Soil Physical Properties of Aging Golf Course Putting Greens

J. D. Lewis, R. E. Gaussoin,* R. C. Shearman, M. Mamo, and C. S. Wortmann

ABSTRACT

United States Golf Association (USGA) specification putting greens are designed to limit excess soil water and compaction; but these soil properties change over time. Objectives were to define soil physical properties of sand-amended rootzones as affected by (i) rootzone mixture, (ii) establishment treatment, and (iii) putting green age. The USGA specification rootzones were built and established with Agrostis stolonifera L. in four sequential years. Rootzone treatments were 80:20 (v:v) sand and sphagnum peat and an 80:15:5 (v:v) sand, sphagnum peat, and soil. An accelerated establishment treatment applied 2.5, 3, and 2.5 times N, P, and K, levels, respectively, than the control treatment. Data were collected on rootzone particle size distribution and saturated hydraulic conductivity (K_{sat}), bulk density, total, air-filled and capillary porosity for 8 yr, infiltration rate for 10 yr. All soil physical properties changed with age, but were not influenced by establishment treatment. Infiltration declined 73% but remained adequate (≥0.15 m h⁻¹) for location precipitation. Capillary porosity and bulk density increased 32 and 7%, respectively, while air-filled porosity decreased 38%. Capillary and air-filled porosity still met USGA specification after 8 yr. Addition of soil to the sand-based rootzone mixture had no negative effect on soil physical properties. Fine sand from topdressing and surface organic matter accumulation were thought to account for these changes.

Turfgrass establishment and sustained turfgrass performance on sand putting green rootzones is an agronomic challenge for turfgrass managers. Part of this challenge is managing the soil physical properties as the putting green ages. The suitability of a rootzone mixture for putting green construction is commonly evaluated by laboratory testing of soil physical properties and is frequently based on USGA specifications delineated by research initiated in the 1950s (USGA Green Section Staff, 1960). This construction technique features a high sand content rootzone with high macroporosity. The resulting putting green is more resistant to problems associated with compaction and has relatively high infiltration and percolation rates, but has reduced nutrient retention capacity, especially during the establishment year (Carrow et al., 2001). However, the soil physical properties of a sand based putting green rootzone can change within 2 mo of construction and continues to change with age (Curtis and Pulis, 2001; Hartwiger, 2004). Changes in rootzone soil physical properties during the establishment year may be due to establishment protocol while the changes in the soil physical properties with time have been attributed to several causes including: fine particle migration into the rootzone (Habeck and Christians, 2000; Callahan et al., 1997), peat decomposition, (Huang and Petrovic, 1995) and surface organic matter accumulation (Murphy et al., 1993; Baker et al., 1999; Habeck and Christians, 2000; Ok et al., 2003; Baker, 2004).
McClellan et al. (2007) investigated nutrient and chemical properties of USGA specification putting greens for 7 yr, but soil physical properties were not recorded. Additionally McClellan et al. (2009) documented an organic matter path developing with age that had different chemical properties than the original rootzone. A developing mat layer high in organic matter may affect the soil physical properties of a sand rootzone as well. Putting green rootzone reconstruction may be necessary if turfgrass growth is limited due to the reduced infiltration rate and air-filled porosity commonly associated with the aging process.

Previous studies of putting green soil physical properties changing with time have been just a 3–6-yr duration, (Curtis and Pulis, 2001; Gibbs et al., 2001; Ok et al., 2003; Baker, 2004) or sampling greens of different locations and ages to infer long-term trends (Murphy et al., 1993; Habeck and Christians, 2000). Curtis and Pulis (2001) concluded that rootzone soil physical properties continued to change after 5 yr. However, research is lacking on long-term studies that characterize the changes of soil physical properties and the effect of establishment protocol on rootzone soil physical properties as they age. Understanding rootzone soil physical property changes with time may lead to improved management practices, better construction and establishment protocols, and a longer putting green life expectancy. The objective of this study was to characterize soil physical properties of sand-amended putting green rootzones as affected by (i) rootzone mixture, (ii) establishment treatment, and (iii) putting green age.

