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Physical and hydraulic properties of inorganic amendments and modeling their effects on water movement in sand-based root zones

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Abstract The objective of this study was to evaluate the physical and hydraulic properties of selected inorganic amendments and their mixtures with sand (85:15% v/v), and model how they affect the water movement in sand-based root zones of sports fields. The amendments are composed of: calcined diatomaceous earth materials (Axis and Isolite); zeolites (Clinolite and Ecolite); and calcined clays (Moltan Plus, Profile, and Pro's Choice). The bulk density, particle density, porosity, particle-size distribution, saturated hydraulic conductivity, water retention and available water-holding capacity were analyzed. A numerical model was applied to simulate soil water movement for a scenario with and without amendment incorporation. The results showed that amendments significantly ($P < 0.05$) improved the physical and hydraulic properties of root zone. Modeling results revealed reduced surface dryness, higher volumetric water content and storage and higher initial root water uptake rate for the root zones with amendments. These results suggest there are multiple benefits of amended root zones in terms of improvement of the physical and hydraulic properties of sand-based root zones.

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Introduction

Sports fields are usually constructed on sand-based root zones, which provide an ideal medium for turf systems with respect to physical characteristics, viz., high infiltration and hydraulic conductivity that enhance rapid drainage, reduced soil compaction and increased aeration for root growth (Beard 1973; Bingaman and Kohnke 1970). However, sand has low water and nutrient-holding capacities, which leads to water and nutrient stresses in the root zone, which lower turf quality. Taylor and Blake (1981) reported that when sand is subjected to years of continuous traffic, individual sand particles can be displaced and become tightly packed.

The United States Golf Association (USGA 1993) has provided specifications for rooting zone construction of golf putting greens (Fig. 1, Table 1), which are composed predominantly of sand mixed with amendments (Kussow 1987). The idea is to provide a mixture that improves compaction resistance, water infiltration and retention, nutrient retention and root zone aeration (Wehtje et al. 2000). Modification by applying organic and inorganic amendments in the root zone is a suggested method of reducing compaction and leaching, while increasing plant available water and nutrient-holding capacity (Waltz et al. 2003). Addition of organic amendments offer benefits of increased soil water retention, reduced bulk density, improved root zone aeration, increased nutrient retention and improved turfgrass germination (Bigelow et al. 1999; Juncker and Madison 1967; McCoy 1992). Sphagnum moss or reed sedge and peat are the most common amendments used in putting green construction (Waddington 1992). However, these organic amendments decompose over time, losing their desirable characteristics (Huang and Petrovic 1995). Decomposition of organic matter has been reported to reduce hydraulic conductivity and air-filled porosity compared to non-amended sand (McCoy 1992). Peat has limited effectiveness in reducing nitrate leaching (Ervin et al. 1999). Furthermore, since peat is a naturally occurring resource, the supply is limited (Waltz et al. 2003). Suitable amendments for putting green root zones are being sought for possible replacement of peat, and those that retain physical properties for extended period are desired. In recent years, there has been a trend toward use of inorganic amendments in sports-type turf, and these amendments can either be incorporated into the rooting media prior to turf establishment or be applied to the surface after core-aeration (Wehtje et al. 2000). Inorganic amendments such as pumice, perlite, expanded shale, sintered fly ash, slag, calcined clays, diatomaceous earths and zeolites have been identified as possible substitutes for peat in high sand content root zones (Carrow 1993; Ervin et al. 1999; Ok et al. 2003; Waltz et al. 2003. They are more resistant to decomposition; they improve the water-holding capacity; they improve drainage; they are more permanent additions to the root zone, and they reduce the potential to harbor pathogenic organisms. Some of the materials possess high cation exchange capacities (CECs) and water-holding capacities without reducing air-filled porosity (Huang and Petrovic 1994). Although inorganic amendment materials are large in size compared to sand, they are characterized by internal pore space and surfaces, thereby increasing soil water retention and porosity.

Wehtje et al. (2000) reported that most of the amendment products on the market are produced from three types of natural deposits: clays including montmorillonite and attapulgite; zeolites, which are predominantly composed of the mineral clinoptile; and diatomaceous earths, which are the siliceous skeletal remains of diatoms. The minerals are screened to a narrow particle range, approximately equivalent to that of coarse sand (0.5–1.0 mm) to maintain high percolation rates (Bigelow et al. 2004). The clays and diatomaceous earth-based amendments are calcined (fired) at 1,500–1,700 C to make the particles stable. Zeolite-based amendments usually are not calcined. The studies of effect of inorganic amendments on soil physical properties have been limited to some zeolites, mainly clinoptilolite (Ferguson et al. 1986; Huang and Petrovic 1995) and calcined clays (Waddington et al. 1974). Previous research has revealed conflicting results on the success of inorganic amendments (Bigelow et al. 2004; Ferguson et al. 1986; Kussow 1996; McCoy and Stehouwer 1998; Waddington et al. 1974; Waltz et al. 2003; Wehtje et al. 2003). A disadvantage that has been reported on use of inorganic amendments is that much of the water held internally may be tightly held for plant extraction and therefore unavailable to turfgrass. Knowledge of the physical and hydraulic properties of inorganic amendments is essential for understanding the suitability of amending sand-based root zones. An ideal amendment or amendment mixture should possess both micropores and macropores. Macropores enhance drainage and aeration while micropores help to retain water. Limited information has been collected to compare the effects of most amendments on the soil physical properties of a sand-based golf putting green (Li et al. 2000). Water is required in all plants, turfgrasses included, for germination, growth and reproduction, mechanical support, photosynthesis, as well as forming part of the plant system. Hence, in most turf systems,

