Profile Layering, Root Zone Permeability, and Slope Affect on Soil Water Content during Putting Green Drainage

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ABSTRACT

Laterally uniform soil water content should aid in turf management on high sand content putting greens. This study examined soil profile layering, root zone permeability, and slope effects on soil water content within experimental putting green root zones. Either a one-tier (subgrade underlying root zone) or two-tier (gravel underlying root zone) putting green soil profile was used, with each containing root zones having either 530 mm h^{-1} (higher permeability, HP) or 320 mm h^{-1} (lower permeability, LP) water permeability of the freshly prepared root zone. The 1.2- by 7.3-m greens were adjusted to slopes of 0, 2, and 4% and simulated rain was applied at either 45 or 112 mm h^{-1} for 3 h. Soil water contents at five lateral locations and three depths within each green were monitored during rainfall and for 48 h after rain stopped. In the early drainage period (1 to 9 h), the two-tier greens had smaller water contents that were more uniform laterally and with root zone depth. The one-tier greens showed effects of drainpipe spacing with greater water contents midway between the drainage elements. Expected greater water contents were observed for the LP than the HP root zones. Later in the drainage period (27 to 45 h), increased green slope contributed to upslope drying of all root zones with larger lateral water content gradients occurring in the LP and one-tier systems. The presence of a gravel layer beneath the root zone yielded reduced and more uniform water contents than in its absence. Slope-induced lateral water movement was apparent, however, in all greens.

Currently, the two most common putting green soil profile designs are the University of California (Davis et al., 1990) and the USGA (USGA Green Section Staff, 1993) putting green construction techniques. Both greens are built on a compacted subgrade consisting of soil native to the site and both contain a closely spaced array of subsurface drainpipes placed in gravel-filled trenches cut into the subgrade. Both also contain a 0.3-m root zone depth. The principal soil profile difference in these construction methods is the presence of a gravel layer (≈0.1 m thick) underlying the root zone in a USGA green. Thus, a USGA profile containing a gravel layer underlying the root zone is commonly referred to as a two-tier design. A University of California profile may be referred to as a one-tier design due to the absence of the gravel layer. Another major difference in these construction methods is a typically higher saturated hydraulic conductivity of the root zone in a California green.

Subsurface drainage of putting green root zones has both intensity and capacity attributes. Intensity of subsurface drainage is the rate of water removal and delivery to the drains. Capacity of drainage, on the other hand, is the volume of water removed after root zone drainage rates become small. A comparison between one- and two-tier putting green soil profiles showed a greater drainage intensity during rainfall in the two-tier design (Prettyman and McCoy, 2002). Further, across a 100-mm h^{-1} range of saturated hydraulic conductivity, drainage rate in the two-tier greens was not influenced by root zone permeability. Yet, drainage rate in the one-tier greens was significantly greater for a HP root zone than a LP root zone.

The drainage intensity behavior of one- and two-tier greens is explained by an interaction of the hydraulic gradient along the streamlines (curves within the flow domain that are at every point, tangent to the direction of flow) and the root zone hydraulic conductivity (van Schilfgaarde et al., 1957). In a two-tier (representing the soil profile of a USGA putting green) design, the streamlines for drainage into the gravel are principally vertical and span only the 0.3-m thickness of the root zone. In a one-tier (representing the soil profile of a University of California green) design, the streamlines through the root zone have both vertical and horizontal components, with their respective proportions dependent on lateral location relative to drainpipe placement. Thus, over a drainpipe the streamlines are principally vertical and span the 0.3-m thickness of the root zone, whereas between the drainpipes streamlines are principally horizontal and span distances controlled by drainpipe spacing of from 3 to 6 m. This rather long and horizontal flow path entirely through the root zone contributed to a greater dependence on root zone permeability. Correspondingly, differences in the intensity of subsurface drainage between California and USGA greens are due to the interaction of root zone conductivity and the presence of a gravel layer.

Root zone soil water status during drainage has been investigated for systems somewhat analogous to one- and two-tier putting green profiles. When a sand-dominated root zone overlays a finer-textured subsoil, the hydraulic conductivity of the subsoil controls water drainage from the root zone. Following sufficient rainfall to thoroughly wet the profile, this results in elevated water contents within the root zone whose duration is inversely related to the subsoil hydraulic conductivity (van Wijk, 1980). Indeed, it has been suggested that for such a layered soil situation, the subsoil essentially behaves as an impermeable barrier if its hydraulic conductivity is one-fifth that of the overlying soil (Fausey, 1977). Increased water retention of the root zone is also observed when a sand-dominated root zone overlays a coarse-textured material that contains appropriate par-

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Abbreviations: HP, higher permeability; LP, lower permeability; PVC, polyvinyl chloride; USGA, United States Golf Association.

ticle sizes to maintain layer integrity (Brown and Duble, 1975). In this case, as the particle size difference between the layers increase, the amount of water retained in the root zone also increases (Waddington, 1992, Taylor et al., 1993).

Previous research on putting green drainage employed soil columns (Brown and Duble, 1975; Taylor and Blake, 1979; Taylor et al., 1993; Taylor and Nelson, 1997) or small field plots (Waddington et al., 1974). Several aspects of column and small-plot research into drainage of putting greens represent substantial simplification relative to actual greens construction. First, in this earlier work, there was always a close proximity between the root zone under investigation and the drainage elements. In actual greens, some portions of the root zone may be located at a distance from subsurface drainage elements. Second, previous research did not consider the effect of green slope on root zone drainage. Putting greens on golf courses, however, are all sloped to some degree. Even though these slopes are slight, they do represent a hydraulic gradient for lateral water movement within the greens profile and may influence both the intensity and capacity of subsurface drainage. To our knowledge, however, no previously reported research on putting green drainage has examined green slope effects.

The objective of this study was to examine the effects of putting green soil profile, root zone permeability, and slope on the magnitude and spatial pattern of soil water within a putting green root zone. The study period spanned 2 d after rainfall and thus reflected the drainage capacity of the experimental greens.

