1-1-1964

Influence of soil aeration on the growth of three grass species.

D. V. Waddington
University of Massachusetts Amherst

Recommended Citation

Waddington, D. V., "Influence of soil aeration on the growth of three grass species." (1964). *Doctoral Dissertations 1896 - February 2014*. 5860.
https://scholarworks.umass.edu/dissertations_1/5860

INFLUENCE OF SOIL AERATION ON THE GROWTH OF THREE GRASS SPECIES

by

Donald V. Waddington

B.S. Pennsylvania State College
M.S. Rutgers University

A Thesis

Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Doctor of Philosophy

University of Massachusetts, Amherst.
May 1964

TABLE OF CONTENTS

INTRODUCTION

Normal growth of many plants is dependent on adequate soil aeration. Soil compaction and excessive soil moisture may create unfavorable oxygen and carbon dioxide concentrations in the soil which could hinder plant growth. In compacted soils normal root growth may be further restricted by mechanical impedance. Information concerning the oxygen needs and carbon dioxide tolerances of plants, whether concerned with these gases individually or with their combined effects, should be useful in determining the soil management practices which will improve or provide temporary relief of unfavorable aeration conditions. Knowledge of critical levels of aeration would be helpful in evaluating the potential value of land which could be drained or altered to facilitate wider use. Also, such data would aid in the choice of plant species for use in areas where poor soil aeration is a limiting factor.

The effects of soil physical properties on plant growth are of concern to individuals in all phases of agriculture. Grass covered areas, whether pastures, hay fields, or specialized turf areas, are often subject to excessive compaction which adversely affects grass growth. Depending on the use of the area, compaction may be brought about by grazing animals, machinery, and man. Special aerification equipment has been used to reduce the effects of compaction on specialized turf areas. Poor performance and shallow root systems of grass growing on compacted soils could be due to mechanical impedance to root growth, unfavorable gaseous concentrations in the soil atmosphere and water, and impeded movement of water and fertilizer into the soil. It is debatable which of these is the major cause of poor turf in compacted soil. There is need for research which will help to define critical levels of mechanical impedance and soil aeration for grass growth in order that the response of grass to compacted soils may be better understood.

The purpose of the investigations reported and discussed in this thesis was to determine the effects of limited soil aeration on growth of three grass species: Agrostis palustis Huds., Eleusine indica (L.) Gaertn., and Poa pratensis L. These experiments were planned so that aeration, and not mechanical impedance or fertility, would be the limiting factor in the growth of the grass plants.

LITERATURE REVIEW

General Considerations

The Terminology Committee of the Soil Science Society of America (58) has defined soil aeration as: " The process by which air and other gases in the soil are renewed. The rate of soil aeration depends largely on the size and number of soil pores and on the amount of water clogging the pores. A soil with many large pores open to permit rapid aeration is said to be well aerated, while a poorly aerated soil either has few large pores or has most of those present blocked by water." Gaseous diffusion and concentration is dependent on various soil physical properties, including pore size, soil moisture tension, and size of aggregates (7, 13, 39, 64, 69). Baver (2) has stated that perhaps inadequate soil aeration is the most important factor limiting root development of plants.

There is ample evidence showing the need of oxygen in the root zone and the harmful effects to plant growth when supplies are lacking. These effects have been shown in solution and sand cultures (20,25,27) as well as in soil. Oxygen supply in the soil has been shown to affect the growth and yield of many plants, including peas (12), tobacco (25), cotton (44, 45), sunflowers (44, 45), green beans (44), snapdragons (43, 60), tomatoes (39), and sugar beets (3,70). Under limited oxygen supply, uptake of nutrients and water is often decreased. Reference to such studies will be made later.

The effects of carbon dioxide accumulation in poorly aerated soil have not received as much attention as the effects of oxygen deficiencies. It is the feeling of some workers that under field conditions oxygen will probably become too low before CO_2 becomes too high (15,35). Most studies concerning CO_2 in the root zone have been performed by passing various concentrations of CO_2 through solution and sand cultures. Work of this nature has established the fact that as the CO_2 content increases, the absorption of water and nutrients is reduced (10,23,25,34,65). Root respiration has been shown to decrease as CO_2 content increases (52).

Russell (57) mentioned a third factor which may be involved in poorly aerated soils, namely, the content of by-products of anaerobic decomposition such as hydrogen sulfide, methane, and hydrogen. He further stated that this factor had not been studied in any great detail, and that the effects of oxygen, carbon dioxide, and by-product gases have rarely been separated in field studies of root growth.

When poor aeration is a result of soil compaction, mechanical impedance may also be a factor in the growth and distribution of roots. Many observations have been made on the rooting habits of plants as affected by soil physical conditions, but in many instances an explanation of the exact causes of poor root growth has not been offered. Brown and Lacate (5) and Horton (29) have reported on the rooting habits of several species of pine trees. Studies have been conducted which show that root growth of various agronomic and vegetable crops is restricted in compacted soil (21,50,56,64,66,71). According to Flocker, et al.(19), the slowing of metabolic processes of plants grown in compacted soil may be attributed to one or a combination of several factors, including poor water utilization, restricted nutrient uptake, lack of oxygen, accumulation of CO_2, and mechanical impedance to root penetration.

Gill and Miller (21) developed an apparatus which permitted the simultaneous study of the effects of mechanical impedance and oxygen supply. They found that unimpeded roots slowed in growth when the oxygen concentration was below 10%, and that growth was more severely reduced on impeded roots. A distortion of the normal shape was noted on roots which met severe mechanical restraint. Phillips and Kirkham (54) concluded that mechanical impedance and not the lack of adequate aeration limited corn root growth in artificially packed soil. They also grew corn seedlings in sand contained in glass tubes of various diameters and demonstrated that even with very high levels of aeration, root growth is influenced by mechanical impedance. Wiersum (71) has also shown the importance of rigidity of pore structure in inhibiting root growth.

From the foregoing it must be concluded that root growth in compacted soils may be influenced by mechanical impedance and aeration, either individually or in combination with each other.

Oxygen in the Root Zone

As stated previously, the need for oxygen in the root zone is well established. Clements (11) and Peterson (53) have reviewed literature pertaining to the relationships between soil air, root activity, and plant growth. The amount of oxygen utilized during respiration varies depending on the plant (22,26,42), and the peak rate of respiration takes place in the root tips at the region of maximum cell division (22,42). Lemon (38) has presented a theoretical approach to the problem of sufficient oxygen for normal root respiration in soil. He has shown that the two factors concerned, oxygen "demand" of the root and oxygen supplying characteristics of the soil, are interdependent and cannot be separated. Lemon and Wiegand (42) considered the rate of oxygen consumption to be dependent on the characteristics associated with the genetic background and physiological age of cells, the rate of delivery of reactants to or removal of products from the loci of reaction, and the rate of reaction at the loci.

Differences in tolerance to limiting oxygen supply have been shown by Cannon (9), who measured root elongation of plants grown with the roots exposed to various oxygen concentrations. He noted that species which naturally occur where the soil may be puddled or water saturated all or part of the year, exhibit a greater tolerance to oxygen deficiency, and that no species requiring a high percentage of oxygen for root growth has been found to occur in areas where the substratum is saturated part of the year. For instance, _Juncus effusus_ and _Nasturtium officinale_ (water cress) were found to be tolerant of low oxygen, whereas _Medicago sativa_ (alfalfa) was not. Russell (57) reported that rice, buckwheat, and some willows grow well when the air supply in the root zone is restricted, while tomatoes, and possibly peas and corn, need a very good air supply. Edminster and Reeve (15) stated that plants normally grown on well-drained and aerated soils usually are most sensitive to low oxygen levels, and that those plants which tolerate long periods of little oxygen have special tissues in their stems and roots that can conduct oxygen to the roots. Gas spaces in roots of rice plants constitute 5-30% of the root tissue, whereas in barley roots they constitute less than 1% of the volume (1). High soil moisture has been shown to favor the development of large intercellular spaces in grass roots (63) and grass leaves (51). Grass species which grow best on wet or moist soils have larger intercellular spaces than those grasses found on drier sites, and deeper rooted grasses have larger spaces than shallow rooted grasses (33). The movement of oxygen through the air spaces of various plant species has been measured using the short-lived radio-isotope oxygen-15 (1,17).

The uptake of water and nutrients is often decreased by conditions of poor aeration. An adequate supply of oxygen is needed for both cation and anion absorption (27). Harris and van Bavel (25) found that nutrient uptake by tobacco plants was relatively constant until the oxygen content dropped below 10%. They reported that the sensitivity of several nutrients to decreasing oxygen and increasing CO_2 contents seems to be $K > N > P > Mg \geq Ca$. Letey, et al. (43) reported that increasing oxygen concentration brought about increases in phosphorus and potassium content and a decrease in sodium content of snapdragon plants. Similar results were reported for sunflower (47), Kentucky bluegrass (46), and barley (48). Calcium and phosphorus accumulation in sunflowers and cotton plants was stimulated by increasing soil oxygen supply (45). Lawton (36) reported that absorption of potassium by corn is more dependent on aeration than is the uptake of N, Ca, Mg, or P. Hopkins, et al. (28) found that potassium and phosphorus uptake was affected the most by oxygen supply. Cline and Erickson (12) found that nitrogen, phosphorus, and potassium contents of pea plants increased with increasing soil oxygen supply, and that calcium and magnesium tended to increase at low oxygen supplies. It is of interest to note that the work of Chang and Loomis (10) shows that potassium uptake was affected the greatest by increasing the carbon dioxide content. They ranked the nutrients in order of reduced uptake as being K > N > P > Ca > Mg. Studies using labeled elements have indicated that the reduction in nutrient uptake occurs immediately when the plants are subjected to poor aeration (25,28). Decreased oxygen content, like increased carbon dioxide content (10,34), will decrease the water uptake by plants (24,43,44). Water absorption is usually reduced more rapidly by a high concentration of carbon dioxide than by a low concentration of oxygen (35). Letey, et al.(44) mentioned that plants in waterlogged soils are ineffective in correcting this soil condition because transpiration is reduced in these plants.

The level of plant nutrients in the root zone has been observed to affect the ability of plants to withstand poor aeration. Woodford and Gregory (74) found that growth of plants in unaerated solutions was increased when the nutrient concentration was four times that required for plants grown in aerated solutions. Cline and Erickson (12) reported that increased fertilizer rates partially reduced the effects of low oxygen supply. Wiegand and Lemon (69) discussed the addition of fertilizer to overcome the effects of poor structure, and listed more root growth and higher concentration of nutrients as factors which may be involved. They also mentioned that in cases where a higher concentration of nutrients is the only factor involved, enough water may not be available to get the benefit of the added nutrients. Applications of fertilizer have been shown to reduce the oxygen content in soils, probably due to increased microbial activity (4). Gilbert and Shive (20) reported that nitrate absorption is high under low oxygen conditions, and the reduction of nitrate in root tissue releases oxygen which can supplement the external oxygen source. Wiersma and Mortland (70) have obtained results which indicate that fertilization with calcium peroxide may decrease the harmful effects of low oxygen diffusion.

