TURFGRASS ROOTING RESPONSES
IN HYDROPONICS

by

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TURFGRASS ROOTING RESPONSES

IN HYDROPONICS

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Greenhouse hydroponic studies were conducted using Kentucky bluegrass (Poa pratensis L.) and tall fescue (Festuca arundinacea Schreb.) to: 1) determine intraspecific rooting differences, 2) compare rooting response of field and hydroponic grown turfs, and 3) determine potential of the hydroponic system as a turfgrass breeding and selection tool for screening rooting differences.

Turfgrasses were grown hydroponically in greenhouse studies to observe root growth and distribution. The nutrient solution was allowed to decrease by evapotranspirational (ET) demand. The solution was changed weekly to maintain nutrient concentration and prevent salt build-up.

Root growth of tall fescue clones varied by 44% in response to declining moisture levels. Eight of the fifteen clones studied had the ability to redistribute their root systems into the 600 mm to 750 mm profile. Clonal root growth in hydroponics agreed with growth measured under field conditions in a Sharpsburg silty-clay loam (Typic Argiudoll). Two-thirds of the clones

identified as having deep rooting characteristics under field conditions were similarly identified in the hydroponic system.

Kentucky bluegrass cultivars differed by 34% in total root growth under declining moisture levels. 'Touchdown', 'Dormie', 'Baron', and 'Ram I' had greater topgrowth and percentage of supporting root growth than the other twelve cultivars in the study. 'Aspen' and 'Georgetown' had high topgrowth production but low supporting root growth percentage. This combination of root and topgrowth characteristics would be undesirable. These plants would have reduced soil moisture extraction potential at greater soil depths, making them less likely to meet their ET demand as soil moisture declined, than those plants with greater support root percentages.

The hydroponic technique was satisfactory for separating genetic differences in root production, distribution and redistribution. The system would be applicable for relative comparisons, screening of turfgrass selections, or both.

To

Mary Ellen Bowler

and

Sister Mary Thomasita Ross B.V.M.

Two people who represent the ideal teacher

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LITERATURE REVIEW

Turfgrasses play an important role in our society. Turf is used as an integral part of home and business landscapes to improve aesthetic and property values. Recreational activities ranging from backyard play to professional sports, use turfgrasses as a playing surface and added safety cushion. Businesses involving installation, sales, consulting, equipment, and supply of turf related products provide a wide range of products, services, and economic stimulation. Turfgrasses also have the ability to modify the environment by reducing erosion, noise, dust, and provide transpirational cooling.

Water is a critical component needed for turfgrass growth and development. As demand on available water supplies increase, restrictions are sometimes applied to the turfgrass industry to reduce water usage. Water restrictions in drought stricken areas can include the banning of home lawn and cemetery irrigation. Recreational turfs may be restricted to the amount, frequency, and timing of irrigation. Over an extended period of time this can affect businesses related to the

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The style and format of this thesis are similar to those followed by the American Society for Horticultural Science.

turfgrass industry.

As water restrictions are imposed, the study, identification, and development of turfgrasses with drought avoidance characteristics are needed. Identifying grasses with reduced evapotranspiration rates and deep, extensive root systems is important for long range genetic improvement.

Drought Resistance

Drought describes a condition when growth is limited due to a prolonged period of water stress (2). Plants use varying mechanisms to resist drought stress. Resistance can occur through tolerance, avoidance, and escape mechanisms.

Drought tolerance mechanisms allow the plant to survive during periods of water stress. Drought tolerant plants have adaptations to tolerate low internal water potentials (42). Tolerance occurs when the plant maintains turgor pressure as internal water potential declines or the cell protoplasm has the ability to survive under severe desiccation.

Drought avoidance is accomplished by anatomical and morphological adaptations that allow for sufficient uptake of water, reduced water loss, or both (37). Avoidance can involve a combination of characteristics including rolling of the leaf blades, thickened cuticle, deep and extensive root system, and stomatal closure.

Drought escape is another resistance mechanism. It is also considered a method of drought avoidance. Some plants have the ability to avoid drought by completing their life cycles in a short time period. Poa annua var annua (L.) Timm can germinate, mature, and set seed during a short period of cool, moist weather. This escape mechanism allows the plant to complete its life cycle before periods of low soil moisture. Seed dormancy during dry periods is an escape mechanism which delays germination until favorable growth conditions prevail.

Genetic Variability

Turfgrass species or cultivars ability to develop deep and extensive root systems could be key to their survival during an extended drought. A deeper root system may have the potential to draw upon a larger soil moisture reserve. A deep root profile alone may not signify a drought tolerant plant but it may increase the possibilities for the plant to absorb moisture from lower soil profiles and longer withstand a drought period. If the plant's ability to redistribute its root system could be identified, breeding could possibly be used to enhance this trait.

Root Systems Species vary in root growth as well as in topgrowth. Tall fescue (Festuca arundinacea Schreb.) and bermudagrass (Cynodon dactylon L.C. Rich) have the ability to develop deep and extensive root systems (2). Root growth has been observed to extend to depths of 2.4 meters for Coastal bermudagrass (11) and 1.2 meters in tall fescue (4). Tall fescue and perennial ryegrass roots are coarse, less branched, and turn dark brown as they mature (25). Creeping bentgrass roots are fine and light brown at maturity. Kentucky bluegrass roots are slightly coarse, highly branched, and dark brown when older (2, 25).

The greatest concentration of root growth occurs in the upper 7.6 cm of soil. Total root growth percentages ranging from 50% (4, 16) to almost 80% (40) have been reported to occur in this portion of turfgrass soil profile. The upper 30 cm of soil profile contain the major portion of total root growth. The amount of roots below 30 cm decreases with increasing depth. When a soil profile is uniformly wetted, moisture extraction occurs first in the upper profile and then deeper as moisture is depleted (16).

Development of new roots and elongation of the existing root system occurs for cool season species during spring and early summer (34, 36). Root growth diminishes during summer months under supraoptimal air and soil temperatures. As soil temperatures decrease, conditions become favorable for root growth. Root growth continues in the fall and early winter until soil temperatures reach 0° C (18, 36).

Root systems can be classified as annual or perennial types. Stuckey (36) defined perennial root systems as maximum production of a root system occurring during one year and this root system persisting and functioning for more than one year. Kentucky bluegrass (Poa pratensis L.), orchardgrass (Dactylis glomerata L.), Canada bluegrass (Poa compressa L.), and crested wheatgrass (Agropyron desertorum (Fisch.) Schult.) have perennial root systems. Annual root systems regenerate roots each growing season with the old roots disintegrating after the new ones become established. Redtop (Agrostis alba L.) and perennial ryegrass (Lolium perenne L.) possess an annual root system.

Genetic variability for rooting characteristics has been investigated over a wide range of plant species. Root characteristics of sorghum (Sorghum bicolor (L.) Moench) has been studied by Bhan et al (5), Blum et al (6), and Jordan et al (22). Jordan and Miller (23) attempted to identify sources of genetic variability in sorghum root systems for purposes of separating superior rooting characteristics. Taylor (39) concluded that trying to increase the rooting depth of cotton (Gossypium hirsutum) and soybean (Glycine max) and selecting cultivars with faster root extension rates, showed promise in delaying signs of water stress.

Environmental Effects

Moisture Stress Bennett and Doss (4) determined soil moisture level effects on rooting depth of eight cool season forage species. They found that all eight species had a high root percentage in the upper 30 cm of soil. Rooting depth varied with species and soil moisture level but as soil moisture increased the effective rooting depth of the plant decreased. Burton et al (11, 12) looked at moisture effect on root penetration and distribution of five warm season species. Coastal and Swannee Bermudagrass were more drought tolerant than common Bermudagrass, Pensacola Bahiagrass (Paspalum notatum Flugge.), or Pangolagrass (Digitaria decumbens). Most of the roots of the more drought susceptible grasses were found in the upper 61 cm of soil, but Coastal and Swannee Bermudagrass had only 65.1% and 68.8%, respectively, in the upper 61 cm soil layer.

Perennial ryegrass (30, 31, 40), tall fescue (24, 30, 31), and Kentucky bluegrass (30, 31) response to moisture stress have been well-studied. Tall fescue root samples had a larger portion of roots at lower depths (84 cm) and absorbed more soil moisture from this region than Kentucky bluegrass. Perennial ryegrass was intermediate in root growth to tall fescue and Kentucky bluegrass (30).