MATERIALS AND METHODS

The data for this research come from the experiment described in Prettyman and McCoy (2002). Briefly, this study employed four soil profile and root zone mix treatment combinations consisting of (i) a one-tier soil profile containing a 9:1 (volume ratio) sand:sphagnum root zone, (ii) a one-tier profile containing a 6:2:2 (volume ratio) sand:biosolids compost:topsoil root zone, (iii) a two-tier soil profile containing the 9:1 sand:sphagnum mix, and (iv) a two-tier profile containing the 6:2:2 sand:compost:topsoil mix. The topsoil amendment was a Mahoning silt loam (fine, illitic, mesic Aeric Epiaqualfs).

Properties of the Root Zone and Gravel Materials

The 9:1 sand:sphagnum root zone contained 98.0% sand, 1.2% silt, and 0.8% clay; with the majority of the sand particles in the medium to coarse range (Prettyman and McCoy, 2002). The 6:2:2 sand:compost:topsoil root zone contained 94.8% sand, 3.8% silt, and 1.4% clay with the majority of the sand particles in the medium range.

Both root zone mixtures met the particle size distribution and physical property criteria (Prettyman and McCoy, 2002) for a USGA putting green (USGA Green Section Staff, 1993). Additionally, the 9:1 sand:sphagnum root zone, although not pure sand, met the recently proposed physical property criteria of a California green root zone (Hummel, 1998). The 9:1 sand:sphagnum root zone had an initial saturated hydraulic conductivity of 530 mm h^{-1} and the 6:2:2 sand:compost:topsoil root zone had an initial saturated hydraulic conductivity of 320 mm h^{-1}. Hereafter, these root zones will be referred to as the HP and LP root zones, respectively.

Gravel selection for the drainage layer of the two-tier greens and for the drainpipe trenches of the one-tier greens was based on the particle sizes of the respective root zones corresponding to USGA specifications for two-tier greens construction (USGA Green Section Staff, 1993). On the basis of particle sizes of the root zone and gravel, presented in Prettyman and McCoy (2002) the coarser gravel met USGA two-tier requirements for the HP root zone and the finer gravel met the requirements for the LP root zone.

The two profile design and root zone mix treatment combinations were replicated three times for a total of 12 experimental greens. At the time of the study, the greens contained a 15-mo-old Penncross creeping bentgrass [*Agrostis palustris* Huds. (= *Agrostis stolonifera* var. *palustris* (Huds.) Farw.] turf maintained at a mowing height of 4.7 mm.

Experimental Green Construction and Instrumentation

The experimental putting greens were constructed within 1.2- by 7.3-m wood boxes supported by a legged, metal framework and placed on a concrete pad. The depth of the one-tier experimental units was 0.3 m since these greens contained only a 0.3-m deep root zone. The depth of the two-tier units was 0.4 m because these greens contained a 0.3-m-deep root zone and a 0.1-m-deep gravel layer. Drainpipe trenches (0.15 m wide by 0.2 m deep), fabricated from sheet metal with a 50-mm outlet, were placed within gaps in the bottom of each box, perpendicular to long axis. The drainpipe trenches were located in each unit at 0.6, 3.7, 5.2, and 6.7 m from the down slope end. Nominal 5-cm polyvinyl chloride (PVC) pipe was connected to the outlet of each drainpipe trench and fitted with a valve for selective closure. The present study was conducted with only the 0.6- and 5.2-m drain lines open, effectively yielding a drain spacing of 4.6 m. The 12 experimental greens were placed, in a randomized complete block design, on a 24- by 8.5-m concrete pad poured at a 4% slope. This allowed adjustment of the green slope by jacking and blocking the metal legs. Green slopes used in this study were 0, 2, and 4%.

The appropriate gravel, root zone mix, and nominal 10-cm PVC drainpipe were placed in the experimental greens following recommended procedures (Davis et al., 1990; USGA Green Section Staff, 1993). The root zones were settled and firmed by irrigation and rolling. Following construction of the experimental profiles, but before seeding, buriable TDR wave guides (Soil Moisture Equip. Co., Santa Barbara, CA) were horizontally inserted into the profile at three depths (0.076, 0.15, and 0.23 m) and five locations (0.6, 2.1, 3.7, 5.2, and 6.7 m from the down slope end) for a total of 15 locations per unit. The wave-guides were multiplexed to a TRASE-BE (Soil Moisture Equipment Co.) for soil water content measurement.

Data Collection

The overall study was conducted as a series of 18 individual experimental runs consisting of all combinations of slope and rain rate for the three replications (blocks). Each green was used for six experimental runs during the course of the overall study.

Before an experimental run, individual greens were configured to a randomly predetermined slope of 0, 2, or 4%. Subsequently, each green received rain from an overhead device delivering a 45- or 112-mm h^{-1} rainfall rate (Prettyman and McCoy, 2002). Continuous measurements of drainage outflow (Prettyman and McCoy, 2002) and soil water contents (reported herein) commenced with the beginning of the rainfall period. Rainfall was applied for 3 h to ensure that a constant drainage rate was achieved. At the end of the rainfall period, drainage outflow and water content measurements continued for an additional 48 h. Soil water contents were measured every 20 min for the first 27 h and hourly for the remaining 24 h. Subsequently, the next block was configured for an experimental run and the process repeated. The study began on 6 Aug. 1997 and ended on 30 Oct. 1997.

