Measuring Soil Water Potential with Gypsum Blocks: Calibration and Sensitivity

Ken Aho[1], Department of Ecology, Montana State University, Bozeman, MT, 59717-3460
Tad Weaver, Department of Ecology, Montana State University, Bozeman, MT, 59717-3460

Abstract

Gypsum block soil sensors have been a useful tool for measuring soil water for over sixty years. We improve their usefulness by 1) demonstrating a new gypsum block calibration procedure, 2) determining equilibration times for two types of commercial blocks (Delmhorst GS-1, and Bouyoucos) across a range of water potentials (-4.3, -1.2, -0.56, -0.2, -0.08, -0.05, and -0.02 MPa), 3) providing calibration curves for Delmhorst and Bouyoucos instruments, and 4) quantifying the sensitivity of gypsum blocks by finding which soil water potentials are statistically distinguishable. Our procedure yielded calibration curves which are appropriate for Delmhorst and Bouyoucos instruments in well aggregated soils. Dry blocks imbedded in soils reached equilibration (variability of sensor readings stabilized) after ~ 150 hours for Delmhorst, and ~ 300 hrs for larger Bouyoucos blocks. In the water potential series described above, sensor readings of blocks between -4.3 and -0.08 MPa were statistically distinguishable ($\alpha = 0.05$) for both Delmhorst and Bouyoucos blocks. While sensor readings from blocks at the two highest water potentials (-0.02 and -0.05 MPa) were not significantly different for either Delmhorst or Bouyoucos blocks, readings for -0.02 MPa soils were significantly different from soils $\leq$ -0.08 MPa for both blocks types.

Key words: Soil water potential, gypsum blocks, calibration procedure, equilibration time, precision of soil sensor readings, gypsum block sensitivity.

Introduction

Water availability largely controls plant productivity in both natural and agricultural settings (Lambers et al. 1998). In natural environments availability of water largely determines the distribution and primary productivity of terrestrial ecosystems (Holdridge 1947, Lieth 1975). In agricultural settings crop yield losses from water stress exceed losses from all other biotic and abiotic factors combined (Boyer 1985).

Plant water uptake is largely determined by the water potential gradient from soil to root to stoma to air. As soil water potential drops towards the 'permanent wilting point' (conventionally defined as $\Psi = -1.5$ MPa), a plant will become increasingly unable to extract water from soil. Water stress symptoms may occur including stomatal closure, decreased growth, decreased nutrient uptake, and even cavitation. In flooded soils ($\Psi \cong 0$ MPa) plants may have similar symptoms including stomatal closure and wilting (Lambers et al. 1998). Reliable methods are needed for measurement of soil water potential because of its strong influence on plant physiological processes.

Gypsum block sensors (Bouyoucos and Mick 1940, Taylor et al. 1961) are a time-tested, inexpensive, and reliable tool for measuring soil water across a diversity of field sites (Scanlon et al 2002). Sensor readings of blocks reflect their decreased electrical resistivity with increasing soil water content. Slight dissolution of $CaSO_4$ in blocks creates a weak in-block ion solution which simultaneously controls against the confounding effect of soil salinity on electrical resistance (Weaver 1987, Scanlon et al. 2002). Drawbacks of gypsum blocks include time for equilibration with soils, and an inability to distinguish matric potentials higher than the air entry pressure of the blocks (-0.03 MPa; Scanlon et al. 2002). Other methods for measuring soil water

[1]Current address: Department of Biology, Idaho State University, Pocatello, ID 83209-8007.

potential including piezometry, neutron thermalization, thermocouple psychometry, and time delay reflectometry are reviewed by Reeve (1986), Hignett and Evett (2002), Andraski and Scanlon (2002), and Robinson et al. (2003), respectively.

This paper provides four products that we hope will increase the usefulness of gypsum blocks. We 1) demonstrate a new gypsum block calibration procedure involving equilibration of blocks in soils of known water potentials; 2) determine equilibration times for dry blocks inserted in samples of a sandy loam at seven water potentials; 3) provide calibration curves for two types of commercial plaster blocks (Delmhorst GB-1 and Bouyoucos); and, 4) demonstrate the useful range of both block types by determining what soil water potentials are statistically distinguishable.