Soil Temperature The optimum temperature range for cool season turfgrass root growth is 10° C to 18° C. Optimum root growth for warm season species ranges from 24° C to 39° C (2). Growing within the optimum temperature range roots are white in color, thick, and branched. Root growth is sustained under high air temperatures as long as soil temperatures are favorable.

Root growth declines as soil temperatures increase above the species' optimum temperature range (3, 14, 36, 37). Stuckey reported that during periods of high soil temperatures, root growth of the twelve species studied ceased altogether during the summer months (36). As temperatures increase above the species' optimum, roots mature more rapidly becoming brown and fine in texture. Beard (3) found at a range of soil temperatures of 16° C, 21° C and 27° C total colonial bentgrass (*Agrostis tenuis* Sibth.) root production decreased as soil temperatures increased. At 32° C root production had been significantly reduced.

Growth occurs under suboptimal root growth temperatures, but at a slower rate than at optimal ranges. Active Kentucky bluegrass root growth has been observed at soil temperatures near 0° C (36). Growth was measured by visual observation and the presence of dividing cells at the root tip. Other researchers have noted root growth occurring during periods of suboptimal soil temperatures (18, 40).

Cultural Effects

Fertilization Turf fertilization recommendations have emphasized the benefits of late season applications of nitrogen (18). An application made prior to low temperatures will aid in root development without stimulating an excessive amount of topgrowth. The potential gain in plant vigor can result in a lower amount of nitrogen required in the spring.

Irrigation Irrigation interval affects the depth of turfgrass rooting. Turfgrass stands irrigated deeply and infrequently establish a deep, extensive root system (4, 11, 16, 26, 28). Frequent irrigation results in shallow and few roots (26). Excess irrigation affects both topgrowth and root growth resulting in a plant with less vigor and quality and more susceptible to injury from diseases, insects, and stress.

Cutting Height The influence of frequency and quantity of defoliation on turfgrass root growth was investigated by Crider (13). Studies were conducted to look at effects of foliage removal on root growth. Species investigated included: smooth brome (*Bromus inermis* Leyss.), tall fescue, orchardgrass, Florida paspalum (*Paspalum floridanum*), King Range bluestem (*Andropogon ischaemum*), swithchgrass (*Panicum virgatum* L.), blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud), and bermudagrass. Using plants growing in the field and greenhouse he concluded root growth stopped in proportion to the amount of topgrowth removed.

A study considering the effect of different clipping percentages in a single mowing concluded that topgrowth removal of 40 percent or less did not stop root growth. Foliage removal of 50 percent or more caused root growth to discontinue to some extent. The time required for root growth to resume depended directly upon the amount of foliage removed. As percentage of foliage removal increased, root growth stopped for longer periods. Similar results were found in a study involving repeated mowing and varying clipping percentages. Root growth stoppage occurred for longer periods as mowing was repeated over time.

Higher percentages of foliage removal resulted in a decrease in root production and poor development of the overall grass plant. Continued defoliation caused a reduction in root number, branching, root diameter, and depth of root growth. This has been reported by other researchers (9, 26, 29, 41). Frequent mowing and too great a reduction in topgrowth results in declining plant vigor. The damage may influence root growth before any visible effects to topgrowth.

Research Techniques

Many different aspects of cultural practices and environmental effects on topgrowth have been studied. Much of this is due to the importance of producing a high quality topgrowth and the difficulty in conducting root research. Root research is difficult to conduct due to the tedious and time consuming methods used to gather data and complications in studying undisturbed growth.

A wide variety of methods have been used to look at root growth. Core samples of the plants have been taken, soil washed from the sample, the root material dried, and comparative root weights measured (4, 17, 26, 36, 40). Canisters are placed in the soil so that plant growth and soil can be removed at the time of harvest (18). Monolith samples are taken allowing removal of a column of soil including the plant growth (4, 29). Soil is then gently washed away before observing the root growth. Root penetration has been measured by placing radiophosphorus (P^{32}) at various depths. Radioactivity is then measured in the leaves. The presence of P^{32} indicates that root growth has penetrated to the depth of P^{32} placement (11, 31). Systematic studies on root systems are continually modified to further perfect technique and accuracy (8).

Greenhouse investigations of root growth have been accomplished using long sectioned cylinders as growing containers (12). Water can be applied in different areas of the container to look at resulting root growth and distribution. At the completion of the study the tube is sectioned, growing media washed away, and roots dried and weighed. Boxes with glass panels are used in greenhouses and rhizotrons to observe root growth in an undisturbed state. Rhizotrons are an underground field laboratory with glass paneled boxes that allow observation of plant root growth. Daily observations of root elongation can be recorded (3, 8, 13). This method has the advantage of allowing continual study of the root growth over time without disruption of the plant material.

Hydroponics Hydroponics (i.e. growing plants in a nutrient solution) is used for growing a wide variety of crops both in the greenhouse and field. It has the advantages of producing crops in arid regions or areas with poor soil conditions and providing food production in a limited area. Hydroponics allows for removal and reinsertion of plant material without destroying root growth.

The development and use of the hydroponic technique contributed information on essential element requirements, proportions and concentrations needed for plant growth, and physical and chemical effects of the nutrient solution. The technique itself has been modified by varying nutrient concentrations and recognition of the benefits and importance of solution aeration (19).

Hydroponics has been used as research technique to study root growth. Growing plants in a nutrient solution has the advantages of 1) maintaining pH and nutrient concentrations, 2) regulating drought stress, 3) ease of observing root growth using a nondestructive technique, and 4) the capacity to screen a large number of plants simultaneously. Hoagland and Aaron (19) conducted investigations to develop techniques used in hydroponics. Their nutrient solution is cited as the basis of many hydroponic studies.

Work with hydroponics to determine genetic variability in sorghum (Sorghum bicolor L. Moench) has been used (6, 7, 22, 38). Jordan (22) distinguished differences among shoot and root growth of thirty sorghum genotypes. Sullivan (38) used hydroponics as a means to inflict drought stress on the plants and observe resulting root growth. Blum (6) concluded that hydroponics was a suitable method to study sorghum root systems.

Hydroponics has proved itself to be a useful technique in the study of turfgrass growth. The technique allows for the germination and growth of individual seedlings using a nutrient solution (1, 33). Root growth can be studied over a period of time while allowing the plant to be removed and reinserted without injury to the root system. Effects of moisture stress (21, 27), and salinity (20) can be controlled and the resulting growth monitored.

Results between field work and solution cultures vary in actual results. Variation occurs due to absence of soil resistance on rootgrowth and varying environmental conditions surrounding plant growth. Roots grown in water cultures are more fragile than those growing in soil due to different cell structures (8). Though actual results may vary researchers have reported correlation between soil and solution culture systems and suitability of the use of hydroponics to study plant growth (1, 6, 10, 22, 24, 38).

With this background information in mind research was initiated with the following objectives:

1. Determine rooting differences of Kentucky bluegrass cultivars grown in hydroponic solution under declining moisture levels.
2. Relate rooting responses of hydroponic and field grown turfs.
3. Determine the potential of the hydroponic system for screening turfgrass root response to declining moisture levels.

MATERIALS AND METHODS

Three greenhouse hydroponic studies were conducted using Kentucky bluegrass and tall fescue to determine root growth and distribution under declining moisture levels.

The hydroponic system growing containers constructed with 102 mm diameter by 750 mm length polyvinylchloride (PVC) pipe (Figure 1). PVC tubes were capped, on the bottom, with 102 mm diameter sewer pipe caps and sealed with silicone sealant to eliminate leakage of the hydroponic solution. Tops were constructed using 19 mm thick styrofoam, cut 102 mm in diameter to fit on top of the PVC pipe. A center hole was drilled in the styrofoam top with a 25 mm hole saw to allow insertion of the plant material. The cap was painted with white latex paint to remove the possibility of toxicity from petroleum based compounds in the styrofoam. PVC tubes were painted on the outside with black, latex paint to minimize light penetration. A coat of white, latex paint was added to reduce heat absorption and return the tubes to their original appearance.

