PART II

DEVELOPMENT OF METHODS

Chapter 4

A Field Comparison of the Puncture Tensiometer and Filter Paper Techniques for Measuring Soil Moisture Tension

Abstract

The filter paper and puncture tensiometer techniques are both potentially suitable for routine determination of soil moisture tension in the field. However, filter papers are generally regarded as being less accurate than puncture tensiometers. In field situations with high spatial variability, the lesser accuracy of the filter paper technique may not be a concern. In this paper, the two techniques are compared in a grazing trial. The puncture tensiometers were found to have a lower air entry value than expected while filter papers may have problems because of hysteresis. Where these problems were not evident, a paired t-test showed there were no significant differences between the soil moisture tensions measured by the two techniques. Further research is required to determine the magnitude of the hysteresis effect on filter papers at low tensions and to compare the two techniques at a greater range of soil moisture tensions.

Introduction

A simple, inexpensive, non-destructive method for measuring soil moisture tension in the field would be useful for irrigation scheduling, determination of the soil moisture characteristic *in situ* and many other applications in soil-water research and management. Two techniques fit these requirements: filter papers and puncture tensiometers. The filter paper technique has been used in the field by Hamblin (1981) and in large undisturbed cores by Greacen *et al.*

(1987). Puncture tensiometers, developed by Marthaler *et al.* (1983), are also suitable for routine field use.

However, the accuracy of filter papers is generally not as high as that for puncture tensiometers. In laboratory studies, measurements of soil moisture tension using puncture tensiometers had a coefficient of variation of less than 5% (Greenwood and Daniel 1996) while the coefficient of variation for filter papers varied between 2 and 12% (Deka *et al.* 1995). Filter papers had a greater error at lower soil moisture tensions. These errors are likely to be higher under field use where there is greater opportunity for water loss from the paper before weighing.

Precision of individual measurements may not be a major concern where field variability is high and within-plot measurements are made to reduce this variability. In this chapter, I test the hypothesis that, under field conditions, the filter paper technique will give comparable results to puncture tensiometers. The time and costs involved for each technique are compared, and I comment on their field performance.

Materials and Methods

The experimental site, used for comparing the puncture tensiometer and filter paper techniques, was part of a long-term grazing trial at Armidale, New South Wales, Australia. The plots used formed 2 blocks: one block was located on a gleyed podzolic, the other on a prairie soil (Schafer 1980). The A horizon of both soils had a loam texture. There were four stocking rate treatments within each block. The individual plots were 45 m by 90 m. One site was randomly chosen within each of four, equal-sized strata per plot.

Puncture tensiometers from two sources were used: ready-made tensiometers from Loktronic and tensiometers manufactured in the local workshop using porous cups purchased from Cooinda Ceramics. The Loktronic tensiometers had cup dimensions of 20 mm by 60 mm, while the cups from Cooinda Ceramics had dimensions of 20 mm by 50 mm. The tensiometers were tested for leaks prior to installation by soaking the tensiometer cups overnight in water, removing the water from inside the tensiometer and applying a pressure of 100 kPa (Cassel and Klute 1986). The pressure was applied for approximately 10 seconds and any leaking tensiometers were repaired or replaced.

At each site, puncture tensiometers and filter papers were installed, not more than 25 cm apart, at depths of 10 and 20 cm. Tensiometers were installed so that the cup fitted snugly within the soil. An oversize hole was augered for the shank of the tensiometer and backfilled with a 50:50 mixture of soil and bentonite to prevent preferential flow of water down the side of the tensiometer (Bruce and Luxmoore 1986).