The appearance of roots often varies according to soil aeration conditions, for example, more lateral roots with good aeration (67), longer and more branched roots on aerated plants (74), unaerated roots greater in diameter (8), coarser roots and fewer lateral roots under low oxygen supply (12), and fewer root hairs at low oxygen concentrations (9). The presence of roots in the soil has been shown to increase the diffusion rate of oxygen; this increase being attributed to discontinuous air spaces in the soil being made continuous by the penetrating roots (31). Other work has shown that oxygen can be transported through growing corn roots (32).

Lemon and Weigand (42) reported that when oxygen is plentiful in the root zone, the rate of oxygen utilization is dependent on the substrate supply; but when the oxygen concentration is below a certain critical level, the rate of oxygen uptake is controlled by diffusion. Wiegand and Lemon (69) concluded that the apparent diffusion path length in the liquid phase about the roots is more often a limiting factor in normal root respiration than is the gaseous composition in the soil pores. Other workers have emphasized that rate of supply or movement to roots is of greater importance than the oxygen concentration (9,30,62).

Gaseous diffusion and permeability in soils has been measured in various ways. Hutchins (30) buried porcelain cones in the soil, used an oxygen free gas to sweep diffused oxygen to an indicator, and observed the time required to obtain a color change in the indicator. Blake and Page (6) placed a weighed porous cup containing carbon disulfide into a hole in the soil, sealed the surface, and after a waiting period removed and reweighed the cup to determine the amount of carbon disulfide vapor which had diffused into the soil. Taylor (62) and Raney (55) measured oxygen diffusion by first flushing out a diffusion chamber with nitrogen and then allowing air to diffuse through the soil into the chamber. The change in oxygen content was measured with a Beckman Oxygen Analyzer. Some air permeability measurements are dependent on the flow of gas under a pressure gradient. Permeameters of this type have been described by Evans and Kirkham (16) and Tanner and Wengel (61). Diffusion of oxygen through soil has been measured by using oxygen labeled with oxygen-18 (31). Lemon and Erickson (39) and others, who will be mentioned later in the discussion, utilized platinum microelectrodes to measure oxygen diffusion. Willey and Tanner (72) have described an oxygen probe which utilizes a polarographic electrode in the measurement of oxygen concentration in the soil. A similar electrode has been used to measure plant tissue respiration (49).

The platinum microelectrode technique is now commonly used to characterize soil aeration conditions. The principle of this method has been presented by Lemon and Erickson (40). The major components of the apparatus used for this measurement are a platinum cathode, an anode such as a saturated calomel or Ag - AgCl electrode, a voltage source, and an ammeter to read current flow. A voltage is applied between the platinum cathode and the anode, and this results in the electrolytic reduction of oxygen at the cathode. After an initial surge of current due to the reduction of the oxygen around the electrode, the current decreases to a point where it is governed by the rate at which oxygen diffuses to the electrode from the surrounding soil solution. Electrons for the reduction are released from the anode. In the case of the Ag - AgCl anode, the chloride ion is oxidized to form silver chloride. The reaction at the cathode has been expressed as follows: $O_2 + 2H_2O + 4e \rightarrow 4OH^-$ (72).

The current, i, in amperes, flowing at time, t, in seconds, has been expressed as $i_t = nFAf$ where n = the number of electrons used per molecule of oxygen electrolyzed, F = faraday (96,500 coulombs), A = area of electrode surface in sq. cm., and f = flux at the electrode or the number of moles of oxygen diffusing to the electrode per second at time, t (40). The oxygen flux or diffusion rate to the electrode has been frequently expressed as grams x 10^{-8}/cm.^{2}/min.

The entire electrode must be moist during operation of the platinum electrodes (40). Lemon and Kristensen (41) reported that the volume of water necessary for diffusion measurements is 30% of the soil volume. They stated that below this moisture content current decreases may be due to a break in water film around the electrode or due to low hydroxyl ion diffusion away from the electrode. The values of oxygen diffusion measured are dependent on the liquid diffusion path length which is affected by variations in soil moisture and soil structure (39,41).

The platinum microelectrode technique has been used to establish critical values of oxygen diffusion for various plants. Oxygen diffusion rates below 20 to 30 x 10^{-8} grams/cm.^{2}/min. have reduced or stopped root growth of snapdragons (60), cotton (45), sunflowers (45,47), corn (4), Kentucky bluegrass (46), and sugar beets (70). Values below 30 to 40 x 10^{-8} grams/cm.^{2}/min. have reduced the growth rate and total green weight of tomato plants (39), and the critical rate for growth and yield of peas has been reported to be in the range of 70 to 100 x 10^{-8} grams/cm.^{2}/min. (12). Timothy, bronzegrass, and reed canary grass were found to make good growth at values below 5 x 10^{-8} grams/cm.^{2}/min. (18). A rate of 15 x 10^{-8} grams/cm.^{2}/min. was found to be critical for root growth of barley, and a rate of 40 x 10^{-8} grams/cm.^{2}/min. was optimum for shoot growth (48). Values of 15 x 10^{-8} grams/cm.^{2}/min. have appeared to be adequate for maximum growth of soybeans, corn, cabbage, and sorghum (73).

Judging from the amount of information being published on the subject, interest in soil aeration seems to be on the increase. One may expect that future research findings will contribute much toward a better understanding of soil aeration problems.

METHODS AND MATERIALS

General

The soil used in these experiments was a Hadley very fine sandy loam, 46.2% sand, 48.1% silt, and 5.7% clay, modified by the addition of 1 part calcined clay to 3 parts soil by volume. This mixture gave a wide range of oxygen diffusion rates when the soil moisture tension was varied from 0 to 100 cm. of water. In the first three experiments oxygen diffusion was varied by subjecting the soil to different soil moisture tensions. In the fourth experiment the soil was subjected to nitrogen-air mixtures of various oxygen concentrations in order to obtain different oxygen diffusion rates.

Soil moisture tension was varied by the use of tension tables. The construction and use of this type of apparatus has been described by Leamer and Shaw (37). The tables consisted of 18" x 24" x 1/4" thick plexiglas trays with reinforcing ribs on the base, a 3/8" inner rib on all four sides, and a center drain. Ordinary window screen and desk blotters were used on the surface. In cases where extremely wet conditions were required, galvanized trays, measuring 18" x 24" x 3" high, were used in order to raise the water level above the base of the soil containers. The soil moisture tension values used throughout are in reference to the 1½ inch depth at which oxygen diffusion measurements were made.

The soil containers used for the experiments in which soil moisture was a variable were cast acrylic cylinders, 5½" O.D. x 5 1/8" I.D. x 6" long. The bottoms were covered with several layers of cheesecloth attached with rubber bands.

In experiment 4, oxygen diffusion rates were varied by changing the gaseous concentration around the soil. Various oxygen concentrations were obtained by feeding compressed air and nitrogen into a manifold having a series of needle valves for adjustment of the mixtures. A diagram of the apparatus used for growing plants in this experiment is shown in figure 1. Individual plants were transplanted through a piece of rubber tissue into 1 1/4" I.D. x 6" long plastic tubes. Six 1/4" holes were drilled through these tubes one inch from the top, and were covered with plastic window screen to prevent soil loss. These holes permitted diffusion into each tube. The tops of the tubes were sealed with rubber tissue held in place by rubber bands. Large cylinders, like those mentioned in the previous paragraph, were covered with cheesecloth on the bottom and about 1/2 inch of soil was added. The tubes were placed in this soil with about 1/4 inch of the tubes projecting from the tops of the cylinders, and then soil was packed around the tubes to a depth of about three inches. Rubber tissue was placed over the top of the cylinders with only the plants projecting. Rubber cement was used to seal this tissue to the rubber tissue on the tubes. The rubber tissue was secured over the cylinder with a rubber band. The gas mixtures were bubbled through water before being introduced into the cylinders. Connections were made using rubber and glass tubing. A flow rate of approximately nine liters per hour was maintained. The oxygen concentrations were checked using a Beckman 777 Oxygen Analyzer.

Oxygen diffusion was measured periodically by using the platinum microelectrode technique (39). The microelectrodes were 4 mm. long and 0.8 mm. in diameter. Readings taken below the 1 1/2 inch depth were made at the conclusion of each experiment so that root growth would not

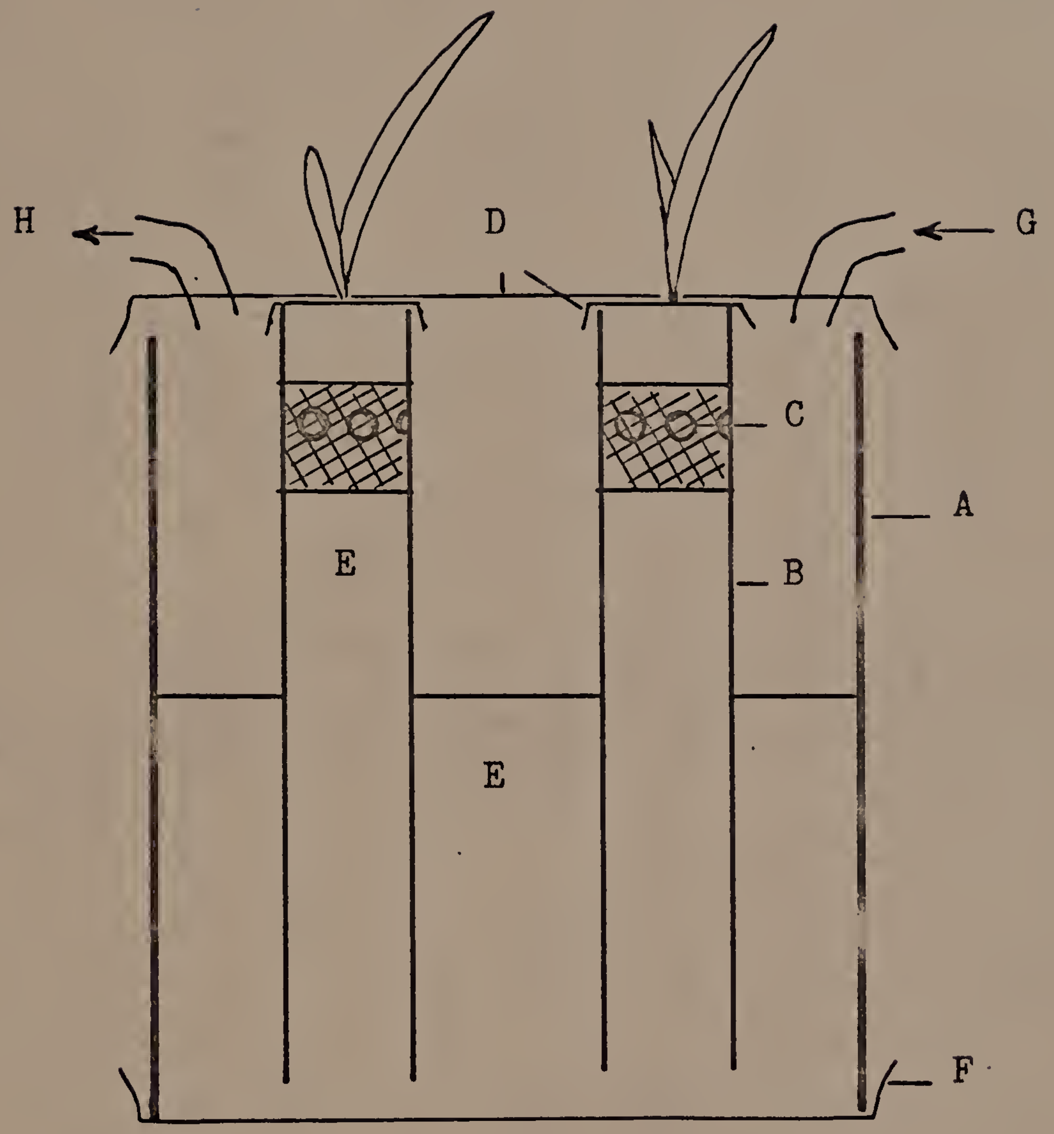


Figure 1. Cross section of the apparatus used for the growth of plants in experiment 4; (A) plexiglas cylinder, (B) plastic tube, (C) screen covered holes, (D) rubber tissue, (E) soil, (F) cheesecloth, (G) gas inlet, and (H) gas outlet.

be influenced by the holes made by the electrodes. The number of electrode readings to characterize each depth is shown in the results. Erratic readings were eliminated in the calculation of oxygen diffusion rates.