The hydroponic solution used as the growing medium consisted of a modified Hoagland and Aaron solution (Tables 1 and 2). Nutrient solution was changed weekly to prevent salt build-up, regulate pH, and maintain nutrient concentrations. The solution was aerated with

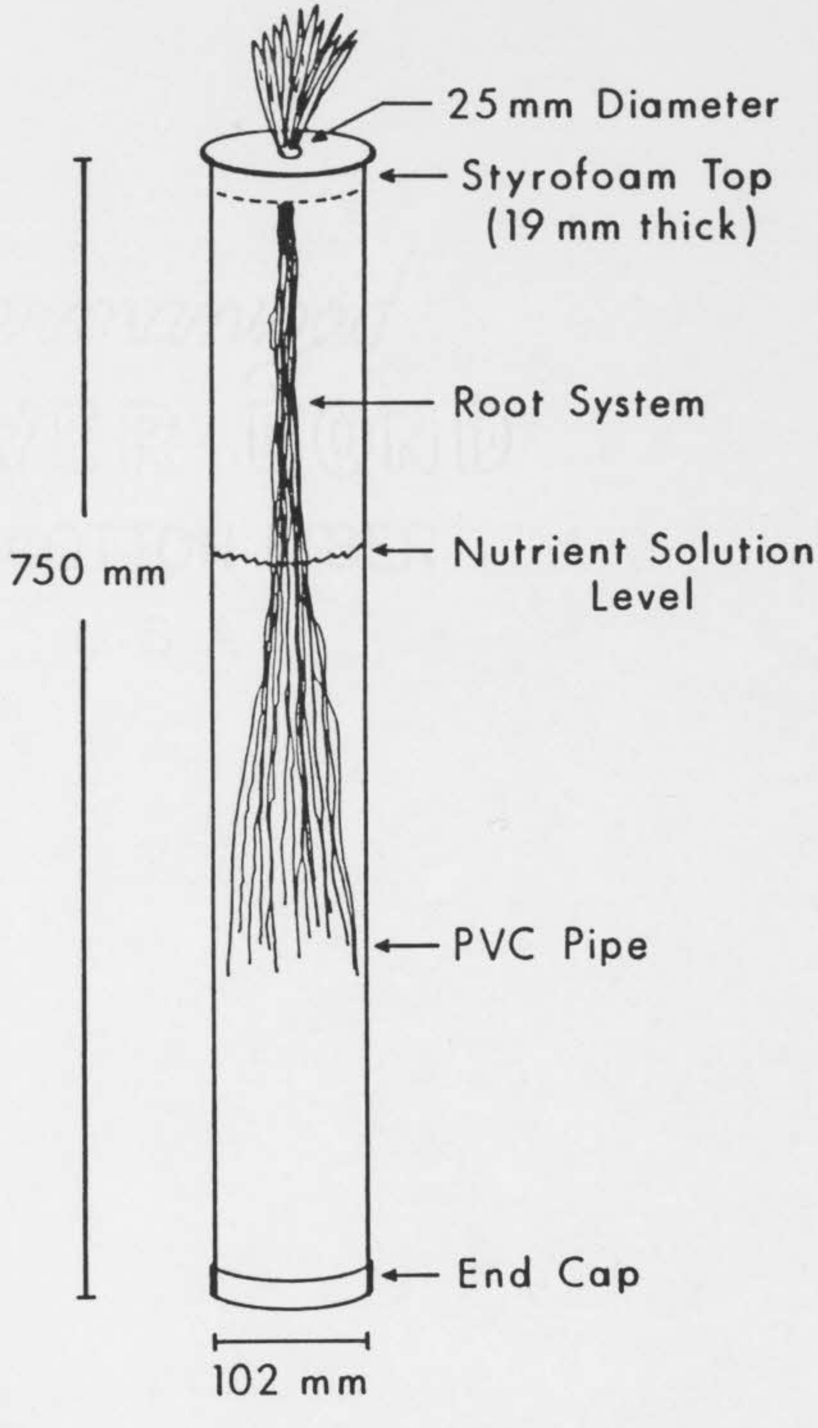

Figure 1. Hydroponic growing container.

Table 1. Stock solution (modified 1/4 strength Hoagland and Arnon solution).

Stock Solutions	Concentration (g/l)
A. KH_2PO_4	136.1
B. KNO_3	101.1
C. $Ca(NO_3)_2 \cdot 4H_2O$	236.2
D. $MgSO_4 \cdot 7H_2O$	246.5
E. Sequestrene Fe[z]	21.4
F. Micronutrients[y]	
H_3BO_3	2.50
$ZnCl_2$	0.50
$CuCl_2 \cdot 2H_2O$	0.56
$Na_2MoO_4 \cdot 2H_2O$	0.05
$MnCl_2 \cdot 4H_2oO$	0.05

z Sequestrene iron and micronutrient stock solutions should be refrigerated.

y Micronutrients are added and dissolved in order listed.

Table 2. Stock solution quantities used to prepare final nutrient solution.

	Quantities (ml)[z]	
Stock[y]	PVC and Tall Fescue Study	K.bluegrass Study
A[x]	0.25	0.13
B	5.50	2.75
C	4.00	2.00
D	3.00	1.50
E	1.00	0.50
F	0.25	0.13

z Solution prepared using the following ml of stock solution per liter of final solution.

y Stock solutions made as in Table 1.

x A through F denoted in Table 1.

aquarium bubble stones attached to 2 mm inner diameter by 950 mm length spaghetti tubing connected to the greenhouse air line. Solution aeration was regulated with pinch clamps to achieve similar bubbling between containers. Aeration was adequate but not enough to disrupt root growth.

Mercury halide lights provided additional lighting for a fourteen hour photoperiod. Light measurements were 155 Wm^{-2} on a typical cloudy day and 770 Wm^{-2} under a bright, sunny day.

The studies were terminated when the first cultivar's root growth, for all replications, reached the bottom of the growing container.

PVC Study Jordan et al (22) reported the possibility of PVC material causing a toxic effect that inhibited root growth. The first study was designed to test the suitability of using PVC pipe as a turfgrass hydroponic growing container. The study objectives were to determine the effects of PVC surfaces, decreasing solution levels, and the interaction of both on turfgrass root and shoot growth.

Experimental design consisted of a split plot with a randomized complete block design, in six blocks. Blocking was based on a temperature gradient present in the greenhouse. Treatments were PVC tube: 1) painted with black, latex paint, 2) lined with a six mil, black, polyethylene sleeve, or 3) untreated. Half of the PVC treatments per block were allowed to decrease the nutrient solution level based on evapotranspiration (ET) demand (i.e. nonfilled) and the second half were maintained with nutrient solution levels at the top of the PVC tube (i.e. filled). The filled solution was replenished every third day. Nutrient solution was changed weekly in all filled and nonfilled tubes. In the nonfilled tubes the nutrient solution was replaced at the level determined by ET demand.

'Birka' Kentucky bluegrass was established from seed. Individual seedlings were transferred to 38 mm diameter by 210 mm depth plastic conetainers, filled with washed, silica sand. Seedlings were fertilized every second day with a modified Hoagland solution (Tables 1 and 2). The sand media was leached weekly to reduce salt build-up. When the seedling root system reached the bottom of the conetainer, the sand was washed from the root system and the crown of the plant wrapped in saran wrap to support the plant in the cap and to allow growth expansion due to tiller formation.

Plants were allowed to equilibrate in the nutrient solution for two weeks and the study initiated 9 February 1985. Plant height was maintained at 75 mm with clippings collected every four days. The study was terminated 23 March 1985 (i.e. six weeks after initiation), when the first roots reached the bottom of the growing containers.

Roots were cut from the crown and separated into five 150 mm segments based on rooting depth. Plant material was dried at 70° C for 72 hours before weighing on a Mettler analytical balance (Model B-6). Growth parameters included clipping yield, verdure, topgrowth (clippings plus verdure), segmented root growth (five 150 mm segments), and total root growth.

Analysis of variance was performed and means were separated by Duncan's multiple range test for comparison of means at the 5% probability level.

Tall Fescue Clone Study This study was conducted to test the suitability of using the hydroponic system for separating rooting differences compared to field results. Objectives of the study were to: 1) evaluate rooting depth, distribution, and production, 2) determine clonal ability to redistribute roots in declining available water, 3) evaluate clonal topgrowth, and 4) determine percentage of root systems supporting topgrowth.