After completion of the drainage study, 55-mm diam. by 30-mm soil cores were collected within Tempe cell sample holders (Soil Moisture Equip. Co.) at depths of 76 and 152 mm. These minimally disturbed cores were used for water retention measurements following the procedure of McCoy and Stehouwer (1998). Water retention measurements were conducted using Tempe cells for pressure heads of −100, −200, −300, −400, −800, −1600, and −5000 mm; pressure chambers at -2.0×10^4 mm; and using thermocouple psychrometry heads exceeding -2.0×10^4 mm. The water content, θ, data ($m^3 \, m^{-3}$) was fit to a modified form of the van Genuchten (1980) equation

$$\Theta = \Theta_1[1 + (\alpha_1 h)^{n1}]^{-m1} + \Theta_2[1 + (\alpha_2 h)^{n2}]^{-m2},$$

where $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r)$, $\Theta_1 = (\theta_s - \theta_i)/(\theta_s - \theta_r)$, $\Theta_2 = (\theta_i - \theta_r)/(\theta_s - \theta_r)$, and $m = 1 - 1/n$. The terms θ_s, θ_i, and θ_r are the saturated, intermediate, and residual water contents ($m^3 \, m^{-3}$), h is the soil water pressure head (mm), and the other terms are adjustable coefficients. Values of θ_s and θ_r were determined experimentally and values of α_1, α_2, n_1, n_2, and θ_i resulted from the fitting procedure.

Finally, constant head, steady rate infiltration measurements were conducted at randomly selected locations within each experimental green set to 0% slope. A double-ring infiltrometer was used with an inner-ring diameter of 200 mm and an outer-ring diameter of 300 mm. For each measurement, individual rings were inserted to a depth of 25 mm. A 41-L Mariott device regulated a 40-mm head within the inner ring. These measurements were first conducted with the sod intact and then at the same location after sod removal to a depth of ≈25 mm. Again, in the same location and after sod-removed infiltration measurements, soil cores were collected to a 76-mm depth for saturated hydraulic conductivity measurements using the constant head protocol.

Data Analysis

Root zone water contents were analyzed for times of 0, 1, 3, 9, 27, and 45 h after rain stopped. For each time, the overall experiment was a split-plot, randomized complete block design with profile design and root zone composition as main plot factors, and green slope and rain rate as split plot factors. The lateral distances and depths of water content measurement were treated as repeated measures with the Huynh-Feldt Epsilon correction factor (Huynh and Feldt, 1970) used in the repeated measures analysis. Time after rain stopped was not considered a factor in the analysis due to the well-established decline in soil water contents following rainfall (Jury et al., 1991). Thus, a six-way analysis of variance was conducted for each time. The expertise of a consulting statistician was employed for all experimental design and analysis steps.

Analysis of the water retention, saturated hydraulic conductivity, and infiltration measurements was conducted using two-way analysis of variance for a randomized complete block design. The factors in this analysis were profile design and root zone composition.

RESULTS AND DISCUSSION

Root Zone Physical Properties

Following completion of the drainage experiment, root zone samples were collected for physical property measurements. Observed differences in water retention curve coefficients were due to root zone composition, where the HP root zones had larger values of Θ_1, α_1, and n_2 (Table 1). Neither profile design nor any interaction terms containing this experimental factor had a significant effect on the water retention curve coefficients. Thus, the values shown in Table 1 are averaged across the one- and two-tier profile designs.

Using the analysis of McCoy and Stehouwer (1998), the water retention curves exhibited a bimodal pore size distribution, with a greater proportion of the total porosity consisting of larger diameter pores for the HP than the LP root zones. Further, the larger α_1 value for the HP root zone suggests that water release from these pores would occur at a small soil water suction. The water retention measurements, therefore, suggest that the HP root zone would retain less water during profile drainage than the LP root zone. Water retention curve differences were also observed due to depth of sampling. In this case, the root zone media residing at a deeper depth had slightly larger saturated water content, θ_{sat}, values than for samples near the surface. This indicated that the bulk density was slightly reduced at deeper depth within the root zones of the experimental greens.

As suggested from the water retention measurements,

Table 1. Root zone water retention curve coefficients from soil cores collected at two depths. Data from the one- and two-tier profile treatments were pooled due to the absence of significant soil profile treatment effects.

Root Zone	Depth	Θ_1	α_1	n_1	Θ_2	α_2	n_2	θ_{sat}
	mm	$m^3 \, m^{-3}$	m^{-1}		$m^3 \, m^{-3}$	m^{-1}		$m^3 \, m^{-3}$
Lower permeability	76	0.72	5.68	3.33	0.28	0.10	1.77	0.48
	152	0.72	6.87	3.60	0.28	0.32	1.66	0.51
Higher permeability	76	0.79	7.68	3.42	0.21	0.13	2.03	0.48
	152	0.82	7.31	3.59	0.18	0.02	1.86	0.51
				ANOVA				
Root zone		**	**	NS†	**	NS	**	NS
Depth		NS	*	NS	NS	NS	NS	**
Root zone × Depth		NS	**	NS	NS	NS	NS	NS
LSD0.05‡		0.014	0.28	0.22	0.014	0.20	0.12	0.015

* Significant at the 0.05 level of probability.
** Significant at the 0.01 level of probability.
† NS, not significant.
‡ Least significant difference ($P = 0.05$) of the root zone × depth interaction.

Table 2. Mean ponded infiltration rate and undisturbed core K_{sat} values for the putting green profile and root zone treatments.

Profile	Root zone	Infiltration rate sod intact	Infiltration rate sod removed	K_{sat}
		mm h^{-1}		
One-tier	**Lower permeability**	**574**	**420**	**894**
	Higher permeability	**787**	**1165**	**1250**
Two-tier	**Lower permeability**	**720**	**673**	**922**
	Higher permeability	**1153**	**1520**	**1356**
	ANOVA			
Profile		*	NS†	NS
Root zone		**	**	*
Profile × Root zone		NS	NS	NS
LSD0.05‡		255	442	537

* Significant at the 0.05 level of probability.
** Significant at the 0.01 level of probability.
† NS, not significant.
‡ Least significant difference ($P = 0.05$) of the highest order interaction.

the HP root zone yielded larger infiltration rates and saturated hydraulic conductivities than the LP root zone (Table 2). The two-tier profile design also showed greater infiltration rates with intact sod than that seen for the one-tier profile. Although following the same trend, profile design did not significantly influence infiltration rate measurements with the sod removed. The profile design influence on infiltration rate implies that the presence of the gravel layer at 0.3-m depth has an influence on ponded water infiltration in these systems. This finding is in agreement with Daniells (1977), who observed the same influence of the buried gravel layer on double ring infiltration measurements. The presence of an impermeable layer at 0.3-m depth apparently reduces infiltration rate measurements. This was likely due to the interruption of the one-dimensional and vertical flow throughout the root zone.