Materials and Methods

We studied two types of commercial blocks, Delmhorst GB-1 (2.5 cm x 2 cm diameter) available from Forestry Suppliers (205 West Rankin Street, P.O. Box 3897 Jackson, MS 39284-8397), and Bouyoucos (3 x 4 x 1.5 cm) manufactured by Backman Instruments (P.O. Box 3100, 2500 Harbor Boulevard, Fullerton, CA).[2] The blocks were read with a Delmhorst KS-D1 digital soil moisture meter available from Forestry Suppliers. KS-D1 sensor readings corresponding to resistances in the range between 1 and 40,000 ohms were measured by Dr. V. Gerez at the Department of Electrical Engineering at Montana State University.

Block Calibration

To calibrate blocks, we measured their electrical resistance at seven known water potentials and plotted water potential against resistivity. As a calibration medium we chose a homogenized sandy loam (60% sand, 16% silt, 24% clay). We used this soil because its clay/silt components would allow good contact with blocks, while its sand component would facilitate mixing and prevent mudding. Calibration involved five steps.

1) A water retention curve was created for the calibration soil by measuring its water contents at -0.03, -0.1, -0.3, -0.5, -0.8, and -1.5 MPa. Soil water potentials were set with a pressure membrane/ceramic plate apparatus by the Montana State University soil testing laboratory (cf. Gardner, 1986). Water contents of soils at these known water potentials were measured gravimetrically (kg kg^{-1}). A regression of water content and water potential was linear after power transformation ($r^2 = 0.992$), allowing interpolation of water potential from water content.

2) We compared sensor readings for gypsum blocks over a useful range of water potentials from approximately -0.01 to -5 MPa. To do so we adjusted soil samples to desired water potentials by repeatedly misting them with water and mixing until the correct water content (and corresponding water potential) was reached. Using this method soils were brought to seven evenly spaced water contents (32, 29, 27, 24, 21, 19, and 16% H_2O) corresponding to water potentials of -0.02, -0.05, -0.08, -0.20, -0.56, -1.2, and -4.3 Mpa, respectively. Note that water potential of the -4.3 MPa soil was outside the calibration range created in step 1 and was therefore extrapolated.

3) We stored soils from the seven different water potentials in separate cylindrical containers (16 cm high × 16 cm dia. ≅ 3200 cm^3) at room temperature (25 °C). To quantify sensor variability, three Delmhorst and three Bouyoucos blocks were placed into each of the seven containers, i.e., six blocks were installed / container. Blocks were neither wetted before installation nor placed into slurries since this would have caused confounding from hysteresis (affected block saturation history) and dramatically altered the water potentials of the containers. To prevent water loss by evaporation/condensation, we sealed containers with duct tape, enclosed them in polyethylene bags, and stored them at room temperature. Ports through which gypsum

[2] Use of these and other products in the manuscript does not imply product endorsement by the authors or publisher.

block cables extended from the cylinders were sealed with silicon rubber, so drying air did not enter as sensors were read. To demonstrate that no water loss occurred, gravimetric measures were repeated at the end of the experiment.

4) To determine block equilibration time, sensor readings for all blocks were taken 10 times over a 36-day period at 0, 8, 27, 99, 166, 267, 335, 439, 600, 774, and 875 hrs. We assumed equilibration to have been reached when post-equilibration sensor readings within a block type (Bouyoucos or Delmhorst) had an average standard deviation (across water potentials) < 1.

5) To represent an equilibrated sensor reading, all post-equilibration block readings were averaged within a block type (Bouyoucos or Delmhorst) for a particular water potential treatment. We created calibration curves by regressing these seven equilibrated block readings against the seven known soil water potentials using curve fitting software.

Analysis

We determined capacity of gypsum blocks to distinguish distinct water potentials by comparing post equilibration readings from the seven water potentials. A single factor analysis of covariance (ANCOVA) was used for these comparisons with water potential as the main effect and time (hrs) as the covariate. Responses were readings from the time frames after equilibration. Thus, readings from separate post-equilibration time frames were not averaged (as they were in calibrating) but were used instead to quantify sensor variability after equilibration. Due to a lack of independence of blocks within a cylinder, i.e., pseudoreplication, readings within a cylinder were averaged to create a single response for each type of block (Delmhorst or Bouyoucos) for each water potential at each post-equilibration time frame. We used Scheffé's procedure (Neter et al. 1996:1024) for multiple pairwise comparisons of water potentials. The ANCOVA and pairwise comparisons were run using the statistical program R (R development core team 2008). Calibration curves were created using Table Curve 2D® (Systat software 2002).