### MATERIALS AND METHODS

Experimental putting greens were built, established, and maintained as previously described in McClellan et al. (2007, 2009). Briefly, four experimental putting greens were constructed in sequential years from 1997 to 2000 following USGA specifications (USGA Green Section Staff, 1993). Treatments included two rootzone mixtures: 80:20 (v:v) sand and sphagnum peat and an 80:15:5 (v:v) sand, sphagnum peat, and soil (Tomely silty clay loam, a fine, smectitic, mesic Pachic Arguidoll) and two establishment treatments: controlled and accelerated. All four experimental greens were sampled including both rootzone treatments, however only the plots receiving the accelerated establishment treatment were sampled since establishment treatment had no effect on the soil physical properties tested. Actively growing roots were removed by combing through the samples. These disturbed samples were sent to Hummel & Co, Inc (Trumansburg, NY) for the same tests of particle size distribution and $K_{sat}$ that were done preconstruction.

Additional rootzone samples were taken in October 2004 from below the visible mat layer to a depth just above the gravel tier. All four experimental greens were sampled including both rootzone treatments, however only the plots receiving the accelerated establishment treatment were sampled since establishment treatment had no effect on the soil physical properties tested. Actively growing roots were removed by combing through the samples. These disturbed samples were sent to Hummel & Co, Inc (Trumansburg, NY) for the same tests of particle size distribution and $K_{sat}$ that were done preconstruction.

Ball roll distance was measured monthly beginning in the establishment year using a modified Stimpmeter (Gaussoin et al., 1995). Turfgrass quality measurements were made monthly, using a visual rating scale of 1 to 9, with 1 = poorest, 7 = acceptable, and 9 = best while turfgrass color ratings were made monthly using a 1 to 9 visual rating scale with 1 = straw brown and 9 = dark green (Skogley and Sawyer, 1992).

Each experimental putting green had a split plot design with the whole plot consisting of putting green age; the rootzone mixture and establishment treatments were arranged in 2 by 2 factorial within a completely randomized block design and three replications. Data collected were analyzed through ANOVA using the mixed models procedure in SAS version 8 (SAS Institute, 1999). Data were analyzed as a split plot in time with a subplot factor of putting green age. Means were separated using Fisher’s protected least significant difference (LSD) at $p = 0.05$ (Fisher, 1960). Regression analysis was done and correlation coefficients were calculated on infiltration rate, bulk density, total, capillary, and air-filled porosity vs. rootzone age using Sigmaplot (Systat Software, Inc., San Jose, CA). A Z-statistic was used to compare preconstruction values of particle size distribution and $K_{sat}$ to the rootzone samples taken in 2004 (Dowdy and Wearden, 1991).

### RESULTS AND DISCUSSION

All soil physical properties tested were affected by age (Table 2). After the establishment year the rootzone...
Table 1. The effect of age on particle size distribution and $K_{sat}$ of rootzone mixtures for United States Golf Association (USGA) specification putting greens built in 1997, 1998, 1999, 2000, rootzone samples taken in 2004, and topdressing sand applied during the study. Plots were located at Mead, NE. Rootzones were an 80:20 (v:v) sand and sphagnum peat mixture and an 80:15:5 (v:v) sand, sphagnum peat, and soil (Tomek silty clay loam) mixture.