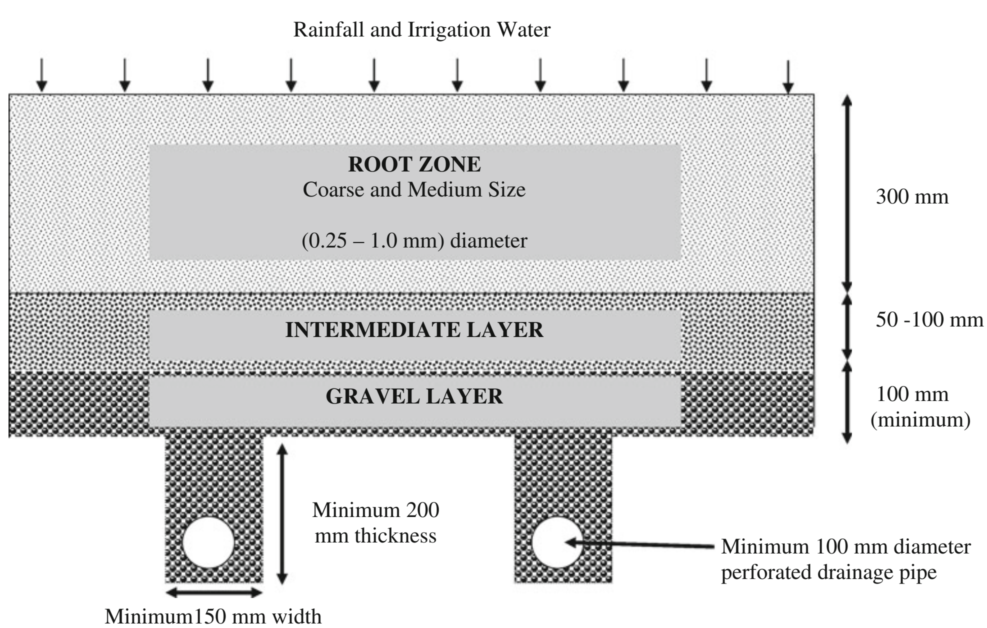

Fig. 1 The USGA recommendation for a putting green root zone design

Table 1 Specification for porosity and saturated hydraulic conductivity for the USGA and California construction systems

System	Porosity [Volumetric content (m^3 m^{-3})]			Saturated hydraulic conductivity (m h^{-1})
	Total	Macro	Capillary	
USGA	0.35–0.55	0.15–0.30	0.10–0.20	0.76
California	0.35–0.55	0.15–0.30	0.15–0.25	0.68

supplemental irrigation is often applied to meet the high demand of water (Githinji et al. 2009). The water absorbed by turf is transpired into the atmosphere, and as it moves, there is nutrient uptake from the soil, as well as elimination of heat buildup from solar radiation. Several studies have been conducted focusing on the process of water movement with root uptake and generally two approaches have been developed. One approach deals with water flow to a single root (radial flow), where a root is considered to be an infinitely long, hollow, cylindrical sink of uniform radius (Mathur and Rao 1999). This approach is often referred to as a microscopic approach (Doussan et al. 1998; Gardner 1960; Nobel and Alm 1993; Personne et al. 2003; Philip 1957; Steudle 1994). The disadvantage of microscopic approach is that it requires detailed information on the geometry of root system, which is practically impossible to acquire (Wu et al. 1999; Vrugt et al. 2001). The other approach considers the root system as a single unit, and it does not take into account the effects of individual roots due to the difficulty in measuring the time-dependent geometry of the root system (Mathur and Rao 1999) and is referred to as a macroscopic approach (Gardner 1964; Mathur and Rao 1999). Most soil water simulation models with plant water uptake use the macroscopic approach, in which water extraction by plant roots is treated as a sink term distributed in the root zone (Wu et al. 1999). The entire root system is assumed to extract water from each differential volume of the root zone at some rate, and the uptake is represented by a volumetric sink term incorporated into Richards (Richards 1931) equation that describes water movement in variably saturated soils (Jury et al. 1991). Mathur and Rao (1999) noted that some researchers classified the water uptake models into a third category—a hybrid approach to take into account root density, root permeability and root water extraction in the extraction relationship.

Although macroscopic models of root water uptake do not give a complete insight into the physical processes of root water uptake, they only need the soil and plant parameters that are readily available. Hence, the use of macroscopic approach is generally favored in many application-oriented hydrological models (Li et al. 2001). Some macroscopic approaches model water potential and hydraulic functions inside plant roots (Hillel et al. 1976), while others are based on transpiration rate, rooting depth and soil water potential (Feddes et al. 1974). The parameters for the latter are easier to collect, and this approach is the one mainly implemented into numerical models (Šimůnek et al. 1992). The numerical models using macroscopic description of root water uptake include HYDRUS (Šimůnek et al. 1998a, b), SWAP (van Dam et al. 1997), UNSATCHEM (Suarez and Simunek 1997) and HYSWASOR (Dirksen et al. 1993).

The objectives of this study were to: (1) evaluate and compare the physical and hydraulic properties of 7 commercially available inorganic amendments used in sand-based root zones and sand; and (2) model soil water movement for scenarios with and without amendment incorporation. The rationale of the study stems from the fact that amendments that improve the physical and hydraulic properties of sand-based root zones can lead to minimization of irrigation water use.

Materials and methods

Seven amendments {Clinolite (Scientific Turf Products, 207 Fox Crossing, Burnet, TX 78611), Ecolite (Western Organics, Inc., 420 E. Southern Ave., Tempe, AZ 85282), Pro’s Choice (Pro’s Choice Products, P.O. Box 20, Barington, IL 60011), Moltan Plus (Moltan Co., 3555 Moltan Drive, Memphis, TN 38115), Isolite (Davisson Golf Inc., 4252 North Point Road, Unit 109, Baltimore, MD 21222), Profile (Applied Industrial Materials Corp., 750 Lake Cook Road, Suite 440, Buffalo Grove, IL 60089), Axis (Eagle-Picher Minerals Inc., P.O. Box 12130, Reno, NV 89510)}, all marketed in the southeastern United States and sand, were evaluated. These amendments are composed of: calcined diatomaceous earth materials (Axis and Isolite); zeolites (Clinolite and Ecolite) and calcined clays (Moltan Plus, Profile, and Pro’s Choice). The mineralogical description and chemical composition of each of the amendment is shown in Table 2. All the amendments are comprised mainly of silica (SiO_2) with minor constituents of metal oxides (Al_2O_3 and Fe_2O_3).

Table 2 Mineralogical description of the materials used for this study

Amendment	Mineralogical description	Chemical composition
Axis	Calcined diatomaceous earth; poorly crystalline silica	SiO_2 (90.0%), Al_2O_3 (6.5%), Fe_2O_3 (2.3%), CaO, MgO, K_2O, Na_2O and TiO_2 (1.2%)
Clinolite	Zeolite; mainly clinoptilolite	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (5%)
Ecolite	Zeolite; mainly clinoptilolite	SiO_2 (69.1%), Al_2O_3 (11.9%), K_2O (3.8%), Fe_2O_3, MnO, CaO, MgO, Na_2O and TiO_2 (3.3%)
Isolite	Calcined diatomaceous earth; crystalline silica	SiO_2 (78%), Al_2O_3 (12%), Fe_2O_3 (5%) K_2O, MnO, CaO, MgO, Na_2O and TiO_2 (5%)
Moltan Plus	Calcined clay; crystalline silica and minor phyllosilicate	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (<5%)
Profile	Calcined clay; phyllosilicate (illite)	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (<5%)
Pro's Choice	Calcined clay; crystalline silica and minor phyllosilicate	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (<5%)
Sand	Quartz	SiO_2 (100%)

