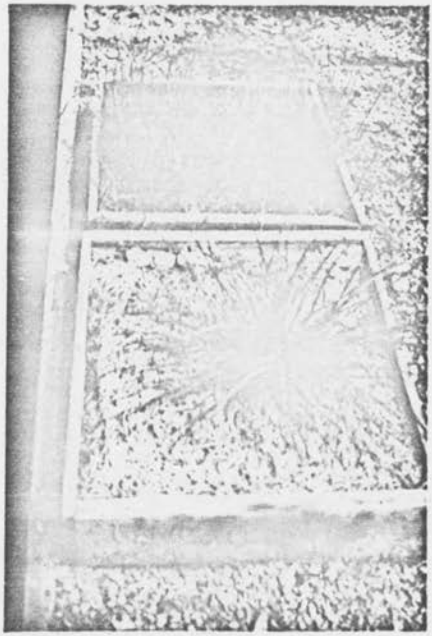
Figure 5 shows the influence of reseeding bluegrass in sod treated with PAX at the 16x rate which had killed all vegetation in the flats. The flat in the foreground was not reseeded and has a single bluegrass plant which grew from a volunteer seed. The flat

Table 14. Dry weights of bluegrass clippings over a two-week growing period, taken fourteen weeks after herbicide application and seven weeks after heavy leaching was begun

	Mean dry weights of clippings per flat (grams)		
Treatments	Regular watering	Heavy watering	Treatment means
Control	4.13 bc	3.03 bcd	3.58 a
1x PAX	4.08 bc	2.23 cd	3.15 a
2x PAX	6.28 a	2.20 cd	4.24 a
4x PAX	4.70 ab	3.48 bcd	4.18 a
8x PAX	1.60 d	2.00 d	1.80 b
16x PAX[1]	0.00	0.00	0.00
Watering means	4.11 a	2 59 b	

[1]All vegetation was killed by this treatment and thus it was not included in the analysis.

Figure 5. Bluegrass establishment in sod treated with the 16x PAX rate. Photo taken six months after herbicide treatment.



Top flat: Reseeded with bluegrass at 3 lb/1000 sq ft rate, one month after PAX application.

Bottom flat: Not reseeded. One volunteer seed germinated and grew.

in the background was reseeded with bluegrass at the rate of 3 lb/1000 sq ft 1 month after herbicide application. The picture was taken 6 months after the herbicides were applied. The reseeded flats had a dense cover of plants at this time.

To determine the effects of herbicide treatments on soil acidity and certain soil nutrients shortly after their application, soil samples were taken 5 weeks after herbicides were applied. Ten half-inch cores of soil were taken from all flats of each treatment, crushed when dry and mixed thoroughly. Soil tests were run on these composite samples and compared with the soil test taken before the herbicide applications.

Table 15 gives the results of the soil tests which were taken at the start of the experiment and 5 weeks after herbicide applications. At high rates, PAX increased soil acidity and soluble salt content. Because all plots received ammonium sulfate, nitrate levels were high in all plots. Phosphorus and potassium levels remained rather constant under all levels of PAX except the 8x rate which showed somewhat higher levels of both. Calcium levels decreased as the acidity increased at the higher levels of PAX. Ammonia levels showed a marked increase in the 4x and 8x rates of PAX. This increase was probably related to the decaying of plants killed at the higher rates of PAX and to greater bacterial activity as well as to the higher initial quantity of ammonium sulfate applied.

Because the results of the preceding experiment suggested that possibly arsenic might be leached from soil, a second experiment was conducted to study the influence of leaching on the

Table 15. Soil test data from composite samples taken before herbicide treatment and five weeks after treatment with five rates of PAX

Variable		pH, soluble salts, and nutrient levels in soil samples taken					
		Before treatment	Five weeks after application of PAX at indicated rates				
			0x	1x	2x	4x	8x
pH		6.8	7.0	6.9	6.6	5.7	5.6
Soluble salts (ppm)		60	85	80	130	170	200
Nitrates[1]	"	33	145	>153	>153	>153	>153
Phosphorus	"	3	3	3	4	4	6
Potassium	"	12	17	15	17	17	27
Calcium	"	150	167	147	150	130	130
Ammonia	"	1	2	1	1	18	30

[1]Nitrate levels over 153, the upper limit used in determining nitrate levels are indicated by >153.

movement of arsenic in two soil types. The experimental procedure used in this experiment followed closely that of Ogle and Warren (46).

Two Minnesota soils, described in Table 16, were used in this experiment. Nutrient levels were "very low" in both soils except that the nitrogen level in soil B was "low." Air-dried lots of both soil types were screened through an eighth-inch screen and then moderately packed into plastic tubes 3 inches in diameter. Each tube had 2.7 lb of soil and was 6 to 8 inches high. Soil A weighed about .44 lb/column inch while soil B weighed .33 lb/column inch. Fifty holes an eighth-inch in diameter were made in the base of each soil-filled bag for drainage.

The soil columns were sub-irrigated with distilled water to field capacity before herbicide treatments were made. PAX at the 1x rate was pulverized using a mortar and pestle. It was mixed thoroughly with .25 ounce of fine, washed quartz sand and spread evenly over the surface of the soil columns. Similarly, a mixture of lead arsenate and arsenous oxide at the same levels as found in the 1x PAX rate was pulverized, mixed with the same amount of quartz sand and applied evenly to the surface of another set of soil columns.

After a 2-hour waiting period to allow for any herbicide-soil reaction, leaching was begun. A fourth-inch pad of glass wool was fitted over the soil surface to break the force of the distilled water which was metered dropwise on the pad until a film of water covered the soil surface. One, 4, and 16 inches of water were used for each herbicide treatment, and 1 inch of water was applied to the controls.

Table 16. Description of two Minnesota soils used in the leaching experiment

Soil type	Clay	Organic matter	pH	Cation exchange capacity	Volume weight	Moisture percentage	
	%	%		m. e. /100 g of soil	g/cc	1/3 atm	15 atm
Soil A: Zimmerman loamy fine sand (Ramsey County)	3	2.4	5.5	6.3	1.67	6.2	3.6
Soil B: Colluvial fine sandy loam (Carver County)	16	4.4	7.0	17.0	1.23	23.5	13.0

Each treatment was replicated four times. Columns were rotated frequently to assure even distribution of water to the soil surface. The entire procedure was arranged so that the various amounts of water were delivered at about the same conclusion time. The flow of water was adjusted frequently to maintain the surface film of water. Replications of each treatment were run on August 22, August 30, September 6, and September 15.

After draining for at least 12 hours, each column was sliced into the following layers as measured from the soil surface: (1) 0-1/2, (2) 1/2-1, (3) 1-1 1/2, (4) 2-2 1/2, and (5) 3-3 1/2 inches. Each slice was placed in a petri dish with the uppermost surface up.