Three grass species were used as the test plants. Seed of Penncross creeping bentgrass (*Agrostis palustris* Huds.) and Merion Kentucky bluegrass (*Poa pratensis* L.) was purchased commercially, and seed of goosegrass (*Eleusine indica* (L.) Gaertn) was harvested from mature plants of this species. Creeping bentgrass and Kentucky bluegrass, both perennial grasses, were chosen for these studies because of their difference in soil adaptation. Kentucky bluegrass is best adapted to moist, well-drained loams or clay loams. On the other hand, creeping bentgrass prefers moist or wet soil and grows aggressively in marshes. Goosegrass is an annual grass, and in literature is referred to as a common weed found in waste places, farm yards, roadsides, fields, and lawns. Very little, if any, has been written concerning its soil preference. The author has observed this species growing in dry, hard, compact soil on and along paths and along roadways where no other plant species will persist. Goosegrass seed used in these experiments came from a near pure stand of goosegrass which was growing luxuriantly in a wet, compact soil in front of a cattle watering trough. It cannot be concluded that goosegrass prefers these heavily traveled and compacted soils; however, it is definitely more tolerant of these conditions than many other grass species, including creeping bentgrass and Kentucky bluegrass.

Except for experiment 3, all experiments were conducted under greenhouse conditions.

Experiment 1 (Greenhouse conditions)

Grass was seeded at the rate of 20 seed per square inch on September 14, 1962. Three replicates were included for each treatment. Soil moisture tensions of 102, 82, 62, 42, and 17 cm. of water were applied on October 26, and on November 1 the grass was clipped to a uniform height. The bentgrass was cut at a 3/4 inch height, and the bluegrass and goosegrass were cut at 1 1/2 inches. Measurements of clipping yield were made biweekly with the final clipping being on January 9, 1963. Fresh weights were measured at clipping time, and these were converted to dry weights from moisture data on the three reps for that treatment. On each clipping date the grass was fertilized with a liquid application of "Fer-Mel 24-12-12" at a rate equivalent to two pounds of dry fertilizer per 1000 square feet. Oxygen diffusion rates were measured biweekly. At the conclusion of the experiment the roots were washed and observations were made. The roots were divided into three portions according to depth, blotted on paper towels, and weighed to obtain fresh weight.

Experiment 2 (Greenhouse conditions)

In this experiment twenty-one seedling plants were transplanted into each cylinder, the bluegrass and bentgrass on January 24, 1963, and the goosegrass on February 8. Soil moisture tensions were lowered in this experiment, and the cylinders in two treatments were sitting in pans of water. The tensions were 62, 42, 24, 11, and 4 cm. of water. Treatments were started on the bluegrass and bentgrass on February 14. Treatments on the goosegrass were begun at a later date, March 14, due to a very slow start in growth after transplanting. The grass was clipped weekly until the experiment ended on April 4. Yield data for bluegrass and bentgrass were taken five times beginning with the March 7 clipping, and for goosegrass the final two clippings were used for yield measurements. The grass was fertilized biweekly at the same rate used in the first experiment. On April 4, roots of one replication were washed for observation. The roots were divided according to three depths, 0-2, 2-4 and 4-6 inches, and were dried to obtain dry weights. The two remaining replicates were held for experiment 2A.

Experiment 2A

Two replicates from each treatment in experiment 2 were subjected to a tension of 11 cm. of H_2O which corresponded to treatment 4 of experiment 2. Clipping was continued on a weekly basis, and fertilization remained biweekly. Clipping yield was measured to see whether a sudden change to very wet conditions would be reflected in the top growth of the treatments previously held at higher moisture tensions. This experiment lasted for five weeks until May 9. At this time root observations were made, and root yield data were collected from the bluegrass.

Experiment 3 (Growth room conditions)

Experiment 3 was a repeat of treatments 1, 2, 4, and 5 of experiment 2. Ten plants were transplanted into each cylinder on June 14,

1963. Three replications were used per treatment; however, one was discarded halfway through the experiment after being washed for root observations, which were inconclusive due to poor growth. Treatments were started on July 5, and the experiment ended on September 9. The grass was clipped and yields measured five times during the experiment. Top growth was quite poor in the growth room, and fertilizer was applied on only two occasions. The light intensity was about 1000 ft. candles, and the daylight period was 14 hours per day. The temperature was about 68° F at night and rose to about 75°F during the daylight period. The relative humidity was usually in the range of 60 to 70 percent.

Experiment 4 (Greenhouse conditions)

In this experiment oxygen diffusion was varied by subjecting the soil to nitrogen-air mixtures having oxygen concentrations of approximately 0, 1, 8, and 21%. The apparatus used was described earlier in this section. Tomato plants were used in this experiment as well as the three grass species. Two goosegrass plants and three plants of the other species were grown under each treatment. All plants were transplanted, and about one week was allowed before subjecting the plants to the treatments. The leaves and roots were cut off to lengths of approximately one inch prior to transplanting. Treatments were begun on January 18, 1964, for the grasses and on January 21 for the tomato plants. The cylinders were placed on tension tables adjusted at 42 cm. of H_2O. All plants were fertilized on January 29 and again on February 20 at the rate mentioned for experiment 1. The bluegrass and bentgrass were cut on February 19 and March 12. The goosegrass top growth was quite slow and no clipping was done on this grass. The experiment was concluded on March 12. The cores of soil were forced out of the tubes, the roots were washed, and the depth of rooting was observed. Oxygen diffusion measurements were made on the last day of the experiment by forcing the electrodes through the rubber tissue which had sealed the soil surface. Three electrodes were used in each tube, thus 33 readings were made for each treatment.

RESULTS

Whenever feasible, statistical analyses were used on the data obtained in the various experiments. Results of these analyses, along with more complete data, can be found in the appendix. In all cases each species was analyzed individually. Except in experiment 4, the cylinders were grouped in blocks, or outcome groups, according to clipping yields made prior to the grass being subjected to the various treatments. Duncan's new multiple range test (59) was used on treatment means, and where differences occurred, the results of this test are shown in the tables.

Experiment 1

Oxygen diffusion rates and average dry weight yields per clipping for the various treatments are shown in table 1. Oxygen diffusion rates varied from 13.4 to 37.0 x 10^{-8} grams/cm.^{2}/min. The difference in clipping yields for bentgrass and goosegrass were not significantly different over this range of diffusion rates. Bluegrass yields increased with the moisture level. The average fresh weight of roots from the various treatments are shown in table 2, and roots of one replicate are shown in figure 2. The weight of bentgrass roots in treatment 5 was significantly greater than the weights obtained for the other treatments. No significant differences due to the oxygen diffusion treatments existed in the root weights of the other two grass species.

Experiments 2 and 2A

By decreasing the soil moisture tension, it was possible to obtain

Table 1. Clipping yields of three grass species grown in soil having various oxygen diffusion rates. (Exp. 1)

Treatment	Soil moisture tension, cm. of H_2O	Ave. O_2 dif. rate at 1 1/2" g. x 10^{-8}/cm.^{2}/min. *	Ave. dry wt. yield per clipping, grams		
			Merion Ky. blue **	Penncross Cr. bent	Goosegrass
1	102	35.5	.19b	.41	.43
2	82	37.0	.19b	.36	.43
3	62	29.8	.22ab	.41	.38
4	42	26.5	.29a	.36	.42
5	17	13.4	.22ab	.36	.46

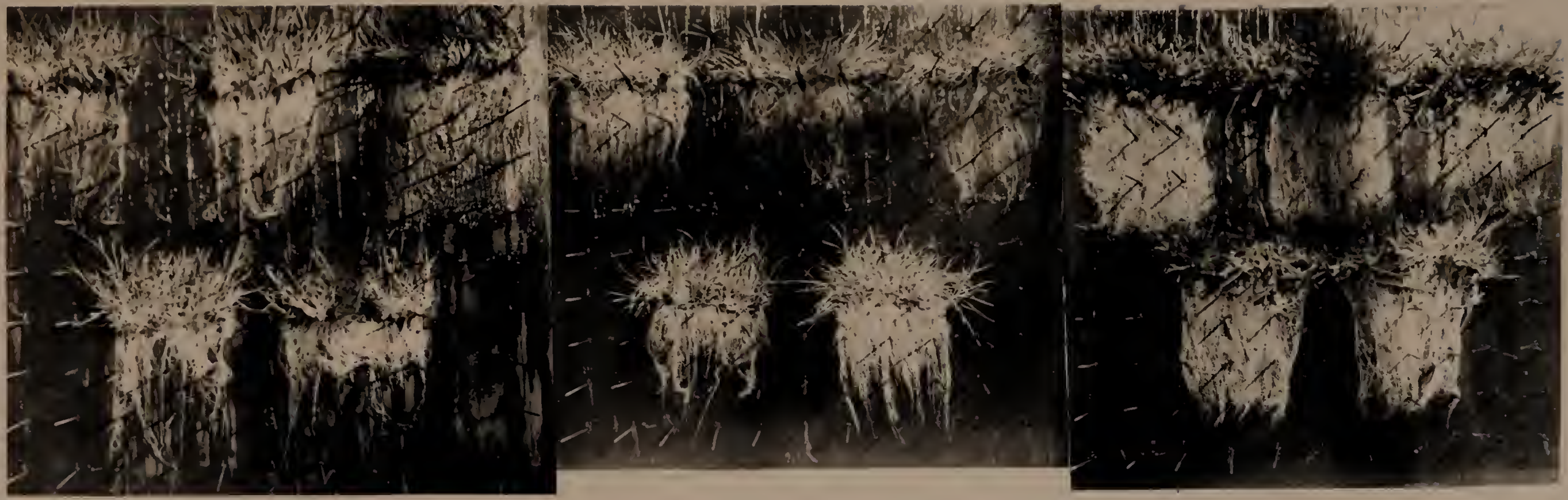
* Each value is the average of 270 electrode readings from six reading dates.

