CHAPTER II

The Effect of Temperature and Water Table Depth on the Development of Bentgrass Roots

REVIEW OF LITERATURE

Turf quality is generally associated with top growth and appearance, but close examination of the root system may provide a better indicator of long term quality with relation to the ability of a turf to withstand stress periods. Development of a root system by bentgrass in excess of its minimal or normal needs is desirable to provide access to a larger volume of soil for absorption of water and nutrients, which helps it to survive droughty conditions.

Factors known to affect root development include: 1. genetic, 2. aeration, 3. temperature, and 4. carbohydrate balance. Within a single variety, root development would depend on the rate of diffusion of oxygen within the rootzone, air and soil temperature, and the effect of clipping and fertilizing practices on the carbohydrate reserves in the root system.

Numerous studies have shown that poor aeration can retard root growth. Oxygen requirement of roots has been known since 1668(17). Baver(2) emphasizes that roots cannot function as absorbing membranes unless they can carry on respiration. Without oxygen for respiration roots undergo anerobic respiration in which carbohydrates are fermented to alcohol producing only a small amount of energy. Nutrient uptake has also been shown to be affected by aerobic metabolism(23,28). The oxygen diffusion rate within a soil is a function of soil moisture, bulk density, temperature, and respiration rates of both roots and microorganisms. Controlled laboratory studies have given quantitative oxygen diffusion rate requirements while field studies have given empirical information of plant response to soil aeration conditions.

Beard and Daniel(3) found temperature to be the most important factor in development of bentgrass roots in studies conducted both under field and controlled climate room conditions. Early work by Stucky(38) showed the seasonal pattern of growth of grasses in which the cessation of growth in summer coincided with high soil temperature. Growth was regenerated beginning in late fall, continued slowly throughout winter and then more rapidly after thaw.

Lemon and Wiegand(22) reported that oxygen consumption by roots during aerobic metabolism is temperature sensitive only when the oxygen content is above the critical level since uptake is dependent upon the chemical reaction of the carbohydrates. However, when the oxygen content is below the critical level, diffusion controls the rate of uptake and is not as temperature sensitive.

Factors which affect carbohydrate balance within a plant include clipping practice, fertility level, temperature, and stage of maturity. Sprague(36) reported that heavy nitrogen application favors top growth at the expense of carbohydrate reserves in roots. Letey et al.(26) showed that clipping height affected root depth of Newport bluegrass at five oxygen levels. In a field lysimeter study, Williamson(46) reported that for soybeans, sorghum, and sweet corn, the oxygen requirement varied with the stage of development and soil temperature.

This study was undertaken to provide further evidence of the interrelationship between temperature and oxygen diffusion rate on the development of bentgrass roots. Some controversy exists in the literature as to which factor is the more important in causing the sudden and serious loss of a root system.

Another objective was to study the capillary properties of a fine and coarse sand so that the information gained can be used to recommend the most desirable water table depth for plastic lined reservoir rootzones.(7)

METHODS AND MATERIALS

The study included two temperatures, 15 and 30°C; three water table depths, 11, 25, and 40 cm; and two sands, each replicated twice. The two sands were sieved from a single source (Western Indiana Aggregates, Inc., Lafayette, Indiana, No. 3 special) to give a coarser and finer fraction. Approximately 5% (by volume) of calcined clay of the same particle size range as the sand and 5% humus (Nitrohumus, Kellogg's Supply Inc., Wilmington, California) were added and thoroughly mixed with sand.

The mechanical analysis data for the two sand mixes presented in Table II-1 show that 78% of the coarser sand mix was between 0.5 and 1.0 mm compared with the finer sand mix, in which 96% of the particles were between 0.125 and 0.5 mm. The steepness of the mechanical analysis curves for the two sands plotted in Figure II-1 shows the uniform particle size of the materials. The Gradation Index, which represents the degree of sorting of a sand (5), was 3.4 for both materials.

The moisture desorption data presented in Table II-2 and plotted in Figure II-2 was determined using the pressure cell method developed by Reginato and van Bavel(48). The sands were packed in the cells by compacting small increments with a rubber tamper. The average bulk density was 1.44 gm/cc for the coarser sand and 1.56 gm/cc for the finer sand. Total pore space was 47.1% in the coarser sand compared with 41.6% for the finer sand.

The desorption curve for the coarser sand in Figure II-2 shows the

TABLE II-1. Mechanical Analysis of Sand Mixtures

	Particle Size - mm						
	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.125	0.125-0.074	0.074-0.053	<0.053
Sand			Percent by Weight				
Coarser	0.6	78.5	17.9	1.7	0.6	0.2	0.5
Finer	0.0	0.8	59.4	36.6	2.2	0.2	0.8