Fifty crabgrass seeds having 68% germination were distributed evenly over the surface of each soil slice and covered lightly with washed quartz sand in bioassay tests to determine the presence of arsenic at the various depths. The petri dishes were covered for the first 3 days to maintain high humidity to aid germination and establishment of the crabgrass. The soil slices were kept moist throughout the experiment by sub-irrigation with distilled water. Temperatures averaged 76 F in the laboratory where the dishes were placed. Covers were removed on the fourth day, and on the sixth day the entire replication was moved to the greenhouse where daytime temperatures averaged 81 F and night temperatures averaged 72 F.

Three weeks after seeding, the crabgrass plants in each petri dish were counted, cut at the soil surface, and dried. Analyses of variance were calculated for total dry weights and stands of crabgrass plants. A split-plot design was used with the fourteen main plots or soil columns in each replication. Each soil had seven treatments consisting of three levels of leaching with two different herbicides plus the control. Subplots were the five depths within each soil column. In the statistical analysis the surface layer, which had no crabgrass establishment, was omitted.

In order to relate the growth and stands of crabgrass in the above test to arsenic levels, a simultaneous test was conducted in which crabgrass seed was planted in soils containing known amounts of PAX or the arsenical compounds. PAX at 1x, .5x, .25x, .13x, .06x, and .03x rates and the arsenicals at the same levels as found in these PAX rates were mixed thoroughly with the weight of a half-inch of each soil type using the same soils and weight of soil as in the leaching study. Soil columns filled with such treated soil were sub-irrigated until moist. After setting for 12 hours, the 2-2 1/2 inch slice from each soil column was cut out, placed in a petri dish, and planted with crabgrass seed as described for the soil slices in the leaching study above. Post-planting care for these seedings was the same as those in the leaching study. Four replications were run with one conducted each time a replication was run in the leaching study.

Results

Crabgrass stands and growth on soil slices taken from various depths of the two types of soil following leaching varied significantly for soils and depths (Appendix Table M). In stands, treatments and the treatment x soil interaction also differed significantly. Only these variances are of interest here.

Table 17 gives the crabgrass stands taken three weeks after seeding soil slices from five depths from soil columns following leaching of surface-applied PAX and the arsenical compounds. None of the crabgrass seeds grew at the 0-1/2 inch layer on either soil following herbicide treatment regardless of amount of leaching. Crabgrass populations on soil slices increased significantly with depth in the soil column. Thus, little leaching of toxic substances downward into the soil column occurred.

As indicated by the stands obtained when crabgrass was grown on soil slices containing known amounts of PAX and the arsenicals (Table 18), the amounts of herbicide leached to depths below the one-half inch depth in the above experiment was very limited. According to the bioassay tests, less than 6% of toxic substances from either PAX or the arsenicals moved below this depth. More crabgrass plants became established and more total dry weight per petri dish were obtained on the loamy soil B than on the more sandy soil A.

Means of the soil x treatment interaction are shown in Table 19. PAX leached to a slight extent in the sandy soil (A) especially at the 1 and 4 inch levels of leaching, but not in the loamy soil (B). Differences in crabgrass stands in the two soils following PAX treatment account for the significant soil x treatment interaction. No appreciable leaching of the arsenical compounds alone occurred regardless of the soil type and the amount of leaching.

The apparent greater mobility of arsenic in combination with nitrogen (i.e., PAX) compared to the arsenicals alone is

Table 17. Crabgrass stands taken three weeks after seeding on soils from indicated depths following leaching of herbicides

Herbicides and rate applied	Leaching water (inches)	Mean stands from 50 seeds planted on soil slices from indicated depths (inches)					Soil x treatment Means (0-1/2 excluded)
		0-1/2	1/2-1	1-1 1/2	2-2 1/2	3-3 1/2	
		Soil A (Zimmerman loamy fine sand)					
None	1	38	31	36	31	32	33 cd
lx PAX	1	0	18	22	24	34	25 a
lx PAX	4	0	22	26	31	33	28 ab
lx PAX	16	0	27	28	38	32	31 bc
lx As	1	0	34	35	32	36	34 cd
lx As	4	0	34	34	35	36	35 cd
lx As	16	0	35	36	38	38	37 cd
		Soil B (colluvial fine sandy loam)					
None	1	36	38	36	37	37	37 cd
lx PAX	1	0	25	33	36	32	32 bc
lx PAX	4	0	32	36	35	34	34 cd
lx PAX	16	0	32	35	36	35	35 cd
lx As	1	0	31	35	33	38	34 cd
lx As	4	0	41	31	38	36	36 cd
lx As	16	0	34	36	34	36	36 cd
Depth means			31 a	33 b	34 c	35 d	

Table 18. Stands and dry weights of crabgrass plants from 50 seeds planted in soils treated with various rates of PAX and arsenical compounds and taken three weeks after seeding.

	Mean stands on:		Mean dry weights (mg) on:	
Herbicide and rate applied	Soil A sandy	Soil B loam	Soil A sandy	Soil B loam
Control	36	33	67	175
1.0 x PAX	0	0	0	0
.5 x PAX	0	0	0	0
.25x PAX	0	1	0	1
.12x PAX	0	6	0	16
.06x PAX	2	17	2	21
.03x PAX	6	33	12	77
1.0 x As	0	0	0	0
.5 x As	0	0	0	0
.25x As	0	1	0	2
.12x As	4	19	2	11
.06x As	7	36	8	42
.03x As	21	38	31	116

Table 19. Stands of crabgrass plants in two soils following surface application and leaching of two herbicides

Herbicide and rate applied	Leaching water (inches)	Mean stands from 50 seeds 3 weeks after seeding on: Soil A	Soil B	Differences (Soil A - Soil B)	Treatment means
None	1	33 cd	37 cd	-4	35 cd
lx PAX	1	25 a	32 bc	-7*	28 a
lx PAX	4	28 ab	34 cd	-6*	31 b
lx PAX	16	31 bc	35 cd	-4	33 bc
lx As	1	34 cd	34 cd	0	34 cd
lx As	4	35 cd	36 cd	-1	35 cd
lx As	16	37 cd	36 cd	1	36 cd
Soil means		32 a	35 b		

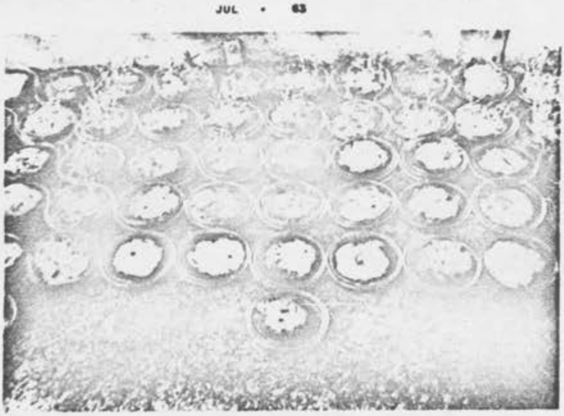
difficult to explain. Possibly the nitrogen, which is known to be mobile in soils, accumulated at toxic concentrations in the shallow sub-surface layers when leached with small amounts of water.