<table>
<thead>
<tr>
<th>Year of putting green construction and rootzone mixture</th>
<th>Particle size, diam. (mm)</th>
<th>Particle size, diam. (% )</th>
<th>$K_{sat}$ (cm h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sampled</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>VCS§</td>
<td>CS</td>
</tr>
<tr>
<td></td>
<td>&gt;2.0</td>
<td>1–2</td>
<td>0.5–1</td>
</tr>
<tr>
<td>1997 80:20 PC†</td>
<td>1.30</td>
<td>8.00</td>
<td>29.10</td>
</tr>
<tr>
<td>2004</td>
<td>0.83*</td>
<td>7.77</td>
<td>26.83*</td>
</tr>
<tr>
<td>1997 80:15:5 PC</td>
<td>1.50</td>
<td>7.80</td>
<td>26.60</td>
</tr>
<tr>
<td>2004</td>
<td>1.20</td>
<td>6.8*</td>
<td>24.27*</td>
</tr>
<tr>
<td>1998 80:20 PC‡</td>
<td>0.80</td>
<td>5.30</td>
<td>19.80</td>
</tr>
<tr>
<td>2004</td>
<td>0.77</td>
<td>5.43*</td>
<td>20.53*</td>
</tr>
<tr>
<td>1998 80:15:5 PC</td>
<td>1.40</td>
<td>6.90</td>
<td>22.00</td>
</tr>
<tr>
<td>2004</td>
<td>0.90*</td>
<td>6.40*</td>
<td>21.33*</td>
</tr>
<tr>
<td>1999 80:20 PC‡</td>
<td>0.10</td>
<td>2.30</td>
<td>16.70</td>
</tr>
<tr>
<td>2004</td>
<td>0.07</td>
<td>2.03*</td>
<td>17.93</td>
</tr>
<tr>
<td>1999 80:15:5 PC</td>
<td>0.60</td>
<td>2.30</td>
<td>15.40</td>
</tr>
<tr>
<td>2004</td>
<td>0.13*</td>
<td>2.33</td>
<td>17.27*</td>
</tr>
<tr>
<td>2000 80:20 PC‡</td>
<td>1.20</td>
<td>8.70</td>
<td>27.00</td>
</tr>
<tr>
<td>2004</td>
<td>1.07*</td>
<td>7.97*</td>
<td>26.20*</td>
</tr>
<tr>
<td>2000 80:15:5 PC</td>
<td>1.40</td>
<td>7.40</td>
<td>25.10</td>
</tr>
<tr>
<td>2004</td>
<td>0.90*</td>
<td>7.57</td>
<td>26.20</td>
</tr>
<tr>
<td>Topdressing sand</td>
<td>0.50</td>
<td>2.80</td>
<td>21.00</td>
</tr>
</tbody>
</table>

* Values in the same column, within the same year and rootzone are significantly different at the $p = 0.05$ level.
†$K_{sat}$ indicates saturated hydraulic conductivity as determined by ASTM F-1815.
‡A Z-statistic test of the preconstruction values compared with samples taken in 2004.
§VCS, CS, MS, FS, and VFS indicate very coarse, coarse, medium, fine, and very fine sand fraction determined by ASTM C 136–96a.
¶PC indicates preconstruction test value.
#na indicates that tests were not performed.

Table 2. Analysis of variance for soil physical properties of four United States Golf Association specification putting green rootzone mixtures built sequentially from 1997 to 2000 at the John Seaton Anderson Research Facility near Mead, NE.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Infiltration rate</th>
<th>df</th>
<th>Air-filled porosity</th>
<th>Capillary porosity</th>
<th>Bulk density</th>
<th>Total porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishment (EST†)</td>
<td>1</td>
<td>ns‡</td>
<td>1</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Rootzone mixture (RZM§)</td>
<td>1</td>
<td>ns</td>
<td>1</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>EST x RZM</td>
<td>1</td>
<td>ns</td>
<td>1</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Putting green age (A¶)</td>
<td>9</td>
<td>***</td>
<td>7</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>EST x A</td>
<td>9</td>
<td>ns</td>
<td>7</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>RZM x A</td>
<td>9</td>
<td>ns</td>
<td>7</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>EST x RZM x A</td>
<td>9</td>
<td>ns</td>
<td>7</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
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<tr>
<td>Replication total (G#)</td>
<td>255</td>
<td>188</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>53</td>
<td>44</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>359</td>
<td>263</td>
<td>263</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
†Establishment treatments were an accelerated or controlled nutrient program.
‡ns, not significant.
§Rootzone mixtures an 80:20 (v:v) sand and sphagnum peat mixture and an 80:15:5 (v:v) sand, sphagnum peat, and soil (Tomek silty clay loam) mixture.
¶Age of the putting green (in years) when the samples were taken.
#Variance components involving replications nested within putting green were combined, and thus the final model included only the total of all replications, including putting green (G), Replication (G x EST x RM), G x EST x RM, G x EST x RM x A.
treatment and putting green age influenced soil physical properties while establishment treatment did not (data not shown). Ball roll distance, turfgrass color, and quality measurements were not significantly different after the establishment year for any establishment treatment, rootzone mixture, or putting green age (data not shown).