Three clonal types (i.e. turf-type, forage-type, and intermediate) were used (Table 3). These plants were selected for their variable rooting characteristics. Numbers assigned to the clones were used to identify the vegetative propagules (24).

Vegetative propagules were established in 38 mm diameter by 210 mm depth conetainers filled with washed, silica sand. Plants were fertilized every two days with a modified Hoagland solution (Tables 1 and 2) to profile

Table 3. Clonal types of tall fescue vegetative propagules[z].

Turf-type		Forage-type	Intermediate
2	15	14	5
25	26	21	19
27	31	22	20
33			29

z Numbers are clonal identification based on system used by Kopec (24).

saturation. The growing media was leached once a week with distilled water to prevent salt build-up.

When propagule root growth reached the bottom of the conetainers the plants were transferred to the PVC growing containers. The plant crown was wrapped in saran wrap before insertion into the styrofoam cap. Nutrient solution was a modified Hoagland solution (Tables 1 and 2) and changed weekly as described previously. Solution level was allowed to decline in each tube according to ET demand. Topgrowth was clipped at 75 mm on a five day cycle. Clippings were collected and accumulated throughout the study.

Experimental design was a randomized complete block with fifteen vegetative propagules and four replications. The study was initiated 5 May 1985 and terminated 3 June 1985 when the first clonal root system reached the bottom of the growing containers. Plants were harvested as described in the PVC study with one additional parameter; final water level was measured and the root growth at that depth subsequently divided. The percentage of root growth in the solution, supporting topgrowth (i.e. supporting root growth [SRG]) was calculated.

Analysis of variance was performed and means were separated by Duncan's multiple range test at the 5% probability level.

<u>Kentucky Bluegrass Cultivar Study</u> The third study conducted was designed to compare Kentucky bluegrass

cultivar rooting differences. Study objectives were to: 1) evaluate rooting depth, distribution, and production, 2) determine cultivar ability to redistribute roots in declining available water, and 3) determine percentage of root systems supporting topgrowth.

After consulting with turfgrass breeders, cultivars were selected because they represented a wide range of potential genetic diversity. Sixteen Kentucky bluegrass cultivars were established by seed in vermiculite (Table 4). Individual seedlings were transferred to 38 mm diameter by 210 mm depth plastic conetainers filled with washed silica sand. The seedlings were fertilized every second day (Tables 1 and 2) and the root zone flushed with distilled water once a week.

When the seedlings were established and root growth had reached the bottom of the conetainer the plants were transferred to the PVC growing containers as described earlier. The nutrient solution was changed weekly and replaced to the level determined by ET demand (Tables 1 and 2).

The study was initiated 15 November 1985 using a randomized complete block design and six blocks. Topgrowth was clipped at 64 mm every five days and the clippings collected. When the first cultivar's root growth reached the bottom of the growing container, in all replications, the study was terminated. This occurred 24 January 1986 ten weeks after initiation of

Table 4. Kentucky bluegrass cultivars used in study to determine root growth and distribution under declining moisture.

America	Glade
Aspen	Kenblue
Baron	Mystic
Birka	Nassau
Challenger	NE 80-88
Dormie	Park
Eclipse	Ram I
Georgetown	Touchdown

the study. Plants were harvested, dried, and growth parameters measured as in the tall fescue clonal study.

The study was repeated in March 1986. Analysis of variance was calculated. Data was combined from the two studies after comparing mean square error terms and determining less than a two-fold difference (35). Combined data was analyzed and separation of means calculated using Duncan's multiple range test at the 5% probability level.

RESULTS AND DISCUSSION

PVC Study Topgrowth varied for the polyvinylchloride (PVC) surface treatments and the two solution level treatments within the tubes (Table 5). Topgrowth was reduced in the painted compared to the nontreated or lined tubes. A significant difference between filled and nonfilled treatment was also noted ($P \geq 0.01$). Painted tubes had a lower topgrowth production than the other combinations of PVC and solution treatments.

Topgrowth declined in lined PVC treatments by 25% for filled versus nonfilled treatments. This decline compares with 5% and 6% for nontreated and painted tubes, respectively. Ethylene may have been released by the polyethylene plastic liner causing a reduction in topgrowth.

Root production declined in lined containers by 15% and nontreated 5% for filled versus nonfilled treatments (Table 5). Root growth in painted containers increased by 13% for filled versus nonfilled treatments. The paint had a possible toxic effect on root growth causing a decrease in production in the filled solution treatment.

Painted containers had reduced topgrowth in both filled and nonfilled treatments. This decline was also evident in root growth production with the filled

Table 5. Topgrowth (clippings and verdure) and root growth responses for 'Birka' Kentucky bluegrass grown in lined, painted, or nontreated polyvinylchloride (PVC) containers with hydroponic solution maintained in filled or nonfilled status.

PVC Treatment	Filled[z]	Nonfilled[y]
Topgrowth (mg)[x]		
lined	9037 a[v]	6732 b
nontreated	8649 a	8186 a
painted	6149 b	5734 b
Root growth (mg)[w]		
lined	144 a	122 a
nontreated	147 a	140 a
painted	115 b	132 a

z Nutrient solution maintained at top of container.
y Nutrient solution allowed to drop according to evapotranspiration demand.
x Verdure + clipping yield expressed as dry weights.
w Total root growth expressed as dry weights.
v Values are means of six replications. Mean separation within columns for a parameter by Duncan's multiple range test, 5% probability level.

solution treatment (Table 5). Reduction in growth likely resulted from the paint, releasing toxic substances which inhibited top and root growth.

Root distribution was evaluated over five, 150 mm segments (i.e. 750 mm rooting profile). Variation in distribution occurred between the filled and nonfilled treatments (Figure 2). The upper 150 mm segment contained 72% of the root growth, when the containers were continually maintained in the filled status. Nonfilled containers had 54% in the same segment. The second segment (i.e. 150 mm to 300 mm) contained 22% and 32% for the filled and nonfilled tubes, respectively. Plants in the nonfilled containers had the ability to redistribute their roots to the lower portion of the profile in response to declining water levels as dictated by plant ET.

Root distribution among the PVC treatments varied for filled and nonfilled solution treatments (Figures 3 and 4). In segments one (i.e. 0 mm to 150 mm) and two (i.e. 150 mm to 300 mm) root growth was similar for lined, painted, and nontreated containers. In the third (i.e. 300 mm to 450 mm), fourth (i.e. 450 mm to 600 mm), and fifth (i.e. 600 i.e. to 750 mm) segments the nontreated had a higher root growth response than the lined or painted tubes.

These preliminary results support the use of unlined PVC pipe as a turfgrass hydroponic growing