Figure 6 shows the growth and establishment of 50 crabgrass seeds planted on soil slices from the 0-1/2, 1/2-1, 1-1 1/2, 2-2 1/2, and 3-3 1/2 inch depths on soil A after surface application of PAX or the arsenicals followed by leaching with 1, 4, or 16 inches of distilled water. Figure 7 shows growth and establishment of the 50 crabgrass seeds per soil slice on soil B with the same treatments as above.

The total dry weights of crabgrass plants under each treatment for each depth on the two soil types are shown in Table 20. The statistical analysis of these data are given in Appendix Table M. A number of differences in the plant stand and dry weight data are apparent. Although plants on the two soils had different dry weights, differences among plants under the PAX and arsenical treatments were not significant. However, plants on the herbicide-treated soil slices had significantly less growth than those in the control. The dry weights of plants on soils from various depths differed significantly as did those in the interactions among depths, soils, and treatments.

Of interest in this study is the depth x treatment interaction as shown in Table 21. Crabgrass growth increased significantly with depth of soil slice from herbicide-treated columns. Although no significant differences in dry weights were shown between the 2-2 1/2 and 3-3 1/2 inch soil slices, a linear tendency is indicated. More total growth on the 1/2-1 inch slices from columns surface-treated with the arsenicals than those treated with PAX and on the

Figure 6. Crabgrass stands (50 seeded per dish) on a sandy soil (A) three weeks after seeding on soil slices taken from indicated depths following surface herbicide treatment and leaching as described below



Rows: Depths from surface (inches)

3-3 1/2

2-2 1/2

1-1 1/2

1/2-1

0-1/2

Non-seeded check

Columns:
Treatments[1]

C As-1 As-4 As-16 PAX-1 PAX-4 PAX-16

[1]C = untreated control, As = arsenical compounds at same levels as in the 1x rate of PAX with 1, 4, or 16 inches of leaching with water and PAX at the 1x rate leached with 1, 4, or 16 inches of water.

Figure 7. Crabgrass stands (50 seeded per dish) on a loamy soil (B) three weeks after seeding on soil slices taken from indicated depths following surface herbicide treatment and leaching as described below

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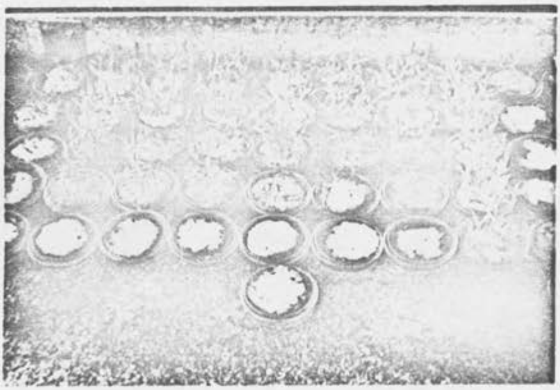


Rows: Depths from surface (inches)

3-3 1/2

2-2 1/2

1-1 1/2

1/2-1

0-1/2

Non-seeded check

Columns:
Treatments[1]

As-1 As-4 As-16 PAX-1 PAX-4 PAX-16 C

[1]As = arsenical compounds at same levels as in the 1x rate of PAX with 1, 4, or 16 inches of leaching with water, PAX at the 1x rate leached with 1, 4, or 16 inches of water and C = untreated control.

Table 20. Total dry weights (mg) of crabgrass plants three weeks after seeding on soils from indicated depths following leaching of herbicides

Herbicides and rate applied	Leaching water (inches)	Mean dry weights (mg) of plants from 50 seeds on soil slices from indicated depths					Soil x treatment means (0-1/2 excluded)
		0-1/2 in	1/2-1 in	1-1 1/2 in	2-2 1/2 in	3-3 1/2 in	
		Soil A (Zimmerman, loamy fine sand)					
None	1	87	77	88	90	102	89
lx PAX	1	0	9	18	72	114	53
lx PAX	4	0	26	45	65	69	51
lx PAX	16	0	34	70	94	86	71
lx As	1	0	44	58	53	98	64
lx As	4	0	46	62	46	65	55
lx As	16	0	50	56	70	73	62
		Soil B (colluvial, fine sandy loam)					
None	1	188	178	187	194	192	188
lx PAX	1	0	58	277	202	165	163
lx PAX	4	0	123	158	191	188	165
lx PAX	16	0	158	188	180	181	177
lx As	1	0	110	152	207	190	165
lx As	4	0	141	142	170	183	159
lx As	16	0	92	130	167	191	145
Depth means			82 a	113 b	129 c	136 c	

Table 21. Total dry weights of tops of crabgrass plants, three weeks after seeding on soil slices taken from four sub-surface layers following surface application of herbicides and leaching with 1, 4, or 16 inches of water

Herbicide and rate applied	Leaching water (inches)	Mean dry weights (mg) of tops of plants from 50 seeds on soil slices from indicated depths			
		1/2-1 in	1-1 1/2 in	2-2 1/2 in	3-3 1/2 in
None	1	128 fghi	138 i	142 i	147 i
1x PAX	1	34 a	123 efghi	137 i	139 i
1x PAX	4	74 bc	102 cdef	128 fghi	128 fghi
1x PAX	16	96 bcde	129 fghi	137 i	134 hi
1x As	1	77 bc	105 defg	130 fghi	144 i
1x As	4	94 bcd	102 cdef	108 defgh	124 efghi
1x As	16	71 b	92 bcd	119 defghi	132 ghi
Depth means		82 a	113 b	129 c	136 c

1-1 1/2 and 2-2 1/2 inch slices from columns surface-treated with PAX than those treated with the arsenicals accounted for the significant depth x treatment interaction.

Significantly less growth was obtained on the 1/2-1 inch slice from columns surface-treated with PAX and leached with 1 inch of water than that on all other soil slices. Possibly the accumulation of a high nitrogen level plus a high soluble arsenic level in this layer resulted in reduced growth of the crabgrass plants. At the same depth and surface treatment with PAX but leached with 4 or 16 inches of water, growth was not significantly different from that under the arsenical treatments. More leaching water might have reduced the nitrogen levels in the 1/2-1 inch soil layer thus lowering the toxic effect of the nitrogen and arsenic combination.

As with crabgrass stands, the dry weight data of Tables 20 and 21, when compared with that obtained with known amounts of herbicide (Table 18), indicate that less than 6% of the surface-applied herbicide moved to depths below the 1/2 inch layer irregardless of soil type or amount of leaching water used.

Site of Action of PAX

The site of action of PAX in preventing the establishment of crabgrass plants was studied in two experiments.

In the first, the action of PAX on imbibed seed and on crabgrass seedlings was studied. Year-old crabgrass seeds were soaked in distilled water using 5 ml of water for each gram of seed. Seeds which had been soaked for 1 or 24 hours were placed in petri dishes and treated with the 1x rate of PAX. PAX was applied dry over the imbibed seeds, and 3 ml of water was added to give an aqueous mixture.