Results

As the criterion for block equilibration, we required that post-equilibration sensor readings have an average standard deviation < 1 (according to Delmhorst Instrument Co. valid readings for the Delmhorst KS-D1 meter range between 0 and 100). Using this criterion, Delmhorst blocks equilibrated with soils after ~ 150 hrs, whereas the larger Bouyoucos blocks equilibrated after ~ 300 hrs (Fig. 1). After these times the average standard deviation of readings across all water potentials was ~ 0.70 for Delmhorst and 0.96 for Bouyoucos blocks (Fig. 1). Equilibration times were shorter in wetter soils (Fig. 1).

We constructed calibration curves for Bouyoucos and Delmhorst blocks by fitting average post-equilibration block readings against known soil water potentials (Fig. 2). The association between sensor readings and soil water potential was well fit with a simple two-parameter logarithmic model for both Delmhorst ($r^2 = 0.9997$) and Bouyoucos ($r^2 = 0.9991$) blocks (Fig. 2). Exact-model predictions of water potentials at particular sensor readings appear in Table 1. We provide equations for models in Appendix 1. The association between soil sensor readings and soil water potential was asymptotic near field capacity for both types of blocks (Fig. 2).

Differences in readings of equilibrated blocks among water potential levels were highly significant ($F_{6,35} = 6678$, $p < 2.0\times10^{-16}$ for Delmhorst; and $F_{6,21} = 3496$, $p < 2.0\times10^{-16}$ for Bouyoucos). Time and the interaction of time and water potential were not significant for either block type. In pairwise comparisons of readings among water potential treatments, all but the highest water potentials (-0.02 and -0.05 MPa) were distinguishable from each other ($\alpha = 0.05$). This lack of distinguishability at high water potential soils was evident for comparisons of both Delmhorst and Bouyoucos blocks. Note, however, the -0.02 MPa treatment was distinguishable from soils ≤ -0.08 MPa for