** Means followed by the same letter do not differ significantly at the.05 level using Duncan's new multiple range test.

Table 2. Fresh weight of roots from three grass species grown in soil having various oxygen diffusion rates. (Exp. 1)

		Fresh weight of roots from three reps at three depths, grams			
	Treatment	0-2"	2-4"	4-6"	Total
Merion Kentucky Bluegrass	1	11.0	1.9	0.5	13.4
	2	10.5	2.2	0.4	13.1
	3	11.4	2.9	0.4	14.7
	4	9.3	2.5	0.6	12.4
	5	8.8	1.9	0.2	10.9
Penncross Creeping Bentgrass	1	11.9	2.9	0.2	15.0b *
	2	8.2	1.3	0.1	9.6b
	3	10.6	2.7	0.8	14.1b
	4	13.6	2.3	0	15.9b
	5	17.2	7.1	1.0	25.3a
Goosegrass	1	30.1	12.3	5.4	47.8
	2	36.8	18.2	8.8	63.8
	3	42.0	25.4	14.0	81.4
	4	36.7	16.0	6.1	58.8
	5	43.1	14.7	4.6	62.4

* Values followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.



Merion Kentucky Bluegrass

Penncross Creeping Bentgrass

Goosegrass

Figure 2. Roots of three grass species grown at five soil moisture tensions in experiment 1. Treatments 1, 2, and 3 are across the top and treatments 4 and 5 are on the bottom for each species.

lower oxygen diffusion rates than those reported for experiment 1. The diffusion rates obtained at three depths are shown in table 3. Due to difficulty in inserting the electrodes, no values are reported for the lower depths in treatment 1. The clipping yields for experiment 2 are shown in table 3. Only the goosegrass yields showed significant differences due to treatment. It is doubtful whether this significance would have occurred had the goosegrass been grown for a longer period under these treatments. Table 4 shows clipping yield data for experiment 2A, in which two replicates of each treatment from experiment 2 were grown for five weeks at treatment 4 (11 cm. of H_2O tension). There were no significant differences in yields, Table 5 shows the weights of tops, rhizomes, and roots from one replicate of experiment 2. The major observation to be made on these data is the absence of bluegrass roots at the lower depths in treatments 4 and 5. Many bluegrass roots were noted at the soil surface in these two treatments. The root growth of bentgrass and goosegrass was not notably affected under these treatments. Root weights of one bluegrass replicate from experiment 2A are shown in table 5A. Restriction of root growth occurred in the 4 to 6 inch increment of all treatments, and placing the treatment 5 cylinder under treatment 4 conditions allowed more growth to occur in the 2 to 4 inch zone. Figure 3 shows the roots grown in experiments 2 and 2A.

Experiment 3

This experiment was only partially successful; however, the results are presented for inspection. Growth of all species was poor in the growth room. Striped smut disease was observed on all species and could

Table 3. Clipping yields of three grass species grown in soil having various oxygen diffusion rates. (Exp. 2)

Treatment	Tension, cm. of H_2O	Average O_2 diffusion rate, g. x 10^{-8}/cm.^{2}/min.			Ave. dry wt. yield per clipping, grams		
		1 1/2" *	3" **	4 1/2" **	Merion Ky. blue	Penncross Cr. bent	Goosegrass***
1	62	40.2	----	----	.23	.36	.44ab
2	42	33.2	30.0	22.5	.23	.31	.53a
3	24	13.7	10.8	8.5	.22	.33	.53a
4	11	12.6	11.2	8.6	.23	.32	.48ab
5	4	11.3	8.6	7.3	.23	.35	.36b

* Each value is the average of 135 electrode readings from three dates --- except treatment 1, 90 readings from two dates.

** Each value is the average of 90 electrode readings made at the conclusion of the experiment.

*** Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Table 4. Clipping yields of three grasses grown at 11 cm. of H_2O tension (treatment 4) after previously being grown at other levels of aeration (Exp. 2A)

	Ave. dry wt. yield per clipping, grams		
Previous treatment	Merion Ky. blue	Penncross Cr. bent	Goosegrass
1	.27	.26	.48
2	.25	.25	.44
3	.24	.26	.48
4	.28	.24	.40
5	.27	.24	.43

Table 5. Dry weights of top growth, rhizomes, and roots of plants grown at various treatments. (Exp. 2)
All weights in grams

Treatment	Tops	Rhizomes	Roots 0-2"	Roots 2-4"	Roots 4-6"	Roots Total
Merion Kentucky Bluegrass						
1	2.538	0.199	1.478	.421	.685	2.584
2	2.484	0.160	1.146	.359	.434	1.939
3	2.626	0.164	1.420	.386	.383	2.189
4	2.266	0.207	1.572	.475	Trace	2.047
5	1.987	0.085	2.170	Trace	Trace	2.170
Penncross Creeping Bent						
1	2.377	----	1.100	.340	.348	1.788
2	1.854	----	0.976	.184	.137	1.297
3	1.867	----	0.970	.318	.132	1.420
4	2.317	----	0.807	.325	.197	1.329
5	2.116	----	0.914	.174	.197	1.285
Goosegrass						
1	2.826	----	.982	.465	.528	1.975
2	2.765	----	.847	.552	.613	2.012
3	2.849	----	.790	.470	.520	1.780
4	2.397	----	.820	.455	.505	1.780
5	2.463	----	.927	.434	.482	1.843

Table 5A. Dry weights of top growth, rhizomes, and roots of Merion Kentucky Bluegrass grown at 11 cm. of H_2O tension (treatment 4) after previously being grown at other levels of aeration. (Exp. 2A)

			Roots			
Treatment	Tops	Rhizomes	0-2"	2-4"	4-6"	Total
1	4.286	.516	3.455	.724	.618	4.797
2	4.212	.563	3.573	.620	.537	4.730
3	4.268	.707	3.210	.582	.421	4.213
4	4.020	.770	2.065	.626	.092	3.683
5	3.820	.708	3.202	.344	.031	3.577

Merion Kentucky Bluegrass

Penncross Creeping Bentgrass

Goosegrass

Merion Kentucky Bluegrass
Exp. 2A

Figure 3. Roots of three grass species grown in experiment 2, and bluegrass roots from experiment 2A. Treatments 1, 2,and 3 are across the top and treatments 4 and 4 are on the bottom for each species.

be blamed somewhat for the lack of vigor of the plants. The bluegrass root growth was so poor that only one replication was washed and used for root weights. The bentgrass and goosegrass roots, as previously, showed good growth in soil having low oxygen diffusion rates. The results from this experiment are shown in tables 6 and 7. The washed roots from one replication are shown in figure 4. Clipping yields under the various treatments differed significantly only in the case of bentgrass, but these differences do not seem to relate to the intensity of treatments. Some factor other than the treatments may have caused this trend which also showed up in the other grasses. Possible causes could be disease or location of tension tables containing the various treatments.

Experiment 4

Sometime prior to the conclusion of this experiment (within the last two weeks) the oxygen concentration in treatment 3 was accidently lowered from 8% to 2%. The oxygen diffusion rates reported for this treatment reflect the influence of a 2% oxygen concentration; however, the plants were grown at the 8% level for the greater part of this experiment. The conclusions drawn from the whole experiment are not affected by the inaccuracy of this treatment. The oxygen diffusion rates at three depths for each treatment are shown in table 8. Table 9 shows the average root weights for each species and the average clipping yields for the bluegrass and bentgrass. Tomato root weight was significantly decreased in soil subjected to low oxygen concentrations. The top growth

Table 6. Clipping yields of three grass species grown in soil having various oxygen diffusion rates. (Exp.3)

		Ave. O_2 diffusion rate g. x 10^{-8}/cm.^{2}/min. *			Ave. dry wt. yield per clipping, grams		
Treatment	Tension, cm. of H_2O	1 1/2"	3"	4 1/2"	Merion Ky. blue	Penncross Cr. bent **	Goosegrass
1	62	----	----	----	.13	.18 ab	.14
2	42	29.3	29.4	24.3	.08	.14 b	.13
3	11	7.4	7.4	6.8	.11	.21 a	.17
4	4	6.0	4.1	3.4	.10	.17 b	.15

* Each value is the average of 60 electrode readings taken at the conclusion of the experiment.

** Values followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Table 7. Dry weight of top growth and roots of three grass species after 9 weeks at various treatments. (Exp. 3) All weights in grams.

Treatment	Tops	Roots 0-2"	Roots 2-4"	Roots 4-6"	Roots Total
Merion Kentucky Bluegrass (1 rep)					
1	.592	.439	.142	.094	.675
2	.545	.063	.103	.000	.166
3	1.086	.251	.157	.016	.424
4	.700	.326	.053	.000	.379
Penncross Creeping Bentgrass (Ave. of 2 reps)					
1	1.018	.263	.171	.172	.606 b *
2	.748	.166	.076	.050	.292 c
3	1.135	.293	.272	.308	.873 a
4	1.058	.325	.328	.244	.897 a
Goosegrass (Ave. of 2 reps)					
1	2.151	.538	.135	.142	.815
2	1.686	.335	.152	.173	.660
3	2.354	.543	.264	.160	.967
4	2.522	.586	.196	.116	.898

* Values followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Merion Kentucky Bluegrass Penncross Creeping Bentgrass Goosegrass

Figure 4. Roots of three grass species grown at four soil moisture tensions in experiment 3. Treatments 1 and 2 are across the top and treatments 3 and 4 are on the bottom for each species.

Table 8. Oxygen diffusion rates at three depths in soil subjected to various oxygen concentrations in the surrounding gaseous phase. (Exp. 4)

Treatment	Oxygen Concentration,%	Oxygen diffusion rate, g. x 10^{-8}/cm.^{2}/min. *		
		1 1/2"	3"	4 1/2"
1	0	3.1	2.6	2.5
2	1	2.7	2.3	1.8
3	8-2	3.1	2.2	2.2
4	21	14.6	18.6	19.5

* Each value is the average of 33 electrode readings.

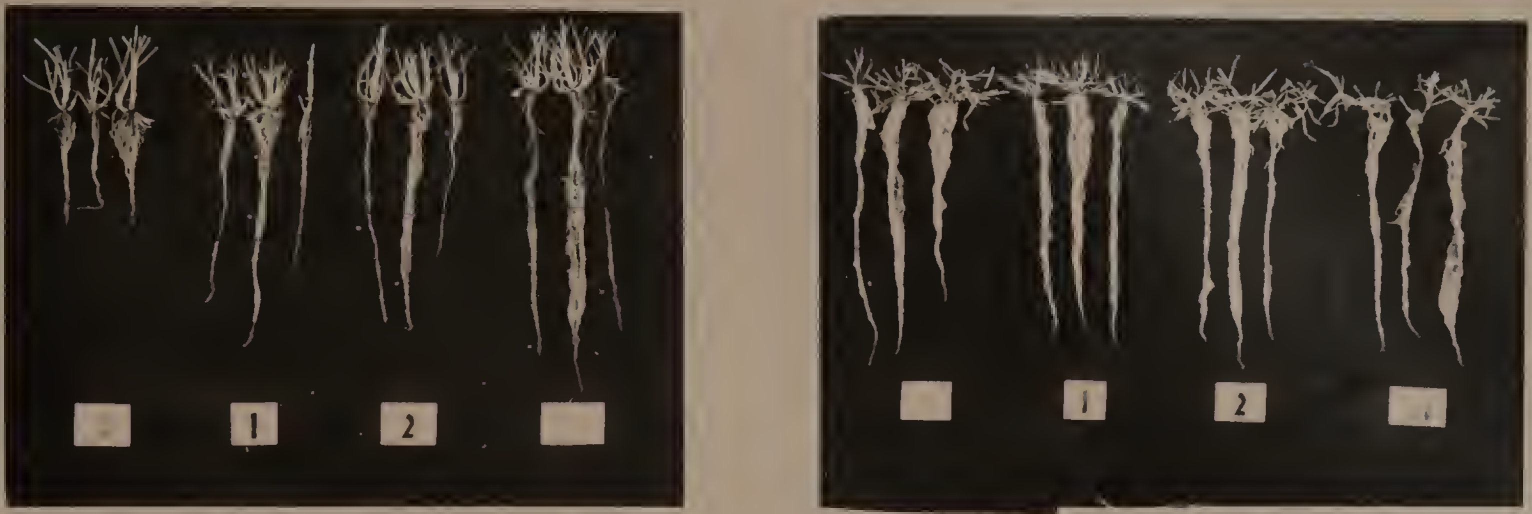
Table 9. Average dry weight root and clipping yields of plants grown in soil subjected to various oxygen concentrations. (Exp. 4) All weights in mg.

