Biologia 64/3: 600—604, 2009
Section Botany
DOI: 10.2478/s11756-009-0088-5

Estimating hydraulic conductivity of a sandy soil under different plant covers using minidisk infiltrometer and a dye tracer experiment

Marián Homolák[1], Jozef Capuliak[1], Viliam Pichler[1] & Ľubomír Lichner[2]

[1] *Technical University in Zvolen, Faculty of Forestry, Dep. Natural Environment, T. G. Masaryka 24, SK-96053 Zvolen, Slovakia; e-mails: homolak@vsld.tuzvo.sk; capuliak@vsld.tuzvo.sk; pichler@vsld.tuzvo.sk*

[2] *Institute of Hydrology, Slovak Academy of Sciences, Račianska 75, SK-83102 Bratislava, Slovakia; e-mail: lichner@uh.savba.sk*

Abstract: The objective of this study was to estimate the hydraulic conductivity of sandy soil under different plant cover at the locality Mláky II at Sekule (southwest Slovakia). Two sites were demarcated at the locality, with mainly moss species at glade site, and pine forest at forest site. The estimation of unsaturated hydraulic conductivity was conducted by (a) minidisk infiltrometer and (b) the analysis of a dye tracer total resident concentration. The latter approach assumed the applicability of the stochastic—convective flow theory in the sandy soil. In the dye tracer experiment, two plots (1 × 1 m each) were established in both sites, and 100 mm of dye tracer (Brilliant Blue FCF) solution was applied on the soil surface. Similar results were obtained in both plots, with more than 70 % area of horizons stained in the depth of 30–50 cm. In some cases, the predicted and measured hydraulic conductivity were found within an order of magnitude, thus revealing similar impact of different plant cover on hydraulic properties of sandy soil studied. In contrast to sandy soils used for agriculture, the influence of the plant/surface humus and topsoil interface extended in the form of a highly heterogeneous matrix flow to the depth of 50–60 cm, where it was dampened by horizontal layering.

Key words: dye tracer; hydraulic conductivity; plant cover; sandy soil; soil moisture

Introduction

The objective of this study was to estimate the hydraulic conductivity of sandy soil under different plant cover at the locality Mláky II at Sekule (southwest Slovakia) using two methods. Among the field methods for the unsaturated hydraulic conductivity estimation, tension infiltrometers are reliable for measurement near saturation (Ankeny et al. 1991). Introduction of minidisk infiltrometer (Zhang 1997) made repeated measurements much easier owing to the extreme portability of the device, but their practical use rests on the approximation of soil type. On the other hand, because forest soils are often texturally coarser, our second approach drew on the assumption of the stochastic-convective flow. In this, a solute added uniformly to the soil surface is transported through stream tubes that form near the surface and remain isolated thereafter (Jury & Scotter 1993). Such conceptualizing can be justified for cases, in which the time required for mixing exceeds the time to reach depths near the surface. Soils, in which the stochastic-convective model has been successfully applied, included a loamy sand (Poletika & Jury 1994) and a fine sandy loam (Ellsworth et al. 1996). Thus, the hydraulic conductivity was measured both with the minidisk infiltrometer and calculated from the dye tracer concentration *vs.* depth distribution. Characterization of three-dimensional water and solute transport in field soils is difficult as the flow pathways of water are in most cases highly irregular (Flury et al. 1994). Dye tracers can provide the means for direct observation for spatial structure of water and solute flow in an entire section of a soil profile (Ghodrati & Jury 1990). As the experimental conditions and the type of dye used differed from study to study, a comparison of the experimental results is rather difficult. To compare directly the flow patterns in different soils, it is necessary to use the same dye and standardized experimental conditions (Flury et al. 1994).

Material and methods

Field experiments were conducted at the locality Mláky II near Sekule on the Borská nížina lowland (southwest Slovakia) where the sand dunes with surface eolian sand occur on about 570 km^2 (Kalivodová et al. 2002). Elevation of the study site is 150 m a.s.l., the average annual air temperature is 9 °C, and annual precipitation total 500–600 mm.

Two sites were demarcated at the locality, with a 30-year old Scots pine (*Pinus sylvestris*) forest at forest site and moss at glade site. In both sites, the soil surface was covered mostly by the moss species *Polytrichum piliferum*, then by lichens (*Cladonia* sp.), and in isolated cases by the grass

Table 1. Physical and chemical properties of soil from the locality Mláky II at Sekule.