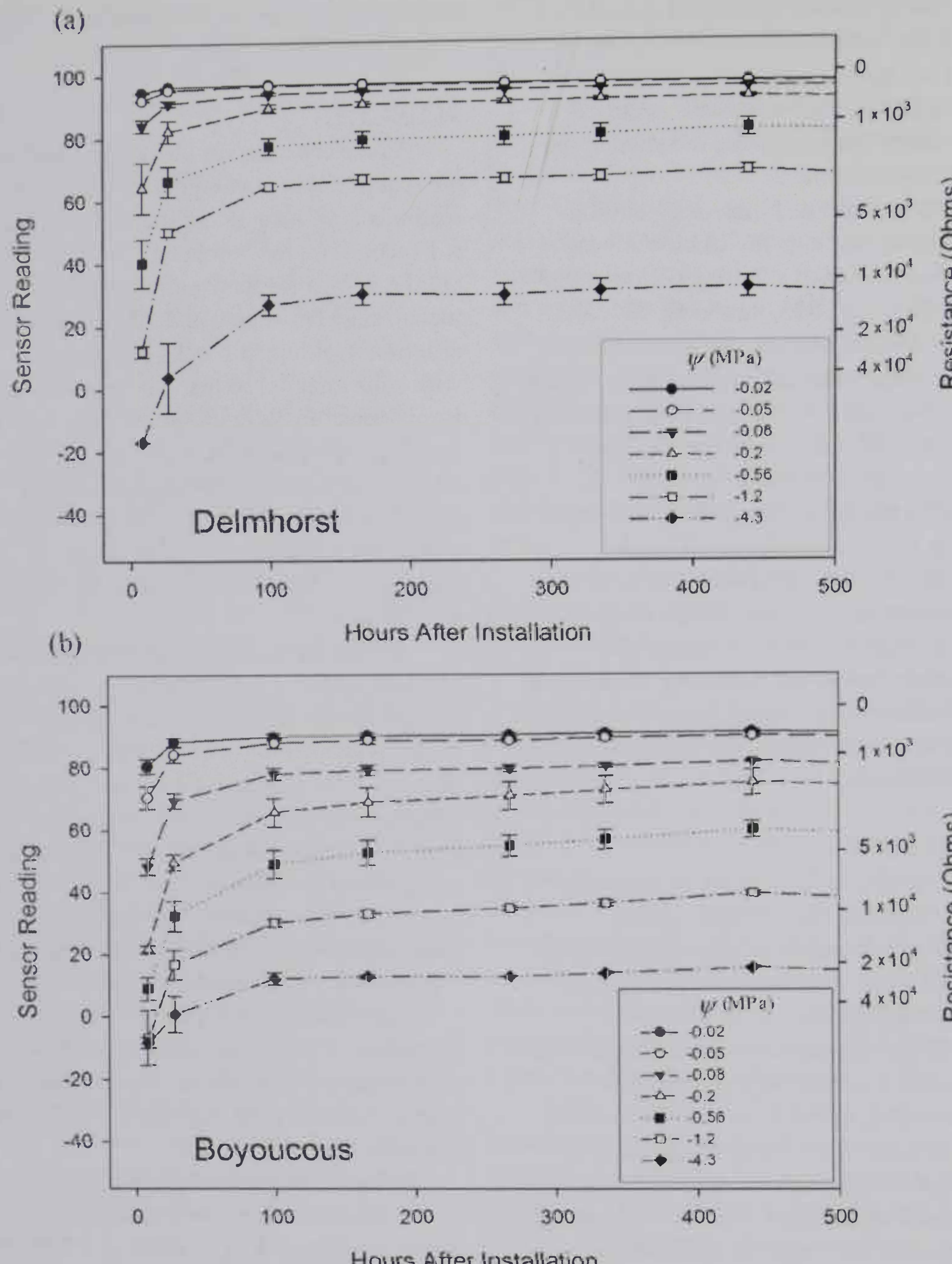

Figure 1. Time required for equilibration of (a) Delmhorst GS-1 and (b) Bouyoucos blocks in soils with water potentials of -0.02 to -4.3 MPa. Bars indicate ±SE

both types of blocks. Pairwise comparisons of water potentials are summarized in Figure 3.

Discussion

Although newer methods with desirable features exist for measuring soil water potential, e.g., zero time for equilibration with time delay reflectometry, gypsum blocks remain a good choice for many applications in terrestrial field ecology. They are time tested, inexpensive, dependable, easy to use, and can quantify water potential soils across different levels of salinity and organic matter content (Weaver 1987, Scanlon et al. 2002). In addition, we show that their readings are repeatable and generally distinguishable in the water potential range of greatest interest