LSD values from infiltration and K_{sat} measurements (Table 2) increased in the order (i) intact sod infiltration, (ii) sod removed infiltration, and (iii) K_{sat}, and this followed a trend of potential soil disturbance in data collection. The measured rates generally increase in order as well. The above information taken together suggests that the most reliable measure of root zone permeability as it would exist for these systems is the infiltration rate with intact sod as measured for the two-tier profiles. The intact sod measurement had the smallest LSD value and was conducted with the least potential soil disturbance that may elevate saturated hydraulic conductivity values. Also, the presence of a gravel layer would allow unimpeded drainage and help ensure one-dimensional flow.

Finally, the infiltration rate and K_{sat} values measured in situ and from sampled cores, were substantially greater than those of the root zone media measured before construction (Prettyman and McCoy, 2002). This, together with the somewhat large θ_{sat} value (and correspondingly small bulk density) from core sampling, suggests that laboratory packing before soil property measurement was greater than experienced during construction and maintenance of the experimental greens.

Water Contents during Root Zone Drainage

Water content measurements were conducted every 20 min for the initial 27 h and hourly for the subsequent 24 h of this study. The times selected for detailed analysis of treatment effects were 0, 1, 3, 9, 27, and 45 h, corresponding to an approximate logarithmic progression. The rationale for a logarithmic progression of analysis times is the well-known logarithmic progression of the soil drainage process (Jury et al., 1991). Further, Prettyman and McCoy (2002) identified, from analysis of drainage rates, three time intervals of distinct drainage behavior for these experimental greens. These time intervals were during rain, from 1 to 9 h after rain ceased (early drainage), and from 27 to 45 h after rain ceased (late drainage). These earlier observations are used to frame the presentation of soil water content results herein.

Whereas results from the lower rain rate and 2% slope were included in the data analysis, space limitations preclude their detailed presentation here. Even though rain rate generally yielded a significant effect, its contribution to the total mean square effect was <5% (Table 3) and the lower rain rate results were generally similar to those from the higher rain rate treatment. Results for the 2% slope treatment were generally intermediate to those observed at the 0 and 4% slopes.

Early Drainage

For times corresponding to the early drainage period, profile design and root zone composition dominated the observed treatment differences explaining from 76 to 84% of the mean square effect (Table 3). Weakly contributing during this period were root zone depth and the profile design × depth interaction.

Root zone water contents (mean values from three replications) as influenced by these treatment variables are shown in Fig. 1 as individual contour plots where the *x* axis is distance upslope along the length of the green and the *y* axis is root zone depth. Gray scale differences shown in these plots correspond to soil water content differences of 0.04 m^3 m^{-3} with darker shading corresponding to larger water contents and lighter shading corresponding to smaller water contents. Finally, the results shown in Fig. 1A corresponds to 0% slope conditions and in Fig. 1B to 4% slope.

Putting green profile design exhibited a dramatic effect on root zone water content even 1 h after rainfall ceased (Fig. 1). The two-tier greens had smaller water

Table 3. Analysis of variance for treatments and interactions influencing soil water contents.

	Soil water content					
Treatment	0 h	1 h	3 h	9 h	27 h	45 h
Profile (PR)	** (62)†	** (65)	** (62)	** (46)	** (35)	** (36)
Root zone (RZ)	** (14)	** (19)	** (14)	** (32)	** (40)	** (35)
Slope (SL)	**	**	**	NS‡	NS	*
Rain rate (RR)	**	**	**	**	NS	*
Depth (DP)	**	** (5)	**	** (11)	** (12)	** (11)
Distance (DS)	**	**	**	**	**	**
PR × RZ	*	NS	NS	NS	**	**
PR × SL	NS	NS	NS	NS	NS	**
PR × RR	NS	**	NS	NS	*	NS
PR × DP	** (5)	**	** (5)	** (5)	** (5)	** (5)
PR × DS	**	**	**	**	**	**
RZ × SL	NS	**	NS	**	**	*
RZ × RR	NS	NS	NS	NS	NS	NS
RZ × DP	**	*	**	**	**	**
RZ × DS	**	**	**	**	**	**
SL × RR	NS	NS	NS	NS	NS	NS
SL × DP	NS	NS	NS	NS	**	**
SL × DS	NS	NS	NS	**	**	**
RR × DP	NS	NS	NS	*	NS	**
RR × DS	*	NS	*	NS	NS	NS
DP × DS	**	**	**	**	**	**
PR × RZ × SL	NS	NS	NS	NS	NS	NS
PR × RZ × RR	NS	*	NS	NS	NS	NS
PR × RZ × DP	NS	NS	**	**	**	**
PR × RZ × DS	**	**	**	**	**	**
PR × SL × RR	NS	NS	NS	NS	NS	NS
PR × SL × DP	NS	NS	NS	NS	**	**
PR × SL × DS	NS	*	NS	**	**	**
PR × RR × DP	NS	NS	NS	NS	NS	NS
PR × RR × DS	NS	*	NS	NS	NS	*
PR × DP × DS	**	**	**	**	**	**
RZ × SL × RR	NS	NS	NS	NS	NS	NS
RZ × SL × DP	NS	NS	NS	NS	**	**
RZ × SL × DS	NS	NS	NS	NS	**	**
RZ × RR × DP	NS	NS	NS	NS	NS	NS
RZ × RR × DS	NS	**	NS	NS	NS	NS
RZ × DP × DS	**	**	**	**	**	**
SL × RR × DP	NS	NS	NS	NS	NS	NS
SL × RR × DS	NS	NS	NS	NS	NS	*
SL × DP × DS	NS	NS	NS	NS	**	**
RR × DP × DS	NS	NS	NS	NS	NS	NS
PR × RZ × SL × RR	NS	NS	NS	NS	NS	NS
PR × RZ × SL × DP	NS	NS	NS	NS	**	**
PR × RZ × SL × DS	NS	NS	NS	NS	*	**
PR × RZ × RR × DP	NS	NS	NS	NS	NS	*
PR × RZ × RR × DS	NS	NS	NS	NS	NS	NS
PR × RZ × DP × DS	**	**	**	**	**	**
PR × SL × RR × DP	NS	NS	NS	NS	NS	NS
PR × SL × RR × DS	NS	NS	NS	NS	NS	NS
PR × SL × DP × DS	NS	NS	NS	*	**	**
PR × RR × DP × DS	NS	NS	NS	NS	NS	NS
RZ × SL × RR × DP	NS	NS	NS	NS	NS	NS
RZ × SL × RR × DS	NS	NS	NS	NS	NS	NS
RZ × SL × DP × DS	NS	NS	NS	NS	**	**
RZ × RR × DP × DS	*	*	*	NS	NS	NS
SL × RR × DP × DS	NS	NS	NS	*	NS	NS
PR × RZ × SL × RR × DP	NS	NS	NS	NS	NS	NS
PR × RZ × SL × RR × DS	NS	NS	NS	NS	NS	NS
PR × RZ × SL × DP × DS	NS	NS	NS	NS	**	**
PR × RZ × RR × DP × DS	*	**	*	NS	*	NS
PR × SL × RR × DP × DS	*	NS	NS	*	NS	NS
RZ × SL × RR × DP × DS	NS	NS	NS	NS	NS	NS
PR × RZ × SL × RR × DP × DS	NS	NS	NS	*	NS	NS
LSD0.05, $\mathrm{m^3\ m^{-3}}$§	0.025	0.028	0.025	0.022	0.016	0.015