Determination of the physical and hydraulic properties

A series of laboratory experiments were conducted to measure the physical and hydraulic properties of pure amendments and of a combination of each of the amendments with sand at 15:85% (amendment/sand ratio on volume basis). The parameters measured were bulk density, particle density, particle-size distribution, saturated hydraulic conductivity (K_{sat}), water retention and available water-holding capacity. Each of the air-dried amendments and sand/amendment mixtures were packed in a standard metal cylinder (6-cm height and 5.35-cm diameter). During packing, successive amounts of about 5 cm^3 of material were added, stirred with the previous added material to avoid layering and the cylinder tapped gently, until it was completely full. All amendments and sand/amendment mixtures were packed in triplicate. For all the parameters under consideration, the values were obtained from the average of the three measurements. The bulk density was calculated from the mass of the air-dry material and the calculated volume of the cylinder. The particle density was determined using the pycnometer method (Flint and Flint 2002), which is based on the determination of the volume of a known mass of soil by liquid displacement. Prior to determining the particle density, the amendments and the mixtures were slightly wetted with water using an aspirator bottle and placed in zip-lock bags and allowed to sit overnight to equilibrate. This was done to overcome the initial hydrophobicity of most of these materials.

Particle-size analysis was achieved by passing the amendment materials through 2.0, 1.0, 0.5, 0.25, 0.1 and 0.05 mm sieves followed by weighing. The United States Department of Agriculture particle-size limit was used (Gee and Or 2002). Total porosity was calculated from particle and bulk density using the following relationship:

$$\phi = \left(1 - \frac{\rho_b}{\rho_p}\right) \quad (1)$$

where ρ_b is the bulk density (g cm^{-3}), ρ_p is the particle density (g cm^{-3}), and ϕ is the total porosity (cm^3 cm^{-3}). Capillary porosity was defined as the amount of pores retaining water at −4 kPa (Bigelow et al. 2004; Waltz et al. 2003), while macroporosity was calculated as the difference between the total porosity and capillary porosity. Saturated hydraulic conductivity (K_{sat}) was determined on the same samples using the constant head method upon substitution of the ceramic plate by cheese cloth (Bootlink and Bouma 2002). A Mariotte flask was used to set the constant head and a wetting solution of 0.005 M $CaCl_2$ was used to prevent particle dispersion. To saturate the samples, we flushed with CO_2 to replace the air present in the pores. The CO_2 readily dissolved in the de-aerated wetting solution during the wetting of the materials, preventing the presence of trapped air. Water flowing through the sample for the first 10 min was discarded. After that, water was allowed to flow through the sample for 6 min with 6 subsamples collected on 1-min interval, measured, and K_{sat} determined according to Darcy's law:

$$q = \pm \frac{V}{At} = -K_s \frac{\Delta H}{\Delta L} \quad (2)$$

where q is the flux density (ms^{-1}), V (m^3) is the volume of water flowing through a cross-sectional area of porous medium A (m^2) during time t (s), K_s is the saturated hydraulic conductivity (ms^{-1}), ΔH (m) is hydraulic head difference between the top and bottom of the sample, and ΔL (m) is the height of the sample. The flux is positive for upward and negative for downward flow.

Water retention for various pressure heads was determined using Tempe pressure cells (Dane and Hopmans 2002). The samples were vacuum saturated with a 0.005 M $CaCl_2$ solution to avoid any possible dispersion. This process lasted for several days due to the initial hydrophobicity of the materials. Upon saturation, the materials were allowed to equilibrate at atmospheric pressure. Hence, the water under the porous ceramic plate was kept at about atmospheric pressure, while a gas phase was applied to the sample at pressures greater than atmospheric. Water flow out of the sample through the porous plate was measured at each applied pressure (0.1, 0.6, 1.5, 2.0, 2.5, 3.5, 4.5, 5.0, 5.5, 6.0, 7.0, 10.0, 12, 15, 25 and 50 kPa) after static equilibrium was established between the soil water and the bulk water in the system below the porous plate. For higher pressures (100, 250, 500, 1,000 and 1,500 kPa), a ceramic plate extractor was used. After applying the highest pressure, the volumetric water content of the samples was determined using the gravimetric method, and all other water content values were calculated from the respective outflow volumes. The matric head was calculated from the applied pressure using the relation from Dane and Hopmans (2002):

$$h_m = -(P_a - P_{atm})/\rho_w g = -h_a \quad (3)$$

where h_m is the matric head (cm), P_a and P_{atm} (=0), refer to applied air and atmospheric pressures, respectively (Pa), and h_a is the applied air pressure head. Water retention curves were plotted from the calculated matric head and the volumetric water content. We defined the available water-holding capacity as the difference between the permanent wilting point and field capacity, with permanent wilting point defined as the water held at −1,500 kPa and field capacity as that water held at −4 kPa as suggested by Bigelow et al. (2004). We divided the AWC into easily available water-holding capacity, moderately available water-holding capacity and less available water-holding capacity. The easily available water-holding capacity, moderately available water-holding capacity and less available water-holding capacity were specified as the water held between −4 to −50, −50 to −500 and −500 to −1,500 kPa, respectively. After plotting the water retention curve, data were fitted to two often used water retention models, the van Genuchten expression (1980) and the Brooks–Corey relation (Brooks and Corey 1964). The van Genuchten relation is:

$$\begin{aligned} S_e &= \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha|h_m|)^n}\right]^m \\ K(h) &= K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \\ m &= 1 - 1/n, \quad n > 1 \end{aligned} \quad (4)$$

where S_e is the effective water content, θ the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, h_m is the matric head (cm), and α, m and n are curve fitting parameters, while l is a pore-connectivity parameter, which is estimated to be about 0.5 as an average for many soils (Mualem 1976). The Brooks–Corey relation is:

$$\begin{aligned} S_e &= \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{h_d}{h_m}\right]^\lambda \quad \text{for} \quad h_m < h_d \\ S_e &= 1 \quad \text{for} \quad h_m > h_d \\ K &= K_s S_e^{2/n+l+2} \end{aligned} \quad (5)$$

where h_d is the displacement pressure, i.e., the matric head value at which water is being displaced by air, and λ is the pore-size distribution index. The basic difference between the van Genuchten and Brooks–Corey relationships is that Brooks–Corey recognizes the air entry value, i.e., the matric head value at which the biggest pores will drain. That is, as long as this air entry value is not reached, the soil will remain saturated.