	Merion Kentucky Bluegrass		Penncross Creeping Bentgrass		Goosegrass	Tomato
Treatment	Roots	Clippings	Roots	Clippings	Roots	Roots
1	23	36	95	125 a *	142	107 a *
2	35	38	92	102 ab	126	123 a
3	32	41	87	78 bc	66	236 b
4	39	40	64	50 c	102	235 b

* Means followed by the same letter do not differ significantly at .05 level using Duncan's new multiple range test.

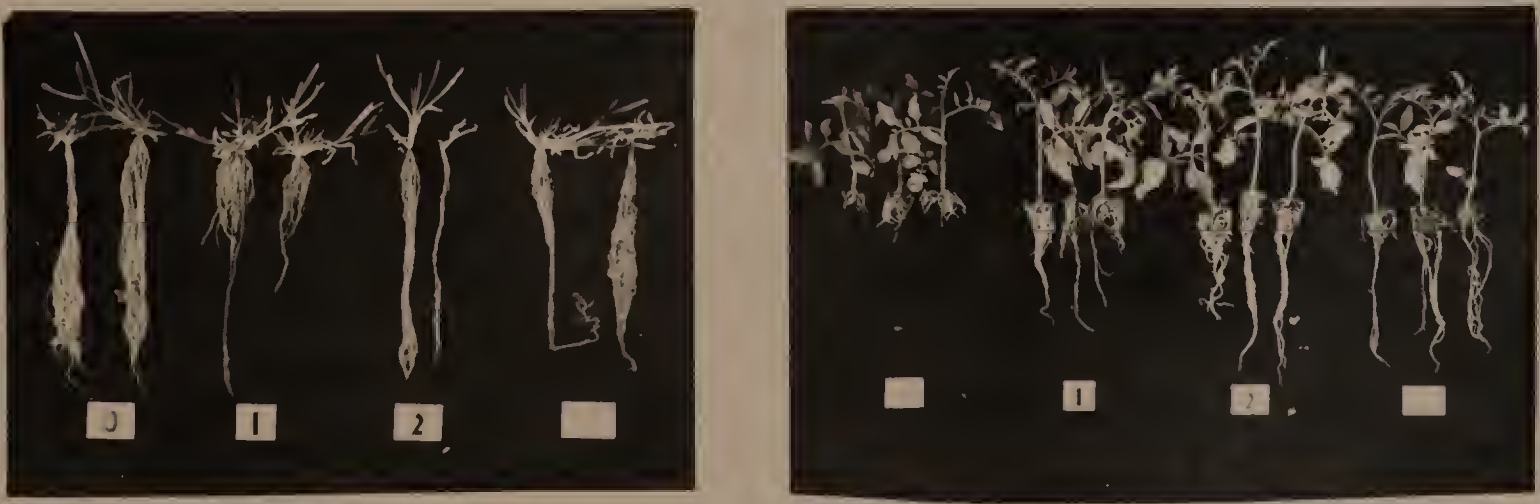
was also observed to be slower at the 0% oxygen treatment. The clipping yields of the bentgrass became significantly higher as the oxygen percentage was decreased. Other root and clipping weight data showed no significant differences; however, it can be seen in figure 5 that root distribution of the bluegrass was affected by the 0% oxygen treatment. Figure 5 shows the root systems obtained in experiment 4. The roots of bentgrass and goosegrass grew as well in the 0% treatment as in 21% treatment, whereas the depth of penetration of bluegrass and tomato roots was affected by the treatments.

The roots of one goosegrass plant in the 1% treatments were broken during washing, and the length of roots as seen in figure 5 is not a result of the treatment. Roots had grown out of the bottoms of the tubes under each treatment.



Merion Kentucky Bluegrass

Penncross Creeping Bentgrass



Goosegrass

Tomato

Figure 5. Roots of three grass species and tomato plants grown at four levels of aeration in experiment 4.

DISCUSSION OF RESULTS AND CONCLUSIONS

These studies have demonstrated the variability in response of different plant species to the effects of poor soil aeration. The grass species studied produced good root growth in soil having oxygen diffusion rates which were lower than values reported as being critical for the root growth of other plants (4, 45, 48, 60, 70, 73). The species grown under the conditions of these experiments differed in their response to low soil oxygen diffusion rates. Merion Kentucky bluegrass root growth was greatly reduced in soil where the oxygen diffusion rate was below 8 to 9 x 10^{-8} g./cm.^{2}/min., but roots of Penncross creeping bentgrass and goosegrass grew well in soil having oxygen diffusion rates below 3 x 10^{-8} g./cm.^{2}/min. Root growth of Kentucky bluegrass seemed to be more tolerant to low oxygen diffusion rates in experiment 4; however, some of this growth may have been favored by the oxygen present in the soil at the beginning of the experiment. The oxygen diffusion rates reported were determined at the conclusion of the experiment when, due to the type of experiment, they would be expected to have reached their lowest points. The roots of all species were observed to be thicker and have fewer laterals under conditions of low oxygen diffusion. These observations are in accord with those of other workers (12,74). This change in root appearance was noted regardless of whether low moisture tensions or low oxygen concentrations were used to limit oxygen diffusion. Many surface roots were noted on the bluegrass when the soil moisture tension was 4 and 11 centimeters of water.

The critical rate for Merion Kentucky bluegrass root growth as determined in these experiments is about one-half the critical value of 20 x 10^{-8} g./cm.^{2}/min. reported for Newport Kentucky bluegrass (46). The tolerance of creeping bentgrass to low oxygen diffusion is in agreement with other studies in which various species of Agrostis have been shown to be especially tolerant to flooding (14) and to produce maximum root growth in soil held at 100% of the moisture capacity (63).

One would normally expect decreased yields under conditions of poor aeration; however, this was not the case with the grasses in these experiments. Only in the case of the shortened observation period for goosegrass in experiment 2 was the clipping yield significantly decreased in the low oxygen diffusion treatment. In experiment 1 bluegrass showed an increase in yield with decreasing soil moisture tension. This probably was due to the moisture variable rather than the variation in oxygen diffusion rates. The only significant decreases in root weights caused by lowering the oxygen diffusion rates were obtained with the tomato plants used in experiment 4. The absence of bluegrass roots at the lower depths of the low oxygen treatments in experiments 2 and 4 was not accompanied by differences in total root weight. In each case more roots were found at the shallower depths. This greater concentration of roots near the surface, along with liberal fertilization during the experiments, was probably instrumental in allowing these plants to yield as high as those receiving better aeration treatments. It is quite probable that such a restriction in root distribution would be reflected in the top growth if the soil was low in fertility. Studies in which fertilization was shown to overcome the effects of poor aeration have been mentioned in the literature review.

Plants which had been grown at tensions of 62, 42, 24, 11, and 4 centimeters of water in experiment 2 were subjected to a tension of 11 cm. for a period of five weeks in experiment 2A to determine whether previous conditioning to a soil moisture level would influence the response of plants to a change in soil moisture. Yields were unaffected. The roots of Merion Kentucky bluegrass were noted to go deeper when the tension was changed from 4 to 11 cm., and increases in root weight in the 4-6 inch zone were quite small in all cases. This reduction of growth in the 4-6 inch depth agrees with the results from the 11 cm. treatment of experiment 2, and supports the conclusion that Merion Kentucky bluegrass root growth is sharply decreased at oxygen diffusion rates below 8 to 9 x 10^{-8} g./$cm.^2$/min.

There have been other studies which have shown the ability of certain grass species to grow well under conditions of poor aeration. Finn et al. (18) grew timothy, bromegrass, and reed canary grass in pots maintained at soil moisture tensions of 0, 25,and 40 centimeters of H_2O for periods of 10, 20, and 30 days. Check pots were watered to approximate field capacity. Oxygen diffusion rates for the four moisture levels were approximately 4.7, 7.8, 15.2, and 23.6 g. x 10^{-8}/$cm.^2$/min. The yields of these grasses tended to increase with increasing moisture levels and with duration of flooding. Root weights tended to decrease with increasing soil moisture tension. Troughton (63) has presented data of Kauter which shows the results of grasses being grown for one season in soil maintained at moisture contents of 40, 55, 70, 85, or 100% of the water capacity. Agrostis alba made the most root growth at 100% water capacity, while Lolium italicum and Phleum pratense produced the most roots at 85% and Dactylis glomerata at 70%. Dactylis glomerata made the most herbage growth at 100%, whereas the other species produced highest yields at 85%. Welton et al. (68) observed decreases in Kentucky bluegrass rhizome and root weights when amounts of water applied by artificial watering exceeded natural rainfall by factors of 1.5, 2.0, and 3.0. This decrease occurred near the surface as well as at lower depths. Excessive leaching may have been a factor in these experiments. Creeping bentgrass was included in the experiments; however, no results on this grass were presented.

It was not within the scope of these studies to investigate why grasses differ in their tolerance to soil aeration; however, possible explanations are offered from information obtained by reviewing literature. Differences in the volume of air space in different grass species has been reported by Kacperska(33). Grasses which naturally occur in a wet environment had a larger percentage of air space than grasses which were found on drier sites, and grasses grown on areas having different soil moisture levels were found to have more air space under the more moist condition. Meusel (51) found that annual bluegrass, Poa annua, grown under wet soil conditions had larger air spaces in the leaves than plants grown on drier soils. This observation was used to explain wilting of the plant, but it could also be related to the ability of the plant to exist under excessively wet soil conditions. It is quite possible that intercellular gas spaces in grass plants affect oxygen supply in two ways: first, by the movement of oxygen through the leaves and stems down to the roots; and second, by increasing the diffusion rate inside the root after oxygen has entered the root via the soil or the upper plant portions. Oxygen has been shown to move downward through plants (1,17,32); and the more air space encountered in the movement through the plant, the faster the diffusion will be (42).