* Significant at the 0.05 level of probability.
** Significant at the 0.01 level of probability.
† Values in parenthesis are percentage of total mean square effect (when greater than 5%) contributed by each treatment and treatment interaction.
‡ NS, not significant.
§ Least significant difference ($P = 0.05$) of the highest order interaction.

contents that were much more evenly distributed with distance upslope and depth within the root zone. The lateral pattern of root zone water observed for the one-tier greens is influenced by open drainage pipe location with smaller water contents observed above drain pipes located at 0.61 and 5.2 m upslope and greater water contents in between. This drain spacing effect was not observed for the two-tier profiles.

As expected, water contents were influenced by root zone composition in the two-tier profiles where larger

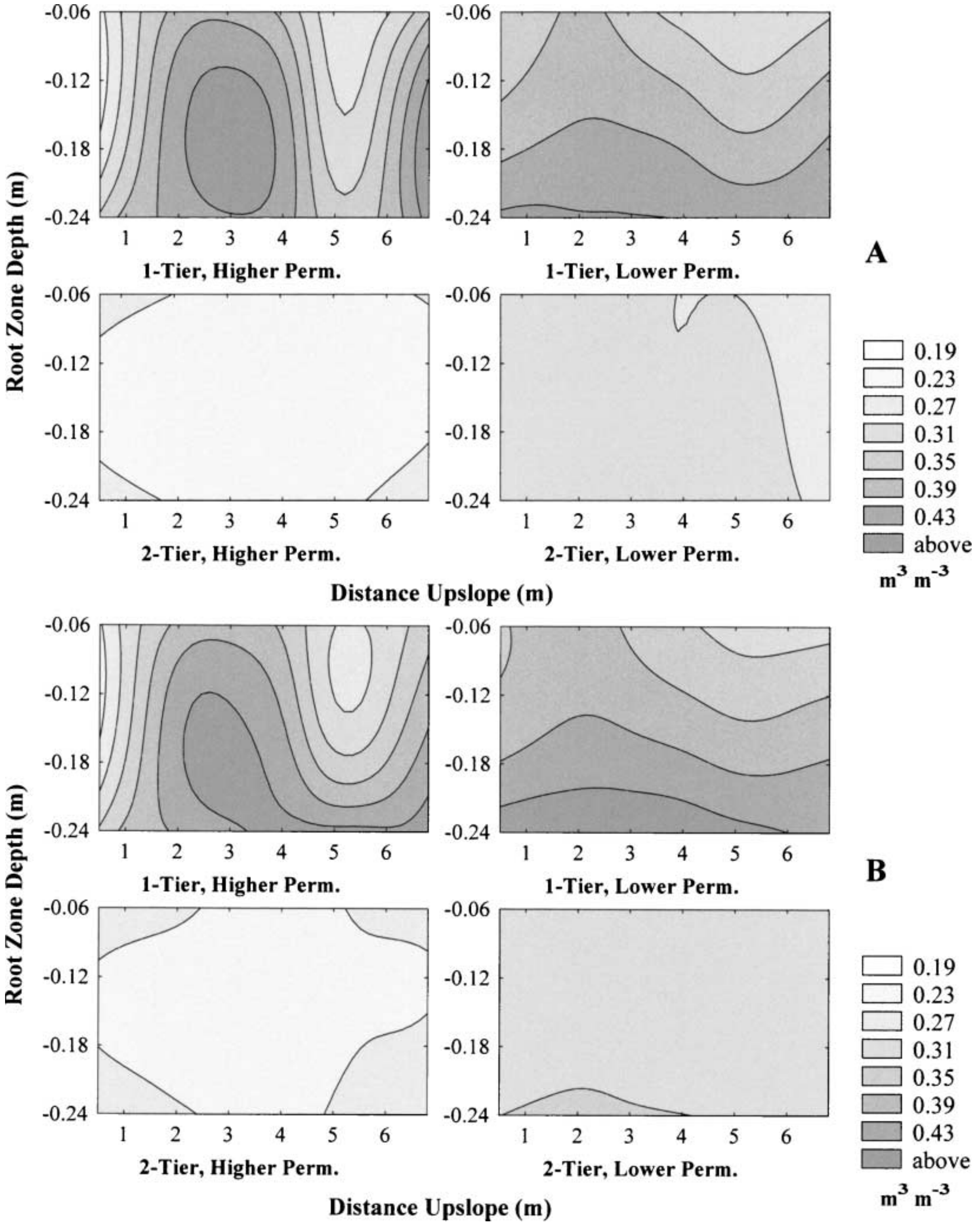

Fig. 1. Mean water content ($m^3\ m^{-3}$) of the experimental putting greens after 1 h of drainage and for rain rates of 112 mm h^{-1}. Results shown are for the (A) 0% slope and (B) 4% slope treatments. Open drain lines were located at 0.6 and 5.2 m upslope.