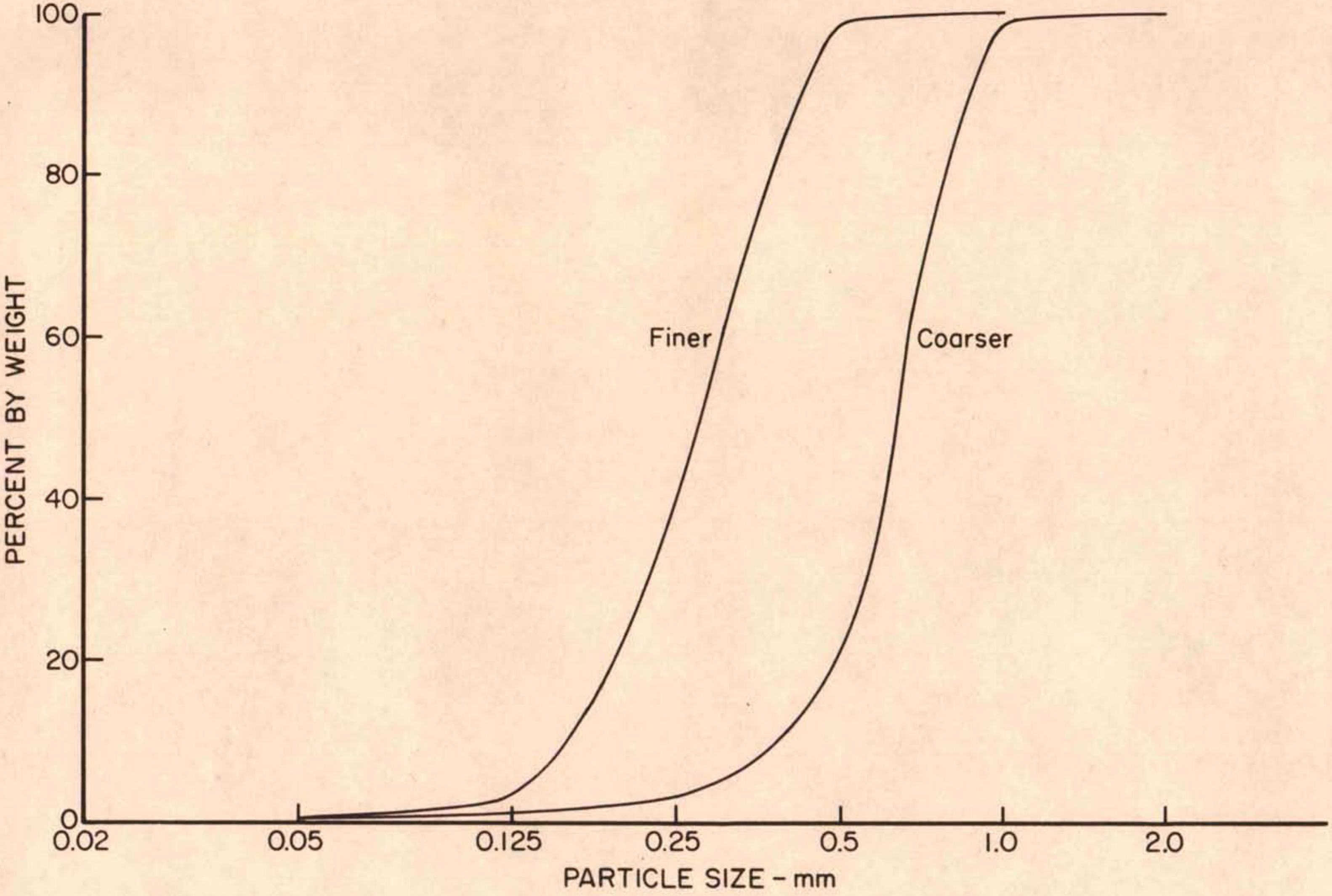

Figure II-1. Cumulative Mechanical Analysis Curves for the Two Sand Mixtures.

TABLE II-2. Moisture Desorption Data and Bulk Density for Sand Mixtures

	Moisture Content								Bulk Density gm/CC
Tension - cm	0	10	25	50	100	200	500	1000	
Sand -				Percent by Volume					
Coarser	47.1	25.3	22.3	17.3	15.7	14.9	14.2	13.1	1.44
Finer	41.6	38.1	30.2	13.2	9.6	8.5	8.3	8.0	1.56

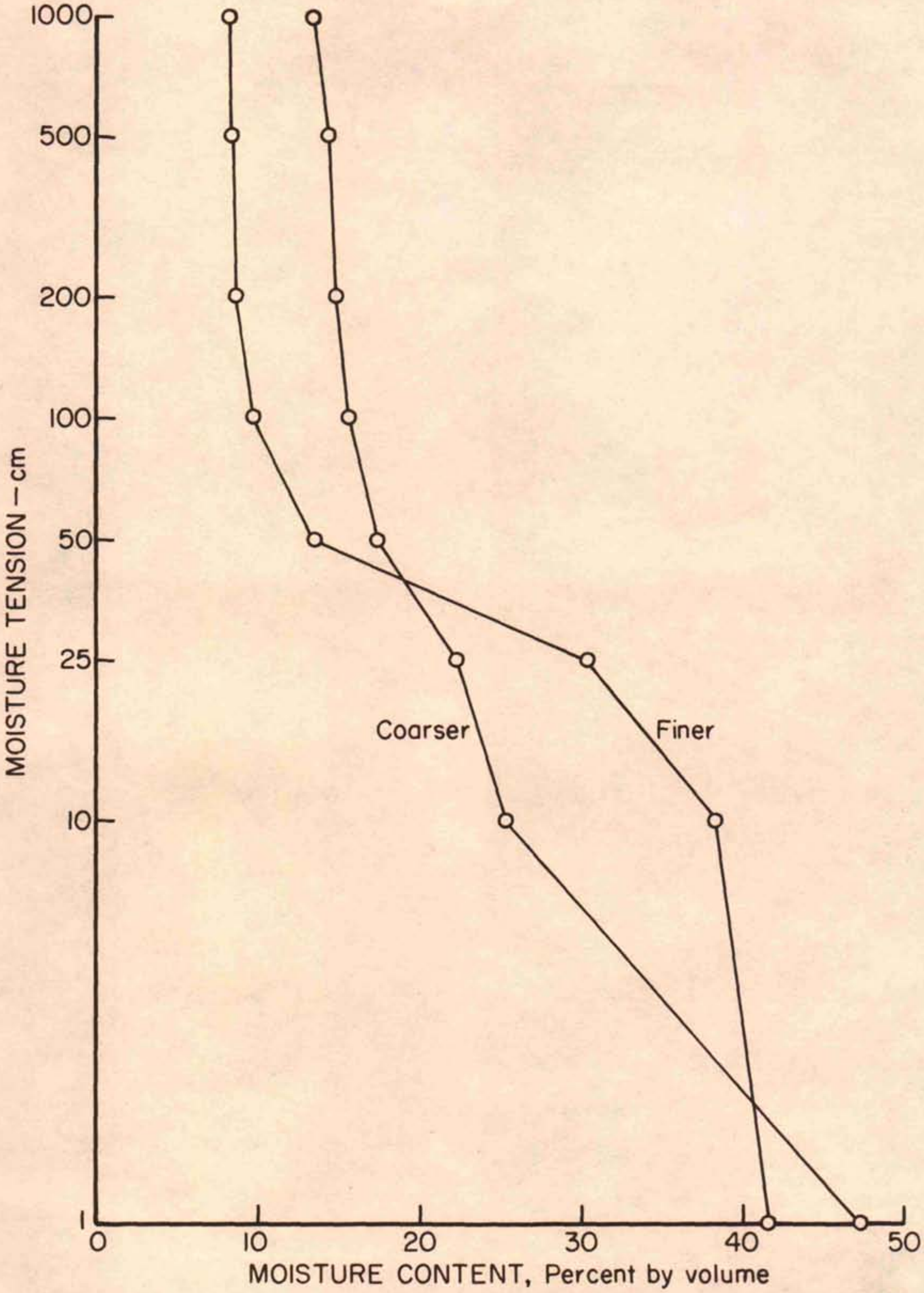

Figure II-2. Moisture Desorption Curves for the Two Sand Mixtures.

rapid loss of water up to 10 cm tension, then slower rate of moisture loss between 10 and 1000 cm tension. In contrast, the finer sand had its highest rate of water loss between 10 and 50 cm tension. The loss of moisture between saturation and 10 cm tension was only 3.5% for the finer sand. It is interesting to note that the two curves cross at 40 cm tension. Above this tension, the percent moisture in the finer sand is less due to the increased capillarity of the finer pores removing more moisture from the humus material in the sand. The capillarity of larger pores in the coarser sand was insufficient to remove this moisture. The moisture content of the two sandsat 1000 cm tension was 8.0 for the finer sand and 13.1 for the coarser sand. There was little moisture lost between 100 and 1000 cm of tension for either material.

For this study, the moisture content in the materials at 10, 25, and 40 cm of tension is of most concern in order to determine water free or aeration pore space at these tensions. Desorption data indicates that the coarser sand under 10 cm tension would have 21.8% water free pores compared to the finer sand at the same tension which would have only 3.5% water free pores. Increasing the tension to 25 cm only increased the water free pores space to 24.8% for the coarser sand but increases the aeration pores to 11.4% in the finer sand. With 40 cm of tension on the moisture in the sands, the coarser sand would have 28.1% water free pores compared to 22.6% for the finer sand. The biggest difference for the coarser sand is between saturation and 10 cm tension and for the finer sand, its between 10 and 40 cm of tension.

It should be pointed out that the actual amount of moisture in pores above a water table for both sands would be less than indicated by the desorption curves due to the hysteresis effect. The curves would accurately predict moisture in the sands immediately after saturation, but for extended periods of time without addition of water from the surface, hysteresis would have to be considered.