Site	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	C (%)	pH (H_2O)	pH (KCl)
Pine forest	0–1	95.14	2.26	2.60	<0.05	0.83	5.65	4.39
Glade	0–5	94.14	0.84	5.02	<0.05	0.11	5.52	3.96
Glade	50–55	94.86	1.74	3.40	<0.05	0.03	5.54	4.20

species *Corynephorus canescens* (Marhold & Hindák 1998). Some areas at glade site had exposed bare soil (Lichner et al. 2005). The soil was a Regosol formed from windblown sand (WRB 1994) and had a sandy texture (Soil Survey Division Staff 1993). Physical and chemical properties of soil samples are presented in Table 1. As the humic top-layer at site 2 was thinner than that at site 1, the samples at site 2 were also collected from 0–1 cm for more correct comparison of both texture composition and organic carbon content C (%). It should be mentioned that thin textural transitions as well as Fe-oxides and Fe-hydroxides, accumulated in 1–2 cm thick layer, were detected in the soil profiles during excavation. The particle size distribution of the layer material was (sand/silt/clay): 90.70/6.56/2.74%, and the amount of total Fe was 3.12 g kg^{-1}.

The hydraulic conductivity $k(h)$ was primarily estimated from the cumulative infiltration (measured in the field at pressure head $h = -2$ cm) data $I = f(t)$ according to Eqs 1 and 2 (Zhang 1997), using $A_1 = 2.4$ for sandy soil and pressure head $h = -2$ cm from Table 2 in the Minidisk infiltrometer user's manual (Decagon 2005):

$$I = C_1(h)t^{1/2} + C_2(h)t \tag{1}$$

$$k(h) = C_2(h)/A_1 \tag{2}$$

The soil water content w [M^3 M^{-3}] was determined after drying at 50 °C, and the soil water content θ [L^3 L^{-3}] was calculated from it using the bulk density of the soil. In parallel to that, an in-situ steady flux method, based on an analysis of resident concentration profiles of a mobile, nonreactive tracer achieved under single flux density at the soil surface q_0 was applied. The latter approach drew on the assumption the convective-lognormal transport as embedded in the stochastic-convective flow theory (e.g. Jury & Scotter 1994) and it was used for a comparison. Two plots (1 × 1 m each) were established in both the forest and glade sites. The experiment can be characterized as a variable solute mass boundary value problem (Toride & Leij 1996). After partial saturation and the establishment of a steady-state flow, water solution of the anionic dye tracer Brilliant Blue FCF (at a concentration 10 g L^{-1}) was applied on the soil surface in 1 hour. The above-mentioned dye tracer can serve to obtain information about spreading with high spatial resolution. The rainfall simulator was used for application of dye tracer with the intensity 100 mm h^{-1} = 2.77 × 10^{-5}m s^{-1}. This intensity should have assured infiltration without ponding (mean value of the saturated hydraulic conductivity, estimated at both forest and glade sites, was about 1.9 × 10^{-4} m s^{-1} (Lichner et al. 2007b)), but spotty ponding was found to occur locally for short periods. After 100 mm of artificial precipitation, six vertical soil profiles were excavated at the distance of 0, 20, 40, 60, 80, and 100 cm from the edge of both plots. The face of soil profile was cleaned by paintbrush and scissors to prevent slides from shadows, caused by small roots and roughness. Clean soil profiles were photographed by digital camera in RAW format, and subsequently, the 2D image analysis was applied on these pictures to obtain stained area and concentration of Brilliant blue of all profiles. The acquisition of high resolution dye concentration profiles was performed according to Forrer et al. (2000). The method uses a second-order polynomial to express the logarithm of the dye concentration within the RGB space. Because the relationship was developed for natural soils, it includes the depth as an explanatory variable. The routine was implemented within the processing framework in GNU R and C, with the help of the ImageMagick image processing library. The method enabled us to determine the resident concentration profile with a spatial resolution of 1 mm. For calibration, thirty soil samples were taken from the stained soil profile and dried for fifteen hours at 80 °C. From each soil sample 0.5 g, was weighed into an extraction column. The columns were put on a vacuum vessel. 10 mL of a 4 : 1 volume ratio of water and acetone was added as an extraction solvent, and the vessel was evacuated with a low pressure of about – 600 hPa. The Brilliant Blue FCF fraction that was extracted by the mixture of the water plus acetone was larger than that extracted by water alone. The extract was filtered through a 0.45 μm filter. The concetration of Brilliant Blue was measured spectrophotometrically at a wavelength of 630 nm. Finally, dye concentration was calculated for every pixel of the soil profile image and stained area (see Figs. 1b, d).