Permanent access holes were made for the filter papers using the *in situ* field method described by Greacen *et al.* (1989). In this method a cylindrical hole, which terminates in a conical shape, is augered from the soil to the required depth. The filter paper is inserted into the soil by attaching it to a conical centrifuge tube which has a suitable length of wooden dowel protruding to the soil surface. Good contact between the filter paper and the soil is ensured by the conical shape. The cylindrical part of the hole was lined with PVC pipe as suggested by Greacen *et al.* (1989), with the modification that an oversize hole was made for the upper part of the liner which was backfilled with the 50:50 mixture of soil and bentonite. The liner was capped at the surface with PVC end caps. Each filter paper was attached to the conical centrifuge tube using cotton thread tied through a hole drilled in the tip of the centrifuge tube, wrapped tightly around the paper and secured to the tube with a small piece of electrical tape.

The filter papers (Whatman No. 42) were installed either 4 or 6 days prior to measurement to allow sufficient equilibration time (Deka *et al.* 1995) and the puncture tensiometers were filled with water on the afternoon of the day prior to measurement. The measurement dates and preceding rainfalls are shown in Table 1. Puncture tensiometer measurements were completed before 9:30 a.m. using the double-puncture technique (Greenwood and Daniel 1996) and the filter papers were collected within the following two hours. The filter paper was removed, loose soil was brushed off or badly soiled parts of the paper were torn off and discarded, before putting the papers as quickly as possible into a scintillation vial to minimise water loss. The vials containing the filter papers were weighed to 0.001 g and oven-dried at 105°C to determine the moisture content of the paper. The moisture content was converted to soil moisture tension using the calibration equations provided by Greacen *et al.* (1989). Records of times for each of these procedures and the time required to enter the data into a spreadsheet program were kept.

Table 1. Measurement dates (1995) and total rainfall (mm) during the preceding 3- and 7-day periods.

	Preceding rainfall	
Date of Measurement	3-day	7-day
17 October	0	0
24 October	10.5	10.5
31 October	0	19.5
7 November	24.5	58.5
21 November	2.7	10.2

The maximum tension the tensiometers could develop in air, by evaporation of water from the ceramic cup (Cassel and Klute 1986), was determined after the field measurements were completed. The tensiometers were removed from the field, cleaned and filled with water. The tension was measured after leaving the upright tensiometers overnight in a well-ventilated area.

The log-transformed data from the two measurement techniques at each site and each depth were compared using a paired difference t-test. An analysis of variance was also undertaken to see whether the effects of stocking rate and depth on soil moisture tension were similar for each measurement technique. Depth was included in the analysis as a split-plot. The within-plot measurements were nested within the analysis of variance.

Results

The soil moisture tensions measured on four dates at each site using the puncture tensiometer and filter paper techniques are compared in Figure 1. Data collected on 7 November were

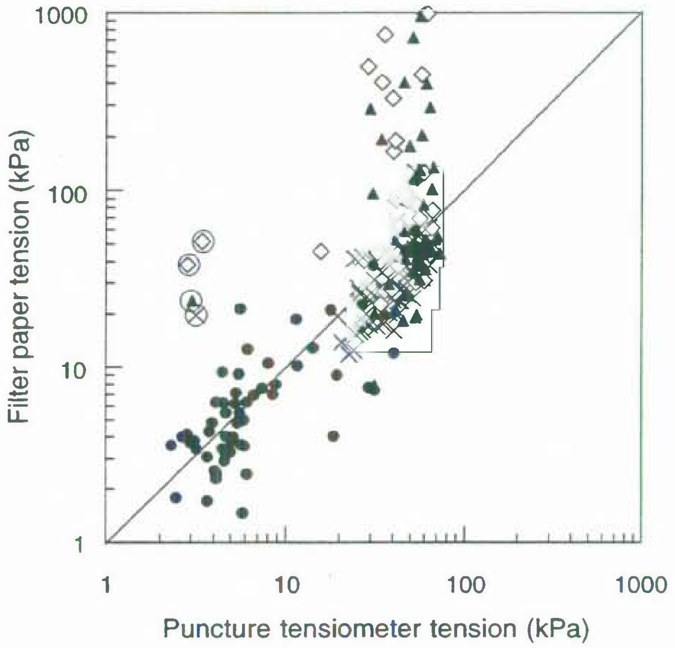

Figure 1. Paired measurements of soil moisture tension using the filter paper and puncture tensiometer techniques. Soil moisture tension was measured on 17 October (×), 24 October (◇), 31 October (▲) and 21 November (●). The coefficients of determination (r^2) for each date were 0.35, 0.01, 0.05, and 0.43. The circled values were omitted from the calculation of the coefficient of determination because the tensiometers were later found to have a very low air entry value. The 1:1 line is also shown.