Water infiltration rate was negatively correlated \( (p < 0.0001, r = -0.79) \) with rootzone age yet infiltration rate remained relatively high after 10 yr, and more than adequate for rainfall in the region, (Fig. 1). Infiltration rate declined 75\%, from 0.61 m h\(^{-1}\) in Year 1 to 0.15 m h\(^{-1}\) in Year 10 after establishment for the 80:20 rootzone, while the 80:15:5 rootzone declined 71\% from 0.55 m h\(^{-1}\) in Year 1 to 0.16 m h\(^{-1}\) in Year 10 after establishment. Both still met USGA specifications of 0.1524 m h\(^{-1}\) (USGA Green Section Staff, 1993). Infiltration rate changed quickly from the establishment year value; there were significant decreases in infiltration from Year 1 to Year 2. Then infiltration rate continued to decline each year until Year 8. There were no significant differences from Year 8 to Year 9 or Year 9 to Year 10 indicating that the rate of decline had slowed substantially. Infiltration rate was less with the 80:15:5 compared with the 80:20 rootzone initially, but infiltration rate declined at a similar rate. The rootzone treatment effect was no longer significant 8 yr after establishment suggesting another parameter(s) in the rootzone had become the dominate influence on water infiltration. Several researchers have documented similar decreases in infiltration rate concurrent with changes in rootzone soil physical properties with time (Baker et al., 1999; Baker, 2004; Habeck and Christians, 2000; Curtis and Pulis, 2001; Gibbs et al., 2001; Ok et al., 2003). Waddington (1992) also reported lower infiltration rates for sand-based rootzones amended with soil.

Reductions in rootzone infiltration have been attributed to accumulation of silt and clay particles (Habeck and Christians 2000), organic matter build up (Baker et al., 1999; Baker, 2004), and organic matter layering (Curtis and Pulis, 2001). Callahan et al. (1997) speculated that fine particle migration could clog soil pores and reduce infiltration of sand rootzones as well. The rootzone samples taken in 2004 from below the visible mat layer had no increase in silt and clay accumulation or migration in the rootzone compared to preconstruction values (Table 1). In addition, the soil-amended rootzone infiltration, while initially lower, did not decline at a faster rate than the rootzone without soil (Fig. 1). Curtis and Pulis (2001) reported that infiltration declined from 0.95 to 0.031 m h\(^{-1}\) 3 yr after establishment because of organic matter layering in the rootzone. In our study, no layering of organic matter was observed in the rootzones, because of the frequency of sand topdressing applications.

Surface organic matter accumulation has been reported to cause reduction in infiltration of putting green rootzones (Murphy et al., 1993; Baker et al., 1999; Habeck and Christians, 2000; Curtis and Pulis, 2001; Ok et al., 2003). In our study a mat layer did develop at 0.65 cm yr\(^{-1}\), concurrent with the reduction of infiltration rate.
zone age (McClellan, 2005). Baker et al. (1999) also reported that organic matter accumulated in the upper 2.0 cm of putting green rootzones. After 3 yr increased organic matter increased from 4–25 to 79–122 g kg⁻¹.