Modeling of water movement with root uptake

Root water uptake was simulated for an USGA-specification of sand-based root zone (Fig. 1). The USGA design was selected for this study since it has been the standard design for 45 years and has since become the standard method of green construction throughout the United States and in other parts of the world (Frank et al. 2005). Two scenarios were specified, one with amendment incorporated at a rate of 15% amendment and 85% sand by volume, and one without amendment (100% sand). HYDRUS-1D (Šimunek et al. 1998a, b) code was used, which is a Galerkin finite-element method that numerically solves the Richards equation modified to incorporate a sink term to account for water uptake by plant roots. HYDRUS-1D was selected for this study since in sand-based root zones, the water movement is dominated by vertical flow. This can be explained by gravitational head gradient exceeding the matric head gradient, due to: (i) the root zone being kept at relatively moist condition; and (ii) the relatively high homogeneity of the sand-based root zone, hence low matric head gradient.

To establish the water retention curve and the hydraulic properties of unsaturated amendment-sand mixtures from the point data, the RETC (retention curve model) code by van Genuchten et al. (1991) was used. In this code, the water retention curve is described with the equations of Brooks and Corey (1964) and van Genuchten (1980), with the pore-size distribution models of Burdine and Mualem used to parameterize $h(\theta)$ and $K(h)$ characteristics (van Genuchten et al. 1991). The RETC code may be used to fit any one, several, or all of these parameters simultaneously to the observed data and uses a non-linear least-squares optimization approach to estimate the unknown model parameters from observed retention and/or conductivity or diffusivity data (van Genuchten et al. 1991). The approach is based on the partitioning of the total sum of squares of the observed values into a part described by the fitted equation and a residual part of observed values around those predicted with the model. The aim of the curve fitting process is to find an equation that maximizes the sum of squares associated with the model, while minimizing the residual sum of squares, which reflects the degree of bias and the contribution of random errors. The HYDRUS-1D code (Šimunek et al. 1998a, b) was used to fit the van Genuchten relation with Mualem-based restriction ($m = 1 - 1/n$) for the Tempe pressure cell data. The Brooks–Corey parameters were obtained using the RETC code.

The root water uptake involves introduction of a sink term into the Richards equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S \tag{6}$$

where S is the sink term [$m^3\ m^{-3}\ s^{-1}$]. The equation states that changes in water content over time, $\partial\theta/\partial t$, results from the pressure gradient, the first term in the parenthesis, and gravity flow, the second term in the parenthesis. To solve Eq. 6, one needs 2 boundary conditions, one initial condition and the soil water retention, θ (h_m), and the hydraulic conductivity, K (θ), functions. The θ (h_m) and K (θ) for the van Genuchten and the Brooks and Corey relations were calculated in Eqs. 4 and 5. To set the 2 boundary conditions, we specified the upper boundary condition as zero flux ($\partial H/\partial z = 0$ at $z = 0$) and the lower boundary condition as unit hydraulic head gradient ($\partial H/\partial z = 1$ at $z = -L$), and we began simulation with saturation as the initial condition:

$$h(z,0) = h_i(z,0) \quad \text{for} \quad -L \le z \le 0 \tag{7}$$

where h is a prescribed function of z; h_i (z,0) is the initial pressure head and L the depth of soil profile.

We converted the water content form of Richards equation (Eq. 6) to a pressure form by assuming a single relationship between the volumetric water content (Eq. 8) and matric head, referred to as the water capacity, C:

$$C = \frac{\partial\theta}{\partial h_m} \tag{8}$$

$$C\frac{\partial h_m}{\partial t} = \frac{\partial}{\partial z}\left[K\frac{\partial h_m}{\partial z} + K\right] - S \tag{9}$$

We equated the sink term S as the volume of water removed from a unit volume of soil per unit time due to plant water uptake, as defined by Skaggs et al. (2006). The sink term is a function of the water pressure head, the osmotic pressure head, root characteristics and transpiration. The sink term is proportional to the rooting zone depth, which can either be constant or be variable during the simulation. In HYDRUS, the actual root depth is calculated as the product of the maximum rooting depth and a growth coefficient (Šimůnek and Suarez 1993):

$$R_D(t) = R_M C_r(t) \tag{10}$$

where R_D [L] is the actual root depth, R_M [L] the maximum rooting depth and C_r [−] is a growth coefficient. For the root growth coefficient, C_r, HYDRUS uses the classical Verhulst-Perarl logistic growth function:

$$C_r(t) = \frac{R_0}{R_0 + (R_M - R_0)e^{-rt}} \tag{11}$$

where R_0 [L] is the initial value of the rooting depth at the beginning of the growing season, and r [L] the growth rate and is calculated either from the assumption that 50% of the rooting depth will be reached after 50% of the growing season has elapsed, or from given data (Šimunek et al. 1998a, b).

The water flow parameters were determined from the water retention data points using the RETC code and specifying the Brooks–Corey water retention model. The depth of the simulation was 0.40-m (0.30-m root zone underlain by a 0.10-m thick gravel layer), and the linear element size was taken as 0.01 m. The total simulation period was 10 days with a time step of 1 h. The initial condition was specified in the zero pressure head (0 kPa), which corresponds with a volumetric water content of 0.20 $m^3\ m^{-3}$ for the non-amended root zone and between ~0.40 and 0.70 $m^3\ m^{-3}$ for the amended root zones. The root water uptake parameters for grass were specified in the model with values of 0 kPa for h_4 (the saturation point pressure head), −2.5 kPa for h_3 (value of the pressure head below which roots extract water at the maximum possible rate), −300 cm H_2O for h_2 (pressure head below which roots cannot longer extract water at the maximum rate) and −800 kPa for h_1 (wilting point). We specified the initial root uptake rate of 0.5 cm d^{-1} and used the Brooks–Corey model hydraulic model, assuming a case with no hysteresis. We assumed constant potential evapotranspiration (ET) of 2 mm/day during the simulation period.

Statistical analysis

Statistical computations were conducted for the physical and hydraulic properties of the soil and the modeled results using the analysis of variance (ANOVA) for a complete random design (RCBD) with three replicates using SAS (SAS Institute 1999). Proc. GLM was used and where significant, the means were separated by Fisher's Least Significant Difference (LSD) test and alpha values of 0.05 were used for all the parameters measured.