The seeds which had been soaked for an hour in water before PAX treatments were removed from the PAX-water mixture after 1/4, 1/2, 1, and 3 hour exposures. The seeds which had been soaked for 24 hours in water were removed from the PAX treatment at 1/4, 1/2, 1, 3, 6, 12, and 24 hours. After removal, the seeds were thoroughly rinsed in tap water and placed in covered petri dishes on 50 grams washed quartz sand. The sand was kept moist by adding distilled water when necessary. Ten seeds were used per replication with ten replications for each soaking and exposure time to PAX.

In addition to the above tests with imbibed seeds, seedlings with plumules 7-10 mm and radicles 5-7 mm were treated with the PAX-mixture described above for 1/4, 1/2, 1, and 3 hours and were handled as above after treatment. Seedlings for these tests were obtained by soaking seed in water for 24 hours and then germinating them on moist paper towels under a bell jar.

Temperatures in the laboratory averaged 77 F during the experiment. Observations on plant condition were made 7 and 10 days after and numbers of live seedlings were recorded 14 days after herbicide treatment.

Results

The survival percentages of imbibed crabgrass seeds and seedling plants following various intervals of exposure to a PAX-water mixture are shown in Table 22. No significant differences were found in survival percentages of crabgrass whether the seeds were soaked for 1 or 24 hours prior to PAX treatment. Seeds soaked for 24 hours were kept in the PAX-water mixture up to 24

Table 22. Survival percentages two weeks after exposure of imbibed crabgrass seeds and crabgrass seedlings to the 1x rate of PAX in petri dishes with 3 ml of distilled water

Duration of exposure to PAX (hours)	Percent survival of crabgrass: Seeds soaked prior to treatment, 1 hr.	24 hr.	Size of seedlings prior to treatment: Radicle just showing	Plumule 7-10 mm Radicle 5-7 mm
0	71	68	100	100
1/4	73	79	0	9
1/2	71	73	0	5
1	79	72	0	3
3	72	69	0	0
6	--	75	--	--
12	--	73	--	--
24	--	71	--	--

hours as previous laboratory tests had shown that soaked seeds germinated in 48 hours. In those seeds which were soaked in water for 24 hours, the radicles had not burst the seed coat when the seeds were removed from the mixture.

Some of the seedlings with the radicles just showing at the time of treatment were alive a week after treatment but showed severe root injury. Ten days after treatment all plants were dead. Seedling plants which had 7 to 10 mm tops and roots 5 to 7 mm long when exposed to the PAX mixture also showed severe injury a week after treatment. Plants were yellow and root damage severe. Ten days after treatment, survival was 9, 5, 3, and 0%, respectively, for the 1/4, 1/2, 1, and 3 hour exposures. Seedlings which had survived showed loss of the primary root. Adventitious roots developed from the epicotyl region to sustain these plants.

Seedling plants approximately the same size as those mentioned above were placed in a PAX-water mixture, removed at 5-minute intervals, rinsed, and observed under a microscope. In the controls, the roots were milky white and root hairs were turgid and protruded from the primary root almost perpendicular to the main axis. Seedlings treated for 5 minutes in the PAX mixture had disarranged, broken, and tangled root hairs. The root hairs appeared to be flaccid. Plants which were exposed to the PAX mixture for 10 to 15 minutes before rinsing, had flaccid and tan root hairs. The root tip appeared to be injured. At the end of a 30-minute period in the PAX mixture, the entire primary root showed shrivelling and the epicotyl region was injured. After an hour of exposure to a PAX mixture, the epicotyl region was flaccid and the plumule was water-soaked and severely damaged. The principal action of PAX was injury to the root. The radicle as it emerged through the seedcoat was severely damaged when it contacted a PAX-water mixture.

In the previous experiment, crabgrass roots exposed to PAX in water were killed. A second experiment was conducted to determine if crabgrass roots would penetrate into and grow in soil containing PAX. Since ammonium sulfate is a component of PAX, the effects of its placement on established crabgrass plants were also studied.

Year-old crabgrass seed was germinated on moist paper toweling, and the seedling plants were transplanted into 1 1/2-inch peat pots in a sandy loam greenhouse soil and grown to the four-leaf stage.

At this time, the peat pots containing crabgrass plants were set into 4-inch clay pots of soil treated with PAX or ammonium sulfate. The following four treatments were used:

(1) Treatment A: PAX was applied at the rate of 25 lb/1000 sq ft to the surface of the soil surrounding the peat pot.

(2) Treatment B: PAX was applied as above in a layer about 2 1/2 inches from the top of the clay pot. The peat pot was set on the PAX layer, and untreated soil was used to fill the clay pot to the same level as that in the inserted peat pot.

(3) Treatment C: The same placement was used as in treatment A except that ammonium sulfate (N) was applied at a rate equal to that in the PAX application.

(4) Treatment D: The same placement was used as in treatment B except that ammonium sulfate (N) was applied at a rate equal to that in the PAX application.

The four treatments described above were applied to four pots in each of six replications.

The soil used in the clay pots was a colluvial sandy loam. The PAX or ammonium sulfate was finely ground and mixed with 10 grams of washed quartz sand to enable uniform distribution to the soil surface.

To induce tillering, plant tops were clipped to remove the growing point when the plants reached the five-leaf stage. All flowers were removed during the experimental period to induce more vegetative growth. During the first 7 weeks the plants were grown at temperatures of 70 F. Incandescent light was used to extend the photoperiod to 16 hours daily. After the first 7 weeks, the experiment was transferred to another greenhouse where temperatures averaged 73 F with fluctuations between 68 and 85 F. Long day conditions were then maintained by interrupting the middle of the night with 3 hours of light from 100 watt reflectorized incandescent bulbs. Four weeks after the experiment began, ammonium sulfate at 0.5 oz/gal of distilled water was applied at the rate of 50 ml per pot. Vegetative growth continued to be slow so a soluble complete fertilizer was used at the end of the second month and every 4 weeks thereafter. Each pot received 50 ml of a solution containing 0.5 oz/gal of a 17-17-17 fertilizer. Throughout the experiment, plants were watered with distilled water when necessary to keep the soil moist at all times.

The experiment was terminated after 5 months when the tops and roots were harvested separately and dried. Dry weights of tops and roots were recorded.

Results

As shown in the analysis of variance (Appendix Table N), dry weights of tops and roots varied significantly among treatments. The dry weight means for each treatment are shown in Table 23. Top and root growth of plants grown in the ammonium sulfate-treated pots was significantly greater than for those in the PAX-treated pots. The arsenicals in PAX inhibited the growth of both tops and roots of crabgrass plants regardless of its placement.

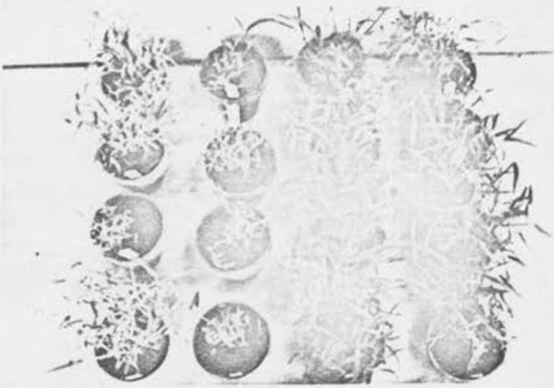
Figure 8 shows the four plants in each treatment for a single replication at the termination of the experiment 5 months after treatments were applied. Reductions in top growth are apparent in the PAX treatments (A and B). No apparent differences were seen in plants from treatments receiving ammonium sulfate only (C and D) at the same rate as the PAX treatments.