Lemon and Wiegand (42) presented the following formula for determining the critical concentration at which oxygen will be limiting for normal respiration: $c_r' = q\ R^2/4D_i$, where c_r' (g./cm.^{3}) is the critical oxygen concentration at the root surface; q (g./cm.^{3}/sec.) is the rate of oxygen consumption by the root tissue; R (cm.) is the radius of the root; and D_i (cm.^{2}/sec.) is the diffusion coefficient inside the root and was assumed to be 8.0×10^{-6} cm.^{2}/sec. If q and D_i are constant, then c_r' is defined by the root radius and goes up as the square of the radius. As mentioned previously, roots were observed to be thicker under conditions of poor aeration. If it is assumed that these thicker roots had the same q and D_i values as the roots grown in better aerated soil, then one would conclude that c_r' would be higher for these roots; however, a higher c_r' for these thicker roots seems unlikely because they grew under conditions of poorer aeration than the finer roots. In limited preliminary studies by the author, goosegrass and bluegrass roots grown in well-aerated solution cultures were found to have similar respiration rates, but the roots of goosegrass had larger radii than the bluegrass roots. If D_i is assumed to be the same for each species, then the c_r' for goosegrass would be higher than that for bluegrass. The findings reported in this thesis do not substantiate such a difference. Bluegrass was found to be less tolerant than goosegrass to conditions of poor aeration. The apparent failure of the above formula in these cases may be due to the assumption that D_i did not vary between species or between different size roots. Lemon and Wiegand (42) mentioned that the presence of gaseous voids would lower the value of c_r' because the effective D_i would be greater. It is possible that differences in the amount of gaseous spaces could be used to explain the differences in the tolerance of plants to poor aeration. Preliminary observations by the author have shown that goosegrass and bluegrass roots grown in aerated solution culture are quite variable in air space content and that probably no significant difference occurs between the two species. Whether this relationship would hold true for roots grown under poorly aerated conditions is not known; however, previous work (33,63) would lead one to conclude that the roots grown under low oxygen treatments would have a larger percentage of voids, resulting in a higher diffusion coefficient and lower critical oxygen concentration. These changes would no doubt vary in intensity depending on the species.

Although the above discussion has been based on air space content within roots and the effect of the air space on the diffusion coefficient within the root, one must also consider that any movement of oxygen from the upper portions of the plant into the roots would be influenced by the gaseous voids throughout the plant. More work is needed in these areas in order to explain the tolerance of these grasses to low soil oxygen levels.

The data presented in this thesis show that the three grass species were tolerant to low oxygen diffusion rates; however, one should not conclude that they will make good growth in all soils having low oxygen diffusion rates. It is possible that factors such as mechanical impedance, temperature, disease, and impeded fertilizer and water movement may be limiting plant growth in soils having low oxygen diffusion rates. All of these factors undoubtedly interact to some degree. Oxygen diffusion measurements give an indication of the physical condition of soils; and in soils where plant growth is poor and diffusion rates are low, other variables should be carefully weighed before one concludes that the poor growth is due to an insufficient amount of oxygen reaching the roots.

SUMMARY

The effects of soil aeration on top growth and root growth were determined for three grass species: Merion Kentucky bluegrass (*Poa pratensis* L.), Penncross creeping bentgrass (*Agrostis palustris* Huds.), and goosegrass (*Eleusine indica* (L.) Gaertn). These species were grown in soil at different soil moisture tensions ranging from 4 to 102 centimeters of water. Oxygen diffusion rates, as determined with platinum microelectrodes, varied from values of less than 5×10^{-8} g./cm.^{2}/min. up to 37×10^{-8} g./cm.^{2}/min. In one experiment the oxygen diffusion rates were altered by varying the oxygen concentration of the gaseous phase allowed to come in contact with the soil. All of these grasses were found to be more tolerant to low oxygen diffusion rates than many other plants reported in the literature. These grasses differed in their response to poor aeration.

Root growth of Merion Kentucky bluegrass was greatly reduced or stopped in soil where the oxygen diffusion rate was less than 8 to 9×10^{-8} g./cm.^{2}/min. Creeping bentgrass and goosegrass roots made good growth at all levels of oxygen diffusion obtained in the studies and in some cases, growth was better in the poorly aerated treatments. Although root penetration of the bluegrass was decreased under conditions of low oxygen diffusion, the root weights and clipping yields were unaffected by these treatments. This similarity in growth was attributed to the combined effect of the high concentration of roots near the surface in the poorly aerated treatments and the liberal fertilization practices.

Kentucky bluegrass produced many roots at and on the soil surface when grown at soil moisture tensions of 4 and 11 centimeters of water. This characteristic was not noted with the other grasses. Each grass was observed to produce thicker roots with fewer laterals under conditions of poor aeration, regardless of the method employed to limit oxygen diffusion.

It is postulated that the response of these grasses to conditions of low oxygen diffusion may be related to differences in intercellular air spaces with these differences occuring between species and within species grown at different levels of soil aeration.

LITERATURE CITED

1. Barber, D.A., Ebert, M., and Evans, N.T.S. The movement of 0-15 through barley and rice plants. J. Exp. Bot. 13:397-403. 1962.

2. Baver, L.D. The effect of physical properties of soil on the efficient use of fertilizers. Agron. J. 43: 359-363. 1951.

3. Baver, L.D., and Farnsworth, R.B. Soil structure effects in the growth of sugar beets. Soil Sci. Soc. Am. Proc. 5:45-48. 1940.

4. Bertrand, A.R., and Kohnke, H. Subsoil conditions and their effects on oxygen supply and growth of corn roots. Soil Sci. Soc. Am. Proc. 21:135-140. 1957.

5. Brown, W.G.E., and Lacate, D.S. Rooting habits of white and red pine. Canada Dept. of For., For. Res. Br., Tech. Note No. 108. 1961.

6. Blake, G.B., and Page, J.B. Direct measurement of gaseous diffusion in soils. Soil Sci. Soc. Am. Proc. 13:37-42. 1948.

7. Bruce, R.R., and Webber, L.R. The use of a diffusion chamber as a measure of the rate of oxygen supplied by a soil. Can. J. Agr. Sci. 33:430-436. 1953.

8. Bryant, A.E. Comparison of anatomical and histological differences between roots of barley grown in aerated and in non-aerated culture solutions. Pl. Phys. 9:389-391. 1934.

9. Cannon, W.A. Physiological features of roots, with especial reference to the relation of roots to aeration of the soil. Carnegie Inst. of Wash. Publ. No. 368. 1925.

10. Chang, H.T., and Loomis, W.E. Effect of carbon dioxide on absorption of water and nutrients by roots. Pl. Phys. 20:220-232. 1945.

11. Clements, F.E. Aeration and air content. The role of oxygen in root activity. Carnegie Inst. of Wash. Publ. No. 315. 1921.

12. Cline, R.A., and Erickson, A.E. The effect of oxygen diffusion rate and applied fertilizer on the growth, yield, and chemical composition of peas. Soil Sci. Soc. Am. Proc. 23:333-335. 1959.

13. Currie, J.A. Gaseous diffusion in the aeration of aggregated soils. Soil Sci. 92:40-45. 1961.

14. Davis, A.G., and Martin, B.F. Observations on the effect of artificial flooding on certain herbage plants. J. Brit. Grassl. Soc. 4: 63-64. 1949.

15. Edminster, T.W., and Reeve, R.C. Drainage problems and methods. U.S.D.A. Yearbook, 378-385. 1957.

16. Evans, D.D., and Kirkham, Don. Measurement of the air permeability of soil in situ. Soil Sci. Soc. Am. Proc. 14:65-73. 1949.

17. Evans, N.T.S., and Ebert, M. Radioactive oxygen in the study of gas transport down the root of Vicia faba. J. Exp. Bot. 11:246-257. 1960.

18. Finn, B.J., Bourget, S.J., Nielsen, K.F., and Dow, B.K. Effects of different soil moisture tensions on grass and legume species. Can. J. Soil Sci. 41:16-23. 1961.

19. Flocker, W.J., Vomocil, J.A., and Howard, F.D. Some growth responses of tomatoes to soil compaction. Soil Sci. Soc. Am. Proc. 23:188-191. 1959.

20. Gilbert, S.G., and Shive, J.W. The significance of oxygen in nutrient substrates for plants: I. The oxygen requirement. Soil Sci. 53:141-152. 1942.

21. Gill, W.R., and Miller, R.D. A method for study of the influence of mechanical impedance and aeration on the growth of seedling roots. Soil Sci. Soc. Am. Proc. 20:154-157. 1956.

22. Goddard, D.R., and Bonner, W.D. Cellular Respiration. In F.C. Steward ed. Plant Physiology IA. Academic Press, New York. pp. 209-312. 1960.

23. Hammond, L.C., Allaway, W.H., and Loomis, W.E. Effects of oxygen and carbon dioxide levels upon absorption of potassium by plants. Pl. Phys. 30:155-161. 1955.

24. Harris, D.G., and van Bavel, C.H.M. Growth, yield, and water absorption of tobacco plants as affected by the composition of the root atmosphere. Agron. J. 49:11-14. 1957.

25. Harris, D.G., and van Bavel, C.H.M. Nutrient uptake and chemical composition of tobacco plants as affected by the composition of the root atmosphere. Agron. J. 49:176-181. 1957.

26. Harris, D.G., and van Bavel, C.H.M. Root respiration of tobacco, corn, and cotton plants. Agron. J. 49:182-184. 1957.

27. Hoagland, D.R., and Broyer, T.C. General nature of the process of salt accumulation by roots with description of experimental methods. Pl. Phys. 11:471-507. 1936.

28. Hopkins, H.T., Specht, A.W., and Hendricks, S.B. Growth and nutrient accumulation as controlled by oxygen supply to plant roots. Pl. Phys. 25:193-209. 1950.

29. Horton, K.W. Rooting habits of lodgepole pine. Can. Dept. of Northern Affairs and Natural Resources, For. Res. Div. Tech. Note No. 67. 1958.

30. Hutchins, L.M. Studies on the oxygen supplying power of soil together with quantitative observations on the oxygen supplying power requisite for seed germination. Pl. Phys. 1:95-150. 1926.

31. Jensen, C.R., and Kirkham, Don. Labeled oxygen: increased diffusion through soil containing growing corn roots. Science 141: 735-736. 1963.

32. Jensen, C.R., Letey, J., and Stolzy, L.H. Labeled oxygen: transport through growing corn roots. Science 144:550-552. 1964.

33. Kacperska-Palacz, Alina The aeration system in some grasses appearing chiefly on lowland meadows. Polish Agricultural Annals 74-F-2:295-318. 1962.

34. Kramer, P.J. Causes of decreased absorption of water by plants in poorly aerated media. Am. J. Bot. 27:216-220. 1940.

35. Kramer, P.J. Transpiration and water economy of plants. In F. C. Steward ed. Plant Physiology II. Academic Press, New York. pp. 661-687. 1959.

36. Lawton, Kirk The influence of soil aeration on the growth and absorption of nutrients by corn plants. Soil Sci. Soc. Am. Proc. 10:263-268. 1945.

37. Leamer, R.W., and Shaw, B. A simple apparatus for measuring noncapillary porosity on an extensive scale. J. Am. Soc. Agron. 33:1003-1008. 1941.