Additionally, rootzone samples taken in 2004 from below the visible mat layer had lower Ksat than the preconstruction Ksat values (Table 1). The rootzone samples taken in 2004 had increased fine sand amounts in six of the eight rootzones and decreased coarse sand in four of the eight rootzone sampled compared to the preconstruction particle size distribution. Increased fine sand content in the rootzone could result in lowered Ksat from the reduced macroporosity. The increased fine sand content and lowered coarse sand content likely originated from the sand topdressing applications. The USGA recommends that topdressing sand should meet the rootzone particle size distribution (USGA Green Section, 1994). The topdressing sand used in our study had a higher amount of fine sand (0.25–0.15 mm) particles and less coarse sand (0.5–1.0 mm) than the sand used in many of the original rootzone mixtures (Table 1). The fine sand particles may have been placed into the rootzone during core cultivation, especially during the first 2 yr. Zontek (1979) and Vavrek (1995) reported that the long-term affects of continued sand topdressing on putting green soil physical properties are not well defined. The decline in Ksat due to increased fine sand content in the rootzone does not completely explain the reduction of infiltration from in situ testing. Changes in rootzone Ksat were 0.032 m h⁻¹ yr⁻¹ while infiltration rate decreased at approximately 0.043 m h⁻¹ yr⁻¹. McCoy (1992) reported that decreases in air-filled porosity in sand rootzones often resulted in decreased infiltration. The changes in rootzone air-filled and capillary porosity in the visible mat layer may also explain the decrease in infiltration observed in this study.

In a companion study investigating aging putting green nutrient and chemical properties, McClellan et al. (2007) found that a developing mat layer contributed to increased chemical properties, such as CEC and nutrient retention in older putting greens. When the mat layer was analyzed separately from the underlying original rootzone, the chemical properties of the original rootzone were not affected by age (McClellan et al., 2009). Supporting this, Baker (2004) reported that organic accumulation increased with depth, with the top 2 cm of the profile having the largest increase.

Capillary porosity was positively correlated with rootzone age (p < 0.0001, r = 0.56), and rootzone mixture did not affect capillary porosity. Capillary porosity increased 32% from 0.15 m³ m⁻³ in Year 1 to 0.21 m³ m⁻³ in Year 8 and still met USGA specifications (Fig. 2) (USGA Green Section Staff, 1993). Capillary porosity was significantly higher from the Year 1 value in Year 3 of testing. Also there was a significant year to year change from Year 4 to Year 5. Air-filled porosity was negatively correlated with rootzone age (p < 0.0001 r = −0.77) and rootzone mixture was not significant. Air-filled porosity decreased by 38% from 0.29 m³ m⁻³ in Year 1 to 0.18 m³ m⁻³ in Year 8 and still met USGA specifications (Fig. 2) (USGA Green Section Staff, 1993). Air-filled porosity was significant lower from Year 1 in Year 3 of testing, and had a significant year-to-year decrease from Year 2 to Year 3, from Year 4 to Year 5, and from Year 7 to Year 8. Others have reported similar increases in capillary porosity and decreases in air-filled porosity in aging putting green sand rootzones (Murphy et al., 1993; Habeck and Christians, 2000; Ok et al., 2003). Habeck and Christians (2000) reported an increase in capillary porosity and a decrease in air-filled porosity from clay contamination. In our experiment we did not find silt and clay accumulation in the rootzone (Table 1), so the changes in air-filled and capillary porosity must be attributable to something other than silt and clay accumulation. Ok et al. (2003) reported a 19% increase (11–32%) in capillary porosity and a 72% decrease (31.9–8.8%) in air-filled porosity 3.5 yr after establishment. They attributed these changes in pore size distribution to thatch accumulation. It is probable that the light frequent topdressing program in our study resulted in lesser changes in air-filled and capillary porosity than reported by Ok et al. (2003), where topdressing was applied less frequently than in our study. Murphy et al. (1993) reported that air-filled porosity decreased as organic matter increased with rootzone age. Changes in air-filled and capillary porosity may also be attributed partially to the mat layer that developed with time.