The distribution of the roots under the four treatments is shown pictorially in Figure 9 and diagrammatically in Figure 10. Root growth in treatment A, which had PAX applied to the soil surface, was principally vertical beneath the peat pot and had filled the lower third of the pot. In treatment B, which had PAX applied immediately below the peat pot, roots did not penetrate the PAX layer but filled the soil above the layer. In two pots of treatment B, top growth was noticeably better than in the others and upon examination these plants had roots which had grown down

Table 23. Dry weights (mg) of tops and roots of established crabgrass plants grown under two different placements of PAX and ammonium sulfate.

Treatments	Mean dry weights (mg)	
	Tops	Roots
A--PAX, surface	146.0 bc	13.2 b
B--PAX, base of peat pot	71.5 c	6.2 b
C--N, surface	280.3 a	34.2 a
D--N, base of peat pot	241.3 ab	33.0 a

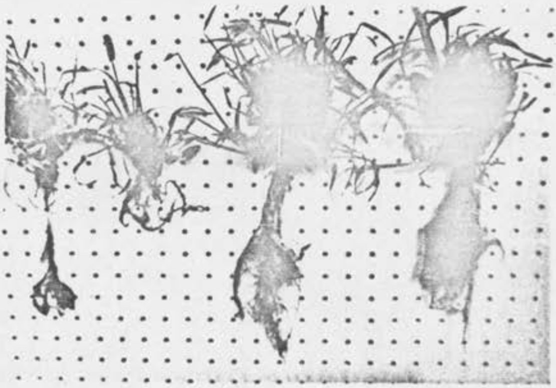
Figure 8. Top growth of established crabgrass on soils treated as below. (Photo was taken five months after treatment.)



Treatments: A B C D

Treatment A--PAX at lx rate applied to the soil surface
Treatment B--PAX at same rate as above but applied below the peat pot
Treatment C--Ammonium sulfate at same rate and placement as in A
Treatment D--Ammonium sulfate at same rate and placement as in B

Figure 9. Typical crabgrass plants from the four treatments listed below. (Photo was taken five months after treatment.)



Treatments: A B C D

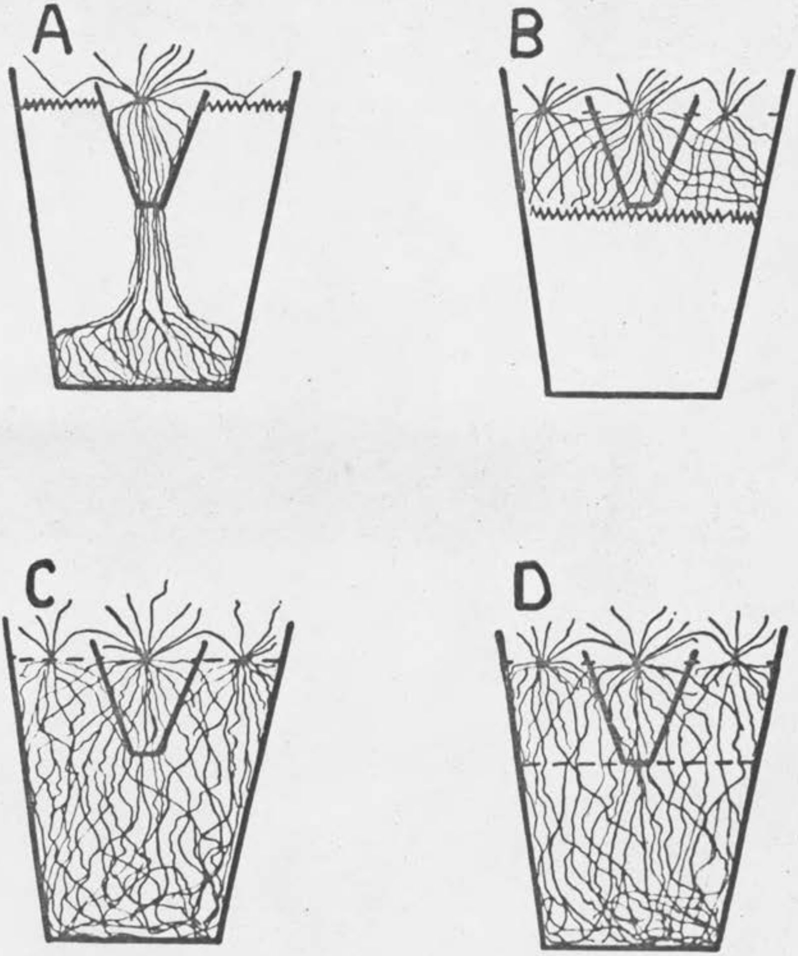
Treatment A--PAX at 1x rate applied to the soil surface

Treatment B--PAX at same rate as above but applied below the peat pot

Treatment C--Ammonium sulfate at same rate and placement as in A

Treatment D--Ammonium sulfate at same rate and placement as in B

Figure 10. Diagrammatic sketches of root growth of established crabgrass five months after applications of PAX (A and B) and ammonium sulfate (C and D)



A--PAX at 1x rate applied to soil surface
B--PAX at same rate applied below the peat pot
C--Ammonium sulfate at same rate and placement as in A
D--Ammonium sulfate at same rate and placement as in B

along the side of the clay pot and occupied the lower third of the pot. Evidently the herbicide had not covered the surface out to the rim of the pot. Roots grew profusely throughout the entire soil mass in treatments C and D. The ammonium sulfate at the base of the peat pot did not prevent roots from penetrating it to the lower area.

As the crabgrass plants grew and stems touched the surface of the soil in the clay pots, adventitious roots formed from the nodes and grew in all treatments except A which had had PAX applied to the surface. Roots developed but died when they contacted the treated soil. This failure of rooting of the stolons probably accounts for the reduced top and root growth under treatment A (Table 23). Leaching of toxic substances from the surface-applied PAX undoubtedly did not occur and thus apparently was not a factor in reducing root growth.

Plants growing in the soil which had PAX applied beneath the peat pot appeared to be nitrogen deficient. In many cases, the growing point was chlorotic. Some of the younger leaves had green veins with yellowish-green interveinal areas. Older leaves tended to show tip burn and complete drying. Since none of these plants died, arsenic was not absorbed in sufficient quantities to build up lethal levels during the 5-month period that plants were growing in this experiment. Probably the principal cause of the chlorosis was a nitrogen deficiency in the restricted root zone above the PAX layer. Roots which had begun to grow into the PAX layer had died when they contacted this layer. The roots above the PAX layer appeared to be healthy. Possible injury to these roots might have caused some of the deficiency symptoms seen in the plant tops.