similar to those for 24 and 31 October and are not shown. While the data for 17 October and 21 November show some correlation between the two measurement techniques, the correlations are poor for 24 and 31 October. On these dates, soil moisture tensions measured by the filter paper technique frequently exceeded 100 kPa while those measured with the puncture tensiometers were less than 70 kPa.

Using the paired difference t-test there was no significant difference (P>0.05) between the two measurement techniques on 21 November. Soil moisture tensions measured using the filter paper method were significantly lower than those from the puncture tensiometers on 17 October by approximately 10 kPa. There were obviously significant differences between the techniques for the 24 and 31 October and 7 November.

The effects of stocking rate and soil depth on the soil moisture tension, measured on 17 October and 21 November, are shown in Table 2. Analysis of variance of these data showed that the two measurement techniques may give different levels of significance for the stocking rate and depth treatment effects. For the two measurement dates analysed, each method nearly resulted in a significant stocking rate effect (P<0.10) on different occasions, but the other measurement of the same date was not significant. The depth effect was significant at 1% for the filter paper technique but at 5% for the puncture tensiometer technique.

Table 2. The effects of stocking rate and depth on the geometric mean of the soil moisture tension (kPa) measured using the filter paper and puncture tensiometer techniques. Significance levels for treatment differences are indicated by: n.s. not significant, + P<0.10, * P<0 05 and ** P<0.01.

	17 October		21 November	
	Filter paper	Puncture tensiometer	Filter paper	Puncture tensiometer
Sheep/ha				
0	29.0	36.3	3.3	4.3
10	28.2	40.1	6.2	7.0
15	21.1	31.2	5.3	7.1
20	31.1	38.9	7.3	8.4
Significance	n.s.	+	+	n.s.
Depth (cm)				
10	31.8	42.3	3.7	4.8
20	23.0	31.4	7.7	8.9
Significance	**	*	**	*

None of the tensiometers were able to develop tensions greater than 75 kPa when left in air overnight. Of the 62 tensiometers tested (two were damaged during removal), only 51 had tensions at the centre of the cup in excess of 50 kPa. The remainder had a geometric mean tension of 12.2 kPa. The outlying puncture tensiometer results shown in Figure 1 were close to the individual tensiometer's air entry value.

Measurement and data entry times for the filter paper technique were more than twice that for puncture tensiometers (Table 3). In wet conditions, the need to re-fill puncture tensiometers with water was not always necessary.

Table 3. Comparison of times (min) required to measure and calculate soil moisture tension using the filter paper and puncture tensiometer techniques. Times are based on 64 measurements using each technique in a 3.2 ha field trial. No travel time between the field site and laboratory is included.

Filter paper		Puncture tensiometer	
Activity	Time	Activity	Time
Attaching filter paper to centrifuge tube	60	Filling tensiometer with water	40
Inserting filter paper into access hole	25		
Transfer of paper from soil to vial	60	Double-puncture measurement	60
Weighing (3 times)	75		
Data entry and calculation	60	Data entry and calculation	20
Total	280		120

Missing data were more common from the puncture tensiometers. At least two puncture tensiometers apparently leaked and could not maintain a partial vacuum. This may have been due to damage during installation or damage by the sheep grazing the pasture. Data were not recorded from puncture tensiometers when the water level could not be seen in the sight tube. Low water levels were probably the result of the failure of the porous cup to be impermeable to air at higher tensions and this problem occurred more frequently as the soil dried. On a few occasions, air entered the tensiometer between the two readings of the double-puncture technique (Greenwood and Daniel 1996), and the second reading had to be estimated.