Bulk density was weakly correlated with rootzone age (p < 0.0001, r = 0.37), and rootzone mixture was not significant (Fig. 3). Bulk density increased by 7% from 1.47 Mg m⁻³ in Year 1 to 1.57 Mg m⁻³ in Year 8. Bulk density was significantly higher from the Year 1 value in Year 4 of testing. There was a significant increase from Year 3 to Year 4 as well. Total porosity decreased with age, and was weakly correlated with age (p < 0.0001, r = −0.46). Rootzone mixture did not affect total porosity. Total porosity decreased 9%, from 0.44 m³ m⁻³ in Year 1 to 0.4 m³ m⁻³ in Year 8 (Fig. 3). After 8 yr, the total porosity of the rootzone mixtures still met USGA specifications (USGA Green Section Staff, 1993). Total porosity was significantly different from the Year 1 value in Year 4 of testing. There were also significant decreases from Year 3 to Year 4, and Year 6 to Year 7 of testing. The observed increased bulk density and decreased total porosity with time may have been the result of fine sand accumulation from the topdressing sand, combined with some compaction. Hannaford and Baker (2000) reported that amendment type affected both bulk density and total porosity. In our study we were unable to detect differences in rootzone mixture after 8 yr. This may be attributed to the mat layer that developed within the sampling depth, which would be the same composition for both rootzone mixtures. McClellan et al. (2009) concluded that although the original rootzone and organic matter layer were very different, both exhibit chemical uniformity within each respective rootzone region for all putting green ages. Few studies have
reported changes in bulk density and total porosity with rootzone age. Ok et al. (2003) reported minimal change in bulk density and total porosity over 3 yr. Habeck and Christians (2000) reported a decrease in bulk density with age, but concluded that this data was not as expected, and concluded that their samples were contaminated with thatch. Murphy et al. (1993) reported an increased total porosity with age, which may have been the result of sampling different locations, while bulk density was not reported.

The decrease in total porosity indicates that the decrease in air-filled porosity (macroporosity) is not totally compensated by the observed increase in capillary porosity. The increase in capillary porosity suggests that excess water retention and a reduced rate of drainage in the rootzone may become problematic. However, it appears that the rate of infiltration rate decrease can be partly controlled by intense sand topdressing applications. After 10 yr the infiltration rate decline had started to slow and both rootzone mixtures had an infiltration rate of around 0.16 m h\(^{-1}\), more than adequate for regional precipitation. The dilution of organic matter by cultivation and topdressing application may explain why in our study the infiltration rate was still declining after 10 yr. Baker (2004) reported that after 6 yr infiltration rate had reached a stable value of \(1.2 \times 10^{-3}\) to \(3.0 \times 10^{-3}\) m h\(^{-1}\); topdressing was applied at 1.5 kg m\(^{-2}\) four to five times annually (Baker et al., 1999). Additionally, Ok et al. (2003) reported a larger decline in infiltration rate (0.15 m h\(^{-1}\)) after 3.5 yr where topdressing
was applied only four times annually combined with yearly aerification compared to a 0.08 m h\(^{-1}\) decline after 3 yr in our study.

After 10 yr, water infiltration of the 80:20 sand/peat and the 80:15:5 sand/peat/soil rootzones (with no negative effect from the addition of the soil) remained adequate for regional rainfall and irrigation amounts. The change in soil physical properties was in part the result of fine sand accumulation from topdressing and increase of soil organic matter in a mat layer near the surface. Placement of fine sand from topdressing sand partially accounted for increased capillary porosity, and decreased air-filled porosity and infiltration rate. The reduction in infiltration rate over time, while statistically significant, remained adequate for location precipitation and still met USGA specifications after 10 yr. Additionally, capillary, air-filled, and total porosity still met USGA specifications after 8 yr (USGA Green Section Staff, 1993).

When properly managed, increased organic matter and topdressing sand at the surface of a sand-based rootzone can produce a satisfactory growing environment. A topdressing program that is light and frequent combined with a timely program of cultivation and heavy topdressing may prevent or slow the potentially negative changes in rootzone soil physical properties as sand-based putting greens age. Future studies of organic matter dynamics with time are needed, as its influence on soil physical properties is not well defined in the turfgrass literature.

Figure 3. United States Golf Association specification putting green age effect on bulk density and total porosity for two rootzones at Mead, NE. An X indicates the first significant change from the Year 1 value, a triangle indicates a significant change from the previous year's value. Rootzone effect was not significant. Rootzones were 80:20 (v:v) sand, and sphagnum peat mixture and 80:15:5 (v:v) sand, sphagnum peat, soil (Tomek silty clay loam) mixture.
References


Boyer, London.