The desired water table depth was maintained throughout the nine week experiment by the use of six "Marriotte-type" water level controls, each of which was connected to four Plexiglas pots as illustrated in the diagram in Figure II-3. The smaller diameter tube was calibrated so that daily evapo-transpiration rates could be measured for the four connected pots. The picture in Figure II-4 shows the complete experimental setup in the 15°C controlled climate room. Note the three "Marriotte-type" reservoir controls, each of which is connected to a series of 4 pots. Blocking was used under shorter pots so that the bentgrass was the same distance from the light source for all three water table treatments. Two platinum electrodes, at 2 and 10 cm, in each of the pots were connected along with the silver-silver chloride reference electrode to the oxygen diffusion meter on the left of the picture to measure oxygen diffusion rates.

The Plexiglas pots were 10 cm (I.D.) by 30, 40, or 50 cm tall for the 11, 25, and 40 cm water tables respectively. Each pot was covered with black self-adhesive plastic except during measurements. Holes were drilled at 2 and 10 cm in each container for insertion of platinum electrodes used in oxygen diffusion measurements.

Prior to filling the pots, the drain in each was covered with a piece of nylon screening and fine gravel was put in the bottom 4 cm. The sand mix was added to standing water in each pot and was compacted by

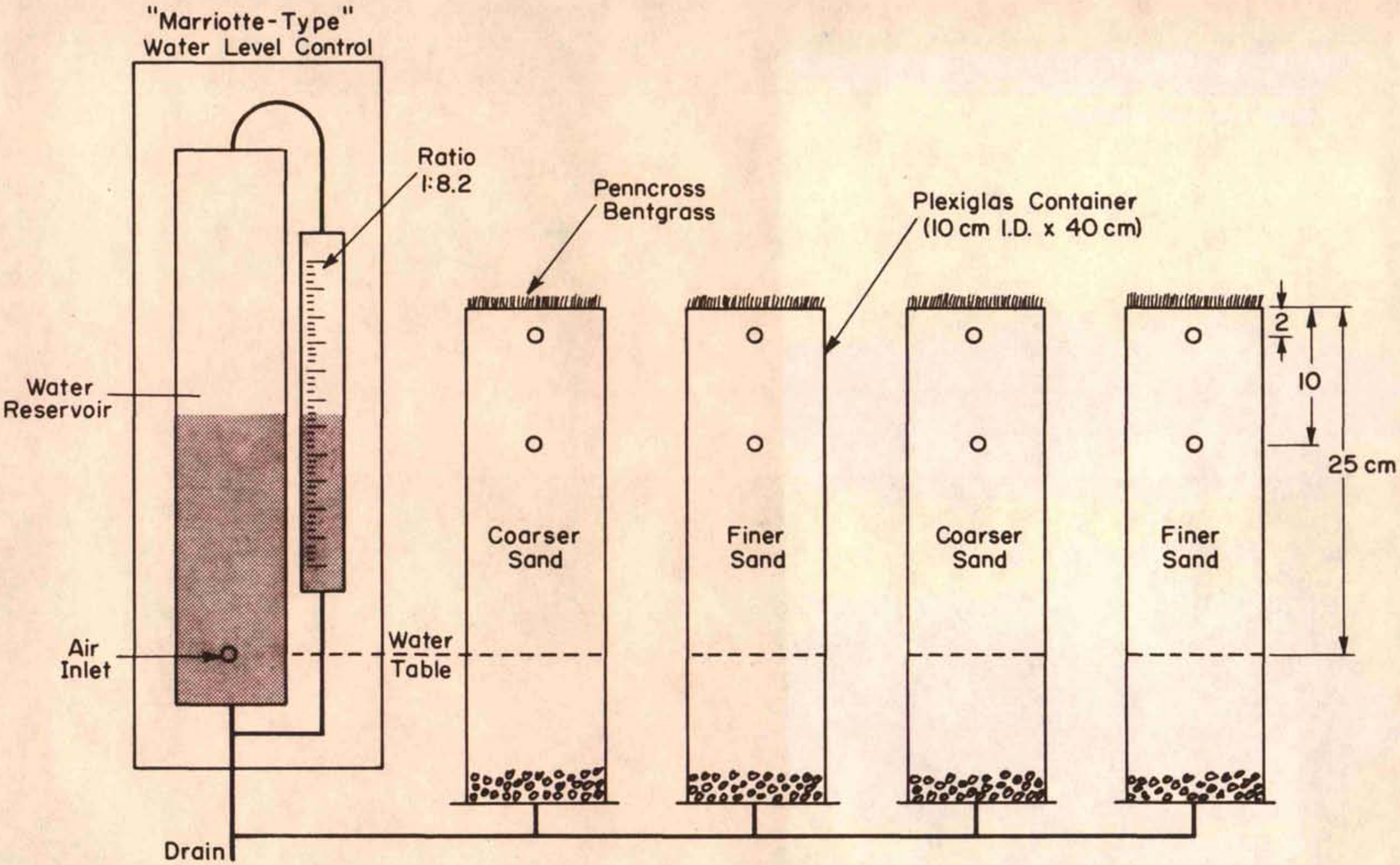

Figure II-3. Schematic of "Marriotte-Type" Water Level Control for 25 cm Water Table Treatment.

Figure II-4. Setup of Experimental Equipment in the 15°C Controlled Climate Room.

tamping continuously until the pot was filled. Each was filled and compacted above the final desired level by use of an extension ring taped to the top of the pot. Excess sand was scraped away to leave a compacted surface.

Sod plugs (10 cm diameter x 1 cm thick) were cut in 3 year old Penncross bentgrass on November 24, 1969, for each pot. Following a one week adjustment period in which all pots were grown under similar conditions in the greenhouse, half of the pots were moved to either the 15 or 30°C controlled climate rooms for the remainder of the nine week experiment. Within each room the temperature remained constant, there was a constant change of air, the photoperiod was 20 hours, and the light intensity was about 1000 foot-candles at plant level.

Nutrition was maintained at an adequate level by the addition of complete nutrient solution at two week intervals, washed in with deionized water so that a total of 100 ml of liquid was added to each pot. All other water was supplied through the "Marriotte-type" reservoirs by sub-surface irrigation. Algaecide was added to the deionized water used in the reservoirs throughout the experiment.

All pots were clipped at a height of 2 cm either two or three times a week, as necessary, and clippings were saved.

Root depth was recorded with a felt marking pen on the side of the containers at the end of the 2nd, 3rd, 4th, 5th, 7th, 8th, and 9th weeks after sodding. The deepest six roots were averaged for the weekly root depth value used for the growth rate. At the end of nine weeks, the initial sod plug was cut from the sample and the sand was removed from the containers in 5 cm segments.

The sand was carefully washed from the roots for each segment. Then, using a procedure developed by Newman$^{(30)}$, the total length of root in each segment was estimated from the average number of intersections between the roots and a line in the microscope eyepiece.

An estimate of root length is given by:

$$R = \frac{\pi N A}{2H}$$

where R is the total length of root, N is the average number of intersections for 40 readings between the root and a straight line, A is the sample area, and H is the total length of the straight line in the microscope eyepiece. The procedure was modified to use a round sieve of either 12 or 20 cm (I.D.) depending on the sample size instead of the suggested rectangle. The roots were randomly dispersed on the sieve by floating them and then quickly removing the sieve from the water. Large samples were subsampled and two 40 count readings were averaged for each sample.

After the length of root was measured, samples were dried for 48 hours at 65°C and weighed. It was noted that sand grains were clinging to the dry roots even after washing three times and storage in water so the dried roots were ashed at 600°C and weighed. The difference in weight between 65 and 600°C was considered to be combustible organic material which was used to calculate the length of root on a unit weight basis for comparison between samples.