Results and discussions

Physical properties of the amendments

The amendments and the amendment-sand mixtures showed significantly ($P < 0.05$) higher porosity values (>0.40 $m^3\ m^{-3}$) compared to 100% porosity value of sand (0.22 $m^3\ m^{-3}$) (Table 3). Axis showed significantly ($P < 0.5$) higher total porosity (0.79 $m^3\ m^{-3}$) values compared to the rest of the amendments. The calcined clays had medium total porosity while zeolites showed the lowest total porosity of all the amendments, but it was still higher than total porosity of non-amended sand. Capillary porosity had the same pattern as total porosity, being significantly higher for Axis (0.50 $m^3\ m^{-3}$), medium for Isolite, Moltan plus, Profile and Pros' Choice (>0.30 $m^3\ m^{-3}$), and lowest for Clinolite and Ecolite (0.25 $m^3\ m^{-3}$). The lowest capillary porosity for the amendments was still much higher compared to that of non-amended sand (0.07 $m^3\ m^{-3}$). The macroporosity values for pure amendments were higher than the maximum value of 0.30 $m^3\ m^{-3}$ that is recommended for the USGA system, except for the Axis amendment which was 0.29 $m^3\ m^{-3}$. The amendment-sand mixtures showed lower (~70% lower) values of total, macro-, and capillary porosity, compared to pure amendments. However, the macro and capillary porosity values were within the recommendations for the USGA construction system (Table 1). These results show that addition of amendments increased the total and capillary porosity values of the sand-amendments mixtures, results which agree with previous findings (Bigelow et al. 2004; Li et al. 2000; McCoy and Stehouwer 1998; Waltz et al. 2003). The high capillary porosity of the amendments indicates the presence of large internal surface areas, which would increase water and nutrient retention. The low capillary porosity of sand (0.07 $m^3\ m^{-3}$) suggests that it would be very difficult to manage a sand-based root zones without incorporating the amendments.

The K_{sat} values for the amendments and amendment-sand mixtures were significantly ($P < 0.05$) higher than for sand (0.41 $m\ h^{-1}$) compared to the amendments. Isolite amendment showed significantly higher K_{sat} value of 1.56 $m\ h^{-1}$, than Clinolite (1.42 $m\ h^{-1}$) and Ecolite

Table 3 Porosity and saturated hydraulic conductivity of the amendments and amendment-sand mixtures

Amendments/sand mixtures	Porosity [Volumetric content ($m^3\ m^{-3}$)]			Saturated hydraulic conductivity ($m\ h^{-1}$)
	Total	Macro porosity	Capillary porosity†	
Axis	0.79[a]	0.29	0.50	0.76[a]
Axis-sand	0.56[1]	0.25	0.31	0.60[1]
Clinolite	0.58[b]	0.32	0.25	1.42[b]
Clinolite-sand	0.41[2]	0.25	0.16	0.78[2]
Ecolite	0.59[b]	0.34	0.25	1.29[c]
Ecolite-sand	0.42[2]	0.26	0.16	0.76[2]
Isolite	0.70[c]	0.33	0.37	1.56[d]
Isolite-sand	0.44[2]	0.19	0.26	0.52[3]
Moltan Plus	0.68[c]	0.32	0.36	0.60[e]
Moltan Plus-sand	0.42[2]	0.17	0.26	0.51[3]
Profile	0.73[d]	0.34	0.39	0.60[e]
Profile-sand	0.42[2]	0.28	0.14	0.47[4]
Pro's choice	0.71[c]	0.40	0.32	0.72[f]
Pro's choice-sand	0.53[1]	0.21	0.32	0.54[3]
Sand	0.22[e,3]	0.15	0.07	0.41[g,5]

Values along the same column with the same number or letter are not significantly different at $P < 0.05$

† Capillary porosity refers to water retained at −40 cm water

Table 4 Particle-size distribution, geometric mean diameter, particle and bulk densities of the amendments and mixtures

Amendments/sand mixtures	Particle-size fractions ($\times 10^{-3}$ m)						Geometric mean diameter (mm)	Particle density (g cm^{-3})	Bulk density (g cm^{-3})
	VCS[a] 1.0–2.0	CS[a] 0.5 –1.0	MS[a] 0.25–0.50	FS[a] 0.10–0.25	VFS[a] 0.05–0.10	Silt + clay[a] <0.05			
Axis	26.4	52.2	19.9	1.5	0.0	0.0	0.51	2.20[a]	0.47[a]
Axis-sand	5.4	39.4	44.0	11.0	0.1	0.0	0.34	2.60[1]	1.49[1]
Clinolite	22.3	69.7	6.6	1.4	0.0	0.0	0.55	2.40[b]	0.97[b]
Clinolite-sand	5.0	42.0	42.0	10.8	0.1	0.0	0.35	2.65[2]	1.57[2]
Ecolite	38.1	52.1	9.1	0.7	0.0	0.0	0.60	2.40[b]	0.95[b]
Ecolite-sand	7.2	39.5	42.3	10.9	0.1	0.0	0.35	2.65[2]	1.56[2]
Isolite	88.0	11.8	0.2	0.0	0.0	0.0	0.92	2.18[c]	0.64[c]
Isolite-sand	14.9	33.4	40.9	10.8	0.1	0.0	0.40	2.60[1]	1.52[2]
Moltan plus	1.2	91.7	6.2	0.9	0.0	0.0	0.47	2.25[d]	0.71[d]
Moltan plus-sand	1.8	45.3	41.8	10.9	0.1	0.0	0.33	2.61[1]	1.53[2]
Profile	0.0	88.0	12.0	0.0	0.0	0.0	0.46	2.24[d]	0.66[e]
Profile-sand	1.5	44.8	42.7	10.9	0.1	0.0	0.33	2.60[1]	1.52[3]
Pro's choice	0.0	92.9	7.0	0.1	0.0	0.0	0.48	2.31[e]	0.67[e]
Pro's choice-sand	1.3	45.6	42.1	10.9	0.1	0.0	0.34	2.62[1]	1.52[3]
Sand	2.0	37.2	48.0	12.7	0.1	0.0	0.31	2.67[f,3]	1.67[f,4]

Values along the same column with the same number or letter are not significantly different at $P < 0.05$

VCS very coarse sand, *CS* coarse sand, *MS* medium sand, *FS* fine sand, *VFS* very fine sand

[a] % By weight

(1.29 m h^{-1}). The rest of the amendments had average K_{sat} values between 0.60 and 0.76 m h^{-1}. The amendment-sand mixtures had lower average K_{sat} values compared to pure amendments and these ranged from 0.47 to 0.78 m h^{-1}, while the recommended USGA K_{sat} range is 0.15–0.61 m h^{-1}. The K_{sat} values for the amendment-sand mixtures were within the USGA root zone recommendations, except for Clinolite-sand which was 0.78 m h^{-1} and Ecolite-sand which was 0.76 m h^{-1}. Although a high value of K_{sat} is important to enhance drainage in the sand-based root zone, too high values exceeding the USGA recommendations, as is the case with Clinolite and Ecolite, suggest it would require frequent irrigation to replenish the water lost by drainage. Our results agree with those reported by Smalley et al. (1962) and Waltz et al. (2003) who reported increased K_{sat} values for amendment-sand mixtures compared to 100% sand.