38. Lemon, E.R. Soil aeration and plant root relations I. theory. Agron. J. 54:167-170. 1962.

39. Lemon, E.R., and Erickson, A.E. The measurement of oxygen diffusion in the soil with a platinum microelectrode. Soil Sci. Soc. Am. Proc. 16:160-163. 1952.

40. Lemon, E.R., and Erickson, A.E. Principle of the platinum microelectrode as a method of characterizing soil aeration. Soil Sci. 79:383-392. 1955.

41. Lemon, E., and Kristensen, J. An edaphic expression of soil structure. Trans. 7th Int. Cong. Soil Sci. Vol. I:232-240. 1960.

42. Lemon, E.R., and Wiegand, C.L. Soil aeration and plant root relations. II. Root respiration. Agron. J. 54:171-175. 1962.

43. Letey, J., Lunt, O.R., Stolzy, L.H., and Szuszkiewicz, T.E. Plant growth, water use and nutritional response to rhizosphere differentials of oxygen concentration. Soil Sci. Soc. Am. Proc. 25:183-186. 1961.

44. Letey, J., Stolzy, L.H., and Blank, G.B. Effect of duration and timing of low soil oxygen content on shoot and root growth. Agron. J. 54:34-37. 1962.

45. Letey, J., Stolzy, L.H., Blank, G.B., and Lunt, O.R. Effect of temperature on oxygen diffusion rates and subsequent shoot growth, root growth, and mineral content of two plant species. Soil Sci. 92:314-321. 1961.

46. Letey, J., Stolzy, L.H., Lunt, O.R., and Valoras, N. Soil oxygen and clipping height. Golf Course Reporter 32(2):16. 1964.

47. Letey, J., Stolzy, L.H., Szuszkiewicz, T.E., and Valoras, N. Soil aeration - essential for plant growth. Calif. Agr. 16(3):6-7. 1962.

48. Letey, J., Stolzy, L.H., Valoras, N., and Szuszkiewicz, T.E. Influence of soil oxygen on growth and mineral concentration of barley. Agron. J. 54:538-540. 1962.

49. Macdonald, I.R., and Laties, G.G. Oxygen electrode measurements of potato slice respiration at 0° C. J. Exp. Bot. 13:435-442. 1962.

50. Meredith, H.L., and Patrick, W.H., Jr. Effects of soil compaction on subsoil root penetration and physical properties of three soils in Louisiana. Agron. J. 53:163-167. 1961.

51. Meusel, H.W. What makes grass wilt? Golf Course Reporter 32(3): 24. 1964.

52. Norris, W.E., Jr., Wiegand, J.D., and Johanson, L. Effect of carbon dioxide on respiration of excised onion root tips in high-oxygen atmosphere. Soil Sci. 88:144-149. 1959.

53. Peterson, J.B. Relation of soil air to roots as factors in plant growth. Soil Sci. 70:175-185. 1950.

54. Phillips, R.E., and Kirkham, Don. Mechanical impedance and corn seedling root growth. Soil Sci. Soc. Am. Proc. 26:319-322. 1962.

55. Raney, W.A. Field measurement of oxygen diffusion through soil. Soil Sci. Soc. Am. Proc. 14:61-65. 1949.

56. Rosenberg, N.J., and Willits, N.A. Yield and physiological response of barley and beans grown in artificially compacted soils. Soil Sci. Soc. Am. Proc. 26:78-82. 1962.

57. Russell, E. John Soil Conditions and Plant Growth. Longmans, Green and Co., London. 1952.

58. Soil Science Society of America, Committee on Terminology. Glossary of terms. Soil Sci. Soc. Am. Proc. 26:305-317. 1962.

59. Steel, R.G.D., and Torrie, J.H. Principle and Procedures of Statistics. McGraw-Hill Book Co., Inc. New York. 1960.

60. Stolzy, L.H., Letey, J., Szuszkiewicz, T.E., and Lunt, O.R. Root growth and diffusion rates as functions of oxygen concentrations. Soil Sci. Soc. Am. Proc. 25:463-467. 1961.

61. Tanner, C.B., and Wengel, R.W. An air permeameter for field and laboratory use. Soil Sci. Soc. Am. Proc. 21:663-664. 1957.

62. Taylor, S.A. Oxygen diffusion in porous media as a measure of soil aeration. Soil Sci. Soc. Am. Proc. 14:55-61. 1949.

63. Troughton, A. The Underground Organs of Herbage Grasses. Bul. No. 44. Commonwealth Bur. of Pastures and Field Crops. Com. Agr. Bur., Farnham Royal, Bucks, England. 163 p. 1957.

64. Trouse, A.C., Jr., and Humbert, R.P. Some effects of soil compaction on the development of sugar cane roots. Soil Sci. 91: 208-217. 1961.

65. Vlamis, J., and Davis, A.R. Effects of oxygen tension on certain physiological responses of rice, barley, and tomatoes. Pl. Phys. 19:33-51. 1944.

66. Veihmeyer, F.J., and Hendrickson, A.H. Soil density and root penetration. Soil Sci. 65:487-493. 1948.

67. Weaver, J.E., and Himmel, W.J. Relation of increased water content and decreased aeration to root development in hydrophytes. Pl. Phys. 5:69-92. 1930.

68. Welton, F.A., Carroll, J.C., and Wilson, J.D. Artificial watering of lawn grass. Ecol. 15:381-387. 1934.

69. Wiegand, C.L., and Lemon, E.R. A field study of some plant-soil relations in aeration. Soil Sci. Soc. Am. Proc. 22:216-221. 1958.

70. Wiersma, D., and Mortland, M.M. Response of sugar beets to peroxide fertilization and its relationship to oxygen diffusion. Soil Sci. 75:355-360. 1953.

71. Wiersum, L.K. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil 9:75-85. 1957.

72. Willey, C.R., and Tanner, C.B. Membrane-covered electrode for measurement of oxygen concentration in soil. Soil Sci. Soc. Am. Proc. 27:511-515. 1963.

73. Williamson, R.E. The effect of root aeration on plant growth. Soil Sci. Soc. Am. Proc. 28:86-90. 1964.

74. Woodford, E.K., and Gregory, F.G. Preliminary results obtained with an apparatus for the study of salt uptake and root respiration of whole plants. Ann. Bot. 12:335-370. 1948.

APPENDIX

LIST OF TABLES

Table A-1. Merion Kentucky bluegrass clipping yields from experiment 1. (Dry weight, mg.)

	Treatment					
Cutting	1	2	3	4	5	Ave.
1	165	230	168	199	174	170
	145	167	168	299	152	
	165	146	168	100	109	
2	234	221	268	322	293	228
	191	155	206	397	215	
	170	176	206	151	214	
3	221	305	438	338	284	259
	199	174	259	378	264	
	176	196	199	259	189	
4	194	182	280	403	196	212
	170	113	160	403	216	
	194	182	140	157	196	
5	256	159	229	317	398	238
	170	205	229	339	216	
	170	182	252	294	149	
Ave.	188b	186b	225ab	290a	218ab	

Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	2	37495.4	
Treatments	4	26775.8	3.49
Error (a)	8	7663.7	
Cuttings	4	16424.8	7.02 **
Cuttings x blocks	8	1012.3	.43
Cuttings x treatments	16	2008.1	.86
Error (b)	32	2339.5	

** significant at .01 level

Table A-2. Penncross creeping bentgrass clipping yields from experiment 1. (Dry weights, mg.)

	Treatment					
Cutting	1	2	3	4	5	Ave.
1	464	438	424	407	386	
	432	438	424	377	386	418
	240	438	581	362	467	
2	497	400	441	394	301	
	497	415	353	340	301	387
	355	356	456	422	284	
3	496	421	375	493	479	
	496	362	390	343	370	401
	408	348	405	357	274	
4	363	296	319	317	409	
	380	296	365	362	353	320
	264	222	243	287	325	
5	429	414	503	358	228	
	458	296	488	343	391	376
	355	296	414	223	440	
Ave.	409	362	412	359	360	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	2	15768.0	
Treatments	4	11368.0	2.13
Error (a)	8	5332.6	
Cuttings	4	20720.5	6.36 **
Cuttings x blocks	8	2753.9	.84
Cuttings x treatments	16	5957.6	1.83
Error (b)	32	3256.4	

** significant at the .01 level

Table A-3. Goosegrass clipping yields from experiment 1. (Dry weights,mg.)

Cutting	Treatment 1	2	3	4	5	Ave.
1	528	623	455	577	675	521
	488	553	416	503	648	
	277	584	364	596	526	
2	510	370	422	411	553	492
	540	563	503	466	635	
	480	483	476	506	459	
3	508	416	467	467	621	515
	606	675	418	408	456	
	590	537	435	584	538	
4	395	346	420	308	326	350
	451	364	300	257	295	
	395	291	300	462	341	
5	199	201	297	232	184	236
	259	224	137	289	276	
	219	201	274	294	294	
Ave.	430	429	379	421	455	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	2	809.0	
Treatments	4	11487.2	1.31
Error (a)	8	8763.0	
Cuttings	4	237059.2	66.90 **
Cuttings x block	8	6766.4	1.91
Cuttings x treatment	16	8038.0	2.27*
Error (b)	32	3543.3	

* significant at the .05 level
** significant at the .01 level

Table A-4. Merion Kentucky bluegrass fresh root weights from experiment 1. (Fresh weights, g.)

	Treatment					
Depth	1	2	3	4	5	Ave.
0-2"	6.3	6.5	5.7	4.8	4.9	
	2.6	2.8	1.9	2.4	2.1	3.40
	2.1	1.2	3.8	2.1	1.8	
2-4"	0.8	1.1	1.5	1.0	1.3	
	1.0	0/9	0.5	0.7	0.5	0.76
	0.1	0.2	0.9	0.8	0.1	
4-6"	0.2	0.1	0.2	0.4	0.1	
	0.3	0.3	0.2	0.2	0.1	0.14
	0.0	0.0	0.0	0.0	0.0	
Ave.	1.49	1.46	1.63	1.38	1.21	

Analysis of Variance

Source	df	Mean square	F	
Blocks	2	9.170	9.57	**
Treatments	4	.216	.22	
Depth	2	44.954	46.92	**
Treatments x depth	8	.132	.14	
Error	28	.958		

** significant at the .01 level

Table A-5. Penncross creeping bentgrass fresh root weights from experiment 1. (Fresh weights, g.)

	Treatment					
Depth	1	2	3	4	5	Ave.
0-2"	5.0	3.2	4.3	7.1	9.1	
	3.9	2.0	2.7	2.6	3.5	4.10
	3.0	3.0	3.6	3.9	4.6	
2-4"	1.4	0.8-	1.7	1.2	4.9	
	0.7	0.3	0.7	0.3	0.7	1.09
	0.8	0.2	0.3	0.8	1.5	
4-6"	0.1	0.1	0.7	0.0	0.9	
	0.1	0.0	0.1	0.0	0.1	.14
	0.0	0.0	0.0	0.0	0.0	
Ave.	1.67b	1.07b	1.57b	1.77b	2.81a	

Averages followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Analysis of Variance

Source	df	Mean square	F	
Blocks	2	9.881	10.91	**
Treatments	4	3.668	4.05	*
Depth	2	64.145	70.80	**
Treatments x depths	8	.929	1.02	
Error	28	.906		

* significant at the .05 level
** significant at the .01 level

Table A-6. Goosegrass fresh root weights from experiment 1. (Fresh weights, g.)