Oxygen diffusion rate was measured following the procedure of Lemon and Erickson(21) in which a constant potential of 0.65 volts was maintained between a platinum microelectrode (4 mm long, 22 Ga. wire) and a silver-silver chloride reference electrode in the sample. The oxygen diffusion meter, 24 platinum microelectrodes and reference electrode were built following detailed plans by Letey and Stolzy(24).

The platinum electrodes were inserted in holes at 2 and 10 cm deep in all pots at one temperature and melted wax was used to seal against entry of air. After a one day adjustment period, a series of 8 four minute readings were taken for each electrode and averaged. Three such series were taken during the 7th thru 9th weeks of the experiment and the average of the three groups (24 readings in total) was used for the oxygen diffusion rate.

To reduce the oxygen content of the deionized water in the reservoirs, nitrogen gas was bubbled through the water in storage containers continuously before it was added to the reservoirs.

RESULTS AND DISCUSSION

Evapo-Transpiration Rate

The evapo-transpiration rates in ml/hr for four connected pots for bare surface and third through eighth week after sodding are presented in Figure II-5. The bare surface evaporation rate was about twice as high for the pots at the 30°C temperature as for the pots at 15°C for the same water table treatments. The bare surface data are the average of nine readings taken over a 10 day period before sodding.

Note the general increase in the evapo-transpiration rate from the third to the seventh week for all three water table treatments at the 15°C temperature compared the rapid decrease in rate for the treatments at the higher temperature. This can be explained by the rate of growth at the two temperatures. Vegetative and root growth at the 15°C temperature was slow initially and then increased steadily throughout the experiment. The increase in transpiration rate was due to the increased water use by the plants for metabolic processes and loss through the stomata of the larger number of leaf blades.

However, at the higher temperature, vegetative and root growth was very rapid at first and then steadily slowed until about the sixth week, after which there was little to no new shoot or root development. By the end of the eighth week the evapo-transpiration rate was at or below the bare surface evaporation rate for all three water tables indicating little loss of water through the plant and a reduction in evaporative loss due

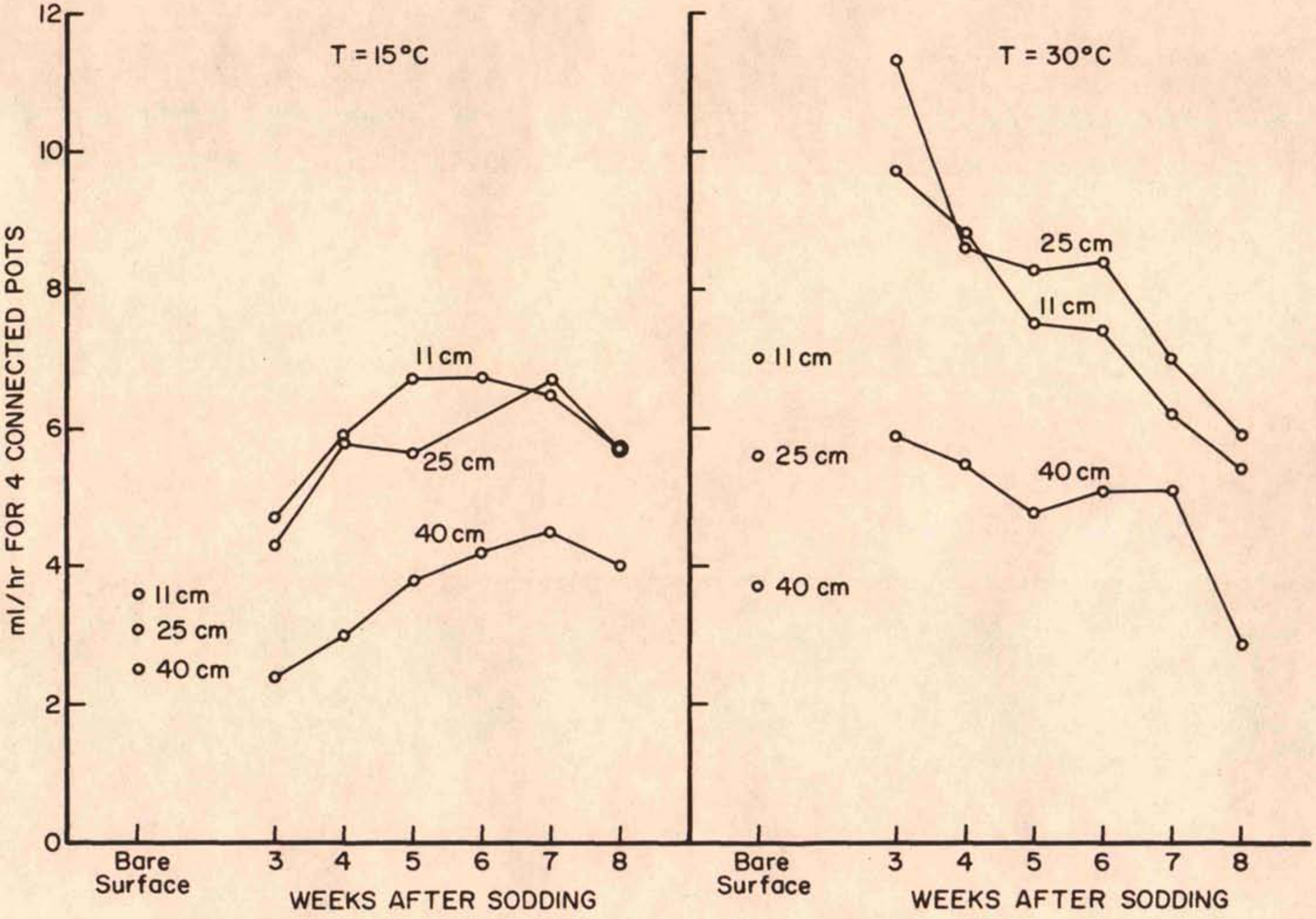

Figure II-5. Weekly Evapo-Transpiration Rates for the Three Water Table Treatments at the Two Temperatures.

to the turf at the surface.

For both temperatures, the curves for the 11 and 25 cm water table treatments were nearly the same and the curve for the 40 cm treatment was considerably lower. The lower evapo-transpiration rate for the deepest water table treatment would be expected due to the increased distance the water needed to rise by capillarity. Therefore, less water would be available for evaporation at the surface or transpiration through the turf as compared with the shallower water table treatments. The height of capillary rise for the 40 cm water table treatments was sufficient to keep the finer sand moist to the surface, but the coarser sand dried out down to about 5 cm after the first two weeks at both temperatures. This dry zone at the surface can be seen in the pictures in Figures II-6 and II-7, which were taken during the eighth week. Transpiration through the turf which had roots below the dry zone in the coarser sand and both evaporation and transpiration for the finer sand would account for the water usage for the 40 cm water table treatment.

Vegetative Growth

The difference in vegetative growth for the two temperatures was very apparent. It was necessary to clip the turf at the 30°C temperature three times before the turf at the lower temperature required clipping. By the sixth week, however, it was necessary to clip the turf at the 15°C temperature three times a week compared to the higher temperature which was clipped twice a week and then only once a week by the eighth week.