The results for the geometric mean diameter, particle-size distribution, particle density and the bulk density (Table 4) show that all the amendments had significantly ($P < 0.05$) larger particles than sand, which had a geometric mean diameter of 0.31 mm. Isolite amendment had the largest particles with a geometric mean diameter of 0.92 mm, while the rest of the amendments were very close in geometric mean diameter values ($\sim$0.50 mm). Classification of particle-size fractions following the USDA particle-size limit placed the amendments in the range of medium-to-very-coarse sand (0.50–2.0 mm) except Isolite that was distributed from coarse-to-very-coarse sand (1.0–2.0 mm). The zeolites and calcined clays had >85% of the particles on weight basis in the coarse-to-very-coarse sand classes, while 100% sand had particles distributed from fine-to-coarse sand classes.

The diatomaceous earth amendments had the lowest particle density values, which were 2.20 Mg m^{-3} for Axis and 2.18 Mg m^{-3} for Isolite, and also the lowest bulk density values, which were 0.47 M g m^{-3} for Axis and 0.64 Mg m^{-3} for Isolite. The calcined clays had medium particle density 2.25, 2.44 and 2.31 Mg m^{-3}, for Moltan plus, Profile, and Pro's choice, respectively) and bulk density values (0.71, 0.66 and 0.67 Mg m^{-3}, for Moltan plus, Profile and Pro's choice, respectively). Zeolites had a particle density value of 0.30 Mg m^{-3} with a bulk density of 0.97 Mg m^{-3} for Clinolite and 0.95 Mg m^{-3} and for Ecolite. All the amendments had significantly lower bulk density and particle density values compared to sand (2.67 and 1.67 Mg m^{-3}). The amendment-sand mixtures had lower bulk density compared to 100% sand, with calcined clays having the lowest values (1.53, 1.52 and 1.52 Mg m^{-3} for Moltan plus, Profile and Pro's choice, respectively), followed by the diatomaceous earths (1.49 and 1.52 g cm^{-3} for Axis and Isolite), and zeolites had the least values (0.97 and 0.95 Mg m^{-3} for Clinolite and Ecolite). The advantage of a low bulk density value relative to the particle density is an increased in pore space, which enhance the potential for aeration and increased water

Table 5 The Van Genuchten parameters from fitted water retention data points

Amendment	θ_r	θ_s	α	n	r^2
Axis	0.453	0.895	2.157	0.126	0.979
Clinolite	0.232	0.582	2.373	0.116	0.960
Ecolite	0.225	0.581	3.163	0.104	0.981
Isolite	0.357	0.709	3.332	0.139	0.978
Moltan plus	0.329	0.656	3.899	0.064	0.977
Profile	0.364	0.696	5.876	0.056	0.983
Pro’s choice	0.299	0.621	5.232	0.053	0.992
Sand	0.039	0.227	4.274	0.039	0.999

Table 6 The Brooks–Corey parameters from fitted water retention data points

Amendment	θ_r	θ_s	h_d (cm H_2O)	λ	r^2
Axis	0.401	0.791	−5.164	0.589	0.936
Clinolite	0.222	0.612	−5.441	1.219	0.959
Ecolite	0.213	0.582	−5.438	1.098	0.972
Isolite	0.352	0.708	−4.915	1.458	0.978
Moltan Plus	0.324	0.640	−12.436	1.972	0.981
Profile	0.357	0.691	−13.791	2.499	0.986
Pro’s Choice	0.293	0.617	−13.955	2.222	0.991
Sand	0.036	0.223	−15.000	1.957	0.996

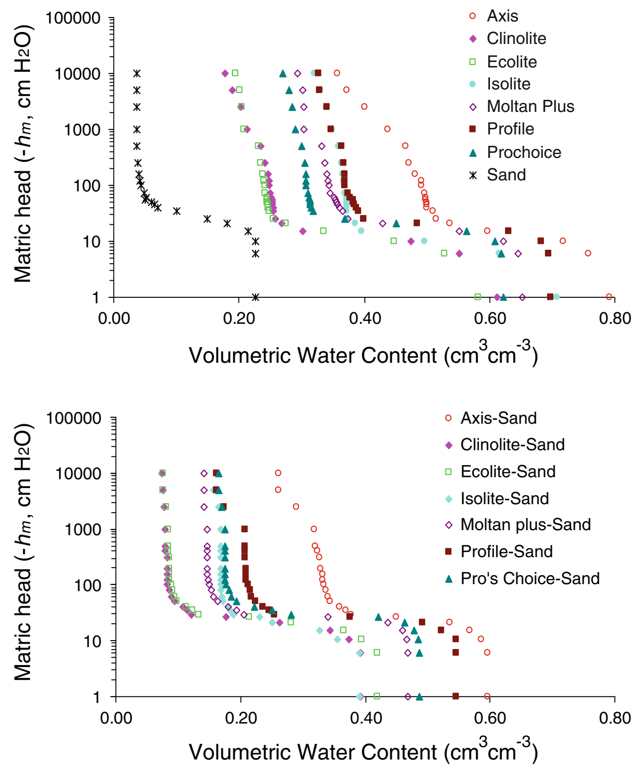

Fig. 2 Water retention curves for pure amendments (*top panel*) and amendment-sand mixtures at 15% amendment and 85% sand by volume (*bottom panel*) determined by Tempe pressure cells and ceramic plate extractor

content. However, according to Bigelow et al. (2004), bulk density alone is not considered to be an adequate indicator of a successful root zone mixture.