Missing data can occur using the filter paper technique when the paper is decomposed by soil organisms during the equilibration period. On two occasions, the PVC end cap which covered the exposed end of the filter paper hole was removed by curious sheep, possibly allowing rain to directly wet the paper. Another cause of missing filter paper data may be the inability to remove the paper from the soil when the securing thread has broken. For samples close to the soil surface, a small wire hook can usually retrieve the paper.

One disturbing fact noted during this study was the large variation in the tare weights of the empty scintillation vials. These weights, which should be constant, can change by up to 0.02 g—a large source of error when determining the filter paper moisture content. Changes in relative humidity were ruled out as the cause of the problem as the maximum possible weight of saturated water vapour in the vial (Weast 1985, p. E-37) was forty times less than the error measured. Due to time constraints, the cause of the variation was not investigated further.

Discussion

At soil moisture tensions less than 10 kPa, the filter paper technique gave comparable results to the puncture tensiometer technique. At tensions between 10 and 50 kPa the filter paper technique tended to underestimate the tension compared with the tensiometer method and at tensions greater than approximately 50 kPa, the tensiometer method appeared to be unreliable due to air entry though the porous cup. However, there was no indication during the field measurements that the air entry value of the puncture tensiometer had been exceeded. Perhaps if the equilibration time had been greater than approximately 16 hours, the lack of water in the sight tube would have indicated air entry into the tensiometer.

Deka *et al.* (1995) found that the moisture contents of filter papers, at the same tension, differed significantly depending whether they were on a wetting or drying curve, due to hysteresis. Their comparison was undertaken at tensions greater than 250 kPa, and further study is required to determine the magnitude of the hysteresis effect at lower tensions. Most calibrations for filter papers are determined on a wetting curve, which will underestimate the soil moisture tension when the filter paper is actually on a drying curve. It was likely that the filter papers collected on 17 October were on a drying curve as there had been no rain in the preceding 7 days (Table 1). Hence, the soil moisture tension may have been underestimated by the filter paper technique, as indicated by the puncture tensiometer data. It may be useful, if using filter papers in the field, to determine a calibration for the drying curve. However, in practice, it may be difficult to determine whether the filter papers are on a wetting or drying curve, and there would be an infinite number of curves within the hysteresis envelope.

The poor performance of some of the tensiometers at soil moisture tensions greater than about 25 kPa was due to inadequate testing of the tensiometers before installation. Although all tensiometers had been pressure tested to 100 kPa prior to installation, the pressure was probably not applied for long enough for small leaks to be detected. A better way to test tensiometers would be to allow them to develop tension by evaporation of water from the cup, as described by Cassel and Klute (1986), and discard or repair the tensiometers not developing the required suction. Pressure testing may still be useful, however, for determining whether the leaks are in the tensiometer joints, which can be repaired, or in the porous cup.

Deka *et al.* (1995) determined that, for the filter paper technique, a minimum equilibration time of 4 days was required at tensions less than 20 kPa. However, at these low tensions, Hamblin (1981) and Greacen *et al.* (1989) considered that equilibration times of less than 2 days would be adequate. Intuitively, a 4-day equilibration time seems excessive and can cause problems with field use because of decomposition of the paper by soil organisms during the equilibration period. Long equilibration times also reduce the frequency with which measurements can be made at the same site. Further work is required to determine whether such long equilibration times are required for field use.

A major factor which may influence the choice between filter papers and puncture tensiometers for routine field use is the large difference in operating range of the two methods. Filter papers may be used for soil moisture tensions between 1 kPa and 100 MPa (Fawcett and Collis-George 1967) whereas, in this study, most tensiometers had an operating range less than 50 kPa. However, tensiometers with an air entry value of 300 kPa are available commercially.

The cost and availability of equipment may also influence the choice of technique. If an accurate balance and oven are available, the filter paper technique will be cheaper with the filter paper units costing approximately $5 each. These units can be made with minimal workshop equipment. Puncture tensiometers can be purchased commercially for about $27, although the cups may not have a high air entry value. The tensiometers can be made in a workshop with a lathe with the major cost being the porous cups at between $5 and $23. The tensiometer monitor would cost an additional $900. The additional time required for the filter paper technique (Table 3) may also be a consideration.