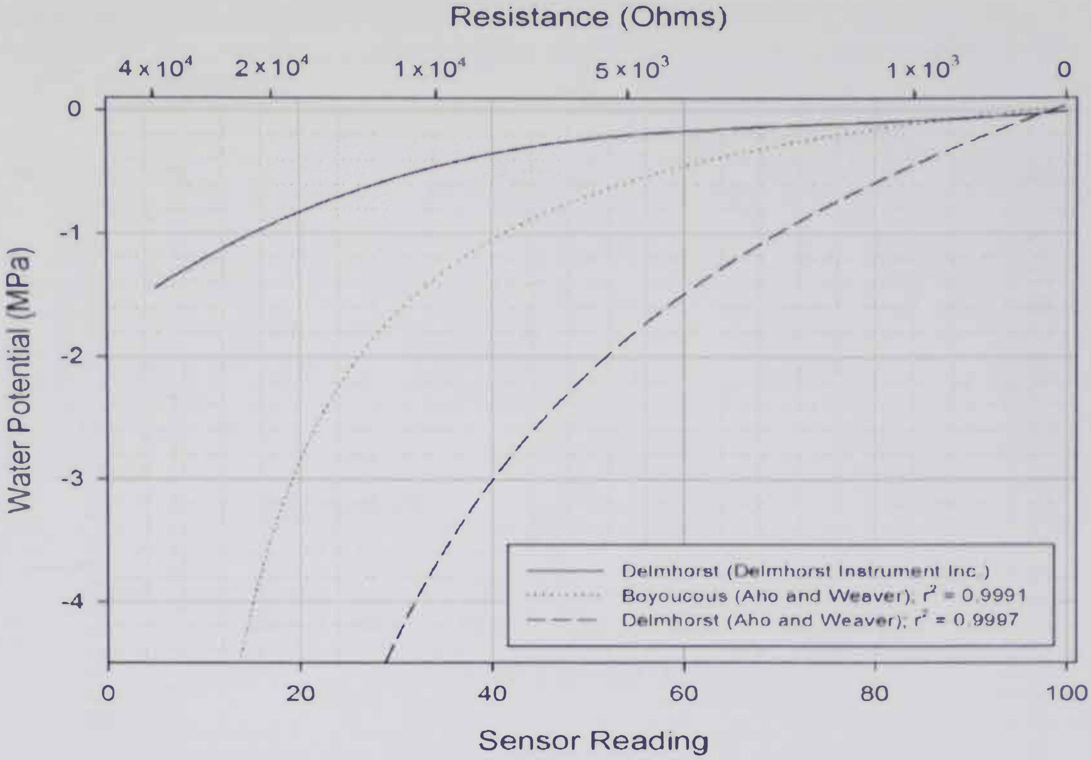

Figure 2. Relationship of soil water potential to meter readings and electrical resistance (ohms) for Delmhorst GS-1 and Bouyoucos blocks (see Appendix 1; Eq. 1). The bottom two curves in the figure were fitted from water potential data gathered for this paper. The top curve is from calibration formulae provided by Delmhorst Instrument Co. for use with their GS-1 blocks and KS-D1 meter (Appendix 1; Eqs. 2, 3).

to ecologists and agriculturists (≅ -0.02 to -4.3 MPa, Fig. 3).

Block Calibration

We introduce a new method for calibrating gypsum blocks in this paper. Our method improved on conventional procedures by simultaneously providing useful measurement units [water potential in megapascals (MPa)] and reducing the time required for calibration.

With regard to measurement units, a common alternative calibration procedure measures block resistivity in soils of known water content (kg kg^{-1}) rather than water potential. Because soils with the same water content may have very different matric potentials, results for this procedure are not general, i.e., they are only applicable to soils used in creating the calibration curve (Gardner 1986).

With regard to time required for equilibration, another alternative procedure involves embedding blocks in soils, reducing water potential incrementally with a pressure plate, and measuring block resistivity at these increments (e.g., Klute 1986, Weaver 1987). While this procedure produces a calibration curve in water potential units, it is very slow (> 6 months, Weaver 1987), and overestimates water potential if the system is not brought to full equilibrium.

Because calibration curves differ among block species, users need curves specific to their brand of blocks (Spaans and Baker 1992). Thus, while some variance may exist among manufacturing runs, our curves (Fig. 2, Table 1) should serve those using either Delmhorst or Bouyoucos blocks inserted dry into well-aggregated soils. While our results were easily read from Figure 2 and Table 1, when working with large data sets it would be more convenient and precise to convert meter readings to water potentials using equations developed for each block type (Appendix A).