DISCUSSION

In this study several experiments were conducted to determine some of the effects of PAX applications in a turf management program. Numerous investigators (9, 15, 36, 42, 47, 48, 52) have reported that PAX gave good to excellent crabgrass control in the season when applications were made. No one has reported on controlled investigations of the residual effects of a single application of PAX. A single application of lead arsenate, one of the ingredients in PAX, at 35 lb/1000 sq ft gave crabgrass control for 10 years in investigations conducted by Welton and Carroll (61). However, the amount of metallic arsenic applied was more than six times the amount in a PAX application of 25 lb/1000 sq ft. In the present study, a single application of PAX at 25 lb/1000 sq ft to a lawn heavily infested with crabgrass gave satisfactory crabgrass control for three seasons. Although the treated areas were not reseeded with crabgrass, these plots were surrounded by crabgrass plants which probably allowed for annual reinfestation with new seeds. On bluegrass sod growing in flats in which crabgrass reseeding was prevented by frequent short clipping, satisfactory crabgrass control was obtained throughout four seasons. In the untreated control, crabgrass emerged each year in spite of the fact that reseeding was prevented. This indicated that PAX remained active even in the fourth season from an application.

Previous investigations disagree as to the effects of preplanting applications of arsenical compounds on turf grass establishment. Gallagher and Otten (21) and Juska (29) reported that PAX and other arsenical compounds prevented seeded turf grasses from becoming established. Juska (29) reported that the seed germinated but seedlings succumbed shortly thereafter. An application of PAX prevented turf grass establishment from plantings made up to three or more months later, according to Juska (30). Delayed germination of turf grasses planted in soils treated with lead arsenate was reported by Leach and Lipp (31) and Morris (40). Many investigators (7, 14, 31, 32, 38, 39, 40, 43) observed no adverse effects to establishment of seeded turf grasses from applications at levels which controlled crabgrass. Throughout the present study seeded turf grasses grew and became established in plantings made following applications of PAX or the arsenical compounds found in PAX. In a field experiment, seeded turf grasses planted in a lawn did not develop into a dense turf until the second season after a PAX application. Kentucky bluegrass and Highland bentgrass grew well, but creeping red fescue seeds showed poor germination and sparse establishment in all treatments including the controls. More research is needed with this turf grass type. In a greenhouse experiment, germination of turf grass seeds was not delayed in soils treated with PAX at rates of .8 to 25 lb/1000 sq ft prior to planting. Top growth of turf grasses in pots treated with these rates of PAX was not significantly different from the untreated control. Germination was delayed 12 weeks when PAX was applied at 50 and 100 lb/1000 sq ft rates but good turf grass establishment resulted later. In another experiment in which PAX was applied at 400 lb/1000 sq ft rate to established sod in flats, all original vegetation was killed. Kentucky bluegrass seeds planted a month after the PAX application germinated and plants became established. Throughout the present study, moisture levels were kept consistently high following PAX treatments. This might have prevented seedlings from dying. Conceivably moisture stresses just after germination on arsenic-treated soils could have been lethal to small seedlings in experiments in which plants failed to become established (21, 29, 30). Duich et al. (14) observed that annual bluegrass was weakened on arsenate-treated soil and was killed during the first moisture stress period in July when temperatures were high. With ample moisture following planting on arsenate-treated soils in the present study, turf grass establishment did not appear to be reduced on typical soils for a lawn seedbed.

Another factor that has been found to influence turf grass establishment following application of arsenicals is soil type. Many investigators (3, 6, 23, 35, 49, 54, 55, 56, 62) have noted that soils high in colloids required higher arsenate levels for toxicity to many plants. In a greenouse experiment designed to determine bluegrass establishment in three soil types planted with bluegrass seed on four dates following arsenical application, stands varied with soil type and date of planting. PAX at 25 lb/1000 sq ft or the arsenicals alone at the same levels were applied before planting. In a washed sand, stands were reduced only when bluegrass was sown immediately after the herbicide application. In a clay soil, the herbicides reduced stands of bluegrass seeded immediately after herbicide application or two weeks later. In a loamy soil, no differences in bluegrass stands were obtained regardless of when plantings were made. Differences in the physical properties of these soil types could explain the differential results obtained. In the washed sand, the absence of adsorptive colloids may have prevented the inactivation of the soluble toxicants at the soil surface accounting for the injury to bluegrass seeded immediately following herbicide application. Subsequent waterings could have diluted or leached away the toxic substances allowing later plantings to develop normally. In the clay soil, slow penetration of water and slow drying of the soil probably resulted in the concentration of the soluble toxicants near the soil surface in direct contact with germinating seeds. However, after two weeks enough of the toxic substances had apparently been adsorbed on and inactivated by the soil colloids to permit normal germination and growth of the bluegrass. In the loamy soil, water movement was good and colloid content high so that both leaching and adsorption of the toxicants occurred rapidly enough to prevent injury to the seeded bluegrass. Thus even on the poorest types of lawn seedbeds (clay and sand) two weeks after PAX had been applied to kill areas infested with crabgrass, the seeding of bluegrass could be expected to result in satisfactory turf establishment.

The investigations of other workers (17, 60) have shown that high rates of arsenical compounds decrease top growth of established bluegrass. Similar results were obtained in the present study. However results obtained in the study reported here also indicate that such growth reductions are modified by the presence of nitrogen in the arsenical herbicide, PAX. Although arsenical compounds alone reduced bluegrass growth throughout a four-month period, PAX treatments at comparable levels of arsenicals and at rates from

25 to 100 lb/ 1000 sq ft gave increased top growth as long as nitrogen was present. After nitrogen supplies were depleted, the inhibitory action of arsenic was manifested by a sharp decline in top growth. At this time, PAX and arsenical treatments containing comparable levels of arsenic had similar effects on top growth. Initial injury from the 200 lb/1000 sq ft rate of PAX or from comparable levels of arsenical compounds was so great that bluegrass recovery failed to occur during the experimental period. Bluegrass recovery following nitrogen application has been reported by Welton and Carroll (60) in lawns previously treated with lead arsenate. It is conceivable that if regular nitrogen applications were made to a lawn after a PAX treatment, the bluegrass would continue to grow well and reduction in growth caused by the arsenic might be minimized.

The effect of arsenical applications on bluegrass stands and root weights in established turf has received little attlention in previous work. Engel and Meggitt (17) and Juska (30) reported a general thinning of bluegrass sod following an application of PAX. Dulch et al. (14) observed no apparent reductions in density in common and Merion bluegrass following an application of PAX at 25 lb/1000 sq ft. Actual plant counts were not reported in this and other studies. In the present study, bluegrass stands in established sod growing in flats were significantly reduced by PAX with reductions increasing with rates. Stands were not significantly reduced from the controls in the 1x and 2x rates of arsenicals alone. However at higher rates of the arsenical compounds, significant reductions in stands occurred. Root weights were reduced by both

PAX and arsenicals but to a lesser extent. Tolerance of roots to arsenic in sand cultures in which seedling bluegrass was growing was studied by Naylor (43). He observed that as the soluble arsenic content was increased more root injury occurred and death resulted. Reductions in the root systems of bluegrass could necessitate more frequent watering and nitrogen fertilization to maintain bluegrass growth on soils that were treated with arsenical compounds. A reduced root system could account for decreased stands and reduced top growth.