water contents were uniformly observed for the LP root zone (Fig. 1). This same effect was also observed at locations above the drainage elements for the one-tier profiles. In addition, the patterns of soil water content in the one-tier profiles were influenced by root zone permeability where laterally varying water contents were more extreme for the HP treatment than for the LP treatment (Fig. 1). Finally, edge effects are apparent in Fig. 1 particularly for the two-tier profile, HP root zone treatment. These edge effects are partially due to slightly smaller water contents near the upslope and downslope edges of the greens, but also are the result of the least squares interpolation routine used by the graphics software.

When the experimental putting greens were adjusted to 4% slope, soil water contents observed 1 h after rain ended (Fig. 2B) were very similar to that observed at 0% slope. The results observed at 2% slope were also similar (not shown). Thus, the range of slope used in this study that is characteristic of those found on actual putting greens did not have a substantial effect on soil water contents early in the drainage process. Comparing results of the 0% (Fig. 1A) and 4% (Fig. 1B) slope treatments also illustrates some nonsystematic effects

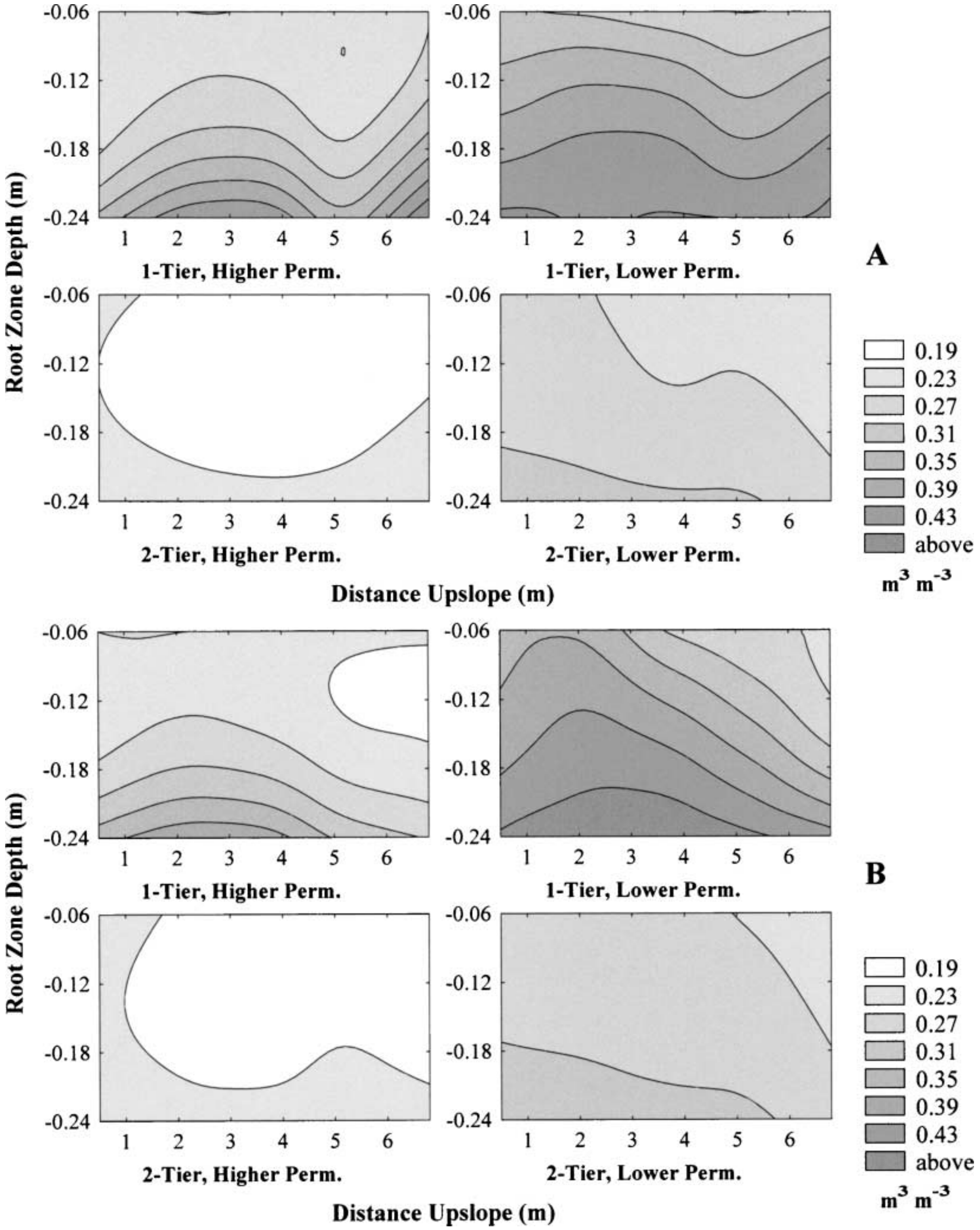

Fig. 2. Mean water content (m^3 m^{-3}) of the experimental putting greens after 27 h of drainage and for rain rates of 112 mm h^{-1}. Results shown are for the (A) 0% slope and (B) 4% slope treatments. Open drain lines were located at 0.6 and 5.2 m upslope.

that are deemed to be of random origin. For example, the slightly smaller water contents observed at greater distances upslope for the two-tier, LP green at 0% slope were absent for the same experimental units at 4% slope. Also, the extent of the edge effects observed for the two-tier, HP root zone treatment are greater at 4% slope than at 0% slope. These nonsystematic effects are occasionally observed at other times as well.