The cumulative distribution function (CDF) was fitted to every concentration profile in Mathematica 6 software package and mean value μ and standard deviation σ of lognormal CDF of dye tracer were obtained. From these fitted values, the model values of hydraulic conductivity $k(z)$ and soil water content $\theta(z)$ for the soil profile of 1 m depth, flux J_w, time t and depth z were calculated (Jury & Roth 1990; Homolák 2008). The presented model requires the following assumptions: (a) steady-state water flow (Jw) and a constant soil water content within the transport volume; (b) gravity flow (valid near the soil surface, at a high flux rate and for a deep water table) across a stationary flow-domain with at least correlated solute travel times in the vertical direction; (c) minimum lateral mixing (i. e. SC flow).

At any depth z, the normalized resident concentration is equal to the fraction of the pore space which contains the solute that has reached z in a fixed time t; i. e., the fractions of the pores with travel distance equal to or longer than z. By the gravity flow assumption, the flux density through the pores with travel distance greater than z equals to the hydraulic conductivity of the system with the slowest pore groups, comprising that fraction of the transport volume between 0 and $\theta \leq \Theta$ (the maximum soil water content), substracted. Therefore:

$$k(z) = \frac{1}{2}\frac{J_w}{\theta_s}\mathrm{erfc}\left[\frac{\mu - \ln(z)}{\sqrt{2}\sigma}\right] \tag{3}$$