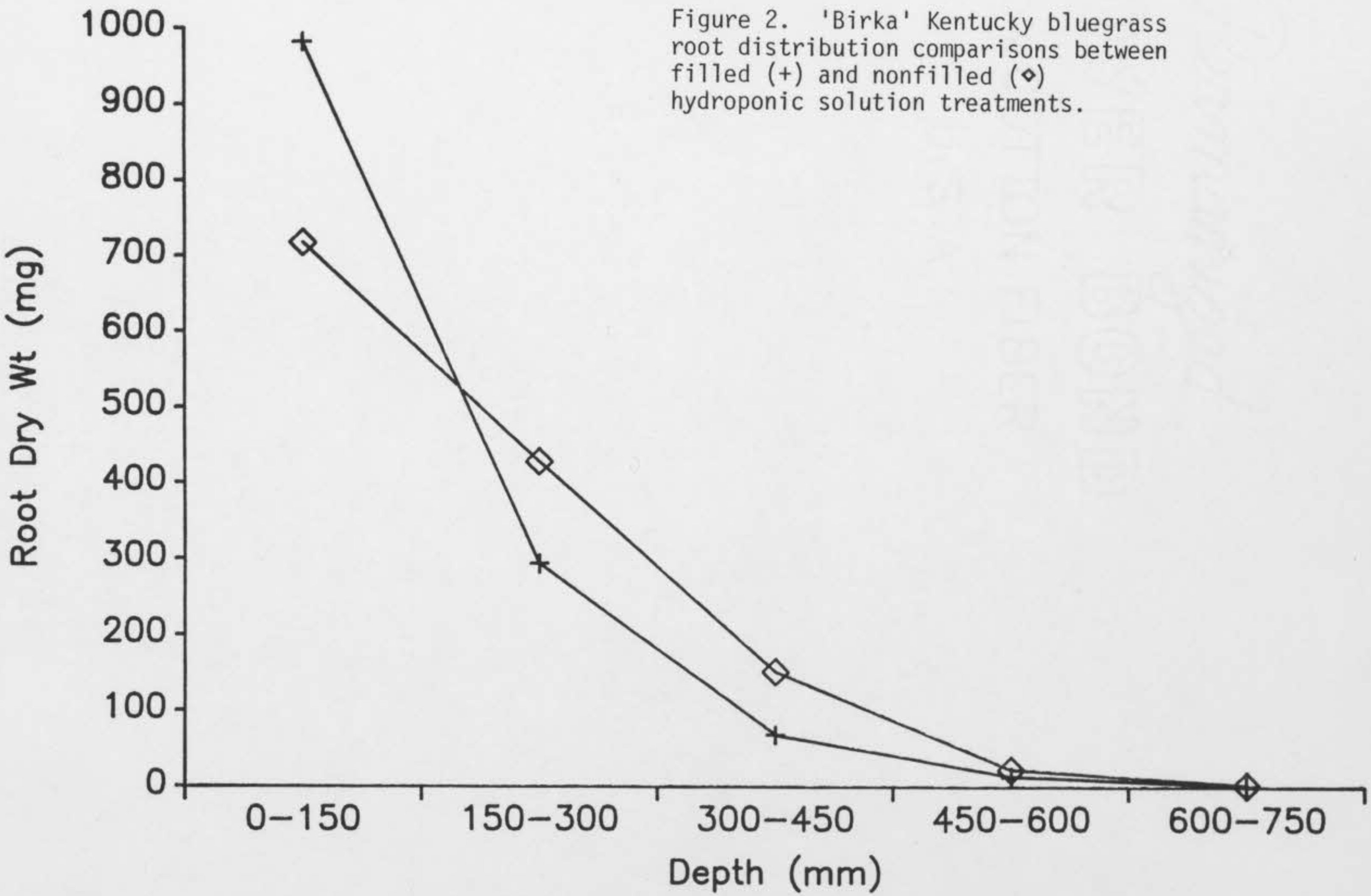

Figure 2. 'Birka' Kentucky bluegrass root distribution comparisons between filled (+) and nonfilled (◇) hydroponic solution treatments.

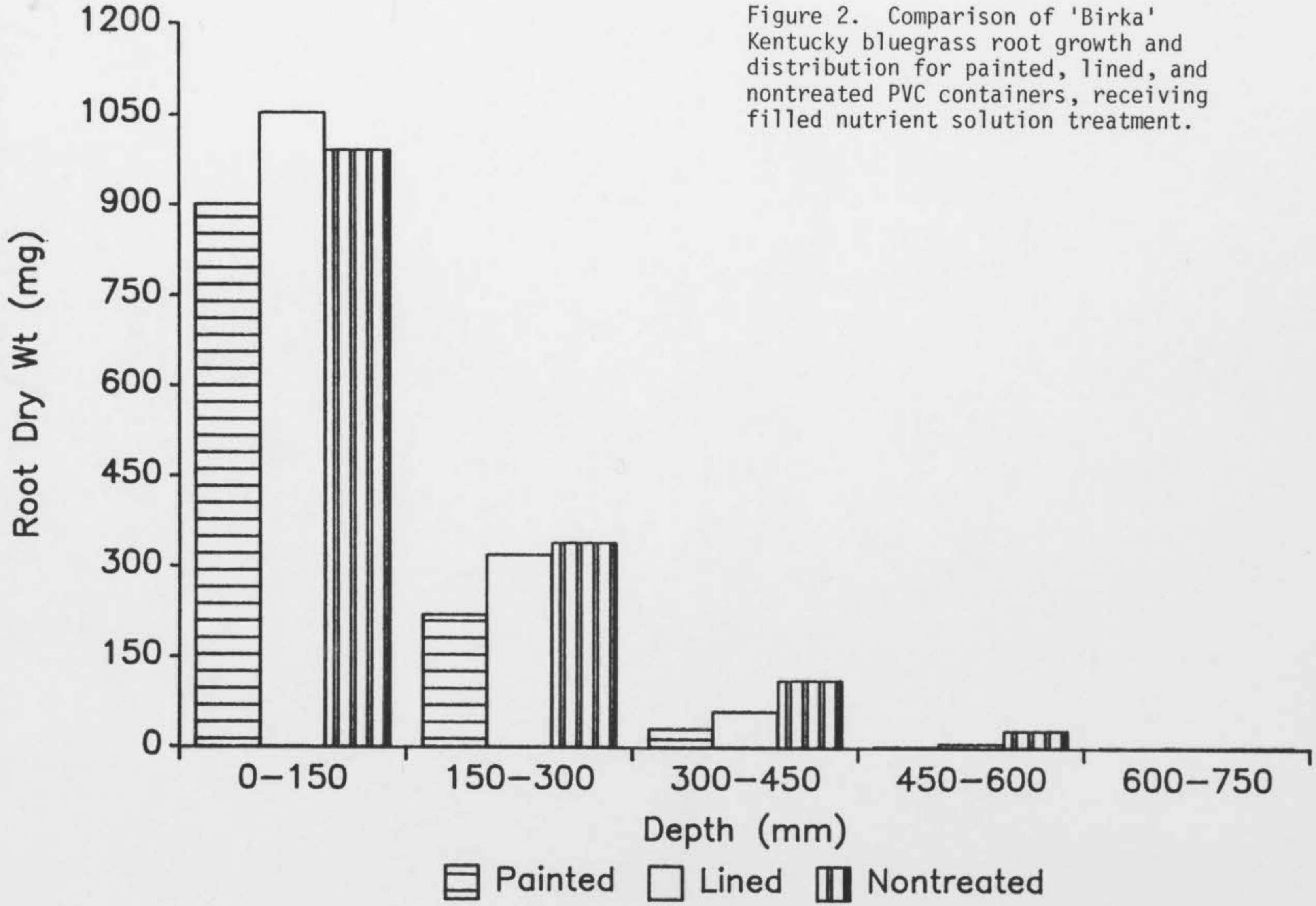

Figure 2. Comparison of 'Birka' Kentucky bluegrass root growth and distribution for painted, lined, and nontreated PVC containers, receiving filled nutrient solution treatment.