Available water-holding capacity

The results for the water retention curves showed that 100% sand retained less water at any tension compared to the amendments and the amendment-sand mixtures (Fig. 2; Tables 5, 6). At low tension of −0.1 kPa, calcined diatomaceous earth amendments showed the highest volumetric water content at saturation (θ_s), which was 0.79 m^3 m^{-3} for Axis and 0.71 m^3 m^{-3} for Isolite. Calcined clays had medium saturation with θ_s of 0.69 cm^3 cm^{-3}, 0.64 m^3 m^{-3} and 0.62 cm^3 cm^{-3}, respectively, for Profile, Moltan Plus and Pros’ Choice. Zeolites exhibited medium saturation, with θ_s of 0.61 cm^3 cm^{-3} for Clinolite amendment and 0.58 m^3 m^{-3} for Ecolite amendment. The 100% sand showed the lowest saturation with θ_s of 0.37 m^3 m^{-3}. The values forθ_s should be identical with total porosity values and this was observed with the amendments and the amendment-sand mixtures. For the 100% sand, θ_s values were less than total porosity values a difference attributed to entrapped air during wetting. The amendments and the amendment-sand mixtures had the most drainage between −0.1 and −4 kPa, and this is due to the drainage of larger pores (macropores). The data for the relationship between matric head and volumetric water content were fitted to the van Genuchten and Brooks–Corey models to obtain the respective hydraulic parameters. Both models showed a high correlation ($r^2 \geq 0.94$) between the input and fitted data (data not shown). Since the fitted water retention curves showed distinct air entry values (the pressure head values that most of the pores will drain) we decided to use the Brooks–Corey relationship for the subsequent water retention analysis.

The available water-holding capacity (AWC) using the Brooks–Corey relationship (Fig. 3) showed the AWC to be significantly ($P < 0.05$) higher for Axis (0.145 m^3 m^{-3}) compared to the other amendments. Isolite (0.135 m^3 m^{-3}), Profile (0.134 m^3 m^{-3}), Moltan plus (0.124 m^3 m^{-3}) and Pros’ choice (0.124 m^3 m^{-3}) had similar values within medium range, while Clinolite (0.036 m^3 m^{-3}) and Ecolite (0.037 m^3 m^{-3}) values were at the lower end. A similar trend was observed with amendment-sand mixtures, but with lower AWC range. The values were 0.140 m^3 m^{-3} for Axis-sand, 0.080 m^3 m^{-3} for Isolite-sand and Pros’ choice-sand, 0.060 m^3 m^{-3} for Moltan plus-sand, 0.040 m^3 m^{-3} for Clinolite-sand, Ecolite-sand and Profile-sand.

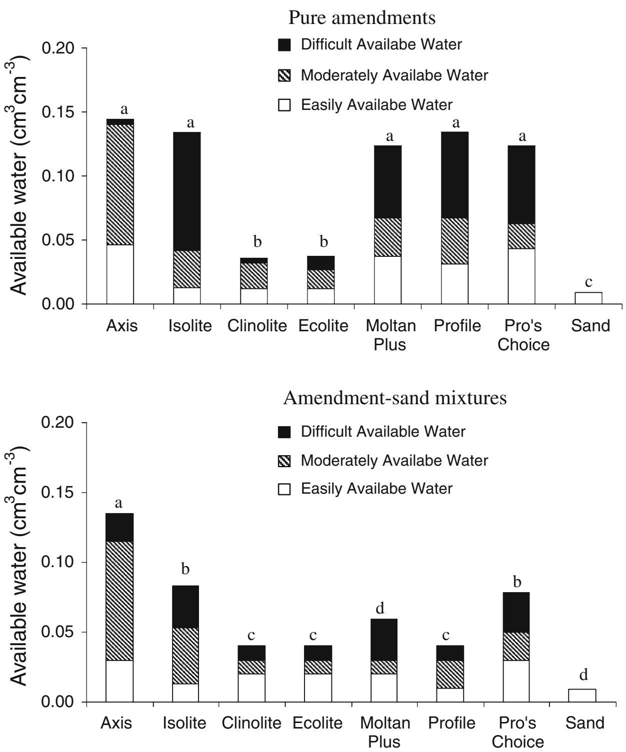

Fig. 3 Available water determined by Brooks–Corey relations for pure amendments (*top panel*) and amendment-sand mixtures at 15% amendment and 85% sand by volume (*bottom panel*). Easily available water is retained between −40 and −500 cm H_2O, moderately available water is retained between −500 and −5,000 cm H_2O, and difficult available water is retained between −5,000 and −15,000 cm H_2O

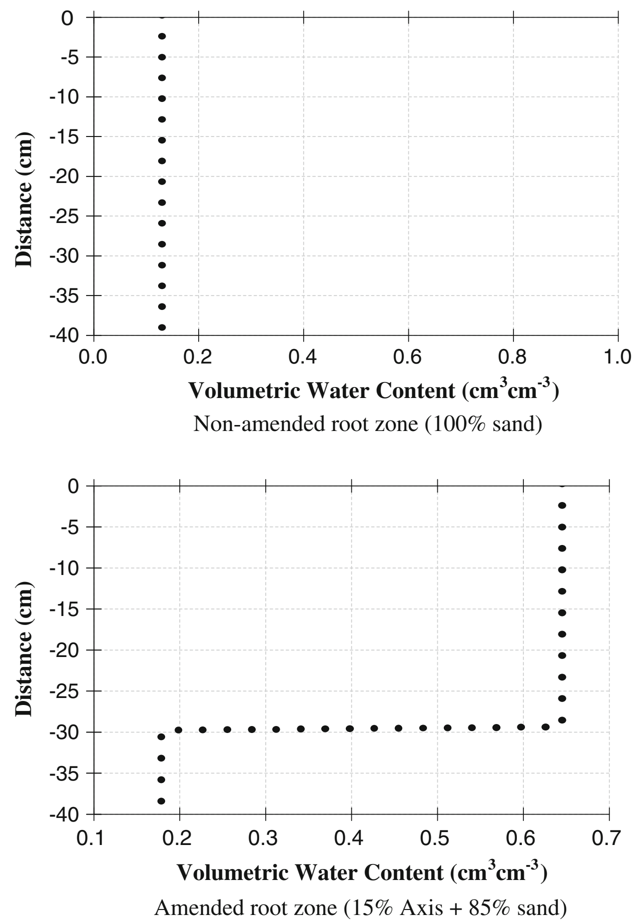

Fig. 4 Volumetric water content with depth after 10-day simulation period for non-amended (*top panel*) and amended (*bottom panel*) root zone

These results show that, though the inorganic amendments hold considerable water, only $\leq$0.145 m^3 m^{-3} is available for plant use as analyzed using laboratory techniques. Bigelow et al. (2004) attributed this apparently low value to water discontinuity on the big pores between the aggregate particles have drained. To estimate the plant available water, we designed a bioassay to determine plant available water. Bahiagrass (*Paspalum notatmu* Flüegge) was selected for this experiment due to its extensive root system. The grass was seeded at 150 kg ha^{-1} and grown in the green house (35/20°C day/night) for 8 weeks on each of the amendment materials and the amendment-sand mixtures packed in plastic pots (20 cm diameter × 25 cm depth). The grass was well watered and fertilized with a soluble fertilizer (20–20–20 N–P–K) at a rate of 100 kg N ha^{-1}. The grass was not mowed to maximize evapotranspiration. With the grass well established, the grass was irrigated up to saturation, thereafter, drought stress was imposed and the canopy monitored daily for signs of wilting. Water content was determined gravimetrically at field capacity (72 h after irrigation), and at wilting point (when the grass showed signs of wilting both during the day and night). The results for the AWC determined by the bioassay method (data not shown) showed between 20 and 70% higher AWC compared to those determined by the laboratory method.