Several investigators (6, 59, 60) have shown that surface-applied arsenicals moved very slowly into the subsoil. Welton and Carroll (60) found that soluble arsenic was retained mainly in the top 2 inches of soil 5 years after a lead arsenate treatment. Crafts and Rosenfels (6) observed deeper penetration of arsenic in soil columns of sandy soil than in a clay soil. Many research workers (3, 6, 24, 35, 49, 54, 55, 56, 62) have reported that soils high in colloids retained more arsenic in the surface layers than soils low in colloids. In the present study, leaching of surface-applied PAX and the arsenicals with 1, 4, or 16 inches of water in two different soil types in soil columns resulted in significant differences in stands and growth of crabgrass subsequently planted on soil slices taken from various depths. Surface-applied PAX and the arsenicals leached to a significantly greater extent in a sandy soil than in a loamy soil. The amount of leaching water used had little effect on the movement of PAX and arsenicals into the soils with the exception that the toxicity of PAX tended to be greater at the 1/2-1 inch depth after leaching with 1 inch of water than after leaching with 4 or 16 inches of water. Since less toxicity occurred when arsenicals at the same rate were leached with the same amount of water, this effect of PAX must have been due to the accumulation of toxic levels of nitrogen in the 1/2-1 inch layer. No crabgrass seeds grew on the 0-1/2 inch layer in either the PAX or arsenical treatments. Comparisons of crabgrass growth on soil slices from surface-treated soils, following leaching with 1 to 16 inches of water, showed that less than 6% of toxic substances from the herbicide had moved below the 1/2 inch depth. These results agree with other workers (6, 59, 60) who reported very little movement of arsenic in treated soils having a high colloid content. In a greenhouse experiment in which a heavy application of several PAX rates was made to established bluegrass sod growing in flats, heavy leaching appeared to remove the soluble nitrates needed to support top growth, leaving behind the arsenical compounds to inhibit bluegrass growth.

Investigators disagree as to the site of action of arsenicals. According to Welton and Carroll (62) crabgrass seeds exposed for a certain period to lead arsenate failed to germinate because the embryo was damaged or killed. Crafts and Robbins (5) proposed that crabgrass failed to grow in arsenic-treated soils because the roots were killed upon contact with the herbicide. In the present study, imbibed crabgrass seeds were not killed when exposed to a PAX-water mixture prior to the time when the radicle broke the seedcoat. Germination was not reduced, and plants grew normally following treatment and rinsing to remove adhering arsenic. However, the radicle of seeds exposed to a PAX-water mixture were killed and death of the seedlings followed. In seedling plants exposed to a PAX-water mixture, initial injury was to the root hairs, followed progressively, as exposure time was increased, by injury to the root tip, the rest of the primary root, the epicotyl, and the plumule.

That the arsenates kill crabgrass only in early pre-emergence applications is generally accepted by turf specialists. Absorption, translocation, and accumulation of arsenic followed by death of seedling crabgrass plants was proposed by Daniel (10) and Daniel and Lee (11). With annual bluegrass, another grassy lawn weed susceptible to arsenic injury, Daniel (8) had noted that seedling roots were confined only to the 1-inch layer of topdressing which had been placed above an arsenic-treated soil surface. In the present study, established crabgrass plants grew and matured with surface treatments of PAX at 25 lb/1000 sq ft rate surrounding the plants. However, the stolons failed to root in the treated soil but did root in the untreated controls. The inhibitory action of PAX to roots was shown also when PAX was applied as a subsurface layer. In pots treated this way, roots were confined to the untreated soil above the treated layer. Roots did not penetrate soil layers containing PAX. Crabgrass plants growing in such PAX-treated soils showed symptoms similar to those expected under a nitrogen deficiency. Injury to the roots, fewer roots, or smaller quantities of available nutrients in the restricted soil area in which the roots grew could have contributed towards a nitrogen deficiency. The main action of PAX in crabgrass control appeared to be on the root system which was injured and killed upon contact with arsenic. This is in agreement with the findings of Crafts and Robbins (5) with crabgrass, and Daniel (8) with annual bluegrass. It does not appear that the arsenic accumulates sufficiently within established seedling crabgrass plants to cause their death as reported by Daniel (10) and Daniel and Lee (11).

SUMMARY

"PAX Ar-76 with chlordane," a proprietary crabgrass control herbicide, and its major components were studied in applications made to established Kentucky bluegrass and in pre-planting applications to lawn seedbeds.

Residual crabgrass control for three or more years was obtained from PAX applied at 25 lb/1000 sq ft to an established lawn. Crabgrass control of 90 to 98% was observed with no visible injury to the bluegrass. However, PAX or the arsenical compounds applied to established bluegrass sod growing in flats reduced stands, top growth, and root development. Increasing reductions occurred with increased rates of the herbicides. The nitrogen present in PAX tended to minimize the reduction in top growth caused by the arsenical compounds in the PAX. After the nitrogen in the PAX was depleted, growth was similar to that in comparable arsenical treatments.

The principal effect of heavy leaching was removal of nitrogen compounds, leaving behind the arsenic to inhibit bluegrass growth. Less than 6% of the toxic materials in either PAX or similar levels of arsenical compounds had moved into the subsurface layers below the 1/2 inch depth in soil columns after leaching with up to 16 inches of water.

Incorporation of PAX at rates of .8 to 25 lb/1000 sq ft in the top inch of colluvial loam soil prior to seeding bluegrass did not significantly reduce top growth. Turf grasses planted in a prepared seedbed following application of PAX suffered excessive competition from weeds other than crabgrass. Such competition

delayed turf grass development in the first season. However, dense stands of bluegrass and bentgrass were observed the following season.

The effects on bluegrass stands of a preplanting application of PAX at 25 lb/1000 sq ft varied with soil type and date of planting. On a loamy soil, no significant reductions in stands occurred regardless of date of planting. However, on a clay soil significant reductions in stands occurred when plantings were made immediately following the PAX applications or 2 weeks later. On a sandy soil, significant stand reductions occurred only when plantings were made on the date PAX was applied.

Bluegrass seeds planted immediately following application of PAX at 50 and 100 lb/1000 sq ft were delayed in germination for a period of 12 weeks after which they germinated and grew normally. Seeds planted one month after PAX at the rate of 400 lb/1000 sq ft had been applied and had killed all original vegetation, grew, and developed a dense sod.

Imbibed crabgrass seeds having intact seedcoats were not killed by a PAX-water mixture. However, seedlings showing radicles were killed by the same treatment. Older seedlings exposed to a PAX-water mixture first showed root hair killing. As the exposure time was increased, root hair injury was followed successively by injury to the root tip, the remainder of the primary root, the epicotyl, and finally the plumule.