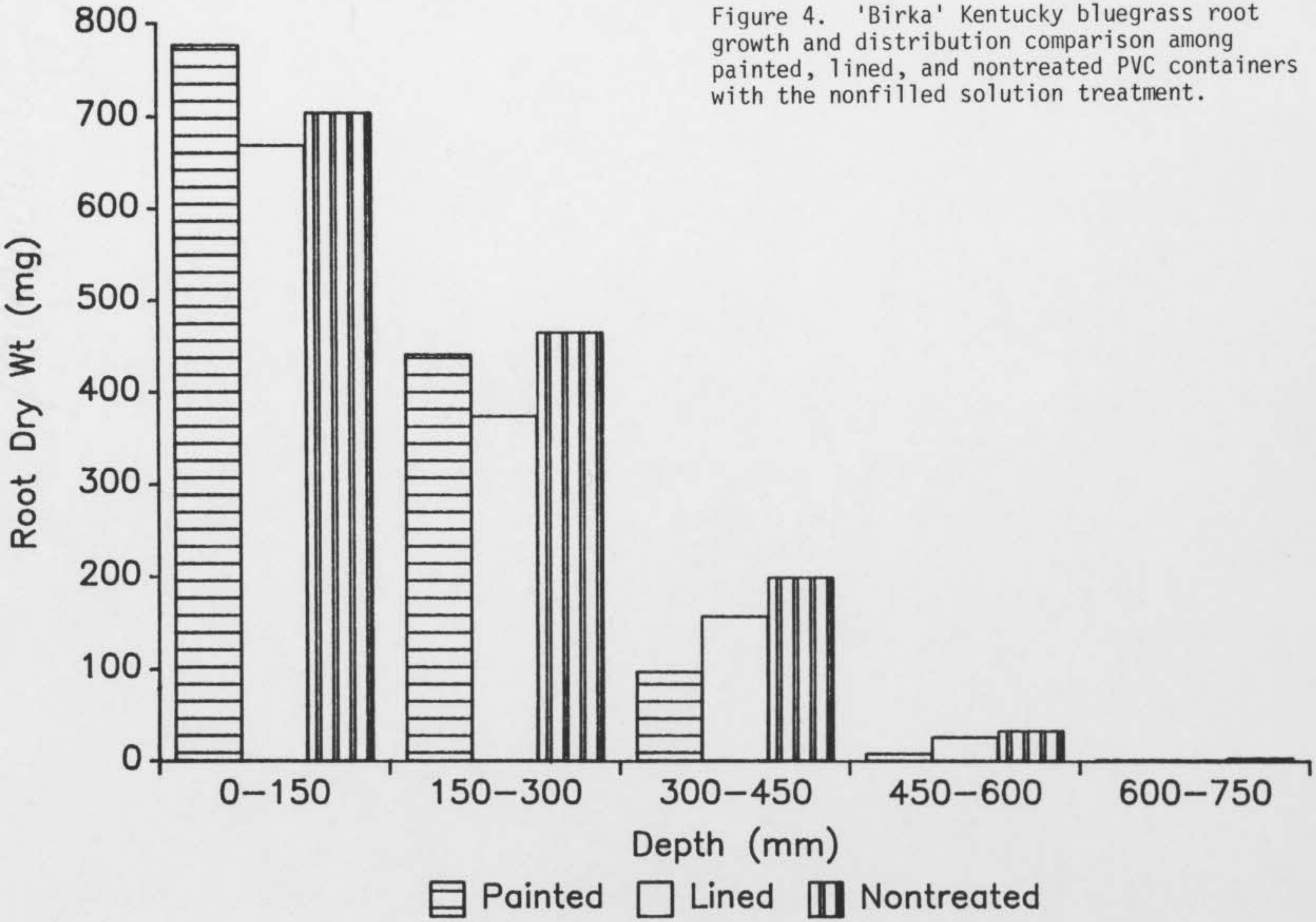

Figure 4. 'Birka' Kentucky bluegrass root growth and distribution comparison among painted, lined, and nontreated PVC containers with the nonfilled solution treatment.

container without harmful effects. Data indicated declining moisture levels influenced root growth and distribution of 'Birka' Kentucky bluegrass.

Tall Fescue Clone Study Total topgrowth varied by 34% among clonal response to declining moisture levels (Table 6). Root growth had a 44% (Table 7) variation for clonal root response.

Clones 2 and 20 produced the highest amount of total topgrowth among the fifteen tested clones. Clone 15 was beginning to show signs of disease at the termination of the study. The leaves were beginning to become mottled and necrotic. Symptoms occurred only on clone 15. The University of Nebraska Plant Diagnostic Laboratory was unable to isolate the specific causal agent.

Thirteen of the clones tested reached the fourth (i.e. 450 mm to 600 mm) segment of the growing container (Table 8). Eight clones had root growth reaching the fifth segment (i.e. 600 mm to 750 mm). The importance of the data is recognizing which clones had the ability to redistribute their root systems under declining moisture levels. Identification of this clonal ability was the objective of the study.

Clones differed in percentage of root growth supporting topgrowth (Table 7). Clone 25 produced the highest percentage of supporting root growth (SRG) at

Table 6. Verdure, clipping yield, and topgrowth of 15 tall fescue clones grown in hydroponic solution.

Clone	Verdure(g)[z]	Clipping Yield(g)[y]	Topgrowth(g)[x]
29	13.2 a[w]	2.5 abcde	15.7 a
2	12.5 a	3.1 abc	15.6 a
27	12.0 ab	3.1 abc	15.0 ab
20	11.9 ab	2.4 bcde	14.3 abc
31	11.6 ab	2.8 abcd	14.4 abc
4	10.8 bc	1.9 de	12.8 cde
25	10.7 bcd	2.9 abcd	13.6 abcd
5	10.0 cde	2.9 abcd	12.9 bcde
22	10.0 cde	3.4 a	13.4 bcd
15	9.1 def	1.7 e	10.8 ef
19	8.8 ef	2.3 bcde	11.0 ef
21	8.7 ef	3.2 abc	11.8 def
33	8.3 f	2.2 cde	10.5 f
26	7.9 f	3.2 ab	11.2 ef
14	7.8 f	2.5 abcde	10.3 f

z Green vegetation above crown after mowing.
y Clippings collected throughout the study. Clipped at 75 mm every five days.
x Verdure + clipping yield, expressed as dry weights.
w Values are means of 4 replications. Means separation within columns by Duncan's multiple range test, 5% probability level.

Table 7. Topgrowth, root growth and percentage of supporting root growth (SRG) of 15 tall fescue clones growin in hydroponic solution.

Clone	Topgrowth (g)[z]	Root growth (g)[y]	% SRG (g)[x]
29	15.7 a[w]	2.4 abc	4.1 abcd
2	15.6 a	2.3 ab	2.2 cd
27	15.0 ab	2.5 a	2.2 cd
31	14.4 abc	2.1 abcd	5.5 abc
20	14.3 abc	2.1 abcd	6.5 ab
25	13.6 abcd	2.3 abc	7.7 a
22	13.4 bcd	2.5 a	2.9 bcd
5	12.9 bcde	1.9 bcde	1.2 d
4	12.8 cde	1.7 de	3.3 abcd
21	11.8 def	2.5 a	3.0 bcd
26	11.2 ef	2.1 abcd	5.5 abc
19	11.0 ef	2.1 abcd	3.2 abcd
15	10.8 ef	1.4 e	7.2 ab
33	10.5 f	2.0 abcd	3.4 abcd
14	10.3 f	1.7 cde	2.8 bcd

[z] Verdure + clipping yield, expressed as dry weights.
[y] Mean root growth of 750 mm profile, expressed as dry weight.
[x] Percentage of total root growth supporting topgrowth based on roots growing in hydroponic solution.
[w] Values are means of four replications. Mean separation within columns by Duncan's multiple range test, 5% probability level.

Table 8. Root production and distribution for 15 tall fescue clones grown in hydroponic solution.

	Root Production (mg)[z]				
Clone	0-150mm[y]	150-300mm	300-450mm	450-600mm	600-750mm
21	1920 a[x]	492 ab	69 abcde	4 a	---
22	1895 a	502 ab	108 abcde	9 a	8 a
2	1833 ab	444 abcd	60 bcde	5 a	1 a
27	1828 ab	538 a	109 abcde	9 a	---
19	1750 ab	328 cde	35 bcde	2 a	---
25	1655 ab	406 abcde	166 a	52 a	38 a
29	1636 ab	478 abc	134 ab	26 a	6 a
33	1585 ab	352 bcde	50 bcde	4 a	---
31	1544 ab	438 abcd	121 abc	13 a	2 a
20	1515 abc	362 bcde	114 abcd	23 a	5 a
5	1515 abc	317 de	20 de	---	---
26	1507 abc	437 abcd	128 ab	36 a	26 a
14	1379 bc	301 de	26 cde	9 a	---
4	1374 bc	264 e	13 e	---	---
15	1064 c	268 e	47 bcde	13 a	3 a

z Root production expressed on a dry weight basis.
y Root distribution was divided in five 150 mm segments.
x Values are mean of four replications. Mean separation within columns by Duncan's multiple range test, 5% level.

7.7%. This compares to clone 5 with the lowest percentage at 1.2% (Figure 5).

The most desirable combination of turfgrass growth characteristics would be a plant with dense topgrowth, prolific root system, and the ability to redistribute its root system with declining soil moisture. A turfgrass sward with a dense canopy loses less water due to canopy resistance (2). Considering these characteristics, clones 20, 25, 29, and 31 had high topgrowth production, root growth, and percentage of SRG. Clones 15 and 26 were lower in topgrowth production than 20, 25, 29, and 31 but did produce a high percentage of SRG. Plants with an intermediate topgrowth density and high SRG percentage would be useful in low maintenance or utility turfs.