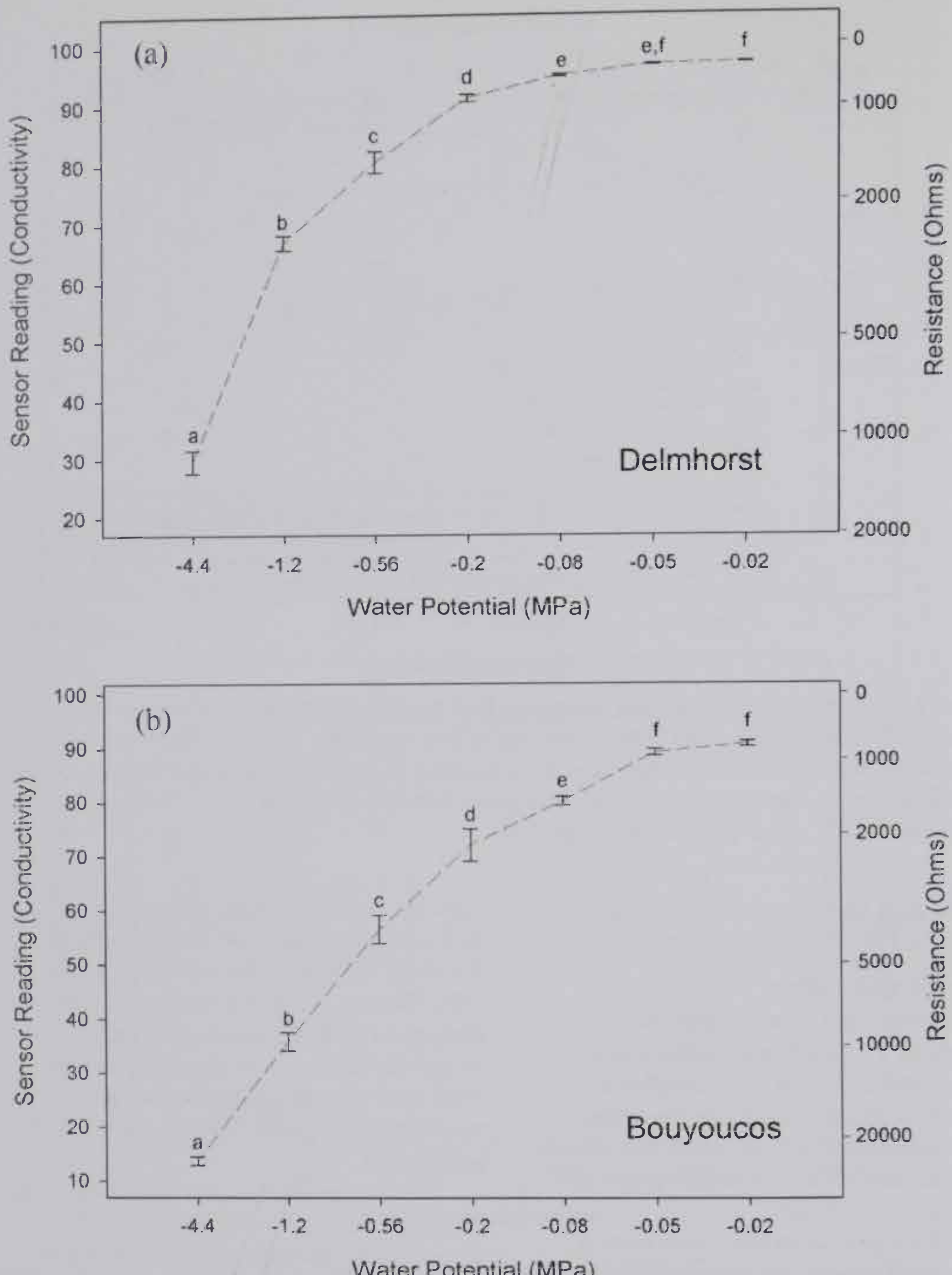

Figure 3. Water potential levels distinguishable with (a) Delmhorst and (a) Bouyoucos gypsum blocks. Water potential levels that are significantly different ($\alpha = 0.05$) are marked with different letters. Scheffé's method was used for simultaneous inference. Bars show 95-percent confidence intervals.

Gypsum block sensor readings will lag behind soil water conditions when blocks are either wetting or drying. Because dry blocks take from 4-8 days to equilibrate (Fig. 1), sensor readings will underestimate soil water potentials if blocks were recently installed or if surrounding soils have been recently wetted. We expect equilibration time to increase with increasing sand content since soil coarseness decreases contact with sensors (cf. Scanlon 2002).

Table 1. Soil water potentials at particular meter readings (Delmhorst KS-D1 meter) for Delmhorst GS-1 and Bouyoucos gypsum blocks. Note that predicted sensor readings below -4.3 MPa are extrapolated.

Sensor reading	Water Potential (MPa)	
	Delmhorst	Bouyoucos
95	-0.096	-0.009
90	-0.25	-0.051
85	-0.41	-0.098
80	-0.58	-0.15
75	-0.78	-0.21
70	-0.99	-0.28
65	-1.23	-0.36
60	-1.49	-0.45
55	-1.79	-0.56
50	-2.13	-0.69
45	-2.53	-0.85
40	-3.01	-1.05
35	-3.58	-1.31
30	-4.30	-1.65
25	-5.25	-2.13
20	-6.55	-2.85
15	-8.56	-4.05
10	-12.23	-6.44
5	-22.80	-13.63