Conclusions

A number of problems with both the filter paper and puncture tensiometer techniques were found during a field comparison of their performance. However, when these problems were not apparent, there were no significant differences between the soil moisture tensions measured by the two techniques. Hysteresis was probably a major problem for the filter paper method in the field. Use of a calibration equation derived from a wetting curve will underestimate the soil moisture tension when the paper is actually on a drying curve. The puncture tensiometers were found to have a lower air entry value than expected from pressure testing and it was not possible to determine in the field when the soil moisture tension was greater than the air entry value of the tensiometer. The choice between the two techniques for routine field use would depend on the likely range of soil moisture tensions to be encountered and availability and cost of equipment.

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Postscript

Measurements of soil moisture tension using the puncture tensiometer and filter paper techniques described in this experiment were originally meant to supplement and/or substitute for the neutron probe measurements of soil water content at 10 and 20 cm in Chapter 7. Due to problems with both the puncture tensiometer and filter paper techniques, as described in this chapter, I decided that the neutron probe measurements of soil water content were probably more reliable.

Chapter 5

Water Repellency Effects on Unsaturated Hydraulic Conductivity Measured using Disk Permeameters

Abstract

The low sorptivity of water repellent soil has the potential to invalidate measurements of unsaturated hydraulic conductivity calculated from the sorptivity and steady-state flow rate. However, if the water repellency of the soil is removed by short-term wetting, calculations of unsaturated hydraulic conductivity based on steady-state flow rates only should be more accurate. In an experiment comparing two treatments designed to overcome water repellency, unsaturated hydraulic conductivity was not significantly affected by the initial soil moisture content but was increased by the use of a wetting agent in the infiltrating fluid. Although the use of the wetting agent increased the unsaturated hydraulic conductivity, it is not clear whether this was due to removal of water repellency or changes to the physical and chemical properties of the infiltrating liquid and their interaction with the soil. It appears sufficient to calculate unsaturated hydraulic conductivity from measurements of the steady-state flow rate using water only as the infiltrating medium.

Introduction

Most soils are water repellent to some extent (Wallis and Horne 1992), although the effects of water repellency are only obvious in severe cases (Marshall and Holmes 1979, p. 240). Tillman *et al.* (1989) define sub-critical repellency where the soil appears to wet normally but the rate of wetting is reduced. The effects of water repellency include a reduced rate of water infiltration with consequent effects on plant growth, runoff and erosion (Wallis and Horne 1992). The most water repellent soils tend to be sandy (Harper and Gilkes 1994) and those under old pasture (Bond 1964).

Soil tends to be most water repellent near permanent wilting point, and repellency decreases rapidly with increasing water content (King 1981). DeBano (1971) postulated a mechanism for the effect of moisture content on water movement through water repellent soils: large liquid-solid contact angles prevent water moving readily as a fluid. However, the cover of hydrophobic coatings is probably not continuous and some water would be preferentially absorbed through the least hydrophobic areas. These droplets may coalesce over adjacent hydrophobic areas reducing the resistance to water flow. This mechanism would explain the increasing infiltration rates with time observed by Bond (1964) and Tillman *et al.* (1989).

Wetting agents may be used as an ameliorant for water repellent soil as they lower the liquid-solid contact angle, thus increasing the rate of infiltration. Wetting agents also reduce the surface tension of the liquid which, in non-repellent soils, will theoretically decrease infiltration rates (Wallis and Horne 1992). Miyamoto (1985) found that some wetting agents increased infiltration rates into wettable soils, although the differences were not large. No wetting agents reduced infiltration rates compared with water.