Clones 2 and 27 were two of the three highest producers of topgrowth, but they also had a low percentage of SRG. This combination of characteristics may indicate a reduced potential to maintain growth under moisture stress conditions (Figure 5).

The suitability of using the hydroponic system can only be justified if the results are similar to those found in studies conducted under field conditions. Relative comparisons can then be made between hydroponic and field growth responses. Two thirds of the clones in the hydroponic study reaching the 600 mm to 750 mm rooting segment agreed with results found in a similar

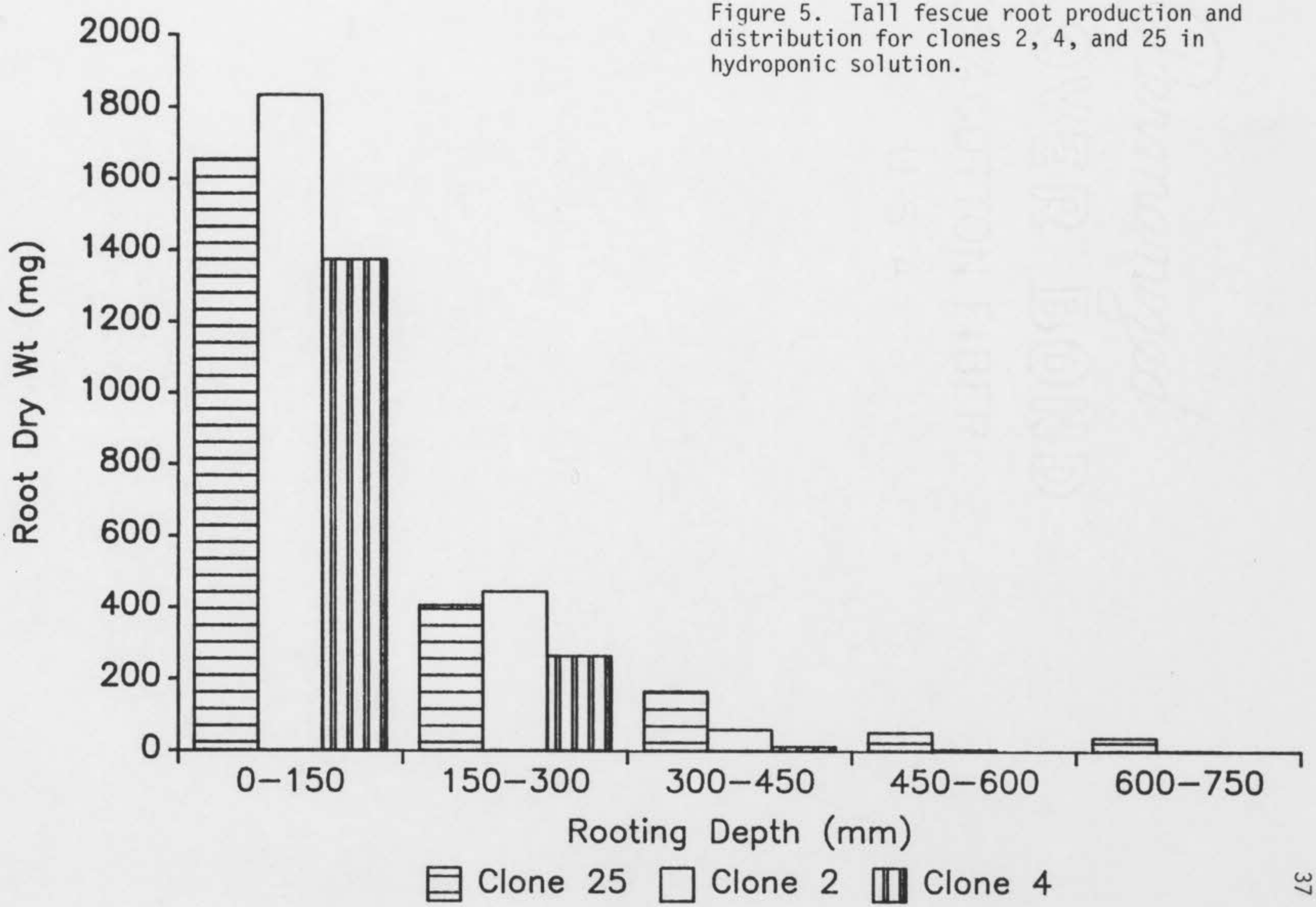

Figure 5. Tall fescue root production and distribution for clones 2, 4, and 25 in hydroponic solution.

field investigation conducted at the University of Nebraska Agricultural Research and Development Center (24). These results support the use of the hydroponic technique for separating genetic differences in root production, extent, and redistribution.

Kentucky Bluegrass Cultivar Study Total topgrowth varied among cultivars by 42% (Table 9). America, Baron, and Aspen produced the greatest amount of topgrowth among the sixteen cultivars in this study.

Cultivar root growth production differed by 34% between Mystic and Nassau (Tables 10 and 11). Mystic produced the highest dry root weight at 1500 mg and Nassau the lowest with 990 mg. All sixteen cultivars reached the 600 mm to 750 mm profile but variation occurred in the quantity of root growth distributed to this segment (Table 10).

The largest SRG percentage was produced by Touchdown with 25% of the total root system supporting the topgrowth. NE 80-88 had the lowest SRG percentage at 8.7%. Variation was calculated at a 68% between high and low cultivar SRG response (Table 10).

Root quantity in the 150 mm segments varied between NE 80-88 and Touchdown (Figure 6). NE 80-88 had 90% of its total root growth in the first 0 mm to 300 mm of the rooting profile. Touchdown, with the highest percentage of SRG, had 90% of its total root growth extending

Table 9. Verdure, clipping yield, and topgrowth of 16 Kentucky bluegrass cultivars grown in hydroponic solution.

Cultivar	Verdure(g)[z]	Clipping Yield(g)[y]	Topgrowth(g)[x]
America	5.7 a[w]	3.5 ab	9.2 a
Baron	5.1 ab	3.4 abc	8.6 a
Aspen	5.0 ab	3.7 a	8.7 a
Glade	5.0 ab	3.1 abcde	8.0 abc
Georgetown	4.8 abc	3.4 abc	8.3 ab
Mystic	4.3 bcd	3.4 abc	7.8 abc
Challenger	4.1 bcd	2.1 f	6.2 d
Dormie	4.1 bcd	2.8 bcdef	6.9 bcd
Birka	3.9 cde	2.7 def	6.6 cd
Eclipse	3.7 de	2.1 f	5.8 d
NE 80-88	3.6 def	2.4 ef	6.0 d
Touchdown	3.6 def	3.2 abcde	6.7 cd
Nassau	3.5 def	2.5 ef	6.0 d
Ram I	3.5 def	2.4 ef	5.9 d
Park	3.0 ef	2.7 cdef	5.7 d
Kenblue	2.6 f	2.8 bcdef	5.4 d

[z] Green vegetation above crown after mowing.

[y] Clippings collected throughout the study. Clipped at 64 mm on a five day cycle.

[x] Verdure + clipping yield, expressed as dry weights.

[w] Mean total of six replications. Mean separation within columns by Duncan's multiple range test, 5% probability level.

Table 10. Root production and distribution of 16 Kentucky bluegrass cultivars grown in hydroponic solution.

	Root Production (mg)[z]				
Cultivar	0-150mm[y]	150-300mm	300-450mm	450-600mm	600-750mm
Georgetown	664 a[x]	537 a	211 abcd	43 bcd	5 b
NE 80-88	613 ab	379 a	92 e	8 d	7 b
Park	610 ab	525 a	221 abc	49 abcd	8 b
Dormie	594 ab	462 a	213 abcd	78 ab	28 ab
Glade	583 ab	498 a	204 abcd	36 bcd	10 ab
Ram I	579 ab	515 a	233 ab	62 abc	16 ab
Mystic	575 ab	491 a	279 a	70 abc	14 ab
Kenblue	574 ab	346 a	139 bcde	48 abcd	15 ab
Challenger	569 ab	438 a	126 cde	39 bcd	23 ab
America	558 ab	388 a	238 ab	64 abc	12 ab
Aspen	549 ab	436 a	223 abc	38 bcd	8 b
Nassau	496 ab	347 a	116 de	28 cd	10 ab
Eclipse	496 ab	469 a	260 a	62 abc	26 ab
Baron	470 ab	502 a	259 a	74 ab	21 ab
Birka	462 ab	435 a	225 abc	80 ab	31 a
Touchdown	431 b	409 a	236 ab	88 a	26 ab

z Root production expressed on a dry weight basis.
y Root distribution divided in five 150 mm segments.
x Values are means of six replications. Mean separation within columns by Duncan's multiple range test, 5% probability level.