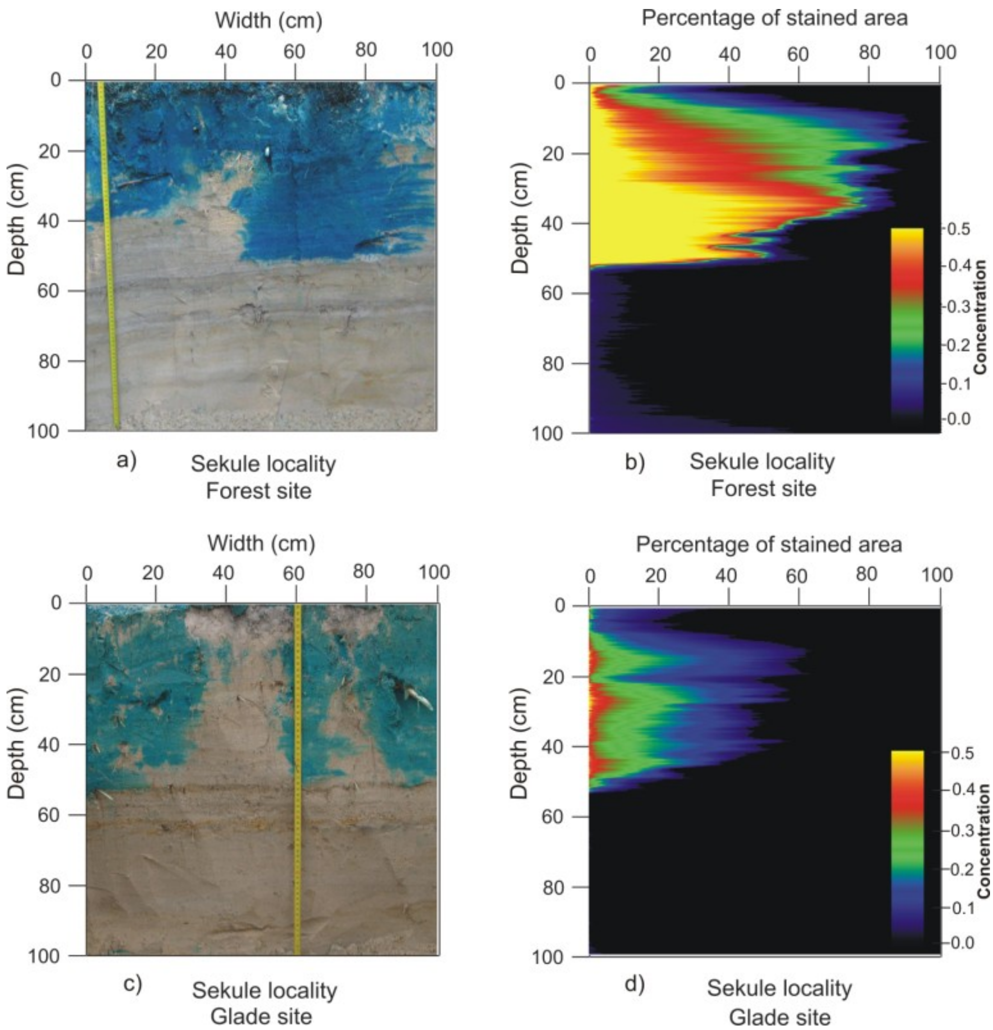

Fig. 1. Images of soil profiles after geometric correction and images analysis: a) Geometric correction of the profile in forest site; b) Image analysis of the profile in forest site; c) Geometric correction of the profile in glade site; d) Image analysis of the profile in glade site.

and

$$\theta(z) = \frac{1}{2}\exp\left[-\mu + \sigma^2/2\right]\frac{J_{\mathrm{w}}t}{\theta_{\mathrm{s}}}\cdot \\ \cdot\left(1 + \operatorname{erf}\left[\frac{-\mu + \sigma^2 + \ln(z)}{\sqrt{2}\sigma}\right]\right). \qquad (4)$$

Results and discussion

Images of soil profiles after geometric correction and images analysis are shown in Fig. 1. The area stained by the dye tracer was calculated for the individual horizons. To do so, every soil profile was divided to horizons of 10 cm in width.

Average share of stained area of all soil profiles was 30% at glade site and 35 % at forest site (Fig. 2). The infiltration and redistribution of water in both forest and glade sites was considerable in the depth of 30–50 cm where more than 70% area of horizons was stained. In deeper horizons until 70 cm the smaller both infiltration and redistribution were observed. Very similar results were obtained in both plots. The width of stained objects was also calculated to determine the predominant flow process. According to the flow process classification (Weiler & Naef 2003) the heterogeneous matrix flow and fingering were supposed to occur as predominant flow processes at both sites.

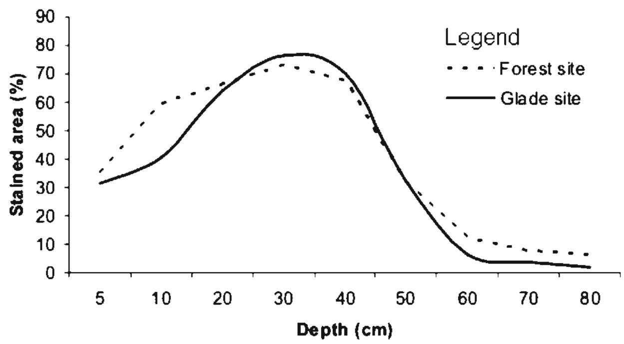

Fig. 2. Percentage share of dye tracer *vs.* depth relationships for forest and glade sites.

Vertical distribution patterns of Brilliant Blue FCF, presented here, are similar to those observed by