Modeling results

Modeling results are presented for amended (15% amendment + 85% sand) and non-amended (100% sand) root zones. Due to similarity in the modeled parameters obtained for the amendments, we decided to present only the results for the Axis amendment. The modeling results revealed that for the non-amended profile, the volumetric water content declines after 10 days to 0.18 m^3 m^{-3} throughout the 40-cm depth profile. For the profile amended with Axis, the upper 30-cm profile depth maintains a volumetric water content of 0.62 m^3 m^{-3}. Only the lower 10-cm depth of the profile seems to dry out to a volumetric water content of 0.18 m^3 m^{-3} (Fig. 4).

The modeled root water uptake rate decreased with time for the entire 10-day simulation period (data not shown).

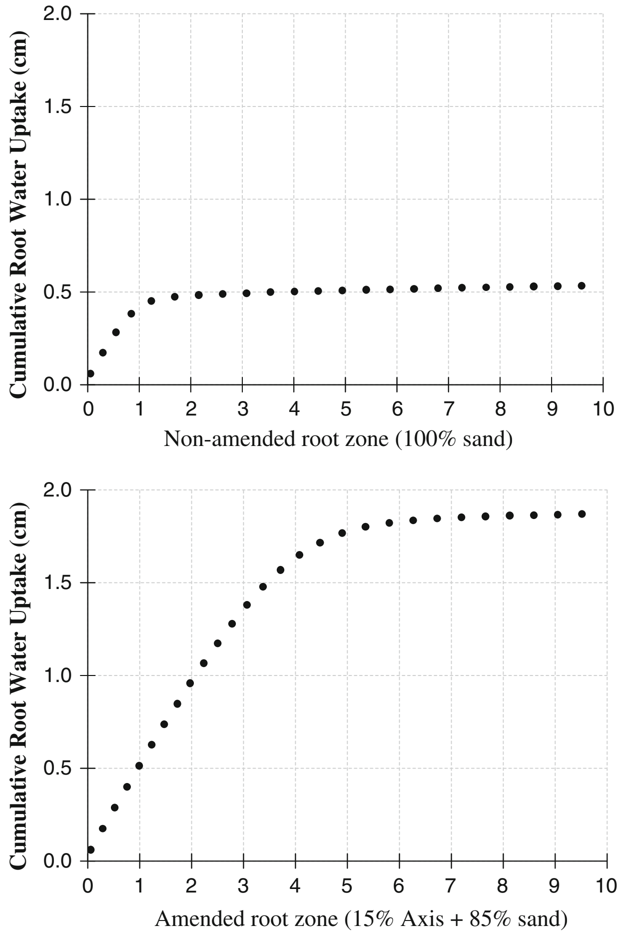

Fig. 5 Cumulative root water uptake rate for a 10-day simulation period for a non-amended (*top panel*) and amended (*bottom panel*) root zone

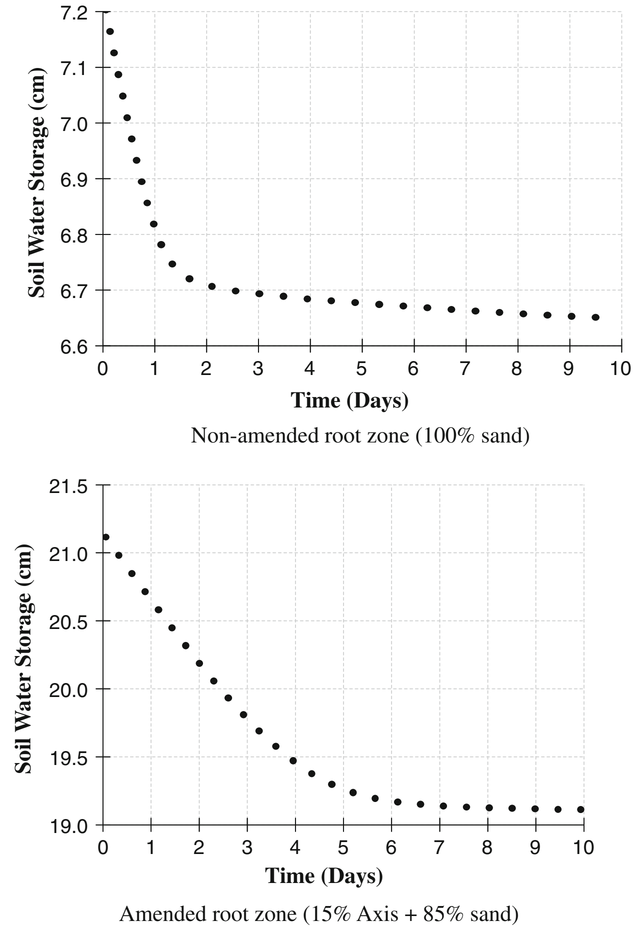

Fig. 6 Soil water storage for a 10-day simulation period for non-amended (*top panel*) and amended (*bottom panel*) root zone

The initial root water uptake rate was 5×10^{-3} m d^{-1} and this reduced to 2×10^{-3} m d^{-1}. For the non-amended root zone, the reduction to the minimum is after 2 days while it is after 7 days for the amended root zone. The cumulative root water uptake at the end of simulation period is about 0.005 m for the non-amended root zone while it is 0.018 m for the amended (Fig. 5).

The results for the water storage in the soil profile for the non-amended profile show initial water storage of 0.072 m, which decreases to 0.066 m after 10-day simulation period (Fig. 6). For the amended profile, the initial water storage is 0.21 m, decreasing to 0.19 m after 10 days.

We conclude that amendments significantly improve the physical and hydraulic properties of root zone, reduced surface dryness, increased volumetric water content and storage and initial root water uptake rate. These results suggest there are multiple benefits of amended root zones in terms of improvement of the physical and hydraulic properties of sand-based root zones. Amendments alter the sand-based root zone by increasing the internal surface as well as reducing drainage.

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