Unsaturated hydraulic conductivity, measured at a range of tensions, has the potential to indicate differences in surface soil structure, particularly in the size and continuity of macropores (Coughlan *et al.* 1991). However, Chan and Heenan (1993) noted that measurements of unsaturated hydraulic conductivity, using disk permeameters, were complicated by water repellency, and they questioned the validity of using sorptivity and hydraulic conductivity, with water as the infiltrating liquid, to estimate the macroporosity of water repellent soils.

Water repellent soils have a lower sorptivity than non-repellent soil but repellency decreases during absorption (Tillman *et al.* 1989). Low sorptivity will overestimate the unsaturated hydraulic conductivity ($K\psi$) calculated from the sorptivity (S) and steady-state flow rate (q) according to the equation of White *et al.* (1992):

$$K_{\psi} = q / \pi r^2 - 4bS^2 / \Delta\theta \pi r \qquad (1)$$

where r is the radius of the sand pad, b is a dimensionless number approximately equal to 0.55, and $\Delta\theta$ is the difference between the initial soil moisture content and the moisture content at the supply tension (ψ).

Alternative methods for calculating hydraulic conductivity, which depend only on measuring the steady-state flow rate (q_1 and q_2) at two tensions (ψ_1 and ψ_2), have been developed by Ankeny *et al.* (1991) and Reynolds and Elrick (1991). Ankeny *et al.* derived the following equations:

$$K_{\psi_1} = q_1 \Big/ \left(\pi r^2 + \frac{2r(\psi_1 - \psi_2)(q_1 + q_2)}{q_1 - q_2} \right) \tag{2}$$

and

$$K_{\psi_2} = q_2 \Big/ \left(\pi r^2 + \frac{2r(\psi_1 - \psi_2)(q_1 + q_2)}{q_1 - q_2} \right). \tag{3}$$

Where two estimates of $K\psi$ are possible from ψ_1, ψ_2 pairs, the arithmetic average is used. These methods should give a more accurate measurement of the unsaturated hydraulic conductivity if the steady-state flow is not affected by the initial, temporary water repellency.

An experiment was undertaken to test the hypothesis that disk permeameter measurements of unsaturated hydraulic conductivity, calculated from the steady-state flow rate only, would not be affected by water repellency, the initial soil moisture conditions, or the use of a wetting agent in the infiltrating liquid.

Methods

The study was undertaken on a heavily grazed pasture, of predominantly crabgrass (*Eluesine tristachya*), near Armidale, New South Wales, Australia. The A horizon of the gleyed podzolic soil (Schafer 1980) had a loam texture. The experimental work was undertaken from 21 to 23 May 1993 and the weather conditions during the preceding week were cool (average maximum 15.7°C) and dry. At the time of the study, the soil appeared to be water repellent as drops of water on the surface failed to infiltrate immediately.

The two main treatments were: (i) pre-wetting of the soil compared with initially dry soil and (ii) use of a wetting agent in the infiltrating water used in the disk permeameters compared with water only. The experiment was set up as a 2x2 factorial design with 4 blocks. After the initially dry measurements were made, 40 mm water was applied to the soil over a period of about one hour using a dripper system and the soil allowed to wet up for 24 hours before the initially wet measurements were taken. The wetting agent added to the infiltrating liquid in the disk permeameters was Brij-35, a non-ionic surfactant, at a rate of 0.1% (v/v). Within a 1 m by 1 m block, treatments were randomly allocated and measurements were at least 60 cm apart. Blocks were at least 1 m apart. The gravimetric moisture content in the top 5 cm was determined when the soil was initially dry, and after pre-wetting, from one sample per block collected while the infiltration measurements were undertaken.

Unsaturated hydraulic conductivity was measured using a disk permeameter (Perroux and White 1988). The pasture was clipped as close to ground level as possible and sand pads of 20 cm diameter and 5 mm nominal thickness were used as contact material between the disk permeameter and the soil surface. Four laboratory-calibrated tensions were used; after correction for the height of the sand pad (Reynolds 1993), these tensions were approximately 35, 25, 15 and 5 mm H_2O. Measurements were always taken in the order highest tension to lowest tension to avoid hysteresis problems (Reynolds and Elrick 1991). Measurements of flow rate were started approximately 1 hr after infiltration commenced, during which time steady-state flow at 35 mm tension was reached. Unsaturated hydraulic conductivity was calculated according to the method of Ankeny *et al.* (1991).