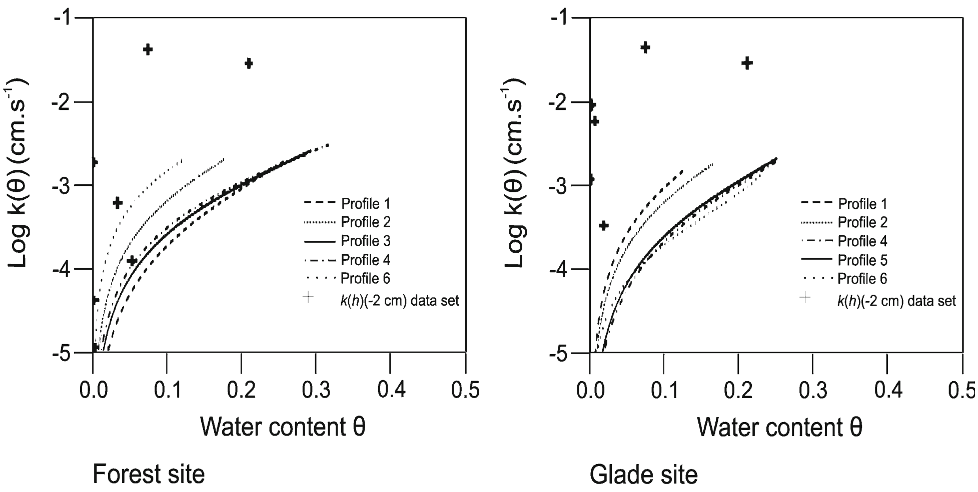

Fig. 3. Relations between soil water content and hydraulic conductivity in forest and glade sites, as estimated from both the concentration profiles using Eqs. 3 and 4, and the cumulative infiltration data using Eqs. 1 and 2.

Ghodrati & Jury (1990) in the structureless loamy sand soil in Etiwanda, CA, in the case of completely disturbed (to a depth of 30 to 40 cm), leveled and slightly packed upper part of soil, where well pronounced fingering and highly irregular flow patterns were found after sprinkler application of water solution of anionic dye Acid Red 1 in increments of 20 mm per day for 5 days (i.e. after 100 mm of artificial precipitation as in our experiment). However, the causes of fingering and highly irregular flow patterns could be different. While the instability of wetting front visualized as fingers below a continuous wetting front during infiltration in Etiwanda could be caused by layering, the instability of wetting front in Sekule could be caused by water repellent top layer of soil, where the soil particles are covered with amphiphilic compounds produced by roots of mosses, decomposing pine needles and soil microscopic fungi.

It could be deduced from the lower amount of dye tracer solution (30 mm) applied during infiltration experiment in Macov (Dohnal et al. 2009) that the maximum penetration depth should be smaller than in Sekule. But root and earthworm channels in this loamy soil let the dye tracer (Brilliant Blue FCF) penetrate up to the depth of 100 cm (of course, in the case of ponding infiltration, not under unsaturated conditions as in Sekule).

Relations between soil water content and hydraulic conductivity in forest and glade sites, as estimated from both the concentration profiles using Eqs 3 and 4, and the cumulative infiltration data using Eqs 1 and 2 are presented in Fig. 3. It can be seen that the values of hydraulic conductivity $k(h)$, estimated with the minidisk infiltrometer at pressure head $h = -2$ cm for different soil water content θ at the soil surface, are quite well (some measurements within a order of magnitude) approximated with the $k(\theta)$ relationships, estimated from the concentration profiles for different vertical soil profiles. The dispersion of values measured by the minidisk infiltrometer was increased by hydrophobicity patterns on the soil surface. The predicted and measured hydraulic conductivity were also similar in both sites, revealing similar impact of different plant cover on hydraulic properties of sandy soil studied. However, dye stains were comparatively less regular in the glade site, in which the hydraulic conductivity decrease was somewhat steeper.

We can state that strongly heterogeneous matrix flow occurred as a predominant flow process at both forest and glade sites, with very similar vertical distribution of Brilliant Blue FCF at both sites. This result of our experiments in an almost homogeneous sandy soil is in a stark contrast to the more homogeneous patterns observed by Flury et al. (1994) in a sandy soil used for agriculture. We attribute these differences to the modifying influence of the plant and humus cover at the Sekule site. The predicted and measured hydraulic conductivity were similar in both sites, revealing similar impact of different plant cover on hydraulic properties of sandy soil studied.

Acknowledgements

The authors thank their colleagues Š. Aschenbrenner (TU Zvolen), Dr. V. Novák and Dr. T. Orfánus (IH SAS Bratislava), as well as Prof. H. Czachor (Institute of Agrophysics PAS Lublin) and Dr. M. Šír (Institute of Hydrodynamics AS CR Prague) for their valuable comments and/or help during the field experiments. Dr. Pavol Faško (Slovak Hydrometeorological Institute, Bratislava) is greatly acknowledged for providing the data from the meteorological station of the Slovak Hydrometeorological Institute in Moravský Svätý Ján. This investigation was supported by scientific grants awarded by the Research and Development Agency APVV-0468–06 and the Scientific Grants Agency of the Ministry of Education and the Slovak Academy of Sciences No. 1/0703/08 and MVTS COST FP0601.