Dry weight of clippings accumulated throughout the experiment for the various treatments are presented in Table II-3. The differences within a single temperature are not significant but the magnitude of difference between the two temperatures is significant. The clippings for the low temperature treatment were slow and steady in accumulating compared to the higher temperature in which almost all of the clippings were obtained within the first five weeks of the experiment. If the experiment were continued longer, the spread in difference in total dry weight between the two temperature treatments would have increased since the turf at the cool temperature was growing and the plants at the 30°C temperature were merely surviving.

Within either temperature, the difference in root growth found for the different water table treatments was not reflected in the clippings yields. This is consistant with findings of other workers who could not detect root differences by analysis of clipping yields. In work done with bentgrass, bluegrass and goosegrass, Waddington and Baker(44) reported that clipping weights did not differ significantly for five moisture tension levels.

Table II-3. Average Total Dry Weight of Clippings

Dry Weight

	Temp	15°C		30°C	
	Sand	Finer gm	Coarser gm	Finer gm	Coarser gm
Water Table Depth	11cm	1.4	1.2	0.5	0.6
	25cm	1.8	1.6	0.4	0.5
	40cm	1.6	0.8	0.6	0.1

The only treatment to show wilt stress at both temperatures was the coarser sand with the 40 cm water table. Comparison of the vegetative appearance during the eighth week for the two temperatures can be seen in the pictures in Figures II-6 and II-7. The picture of the 15°C treatment does not show it very well but there was a noticeable difference in color between the turf on the coarser sand and that on the finer sand. The difference was first noticed during the sixth week when the turf acquired a purplish cast which it retained throughout the remainder of the experiment. Vegetative growth rate at the 15°C temperature was less for the coarser sand, 0.8 g compared to 1.6 g for the finer sand, as a result of the moisture stress. The turf grown on the finer sand with the deep water table did not show any moisture stress.

At the higher temperature, the difference between the moisture supplying ability of the finer and coarser sands for the deep water table was much more striking as shown in Figure II-7. By the middle of the third week, the turf grown in the coarser sand was showing definite wilt symptoms. The sand in the top 5 cm dried out since the height of rise by capillarity was insufficient to supply water use requirements. Throughout the remainder of the experiment, only a relatively few shoots remained alive for this treatment and it was observed that the live shoots near the edge of the pot were the ones which had roots below the dry zone into the moist capillary fringe.

The coarse sand with the 40 cm water table demonstrated the important role that hysteresis effect plays under field conditions. Water retained in the large pores from rain or surface irrigation would be available for turf needs, whereas, water will not move into the large pores by

Figure II-6. Growth at 15°C During Eighth Week for the 40 cm Water Table Treatment

from l. to r. - Finer Coarser Coarser Finer

Figure II-7. Growth at 30°C During Eighth Week for the 40 cm Water Table Treatment.

from l. to r. - Finer Coarser Finer Coarser

Figure II-6.

Figure II-7.

capillary rise when the water table is deep.

The bentgrass in the other treatments at the 30°C temperature did not show wilt stress but did show symptoms of temperature stress. By the sixth week, the turf in most of the high temperature treatments appeared chlorotic, many of the blades had brown tips and some were completely brown. The turf in the finer sand with the 11 cm water table was the first to show the stress due to the combination of the shallow water table and high temperature.

One interesting observation was the apparent reduction of sand due to increased biological activity for the pots at the 30°C temperature. By the eighth week of the experiment, the finer sand was black to the surface for the 11 and 25 cm water table treatments and dark to within 20 cm of the surface for the 40 cm water table treatment. For the coarser sand, it was noted that the sand was dark to the surface for the 11 cm water table treatment, dark to within 16 cm of the surface for the 25 cm water table and dark below the water table for the 40 cm treatment. No reduction of the sand was observed for any of the treatments in the 15°C climate room.

Root Growth

In Figure II-8 is presented the root depth data for the end of the 2nd, 3rd, 4th, 6th, 7th, 8th, and 9th weeks of the experiment for the various treatments. The average of the deepest six roots for each of the two replicates for each sand was used in order to establish a uniform basis of comparison.

The most apparent difference in root growth was the continued rate of growth for all treatments at the 15°C temperature compared to the

Figure II-8. Root Depth Measurements for All Treatments.

Note: Each value is the average of the six deepest roots at the end of the indicated week. Two replicates for each sand.

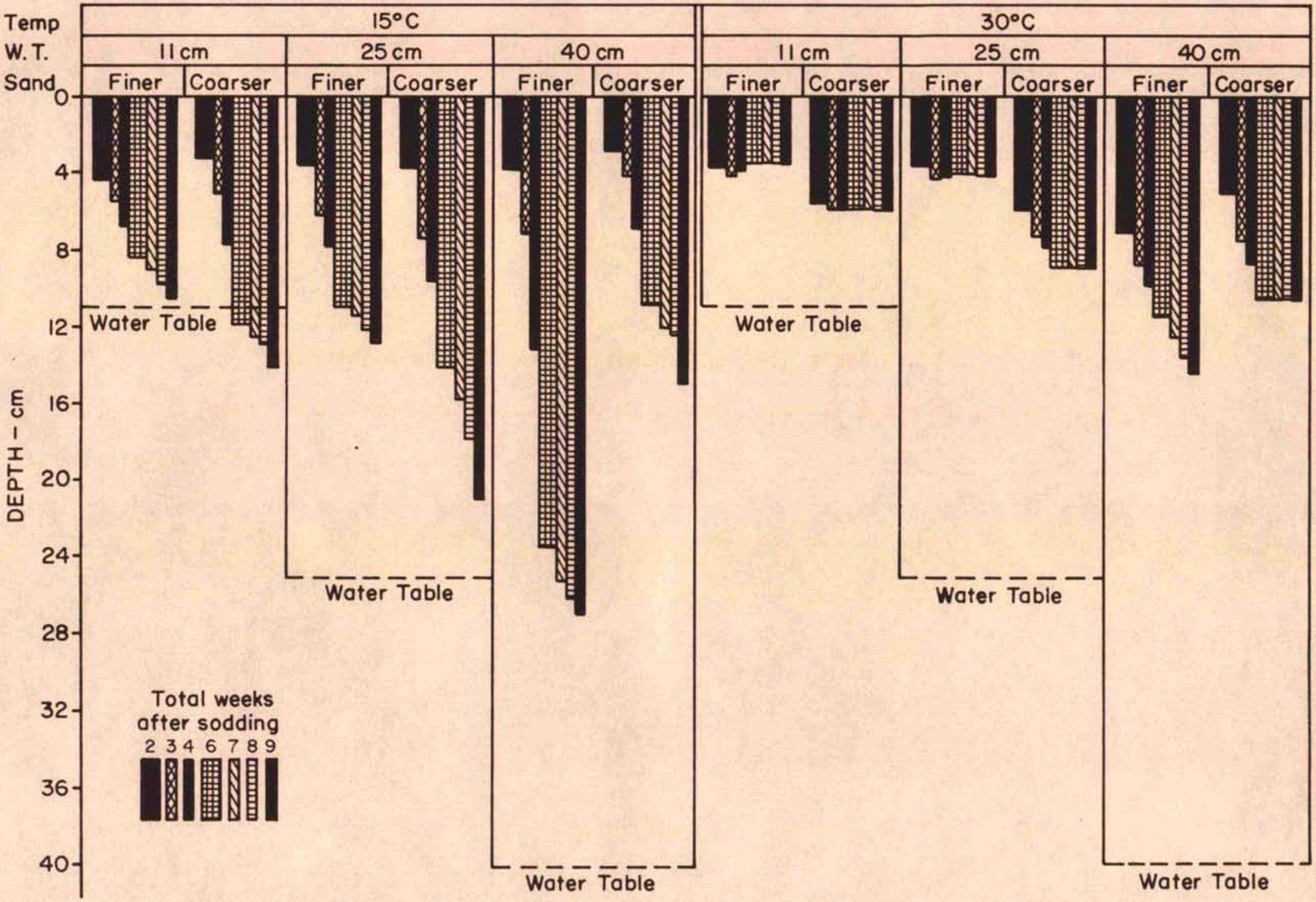
Temp
15°C
30°C
W. T.
11 cm
25 cm
40 cm
Sand
Finer
Coarser
DEPTH – cm
0
4
8
12
16
20
24
28
32
36
40
Water Table
Total weeks after sodding
2 3 4 6 7 8 9

Figure II-8.

cessation of growth for the 11 and 25 cm water table treatments at the higher temperature after the fourth week.