Although not apparent from the results shown in Fig. 1, slope as a treatment variable did have a significant treatment effect on soil water early in the drainage process (Table 3). This response was due to only slightly ($\leq$0.015 m^3 m^{-3}) greater water contents for the 4% slope treatment. Likewise, early in the drainage period, the higher rain rate yielded $\leq$0.015 m^3 m^{-3} larger water contents than the lower rain rate. Even though slope and rain rate yielded significant treatment responses, the practical impact of these differences was deemed minimal.

The results shown in Fig. 1 for 1 h after rain ended are characteristic for the early drainage period of from 1 to 9 h. Overall soil water contents declined during this period; however, the treatment effects were consistent (Table 3).

The lateral pattern of wetter and drier locations in the root zones of one-tier greens corresponded to the spacing of drainage elements. This is expected and explained from the streamlines of water flow to drainpipes in porous media overlying an impermeable barrier (van Schilfgaarde et al., 1957). Directly above the drainpipe, streamlines are vertical across the 0.3-m thickness of the root zone. This allows for rapid flow to drains and drier soil conditions. Midway between drainpipes, the streamlines in this relatively shallow media are principally horizontal, perpendicular to the gravitational gradient, and have lengths up to 2.3 m. This would produce a slower flow to the drains (Prettyman and McCoy, 2002), an accumulation of soil water, and localized wetter conditions. The uniformity of root zone water contents in the two-tier greens and comparably drier condition than the one-tier green is explained, as well, by flow streamlines. Paths of water drainage from the two-tier greens are principally vertical and span the 0.3-m thickness of the root zone. Thus, the hydraulic gradients provide for uniformly rapid drainage at all lateral locations and comparably smaller water contents after 1 h of drainage.

Late Drainage

For times corresponding to the late drainage period (from 27 to 45 h), profile design and root zone composition continued to contribute substantially to the observed treatment differences, explaining 71 and 75% of the mean square effect (Table 3). Also contributing during this period were root zone depth and the profile design × depth interaction.

After 27 h of drainage, the two-tier greens oriented at 0% slope had smaller water contents than the corresponding root zone when built as a one-tier system (Fig. 2A). The profile design differences in water contents near the soil surface have, however, diminished relative to that observed after 1 h of drainage (compare Fig. 1A and 2A). During the intervening 26 h, the two-tier surface water contents have declined by ≈ 0.04 m^3 m^{-3}, whereas the decline in the one-tier greens ranged up to 0.1 m^3 m^{-3} for the LP root zones and 0.2 m^3 m^{-3} for the HP root zone. A much larger variation of soil water content with depth was also observed in the one-tier than the two-tier greens. In this case, water contents increased in one-tier greens by 0.2 m^3 m^{-3} from near the surface to depth. Thus, water content levels observed in these greens after 1 h of drainage were preserved after 27 h of drainage. The depth variation in water contents for the two-tier greens was around one order of magnitude less than the one-tier greens, preserving the relatively uniform water contents of these root zones.

The one-tier greens also continued to exhibit a lateral pattern in water content that corresponded with drainpipe spacing. This sinusoidal pattern displayed a similar amplitude for both the HP and LP root zones. Increased drainage for the HP root zone than the LP root zone during the intervening 26 h (Prettyman and McCoy, 2002) apparently dampened the sinusoidal pattern for this treatment observed after 1 h of drainage (compare Fig. 1A and 2A). Finally, as with soil water observed after 1 h, water contents in the LP root zones were greater than the corresponding HP root zones.

Unlike the early drainage period, a 4% green slope had a very apparent influence on the lateral distribution of soil water contents during the later drainage period. The characteristic behavior for all profile design and root zone treatments was smaller water contents observed at upslope locations (Fig. 2B). Indeed, a quite strong lateral variation in soil water was observed near the surface for the one-tier profile using the LP root zone where water contents ranged from 0.23 to 0.39 m^3 m^{-3}.

Upslope drying of the root zone for more steeply sloped greens was not necessarily accompanied by soil water accumulation downslope. Only slightly greater water contents were observed at downslope locations when greens were sloped at 4% as compared with 0%. This suggests that water moving laterally within the root zone was able to effectively exit the system on reaching the vicinity of the drainage elements. This is in agreement with the findings of Prettyman and McCoy (2002), who observed larger drainage rates at greater slope for times before 27 h.

The magnitude of lateral water variation observed in sloped greens was closely related to the inherent wetness of these green designs. Thus, a two-tier green that contained a HP root zone was drier and contributed little water to lateral flow. Conversely, a one-tier green containing a LP root zone retained larger water contents and subsequently yielded strong lateral water content variation.

It may be surprising that slope as a treatment variable exhibited little significant effect on soil water late in the drainage period (Table 3) when the slope response was most apparent in the water content data. The lack of a statistically significant slope effect was due to the fact that slope has no reference to location in the root zone and cannot by itself account for a lateral water content variation. The accounting for lateral water content differences results from the slope × distance interaction that was significant later in the drainage period (Table 3).

Equilibrium Conditions

There was very little change in the values and spatial pattern of soil water between 27 and 45 h when greens were set at 0% slope (compare Fig. 2A and 3A). This is consistent with their small drainage rates, ranging from 5 to 14 mL min^{-1} at 27 h (Prettyman and McCoy, 2002). Thus, a near equilibrium soil water status was achieved for greens at 0% slope during the first day of drainage. Under these near equilibrium conditions, for example, after 45 h the two-tier greens exhibited an increase in water content with depth in the root zone (Fig. 3A) consistent with the formation of perched water, commonly observed in two-tier greens (Taylor et al., 1993; Taylor and Nelson, 1997). It is surprising, however, that the magnitude of water content increase with depth was rather small (≈ 0.04 m^3 m^{-3}) for both root zones. Also not totally expected was the much greater increase in soil water with depth in the one-tier greens (Fig. 3A).