	Treatment					
Depth	1	2	3	4	5	Ave.
0-2"	8.1	7.8	15.0	9.0	16.5	
	15.1	18.1	12.2	9.7	14.8	12.58
	6.9	10.9	14.8	18.0	11.8	
2-4"	4.6	3.1	11.2	4.2	6.8	
	6.1	9.3	5.3	4.0	4.1	5.77
	1.6	5.8	8.9	7.8	3.8	
4-6"	2.0	1.5	6.8	1.8	2.0	
	2.6	4.2	2.4	1.3	1.5	2.59
	0.8	3.1	4.8	3.0	1.1	
Ave.	5.31	7.09	9.04	6.53	6.93	

Analysis of Variance

Source	df	Mean square	F
Blocks	2	1.902	.22
Treatments	4	16.336	1.93
Depth	2	360.442	42.63 **
Treatments x depth	8	2.890	.34
Error	28	8.455	

** significant at the .01 level

Table A-7. Merion Kentucky bluegrass clipping yields from experiment 2. (Dry weights, mg.)

	Treatment					
Cutting	1	2	3	4	5	Ave.
1	205	99	236	111	185	
	159	159	137	129	185	162
	164	199	117	148	202	
2	244	204	328	263	183	
	272	272	175	182	264	240
	267	204	175	243	325	
3	285	225	238	294	224	
	225	225	214	272	224	246
	166	315	214	294	269	
4	312	243	399	246	246	
	243	243	133	222	246	248
	235	243	187	296	219	
5	197	280	268	247	154	
	280	280	201	225	308	239
	131	233	223	292	263	
Ave.	226	228	216	231	233	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	2	2013.0	
Treatments	4	638.1	.08
Error (a)	8	8450.2	
Cuttings	4	19722.2	12.09 **
Cuttings x blocks	8	1898.2	1.16
Cuttings x treatments	16	1522.8	.93
Error (b)	32	1631.1	

** significant at the .01 level

Table A-8. Penncross creeping bentgrass clipping yields from experiment 2. (Dry weights, mg.)

Cutting	Treatment 1	2	3	4	5	Ave.
1	250 355 474	286 300 150	155 239 493	164 224 209	167 307 208	265
2	376 461 512	418 434 367	288 432 464	403 434 465	702 702 502	464
3	187 224 243	200 200 233	134 218 487	225 321 289	304 320 236	255
4	556 483 445	398 434 362	232 199 580	219 383 274	345 259 345	368
5	271 310 252	335 282 264	294 262 490	480 320 384	316 301 237	320
Ave.	360	311	331	320	350	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	2	15963.7	
Treatments	4	6311.1	.22
Error (a)	8	29014.5	
Cuttings	4	109530.6	29.99 **
Cuttings x blocks	8	4712.1	1.29
Cuttings x treatments	16	16529.5	4.52 **
Error(b)	32	3652.2	

** significant at the .01 level

Table A-9. Goosegrass clipping yields from experiment 2. (Dry weights, mg.)

	Treatment					
Cutting	1	2	3	4	5	Ave.
1	523 541 242	619 586 327	669 435 435	696 391 304	311 275 311	444
2	418 453 471	576 594 468	612 516 489	476 548 438	538 312 417	488
Ave.	441ab	528a	526a	476ab	361b	

Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F	
Blocks	2	58994.4		
Treatments	4	28917.9	3.94	*
Error (a)	8	7344.0		
Cuttings	1	14565.0	1.75	
Cuttings x blocks	2	18624.2	2.24	
Cuttings x treatments	4	3048.9	.37	
Error (b)	8	8303.3		

* significant at the .05 level

Table A-10. Merion Kentucky bluegrass clipping yields from experiment 2A. (Dry weights, mg.)

	Treatment					
Cutting	1	2	3	4	5	Ave.
1	255	225	150	198	181	
	230	168	199	296	283	218
2	226	222	77	237	161	
	142	250	128	263	208	191
3	317	210	296	282	310	
	249	187	296	282	284	271
4	360	326	291	223	308	
	340	245	312	386	308	310
5	316	367	283	350	380	
	274	293	397	325	350	324
Ave.	271	249	243	284	267	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	1	1190.8	
Treatments	4	2805.0	.45
Error (a)	4	6229.5	
Cuttings	4	32588.8	23.52 **
Cuttings x blocks	4	1075.8	.78
Cuttings x treatments	16	2791.6	2.01
Error (b)	16	1385.8	

** significant at .01 level

Table A-11. Penncross creeping bentgrass clipping yields from experiment 2A. (Dry weights, mg.)

	Treatment					
Cutting	1	2	3	4	5	Ave.
1	206	240	207	192	274	
	268	196	269	250	195	230
2	182	125	149	128	125	
	205	188	171	193	94	156
3	235	265	280	203	228	
	274	302	280	257	316	264
4	342	330	371	352	300	
	357	330	310	322	330	334
5	286	265	305	251	309	
	254	234	241	300	242	269
Ave.	261	248	258	245	241	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	1	1039.7	
Treatments	4	737.8	.65
Error (a)	4	1131.4	
Cuttings	4	42289.0	40.10 **
Cuttings x blocks	4	2097.8	1.99
Cuttings x treatments	16	697.8	.66
Error (b)	16	1054.7	

** significant at .01 level

Table A-12. Goosegrass clipping yields from experiment 2A. (Dry weights, mg.)

Cutting	1	2	3	4	5	Ave.
	Treatment					
1	654 437	597 289	502 680	472 452	419 649	515
2	470 594	562 478	295 393	307 483	388 367	434
3	341 426	408 236	307 307	343 242	263 365	324
4	577 470	563 563	612 884	444 592	506 587	580
5	454 346	261 403	445 356	398 221	324 410	362
Ave.	477	436	478	395	428	

Analysis of Variance for Split Plot in Time

Source	df	Mean square	F
Blocks	1	2022.4	
Treatments	4	12317.2	.76
Error (a)	4	16185.8	
Cuttings	4	112002.8	10.15 **
Cuttings x blocks	4	6708.4	.61
Cuttings x treatments	16	8555.3	.78
Error (b)	16	11030.6	

** significant at .01 level

Table A-13. Merion Kentucky bluegrass clipping yields from experiment 3. (Total dry weights, g.)

	Treatment				
	1	2	3	4	Ave.
Rep 1	.912	.422	.635	.566	.634
Rep 2	.414	.405	.428	.429	.419
Ave.	.663	.414	.532	.498	

Analysis of Variance

Source	df	Mean square	F
Blocks	1	.0923	4.42
Treatments	3	.0215	1.03
Error	3	.0209	

Table A-14. Penncross creeping bentgrass clipping yields from experiment 3. (Total dry weights, g.)

	Treatment				
	1	2	3	4	Ave.
Rep 1	.870	.775	1.142	.824	.903
Rep 2	.889	.652	.975	.862	.844
Ave.	.880ab	.714b	1.058a	.843b	

Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Analysis of Variance

Source	df	Mean square	F
Blocks	1	.0068	1.28
Treatments	3	.0405	7.64
Error	3	.0053	

Table A-15. Goosegrass clipping yields from experiment 3. (Total dry weights, G.)

	Treatment				
	1	2	3	4	Ave.
Rep 1	.738	.852	.824	1.083	.874
Rep 2	.693	.451	.896	.444-	.621
Ave.	.716	.652	.860	.764	

Analysis of Variance

Source	df	Mean square	F
Blocks	1	.1283	2.41
Treatments	3	.0154	.29
Error	3	.0533	

Table A-16. Penncross creeping bentgrass root weights from experiment 3. (Dry weights, g.)

	Treatment				
Depth	1	2	3	4	Ave.
0-2"	.310 .216	.215 .116	.360 .225	.432 .218	.261
2-4"	.211 .130	.082 .069	.320 .225	.362 .294	.212
4-6"	.231 .114	.040 .061	.281 .336	.376 .113	.194
Ave.	.202b	.097c	.291a	.298a	

Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Analysis of Variance

Source	df	Mean square	F
Blocks	1	.0507	12.9 **
Treatments	3	.0534	13.4 **
Depths	2	.0098	2.4
Treatments x depths	6	.0028	.7
Error	11	.0040	

** significant at .01 level

Table A-17. Goosegrass root weights from experiment 3. (Dry weights,g.)

Depth	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Ave.
0-2"	.499 .578	.311 .359	.368 .718	.615 .557	.501
2-4"	.197 .073	.151 .152	.202 .326	.219 .174	.187
4-6"	.208 .076	.244 .102	.085 .236	.144 .088	.148
Ave.	.272	.220	.322	.298	

Analysis of Variance

Source	df	Mean square	F
Blocks	1	.0016	.16
Treatments	3	.0117	1.14
Depths	2	.2993	29.06 **
Treatments x depths	6	.0107	1.03
Error	11	.0103	

** significant at the .01 level

Table A-18. Merion Kentucky bluegrass and Penncross creeping bentgrass clipping yields from experiment 4. (Dry weights, mg.)

	Treatment			
	1	2	3	4
Merion Kentucky Bluegrass	26	27	34	67
	45	69	59	12
	38	18	30	42
Ave.	36	38	41	40
Penncross Creeping Bentgrass	149	80	79	37
	98	88	74	55
	128	138	82	57
Ave.	125a	102ab	78bc	50c

Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Analysis of Variance

Merion Kentucky Bluegrass	df	Mean square	F
Treatments	3	14	.03
Error	8	460	

Penncross Creeping Bentgrass			
Treatments	3	3126	7.02 *
Error	8	446	

* significant at the .05 level

Table A-19. Root yields from experiment 4.
(Dry weights, mg.)

		Treatment			
		1	2	3	4
Merion Kentucky Bluegrass		31	18	15	58
		17	63	22	21
		22	24	59	37
	Ave.	23	35	32	39
Penncross Creeping Bentgrass		82	59	76	49
		120	77	61	59
		84	141	123	83
	Ave.	95	92	87	64
Goosegrass		172	63	101	114
		113	188	30	89
	Ave.	142	126	66	102
Tomato		122	161	200	224
		84	103	222	306
		114	104	286	176
	Ave.	107b	123b	236a	235a

Means followed by the same letter do not differ significantly at the .05 level using Duncan's new multiple range test.

Table A-19. (Continued)

Analysis of Variance

Merion Kentucky Bluegrass		df	Mean square	F
	Treatments	3	128	.33
	Error	8	388	
Penncross Creeping Bentgrass				
	Treatments	3	617	.67
	Error	8	917	
Goosegrass				
	Treatments	3	1486	.13
	Error	4	11538	
Tomato				
	Treatments	3	14769	4.6 *
	Error	8	3205	

* significant at the .05 level

ACKNOWLEDGMENTS

The author wishes to express appreciation to Drs. John H. Baker, Arthur C. Gentile, and Martin E. Weeks for their interest and advice during the planning and conduction of these studies. Appreciation is extended to Professor Hrant M. Yegian and Dr. Richard A. Damon Jr. for their helpful suggestions in planning the experimental designs and statistical analyses.

Approved by:

John H. Baker

Arthur C. Gentile

Martin E. Weeks

Date: May 21, 1964