Conversely, wet blocks inserted in drier soils may equilibrate even more slowly due to the slow loss of moisture from blocks. Equilibration is slow because water moves slowly from a fine-pored (block) to a coarser-pored (soil) medium (cf. Brady 1974). In addition, under field situations, water deep in blocks is removed only slowly by adjacent roots since blocks are impenetrable to them. Thus, recently wetted blocks may overestimate soil potentials for an extended period of time. Such overestimates may occur when soils dry around blocks which were previously saturated by melting snow or flooding. Similarly, overestimation may occur when blocks are installed wet or in a slurry as is recommended by block manufacturers (e.g., Delmhorst Instrument Co. 2000). Although use of wet blocks and slurried soils improve block-soil contact (Scanlon et al. 2002), overestimating water potential from these procedures may persist for weeks or months. We demonstrate evidence for overestimation in a comparison of calibration curves in Figure 2, where the manufacturer's curve predicts lower water potentials through most of the -0.1 to -1.5 MPa range than our curves.

Variability in gypsum block sensor readings is likely to be higher in drier soils (Scanlon et al. 2002). We demonstrated this trend for both types of tested sensors (Figs. 1, 3). As a result, we recommend averaging results from multiple sensors as we have done here to describe water potential with gypsum blocks (cf. Taylor et al. 1961, McCann et al. 1992).

Block Useful Range (Precision/ Sensitivity)

We acknowledge that a lack of replication in our experimental design (only one cylinder/water potential treatment) hampers inferential statements concerning block sensitivity. On the other hand, average block reading estimates for water potential treatments were improved by presence of multiple sensors (pseudoreplicates) from each block manufacturer in each cylinder. Independence of readings within cylinders over time (assumed by our analysis) was supported by lack of significance for either time or time x water potential in our analysis of covariance.

Precision of plaster blocks, as indicated by post-equilibration standard deviations of readings, increased as water potential increased (Fig. 3). In contrast, sensitivity of plaster blocks, measured as the capacity of plaster blocks to distinguish different water potentials, decreased in wetter soils (ψ >-0.05 MPa). This is true because the relationship of sensor readings and water potential was logarithmic, and readings were asymptotic as soils approached saturation (Fig. 2; cf. Bourget 1958). Under moist conditions (ψ >-0.05 MPa), where the calibration curve slope approached 0, water potential levels were indistinguishable because differences in readings were small relative to variation around water potential means (Figs. 2 and 3). The limit at which our blocks discriminated water potentials was near the proposed physical upper limit of gypsum blocks (≅ -0.03 MPa, Scanlon 2002). Under drier conditions (ψ < -1.0 MPa), where the calibration curve slope was steepest, water potential levels were readily distinguishable because differences in readings were large relative to variation around water potential means (Figs. 2, 3).

The logarithmic relationship between sensor reading and water potential parallels that of water content and water potential. As a result, soils with higher water content (>27% H_2O) also had very similar water potentials. Recall that our water potentials were -0.02, -0.05, -0.08, -0.2, -0.56, -1.2, and -4.3 MPa, corresponding to evenly spaced soil H_2O contents of 32, 29, 27, 24, 21, 19, and 16 percent. This demonstrated the asymptotic relationship between soil water content and soil water potential near field capacity (Or and Wraith 1999) and the inherent difficulty of distinguishing distinct water potentials among wetter soils.

Acknowledgements

P. Laurentzi of Delmhorst Inc shared his calibration curve equations, A. Swanson and M. Taper provided mathematical advice, V. Gerez measured block resistance, and P. Castiglione and J. Bauder provided reviews and advice. Thanks to all.

Literature Cited

Andraski, B. J. and Scanlon, B. R. 2002. Thermocouple psychrometry. Pp. 609-642 *in* Methods of Soil Analysis Part 4: Physical Methods, J. H. Dane and G. C. Topp, editors, Soil Science Society of America, Madison, WI.

Bouyoucos, C. J. and A. H. Mick. 1940. An Electrical Resistance Method for the Continuous Measurement of Soil Moisture under Field Conditions. Michigan Agricultural Experimental Station, Technical Bulletin 172, East Lansing.

Bourget, S. J., D. E. Elrick, and C. B. Tanner. 1958. Electrical resistance units for moisture measurements: their moisture hysteresis, uniformity and sensitivity. Soil Science 86:298-304.