References

Ankeny M.D., Ahmed M., Kaspar T.C. & Horton R. 1991. Simple field method for determining unsaturated hydraulic conductivity. Soil Sci. Soc. Am. J. **55:** 467–469.

Ciani A., Goss K.U. & Schwarzenbach R.P. 2005. Light penetration in soil and particulate minerals. Eur. J. Soil Sci. **56:** 561–574.

Decagon 2005. Minidisk Infiltrometer User's Manual. Decagon Devices, Inc., Pullman, USA, 22 pp.

Dohnal M., Dušek J., Vogel T., Císlerová M., Lichner Ľ. & Štekauerová V. 2009. Ponded infiltration into soil with biopores – field experiment and modeling. Biologia **64:** 580–584.

Ellsworth T.R., Shouse P.J., Skaggs T.H., Jobes J.A. & Fargerlund J. 1996. Solute transport in unsaturated soil: Experimental design, parameter estimation, and model discrimination. Soil Sci. Soc. Am. J. **60**: 397–407.

Flury M., Flühler H., Jury W.A. & Leuenberger J. 2000. Susceptibility of soils to preferential flow of water: A field study. Water Resour. Res. **30:** 1945–1954.

Forrer I., Papritz A., Kasteel R., Flühler H. & Luca D. 2000. Quantifying dye tracer in soil profiles by image processing. Eur. J. Soil Sci.**51:** 313–322.

Ghodrati M**.** & Jury W.A. 1990. A field study using dyes to characterize preferential flow of water. Soil Sci. Soc. Am. J. **54:** 1558–1563.

Homolák M. 2008. The measurement of transport properties of forest soil as a base for planning of forest's amelioration. PhD Thesis. Technical University Zvolen, 96 pp. (In Slovak)

Jury W.A. & Roth K. 1990. Transfer functions and solute transport through soil: Theory and applications. Birkhaeuser Verlag, Basel, 226 pp.

Jury W.A. & Scotter D.R. 1994. A unified approach to stochastic-convective transport problems. Soil Sci. Soc. Am. J. **58:** 1327–1336.

Kalivodová E., Kubíček F., Bedrna Z., Kalivoda H., Gavlas V., Kollár J., Gajdoš P. & Štepanovičová O. 2002. Sand dunes of Slovakia. Luka-Press, Bratislava, 60 pp. (In Slovak)

Kutilek M. & Nielsen D.R. 1994. Soil Hydrology. Catena, Cremlingen-Destedt, 370 pp.

Lichner Ľ., Nižnanská Z., Faško P., Šír M.& Tesař, M. 2005. The impact of plant cover and weather on soil-hydrological parameters of a water repellent soil at the locality Mláky II at Sekule. Acta Hydrologica Slovaca **6:** 321–329. (In Slovak)

Lichner Ľ., Hallett P.D., Feeney D., Ďugová O., Šír M. & Tesař M. 2007a. Field measurement of the impact of hydrophobicity on soil water transport under different vegetation over time. Biologia **62:** 537–541.

Lichner Ľ., Orfánus T., Nováková K., Šír M.& Tesař M. 2007b. The impact of vegetation on hydraulic conductivity of sandy soil. Soil Water Res. **2:** 59–66.

Marhold K. & Hindák F. 1998. Checklist of non-vascular and vascular plants of Slovakia. Veda, Bratislava, 687 pp. (In Slovak)

Poletika N.N. & Jury W.A. 1994. Effects of soil surface management on water flow distribution and solute dispersion. Soil Sci. Soc. Am. J. **58:** 999–1006.

Soil Survey Division Staff 1993. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18, 437 pp.

Toride N. & Leij F.J. 1996. Convective-dispersive stream tube model for field-scale solute transport: II. Examples and calibration. Soil Sci. Soc. Am. J. **60:** 352–361.

Weiler M. & Naef F. 2003: An experimental tracer study of the role of macropores in infiltration in grassland soil. Hydrol. Processes **17:** 477–493.

WRB 1994: World Reference Base for Soil Resources. Wageningen/Rome, 161 pp.

Zhang R. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci. Soc. Am. J. **61:** 1024–1030.

Received November 27, 2008
Accepted January 22, 2009