The effects of wetting agent in the infiltrating fluid and the initial moisture status of the soil were compared statistically using analysis of variance. The data for each tension were compared separately. No transformation of the data was required for statistical analysis as the data appeared to be normally distributed.

Results

The use of a wetting agent in the infiltrating liquid significantly increased ($P<0.05$) the unsaturated hydraulic conductivity at all tensions by a factor of 1.4 to 1.7 (Table 1). The initial soil moisture content (0.112 kg/kg, s.e. 0.0037 when dry; 0.196 kg/kg, s.e. 0.0069 when wet) did not affect the unsaturated hydraulic conductivity, nor was there any significant interaction between the initial moisture content and the use of a wetting agent. No evidence of water repellency was observed when the soil surface was wet.

Table 1. Mean unsaturated hydraulic conductivities (mm/hr) at four tensions, with and without wetting agent added to the infiltrating liquid. Measurements were made on dry and wet soil.

	Tension (mm H_2O)			
Treatment	35	25	15	5
No wetting agent, initially dry	4.0	6.0	15.5	42
No wetting agent, initially wet	3.6	5.2	12.2	34
With wetting agent, initially dry	6.2	9.1	19.8	60
With wetting agent, initially wet	6.3	9.6	19.9	49
S.e.d. between main treatment means	0.57	0.89	2.24	5.7
S.e.d. between individual means	0.81	1.26	3.17	8.1

Discussion

Unsaturated hydraulic conductivity was not affected by the initial moisture content of the soil. Presumably, any negative effects of water repellency on sorptivity were temporary and did not persist until measurements were commenced after approximately one hour. If unsaturated hydraulic conductivity had been calculated from sorptivity and steady-state flow (Equation 1), and sorptivity only had been reduced by water repellency, an erroneously high value of unsaturated hydraulic conductivity would have been calculated.

The consistently significant increase in unsaturated hydraulic conductivity using the wetting agent in the infiltrating liquid implies that either (i) the soil was water repellent when both wet and dry or (ii) that the wetting agent's effect on the soil-fluid contact angle, surface tension and viscosity affect water movement through the soil. Miyamoto (1985) also found that some, but not all, wetting agents increase infiltration rates into soils that appeared non-repellent. However, Chan and Heenan (1993) found that sorptivity and unsaturated hydraulic conductivity were not affected by the use of a wetting agent on non-repellent soil. The differences in response may be due to the properties of the wetting agents used.

The conclusions drawn from this experiment rely on the assumption that wetting the soil, 24 hours before measurements commenced, removed the effects of water repellency. A better understanding of the temporal effects of soil moisture content on water repellency may have been gained by measuring the initial infiltration rate. However, the positive correlation between soil moisture content and sorptivity (White and Perroux 1987) would make it difficult to interpret the results. Measurement of the repellency index—the ratio of the apparent intrinsic sorptivity of ethanol to that of water—as suggested by Tillman *et al.* (1989), may have been able to detect whether the wet soil was sub-critically repellent. Unfortunately, time and equipment were not available to follow this line of experimentation.

Conclusions

The above evidence suggests that water repellency does not affect the unsaturated hydraulic conductivity calculated from the steady-state flow rate only. The effects of water repellency on infiltration, using water as the infiltrating liquid, are temporary and do not persist after steady-state conditions are reached. The use of a wetting agent in the infiltrating liquid increases the measured unsaturated hydraulic conductivity, probably due to the wetting agent's effect on the physical and chemical properties of the infiltrating liquid and their interaction with the soil. Disk permeameters, using water as the infiltrating liquid, can be used to measure unsaturated hydraulic conductivity in water repellent soil, providing the calculations are based on the steady-state flow rates.

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