Table 11. Percentage support roots, root growth, and topgrowth of 16 Kentucky bluegrass cultivars grown in hydroponic solution.

Cultivar	Support Roots(%)[z]	Root growth(g)[y]	Top growth(g)[x]
Touchdown	27.0 a[w]	1.2 ab	6.7 cd
Eclipse	25.8 ab	1.3 ab	5.8 d
Ram I	25.6 ab	1.4 ab	5.9 d
Park	23.5 abc	1.3 ab	5.7 d
Birka	21.0 abcd	1.3 ab	6.6 cd
Kenblue	17.8 abcde	1.1 ab	5.4 d
Dormie	17.4 abcde	1.4 ab	6.9 bcd
Baron	15.7 bcdef	1.3 ab	8.6 a
Glade	14.9 cdef	1.3 ab	8.0 abc
Nassau	14.3 cdef	1.0 b	6.0 d
America	13.7 cdef	1.3 ab	9.2 a
Mystic	13.7 cdef	1.5 a	7.8 abc
Challenger	12.9 def	1.2 ab	6.2 d
Georgetown	11.2 ef	1.5 ab	8.3 ab
Aspen	10.0 ef	1.3 ab	8.7 a
NE 80-88	8.7 f	1.1 ab	6.0 d

[z] Percentage of total root growth supporting topgrowth based on roots growing in hydroponic solution.

[y] Total root growth in 750 mm rooting profile, expressed as dry weight.

[x] Verdure + clipping yield, expressed as dry weights.

[w] Values are mean of six replication. Mean separation within columns by Duncan's multiple range test, 5% probability level.

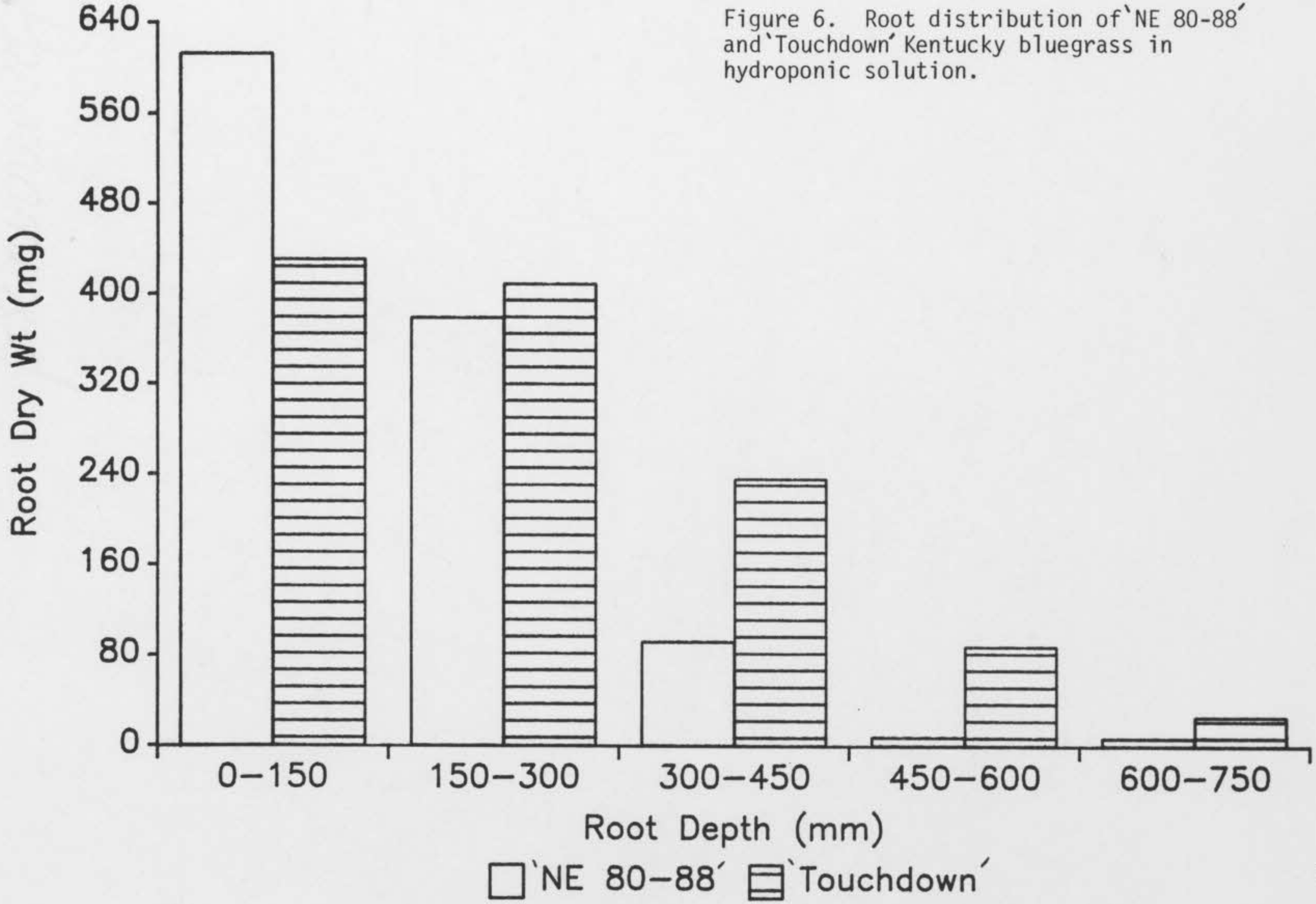

Figure 6. Root distribution of 'NE 80-88' and 'Touchdown' Kentucky bluegrass in hydroponic solution.

450 mm in the rooting profile. Touchdown's ability to redistribute its root system may indicate potential drought avoidance through use of moisture deeper in the rooting profile.

Dormie and Glade produced an intermediate topgrowth, root growth, and SRG percentage. These growth characteristics would be beneficial for areas requiring low maintenance or utility turfgrasses. Under these conditions a dense topgrowth would not be a high priority and an intermediate percentage of SRG should be capable of extracting moisture to meet ET demand.

Aspen produced the second and Georgetown the fourth highest topgrowth of the cultivars studied. In contrast, these were two of the three lowest rated for SRG percentage. This combination of a high topgrowth production and low SRG would be undesirable. A plant with a reduced quantity of root growth supporting shoot growth would have a reduced potential to withdraw soil moisture, particularly at greater soil depths, and possibly limit a plant's ability to avoid drought stress.

In all of the studies conducted, the upper portion of the root systems, not in contact with the nutrient solution, became suberized. Suberization appeared dark brown on the upper portion of the root profile and varied to light brown on the lower root system. Roots in contact with the nutrient solution were white to light tan in color.

The hydroponic technique and subsequent data will be useful in screening cultivar response under declining moisture conditions. The hydroponic system could be used as a tool to prescreen cultivar responses to declining moisture before the initiation of field studies. This system could have the potential to gather preliminary information and data and allow the researcher to better design experiment objectives.

CONCLUSIONS

The following conclusions can be drawn from this investigation:

1. Unlined polyvinylchloride (PVC) pipe may be used as a hydroponic growing container to study turfgrass root growth.

2. Declining moisture influenced root growth and distribution of 'Birka' Kentucky bluegrass.

3. Differences exist among tall fescue clonal ability to redistribute roots in declining available water.

4. Results from the hydroponic tall fescue clonal study were applicable to a similar study conducted under field conditions.

5. Kentucky bluegrass cultivars varied by 34% in topgrowth response under declining moisture.

6. Kentucky bluegrass cultivar root growth varied by 68% in percentage of supporting root growth.

7. Hydroponic technique was satisfactory for separating tall fescue and Kentucky bluegrass genetic differences in root production, distribution, and redistribution.

8. Hydroponic system would be applicable for relative comparisons or screening of turfgrass cultivars.

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