For the 15°C treatment with the water table at 11 cm, the roots grew down to the water table in the finer sand and below the water table for the coarser sand. Apparently the oxygen content and diffusion rate was sufficient in the water to supply the respiration requirements of the roots since the sand was saturated. Bentgrass is a marsh or wet area type of grass so the results are not surprising. With the water table at 25 cm the roots grew deeper in the coarser sand than the finer sand. However, with the water table at 40 cm, the deeper roots were found in the finer sand because the coarser sand tended to be droughty near the surface and the turf was under moisture stress. The deepest roots for any treatment were those found in the finer sand with the deepest water table.

Root growth at the 30°C temperature was markedly different from growth at the cooler temperature. Initial growth was very rapid and roots were deeper after two weeks than for the same treatments at 15°C. Throughout the two week period, the roots were thick, white and actively growing. After three weeks they started to turn yellowish-brown and by the end of the 4th week the roots were brown, thin and appeared to have stopped growing in most instances. Note that for the finer sand with the water table at 11 and 25 cm, the root depth average actually decreased after the third week because a few of the deepest roots decomposed and were not visible except as small black smudges in the sand.

Again for the 30°C treatment as for the lower temperature, the roots were deeper for the coarser than the finer sand with the water table at

11 and 25 cm, but slightly deeper for the finer than the coarser sand for the 40 cm water table. It was noted that the only roots growing in the coarser sand with the deepest water table were the ones which grew below the top 5 cm zone which dried out after the first two weeks. The roots which grew into the moist sand below the dry zone supplied the relatively few blades which remained alive throughout the experiment for this treatment.

Statistical analysis for treatments within each temperature showed a significant sand times water table interaction (see Appendix B).

Root growth results agree with findings of Stucky(38) who reported the best root development a 16°C and very little development at 27°C for bentgrass grown in nutrient solution.

Beard and Daniel(3) found that bentgrass root growth was significantly reduced when grown at 32°C but found no significant difference between growth at 16, 21 and 26°C temperatures. They observed that the roots at the higher temperature were shriveled, turned brown and appeared inactive. They concluded that temperature was the cause of root dieback in summer.

Finn et al.(13) in a study on the effects of different moisture tensions on grass and legume species, concluded that temperature control for such an experiment is necessary.

In a study of Kentucky bluegrass response to variation in temperature, Harrison(19) observed that heavy defoliation depleted carbohydrate reserves and growth stopped after several cuttings at 26°C temperature. He noted that root growth at 16°C was slower but steadier and new growth was initiated from the rhizomes at the lower temperature.

Root Distribution at Harvest

At the end of nine weeks, the sand was removed from the containers in 5 cm segments, the roots were washed, and the total length was measured following the procedure of Newman(30) as outlined. Results for the root distribution shown in Table II-4 are the average of two replicates for each sand.

Root length was greater within the surface 5 cm for the 15°C temperature than for comparable treatments at the 30°C temperature. For the 11 cm water table treatment, the coarser sand had more length than the finer sand. For the 25 cm water table the finer sand had more length in 0-5 cm segment at the 15°C while the coarser sand had more length overall. For the deep water table the finer sand had more total length of roots than the coarser sand for both temperatures.

The big differences between temperature treatments occurred below the surface 5 cm segment. Roots were found down to the water tables for almost all treatments at the 15°C temperature compared to higher temperature in which few roots were found below the surface 5 cm except for the coarser sand with the water table at 25 and 40 cm and the finer sand with the 40 cm water table.

Measurement of a plant root system poses unique problems not encountered in evaluating the vegetative or yield potential of a crop. Nielson (31) points out that the gross size of the root system, whether measured as total fresh weight, total dry weight, length, etc., is not an estimate of its absorbing capacity because a large and changing proportion of the system ceases to absorb.

The most commonly used procedures do not take into consideration the

TABLE II-4. Root Distribution at Harvest - (Each value is average of two replicates)

		Root Length in Meters*											
	Temperature			15°C						30°C			
	Water Table	11 cm		25 cm		40 cm		11 cm		25 cm		40 cm	
	Sand	Finer	Coarser	Finer	Coarser	Finer	Coarser	Finer	Coarser	Finer	Coarser	Finer	Coarser
Depth - cm	0-5	83.6	93.6	156.8	131.4	106.2	62.6	10.2	25.5	37.2	94.2	52.2	22.2
	5-10	44.8	39.0	37.6	60.4	28.7	16.9	<1	<1	1.1	36.4	7.2	21.5
	10-15	3.1	12.8	12.9	25.0	13.9	12.8				2.2	2.3	7.8
	15-20			1.5	11.4	8.8	5.6				<1	<1	<1
	20-25			<1	2.3	7.0	2.0						
	25-30					1.4	<1						
	30-35					<1							

* Volume of 5 cm segment in pot (10 cm diameter) is 392 cm^3

absorbing capacity of the plant. Total dry weight is the method used for comparison purposes most frequently(3,13,18,44). Flocker and Timm(14) weighed tomato roots in 5 cm segments and reported as a percent of the total weight in each segment. The usefulness of the total dry weight method is limited in that the sample is destroyed and the method does not give any indication about root length, thickness, activity, etc.. In this experiment it was noted that even after two sample washings, storage in water, and measurement in water for total length, when the samples were oven dried, sand grains were still found clinging to some of the roots. This greatly affected the oven dry weight of the roots. Therefore, the 65°C oven dry weight values are not reported.

A second procedure used frequently to measure roots is to mark growth at specific time intervals on the side of a translucent container(3,14,23,28). Letey et al.(25) traced rooting patterns from the side of a container onto paper and measured the area with a planimeter. The average depth at a given date was calculated by dividing the measured area by the circumference of the cylinder. This type of measurement is non-destructive but is limited to the use of translucent containers. Also, the assumption must be made that the exposure to light during measurement and wall effect of the container have little influence on rooting depth.

In this experiment, note that measurement by total length of root (Table II-4) showed roots at greater depths than are indicated by the average of the perimeter measurement (Figure II-8) for both sands with the 25 and 40 cm water tables at the 15°C temperature. Two factors are thought to be involved. First, the root depth measurements were the average of 6 deepest roots so there would be roots deeper than the values indicated in Figure II-8. Second, the roots not exposed to light may have grown deeper than those close to the wall. For the finer sand with the 40 cm water table, roots were found in the 5 cm segment just above the water table whereas the average depth of the six deepest roots around the edge of the container was 27 cm.