Boyer, J. S. 1985. Water transport. Annual Review of Plant Physiology 36: 473-513.

Brady, N.C. 1974. The nature and properties of soils. MacMillan Publishers, New York, NY.

Gardner, W. H. 1986. Soil water content. Pp. 493-541 *in* Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 2nd Edition, A. Klute, editor, Soil Science Society of America: Madison, WI.

Holdridge, L. R. 1947. Determination of the world plant formations from simple climatic data. Science 105: 367-368.

Delmhorst Instrument Company. 2000. Model KS-D1 Operating Instructions. Available at: http://www.delmhorst.com/pdf/ks_d1.pdf. (accessed Jun 2007)

Hignett, C. and S. R. Evett, 2002. The soil solution phase: neutron thermalization. Pp. 501-521 *in* Methods of Soil Analysis, Part 4: Physical Methods, J. H. Dane and G. C. Topp editors, Soil Science Society of America, Madison, WI.

Klute, A. 1986. Water retention: laboratory methods. Pp. 645-652 *in* Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 2nd edition, A. Klute, editor, Soil Science Society of America: Madison, WI.

Lambers, H., F. S. Chapin, III, and T. L. Pons. 1998. Plant Physiological Ecology, Springer-Verlag, New York, NY.

Lieth, H. 1975. Modelling primary productivity of the world. Pp. 237-283 *in* Primary Productivity of the Biosphere, H. Lieth and R. H. Whittaker, editors, Springer-Verlag: New York, NY.

McCann, I. R., D. C. Kincaid, and D. Wang. 1992. Operational characteristics of the Watermark Model 200 soil water potential sensor for irrigation management. Applied Engineering in Agriculture 8: 603-609.

Neter, J., M. H. Kutner, C. J. Nachtsheim, and W. Wasserman.1996. Applied linear statistical models, McGraw-Hill, Boston, MA.

Or, D. and J. M. Wraith. 1999. Soil water content and water potential relationships. A-53-A-85 *in* Handbook of Soil Science, M.E. Sumner, editor, CRC Press, Boca Raton, FL.R Development Core Team. 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Reeve, M. H. 1986. Water Potential: Piezometry. Pp. 545-562 *in* Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, A. Klute, editor, American Society of Agronomy Madison, WI.

Robinson, D. A. S. B. Jones, J. M. Wraith, D. Or, and S. P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone Journal 2:244-475.

Scanlon, B. R., B. J. Andraski, and J. Bilskie. 2002. Miscellaneous methods for measuring matric or water potential. Pp. 643-670 *in* Methods of Soil Analysis Part 4: Physical Methods, J. H. Dane and G.C. Topp, editors, Soil Science Society of America, Madison, WI.

Spaans, E. J. A. and J. M. Baker. 1992. Calibration of Watermark soil moisture sensors for soil matric potential and temperature. Plant and Soil 143: 213-217.

Systat Software Inc. 2002. Table Curve 5.01: automated curve fitting and equation Discovery, Systat software, Richmond, CA.

Taylor, S. A., D. D. Evans, and W. D. Kemper. 1961. Evaluating Soil Water, Utah Agricultural Experimental Station, Logan.

Weaver, T. 1987. Effect of salinity on soil water measurement with gypsum resistance Blocks. Montana Academy of Science Proceedings 47:109-112.

Received 28 February 2008
Accepted 12 September 2008

Appendix A

Calibration curve equations (Aho and Weaver).

$$\psi = 12.3179 - 56.5354/\ln(D) \quad (1)$$

$$\psi = 0.7476 - 71.9056/B \quad (2)$$

Where: ψ = water potential (MPa), D = KS-D1 meter reading for Delmhorst GS-1 blocks, and B = KS-D1 meter reading for Boyoucos blocks

Calibration curve equation for Delmhorst GS-1 blocks (Delmhorst Instrument Co. 2000)

For $0 > \psi > -0.15$ MPa

$$\psi = -(13.729 - 0.4343R + 0.00524R^2 - 0.0000226R^3)/10 \quad (3)$$

For $-0.15 > \psi > -1.5$ MPa

$$\psi = -(17.09 - 0.05619R + 0.00652R^2 - 0.000024R^3)/10 \quad (4)$$

Where: ψ = water potential (MPa), R = Delmhorst sensor reading