Roots of established crabgrass plants did not penetrate a PAX layer, nor did adventitious roots grow in PAX-treated soil. Established crabgrass plants did not absorb and accumulate sufficient arsenic during a five-month period to kill the plants. The lethal action of the arsenicals was found to be due primarily to injury to the root system of both crabgrass and bluegrass plants.

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Appendix
Table A. Variances for crabgrass stands from a single application of PAX over a four-year period

Source of variation	D. F.	Crabgrass stands
Replications (R)	2	197.49
Treatments (T)	1	1816.56
Error a	2	195.20
Years (Y)	3	101.31
R x Y	6	45.22
T x Y	3	96.54
Error b	6	44.74

Table A-1. Crabgrass plants /sq ft in each replication of two treatments

	PAX-treated			Untreated		
Year	I	II	III	I	II	III
1958	0.6*	0.3	0.0	4.7	48.7	26.3
1959	1.0	0.0	0.3	5.0	9.0	8.3
1960	0.3	0.7	0.7	3.0	26.7	21.7
1961	0.7	1.7	2.3	16.7	23.0	24.3

*Each value is the mean count of three 1 sq ft areas in each plot.

Appendix
Table B. Variances of crabgrass stands over a four-year period from a single application of three PAX treatments and the untreated control in bluegrass sod growing in flats

Source of variation	D. F.	Crabgrass stands
Replications (R)	11	3171.70
Treatments (T)	3	259718.27**
Error a	33	2948.26
Years (Y)	3	127661.77**
Y x R	33	2746.25
Y x T	9	125598.47**
Error b	99	2715.60

Appendix
Table C. Variances of crabgrass stands over a four-year period from a single application of three PAX treatments made to bluegrass sod growing in flats

Source of variation	D. F.	Crabgrass stands
Replications (R)	11	82.65
Treatments (T)	2	1494.01**
Error a	22	72.62
Years (Y)	3	52.55*
Y x R	33	9.37
Y x T	6	47.80*
Error b	66	16.04

Appendix
Table D. Variances for dry weight of turf grass clippings harvested on three dates following seeding on PAX-treated soils

Source of variation	D. F.	Variances for dry weights (grams) of clippings taken at indicated intervals after seeding			Cumulative data for 3 dates
		6 weeks	10 weeks	13 weeks	
Replications	3	.10	.14	.03	.10
Treatments	6	.19	.21	.17	.27
Error	18	.10	.14	.10	.11

Appendix
Table E. Variances of bluegrass stands (ratio of treated to untreated) in pots of three soil types seeded 0, 2, 6, or 12 weeks after application of PAX at 1x rate

Source of variation	D. F.	Percent Bluegrass stands
Replications (R)	3	2243.40
Dates (D)	3	14016.91**
Soils (S)	2	8825.65**
D x S	6	8296.42**
R x S	6	1200.79
Error	27	1418.48

Appendix
Table F. Variances for crabgrass and other weeds stands in a prepared seedbed with three PAX treatments applied prior to four seedings of three basic turf grasses

Source of variation	D. F.	Stands: Crabgrass	Stands: Other weeds
Replications (R)	3	1435.02	13949.15
Treatments (T)	3	21402.87**	393078.34**
Error a	9	1737.36	10310.67
Seedings (S)	3	321.38	39422.87*
Error b	9	357.17	10316.88
T x S	9	120.26	14204.58
Error c	27	394.04	11758.55
Grass type (G)	2	51.66	91.13
G x T	6	21.25	456.35
G x S	6	111.64	787.14
G x T x S	18	97.23	1201.33
Error d	96	75764.69	1175.43

Appendix
Table G. Variances for visual ratings of crabgrass control in established turf four months after application of PAX, N, or PAX plus N at various rates

Source of variation	D. F.	Ratings
Replications	3	1.52
Treatments	8	49.67**
Error	24	1.50

Appendix
Table H. Variances for visual ratings taken three days after herbicide treatments were applied to Kentucky bluegrass sod

Source of variation	D. F.	Ratings
Replications	3	0.05
Treatments	13	27.57**
Error	39	0.38

Appendix

Table I. Variances for dry weights of bluegrass clippings on each of eight dates and total weights after treatment with four rates each of PAX and ammonium sulfate and five rates of arsenicals

Source of variation	D. F.	Weights of clippings on:								Total Weights
		3/15	3/30	4/15	5/2	5/18	6/2	6/17	7/4	
Replications	3	1.07*	6.26*	11.46*	2.13	11.45*	12.26**	6.91**	18.32**	36.36**
Treatments	13	4.10**	22.97**	23.39**	30.22**	28.70**	36.86**	42.10**	75.34**	175.84**
Error	39	0.27	1.92	0.62	1.54	1.14	1.25	1.02	2.50	1.55

Appendix
Table J. Variances for bluegrass stands and dry weights of roots after treatment with four rates each of PAX and ammonium sulfate, and five rates of arsenicals. Measurements were taken four months after applications were made.

Source of variation	D. F.	Stands	Dry weights of roots
Replications	3	1194.79	155.70
Treatments	13	53216.75**	990.70**
Error	39	1133.43	81.53

Appendix
Table K. Variances of weed percentages in flats of bluegrass treated four months previously with four rates each of PAX and ammonium sulfate and five rates of the arsenical compounds

Source of variation	D. F.	Weed percentages
Replications	3	1.21
Treatments[1]	9	61.84**
Error	27	0.80

[1]Four treatments were excluded from the analysis since they had no weeds.

Appendix
Table L. Variances for dry weights of bluegrass growth over a two-week period from flats treated with four PAX rates followed by heavy or regular watering practices. Clippings were taken seven and fourteen weeks after herbicide application.

Source of variation	D. F.	Dry weights (grams) 7 weeks	14 weeks
Replications (R)	3	2.34**	1.95
Treatments (T)	4	11.72**	7.91**
Waterings (W)	1	1.64	25.76**
T x W	4	.58	5.24*
Error	27	.43	1.36

Appendix

Table M. Variances of stands and dry weights of top growth of crabgrass plants from 50 seeds planted on soil slices from various depths in soil columns, surface-treated with herbicides and leached with distilled water

Source of variation	D. F.	Plant stands (number)	Dry weight (mg)
Replications (R)	3	151.71**	21877.58**
Soils (S)	1	543.75**	586199.47**
Treatments (T)	6	256.42**	4955.90
None vs chemicals	1	96.96	21121.72*
PAX vs As	1	976.50**	1354.69
PAX	2	194.20*	2709.40
As	2	38.34	920.10
S x T	6	70.72*	773.47
Error a	39	27.59	3694.79
Depths (D)	3	164.29**	31888.23**
D x S	3	34.77	3584.12**
D x T	18	42.72	1884.00**
D x S x T	18	30.58	2459.92**
Error b	126	28.01	628.65

Appendix
Table N. Variances for dry weight of tops and roots of established crabgrass plants to two placements of PAX at 1x rate and ammonium sulfate at the same rate

Source of variation	D. F.	Dry weights (mg)	
		Tops	Roots
Replications	5	12327.24	159.57
Treatments	3	53202.71**	1194.37**
Error	15	6871.12	57.24