A third method for measuring roots, one used in this experiment, is measurement of total length of root. The procedure of Newman(30) provides a reasonable estimate of length of root when an adequate number of intersection counts is taken for each sample. Root length is more closely related to absorbing capacity than would be root dry weight since length would indicate a continued root tip development and thus more absorbing surface.

Root Morphology

Root growth in the initial weeks of the experiment was much more rapid at the higher temperature, but roots at both temperatures were thick, white and actively growing. As the experiment progressed, roots visible in the containers at 30°C tended to shrivel, turn brown and in some cases turn black and decompose. At the 15°C temperature, the roots remained thick and healthy throughout the nine weeks. No apparent difference in root diameter for the roots along the sides of the containers was noted for treatments within either temperature during the experiment.

After harvest the difference in diameter of roots observed under the microscope, during the measurement of root length, was very striking. The roots of the 15°C treatments were considerably thicker and whiter than the thin roots of the higher temperature treatment.

An attempt to measure this difference in root thickness was made by

TABEL II-5. Root Length on a Standard Weight Basis.

		Root length per unit weight* - meters/gram											
	Temperature	15°C						30°C					
	Water Table	11 cm		25 cm		40 cm		11 cm		25 cm		40 cm	
	Sand	Finer	Coarser	Finer	Coarser	Finer	Coarser	Finer	Coarser	Finer	Coarser	Finer	Coarser
Depth - cm	0-5	259	218	237	264	301	228	228	706	432	488	765	469
	5-10	284	333	256	337	378	260				681	606	462
	10-15	278	357	388	318	442	442					824	464
	15-20				384	386	317						

* Based on difference in weight between oven dry weight (65°C) and ash weight (600°C).

determining total length per unit weight. Thus, the thinner the root, the greater the length, when weight is held constant. It was found that sand grains were a source of error in the 65°C oven dry weights so the samples were ashed at 600°C and the difference in weight was taken as the combustible organic material of the roots for the comparative weight values.

Root length per unit weight of combustible organic material results are presented in Table II-5. Values for the 15°C temperature ranged from about 200 to 450 m/g with a slight increase in length with increasing depth. Large differences were found for the 30°C treatments, which ranged from about 200 to 800 m/g. The high values obtained for the coarse sand with the water table at 11 and 25 cm and for the fine sand with the water table at 40 cm show that the roots were thin in these treatments.

For the 11 cm water table at both temperatures, the length per unit weight was less for the finer than the coarser sand indicating thicker roots for the finer sand treatment. Waddington and Baker(44) reported that bentgrass, bluegrass and goosegrass all produced thicker roots with fewer laterals under conditions of poor aeration.

Oxygen Diffusion Rate

The platinum microelectrode method of measuring oxygen diffusion rate is subject to some controversy. It is based on the principle that a current is produced in electrolysis of oxygen at the surface of a platinum electrode when a voltage of less than 0.8 volts is applied between the platinum electrode and a large reference electrode(21). Van Doren and Erickson(42) reported on factors which are said to affect the procedure which include dimensions of the platinum wire, effective area of the wire, reproducibility of results, temperature, pH, electrical conductivity, other reducible substances, and poisoning of the electrode.

In a survey of literature pertaining to oxygen diffusion work, Reidy(32) reported that the minimun diffusion rates found by other workers for most plants was 20 x 10^{-8} g/cm^2/min with variations ranging from 15 x 10^{-8} g/cm^2/min for barley to 30 x 10^{-8} g/cm^2/min for tomatoes. Letey et al.(27) found the critical level for Newport bluegrass to be 20 x 10^{-8} g/cm^2/min while the optimum level was 40 x 10^{-8} g/cm^2/min. In a recent study Waddington and Baker(44) found that Penncross bentgrass and goosegrass grew well at rates below 3 x 10^{-8} g/cm^2/min while Merion root growth was stopped at diffusion rates of 5 to 9 x 10^{-8} g/cm^2/min.

Temperature must be considered since oxygen is less soluble with higher temperature and rising temperature causes increased demand for oxygen by roots and aerobic microorganisms. Therefore, a critical oxygen diffusion rate can be reached when temperature rises and the concentration of oxygen is low in the soil solution. Letey et al.(28) found that the oxygen diffusion rate increased 1.8% per degree C rise in soil temperature.

Since it is necessary to allow the platinum electrode to reach equilibrium in each pot, 24 electrodes were built so that they could be installed at two depths in each of 12 pots at one temperature for 24 hours prior to taking measurements. The electrodes were constructed as nearly alike as possible and then standardized in a montmorillonite slurry as suggested by Van Doren and Erickson(42). After 8 individual microampere readings for each electrode were taken the electrodes were moved to the pots in the other controlled climate room. Three groups of 8 readings each were taken for each of the two replicates for each sand. The average

Table II-6. - Oxygen Diffusion Rates - Each value is the average of two replicates for each sand, of which each replicate is composed of 24 individual readings.

Oxygen diffusion rate $\times 10^{-8}$ g./cm.^{2} min.

Water table depth cm	Pt electrode depth cm	Temp	15°C		30°C	
		Sand	Finer	Coarser	Finer	Coarser
11	2		2.4	19.0	2.2	9.0
	10		0.6	1.0	0.6	0.7
25	2		40.2	52.0	57.2	81.1
	10		2.6	42.0	1.4	65.3
40	2		59.6	*	97.9	*
	10		63.6	*	75.6	*

* Sand too dry to obtain reading

of the 48 readings is presented in Table II-6.

For the 11 cm water table the oxygen diffusion rates were all below 3×10^{-8} g/cm^2/min except for the coarser sand at the 2 cm depth. The low diffusion rates could be expected for the finer sand since the sand would be nearly saturated to the surface with the shallow water table as shown by the desorption curve Figure II-2. Thus, air movement within the rootzone would be restricted by water in the pores. What is somewhat surprising is that healthy bentgrass roots were found down to the water table for the fine sand at the 15°C temperature even though the diffusion rate was very low. At the high temperature, however, the combination of the shallow water table and high temperature greatly restricted root development in the finer sand and some of the roots which grew during the first few weeks actually decomposed.

For the coarser sand with the shallow water table, the diffusion rate was adequate near the surface but was near zero at the 10 cm depth. Moisture desorption data indicate that the water free pore space in the coarser sand under 10 cm tension would be 21.8%. Thus the aeration pore space would range from about 20% at the surface to near zero percent at the 11 cm depth in the coarser sands with the shallow water table. Roots were observed down below the water table and 12.8 meters of roots were measured in the 10 - 15 cm segment indicating that the oxygen in the water at the cool temperature was sufficient to supply respiration needs. Engle reported that it has been shown that bentgrass can remain healthy with the amount of oxygen present in fresh water. The water used in the "Marriotte-type" reservoirs was saturated with nitrogen before being put into the reservoirs to reduce the oxygen content of the water.

The oxygen diffusion rates for the 25 cm water table treatment were all above the critical levels reported by others except the 10 cm depth in the finer sand for both temperatures. Referring to Table II-4, it can be seen that there was 157 m of roots in the surface 5 cm. Root lengths decreased rapidly with increasing depth compared to the coarser sand for the same water table. The low oxygen diffusion rate at 10 cm could have been restricting root development to the surface 5 cm for the finer sand compared to the coarser sand in which oxygen was not limiting.

The same conclusion can be made for the 25 cm water table at the higher temperature. Virtually all root growth was in the 0-5 cm segment for the fine sand due to the low diffusion rate and high temperature compared to the coarser sand in which oxygen diffusion was not limiting and roots were found as deep as the 15-20 cm segment.