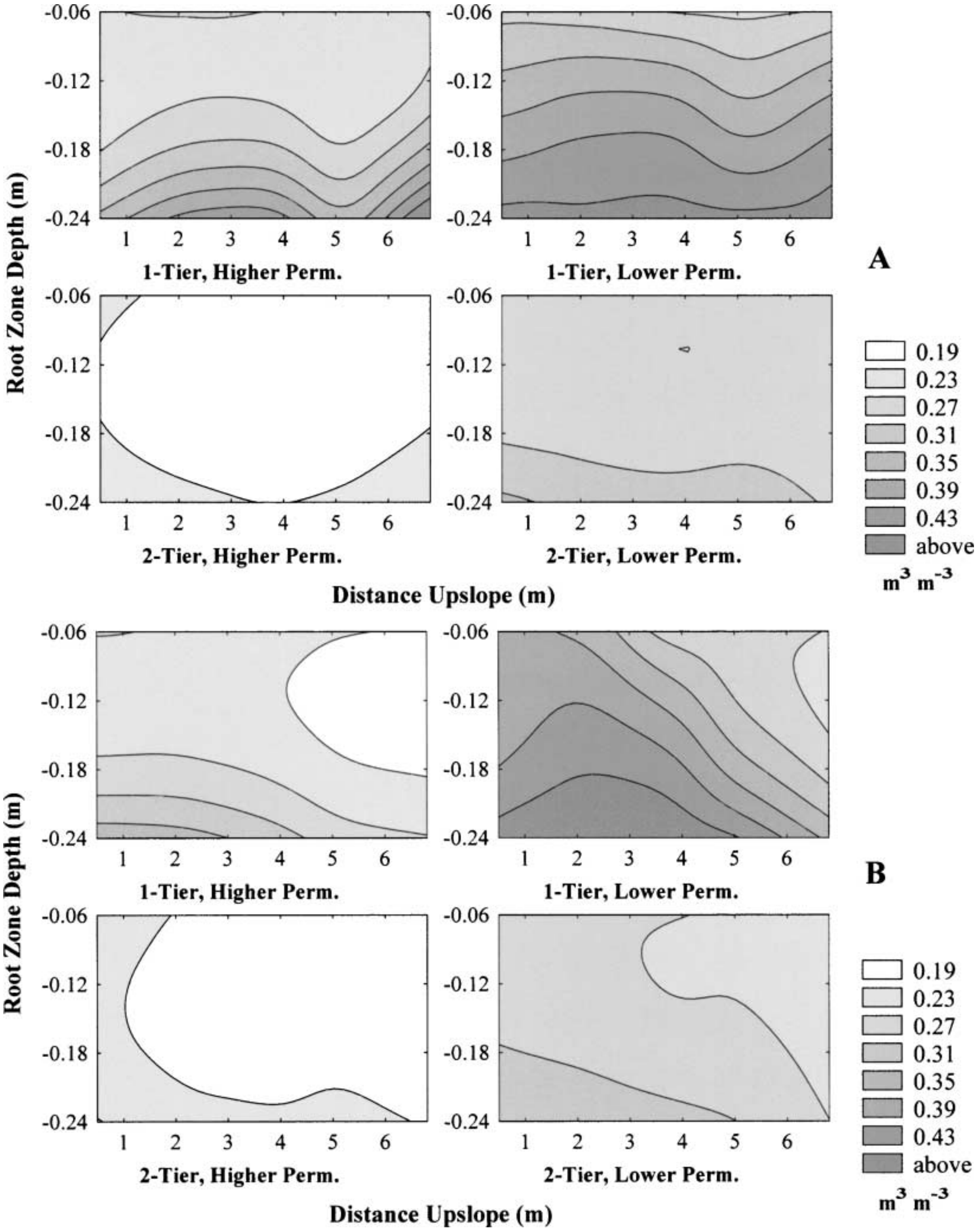

Fig. 3. Mean water content (m^3 m^{-3}) of the experimental putting greens after 45 h of drainage and for rain rates of 112 mm h^{-1}. Results shown are for the (A) 0% slope and (B) 4% slope treatments. Open drain lines were located at 0.6 and 5.2 m upslope.

Seemingly, for level greens, placing the root zone over an impermeable (or nearly so) barrier serves to retain more water within the root zone than a comparable media placed over a gravel layer.

Unlike the situation for 0% slope, when greens are sloped at 4%, equilibrium soil water conditions were not apparent over the duration of this study (compare Fig. 2B and 3B). Although changes were small, there was a consistent reduction in observed water content from 27 to 45 h after rain ended, and this was likely due to downslope water movement.

The root zones of this study differed in their water retention and transmission properties. Yet an equal if not greater influence on overall water content during drainage was the presence or absence of a gravel layer beneath the root zone. Further, the absence of this gravel layer created laterally varying water contents coincident with drainpipe spacing and green slope. The implications are that a fresh view needs to be taken on our current understanding of water content distribution within a putting green root zone. Observations collected from soil columns (Brown and Duble, 1975; Taylor and Blake, 1979; Taylor et al., 1993; Taylor and Nelson, 1997) or level field plots (Waddington et al., 1974) may be closer to or more distant from an actual putting green, depending on whether a gravel layer existed in these studies. The correspondence between these earlier studies and an actual green situation would be closer in the presence of a gravel layer for both experimental and actual situations where water contents are laterally more uniform.

Further, the view that an equilibrium condition (i.e., field capacity) of soil water would at some time occur needs to be reexamined. Since all greens contain some degree of slope, lateral water movement should continue unabated, at least during the early periods of drainage. This questions any implications of the water content distribution predicted from water retention measurements that are conducted under equilibrium conditions. Finally, from the perspective of the current findings, the role of a gravel layer in the creation of perched water seems to be overemphasized. On one hand, the slopes found on actual greens constructed with a gravel layer apparently allows sufficient lateral flow so that perched water would be moved from higher elevation locations before serving as a transpiration reservoir. On the other hand, comparably greater water contents are observed to reside in the lower portions of a root zone when placed directly over a subgrade soil having even moderately slow drainage rates.

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