For the deepest water table treatment the oxygen diffusion rate was more than adequate for the finer sand at both temperatures down to at least 10 cm. It was not possible to measure the rate in the coarser sand because it is necessary to maintain a moisture film around the platinum electrode during the time of measurement and the surface 10 cm was too dry. It can be safely assumed that diffusion rate was not limiting in the coarse sand since the pores near the surface were empty of water.

SUMMARY

This experiment has demonstrated the inter-related effects of temperature and water table depth on bentgrass root development. Temperature was shown to have the greatest effect on root growth, where the rate of growth was steady throughout the nine week experiment for the 15°C treatment compared to the drastic reduction in root growth after the first few weeks for the 30°C treatments. Roots grew down to and below the water table for the cool temperature treatments compared to the higher temperature pots in which most of the roots were confined to the surface 5 cm.

Within each of the two temperature treatments, the water table times sand interaction was significant for root growth. For the 11 and 25 cm water table treatments, root growth was deeper in the coarser than in the finer sand at both temperatures. However, for the 40 cm water table treatment, root growth was better in the finer sand, since the coarser sand tended to be droughty. The better growth in the coarser sand with the 11 and 25 cm water tables was due to better aeration as shown by desorption data for the sands and oxygen diffusion measurements taken during the experiment. The deepest roots were found for the finer sand with the 40 cm water table in the 15°C controlled climate room.

Weekly evapo-transpiration data showed a general increase in rate during the experiment for the cooler temperature treatments compared to a steady decrease in rate for the higher temperature treatments. The evapo-transpiration data reflect the observed difference in vegetative and root growth at the two temperatures. Growth at the 15°C temperature was slow initially and then increased steadily throughout the nine weeks. In contrast, growth at the 30°C temperature was very rapid during the first few weeks, then decreased rapidly until the last few weeks in which there was little or no growth.

The Penncross roots appeared thick and white for both temperature treatments during the first few weeks of the experiment. The roots around the sides of the containers at the cooler temperature continues to grow and remained thick and white compared to the roots at the 30°C temperature which essentially stopped growing after the fourth week, turned brown and appeared thinner. The root length per unit weight data indicate a difference in root diameter between the two temperatures. The values for the cooler temperature ranged from about 200 to 450 m/gm compared to the higher temperature treatments which ranged from about 200 to 800 m/gm.

Root growth at the 15°C temperature was similar to that observed on the experimental green during the winter and spring months. The graph in Figure II-9 shows that the average monthly soil temperature at 10 cm under grass in the Lafayette area are below 15°C until the end of April. From May through October, the average soil temperature is between 15 and 25°C, with days in July and August in which the values are nearly 30°C. Root growth on the green during the summer months was similar to that observed for the 30°C treatments in many respects. The roots were thin and brown there appeared to be very little new growth during the hot weather in the summer months.

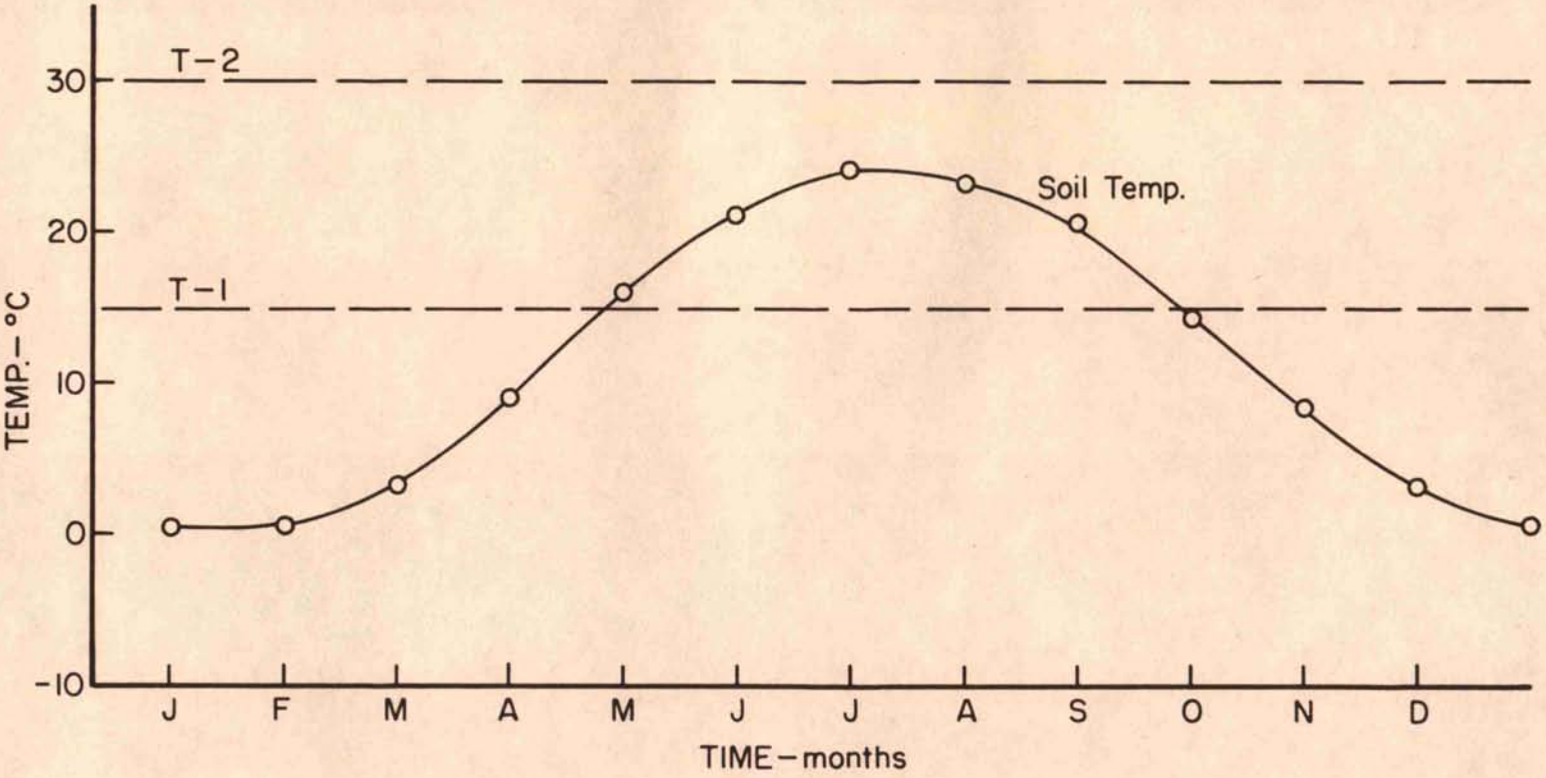

Figure II-9. Average Monthly Soil Temperature at 10 cm Under Grass.

(Data for Purdue Agronomy Farm-seven year average)

The combination of the 30°C temperature and high water table caused anaerobic reduction of the finer sand. The finer sand turned black after about six weeks and remained black to the surface for the 11 and 25 cm water table treatments for the remainder of the experiment. Some reduction of the coarser sand was noted for the 11 cm water table at the higher temperature. This same observation was made for the finer fraction of the dune sand which was subirrigated on the green when the water table was maintained at 20 cm during the summer of 1968. These results indicate the importance of having a deep water table if fine sand is used as the rootzone matrix.