Millimeter-Scale Spatial Variability in Soil Water Sorptivity: Scale, Surface Elevation, and Subcritical Repellency Effects

P. D. Hallett,* N. Nunan, J. T. Douglas, and I. M. Young

ABSTRACT

Recent evidence suggests that reduced water infiltration may be linked to small scale microbial and/or chemical processes that cause subcritical water repellency. We measured water sorptivity on the surface of a large intact block of soil (0.9 m wide, 1.3 m long, 0.25 m deep) taken from a grassland site and examined the effects of surface elevation and water repellency on water sorptivity at the millimeter scale. The soil block was partially dried to 0.22 mm^3 mm^{-3}, appeared to wet readily, and is not severely water repellent at any water content. Water sorptivity varied from 0.1 to 0.8 mm $s^{-1/2}$ across the sampling grid with a coefficient of variation (CV) of 0.57. Water repellency, determined by comparing water and ethanol sorptivities, also varied considerably (CV = 0.47). Geostatistical analyses of water sorptivity and repellency measurements found little evidence of spatial autocorrelation, suggesting a high degree of local variability. These data were compared to larger scale measurements obtained with conventional infiltrometers under tension conditions (40 mm contact radius), and ponded conditions (37 and 55 mm radius rings) where macropores influence infiltration heterogeneity. Larger scale tension infiltrometer measurements were less variable with a CV of 0.22, whereas ponded infiltrometer measurements were more variable, CV > 0.50, presumably because of the influence of macropore flow. Data collected on surface elevation showed that ponded infiltration but not tension infiltration was influenced by surface topography. The results suggested that repellency can induce levels of spatial variability in water transport at small scales comparable to what macropores induce at larger scales.

Low levels of water repellency have been observed in many soils (Hallett et al., 2001; Wallis et al., 1991; Tillman et al., 1989). Although water appears to readily infiltrate these soils, it has been postulated that the slight, yet significant, reduction in infiltration rates through repellency can cause an increase in soil aggregate stability, and in the heterogeneity of overland flow and water infiltration at the field scale (Hallett and Young, 1999). Most studies on the heterogeneity of water infiltration and overland flow have concentrated on the influence of macropores and other dominant soil pore structure features serving as preferential flow pathways (Smettem, 1987; Heuvelmann and McInnes, 1997). We hypothesize that low levels of repellency will also exhibit high levels of spatial variability across the surface of soil, and that this will add additional heterogeneity, particularly under conditions of tension infiltration when macropores are less important.

The concept of low level or subcritical water repellency is not new. Soil physicists are taught the importance of soil–water contact angles early on in their undergraduate syllabus and Philip (1957) recognized the importance of repellency in his original work on sorptivity, but despite this knowledge, it is widely ignored in current research as soil is assumed to be completely nonrepellent. Tillman et al. (1989) developed a simple technique for quantifying repellency and with these data suggested that most soils exhibit subcritical water repellency where despite the soil appearing to uptake water readily, partially hydrophobic soil particle surfaces impede the rate of infiltration. Hallett and Young (1999) combined Tillman et al.'s (1989) approach with a miniaturized infiltrometer developed by Leeds-Harrison et al. (1994) to allow for water repellency to be measured on individual soil aggregates at millimeter resolution. Subsequent work using this new technique showed that repellency had a biological origin controlled by organism type (White et al., 2000), nutrient levels (Hallett and Young, 1999) and exudate chemistry (Czarnes et al., 2000).

The biological origin of repellency suggests that it will have a high spatial and temporal variability at very small scales, because of the submillimeter spatial variability of organic matter, organisms and the microbial environment in soil (Nunan et al., 2002). Using the miniaturized infiltrometer, we measured water sorptivity on the surface of a large intact block of soil to determine its spatial heterogeneity at the microscale and the effect of surface elevation and subcritical water repellency. These data were compared with larger scale measurements obtained with conventional infiltrometers (Logsdon and Jaynes, 1996; Shouse et al., 1994) under ponded conditions where macropores influence infiltration heterogeneity, and under tension conditions where heterogeneity would be expected to be less severe because measurements were above a size threshold where repellency variability is detectable. Data were also collected on surface topography since depressional storage may affect measurements and can operate over a range of scales, perhaps smaller than the size of the infiltrometer (Kamphorst et al., 2000). Geostatistics were applied to measure spatial variability and to detect any potential spatial pattern and dependency in water infiltration at the different spatial resolutions examined.

This work is highly relevant to describing physical and biological phenomena that may impart heterogeneity to the overland flow and infiltration of water in soil at

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Abbreviations: CV, coefficient of variation.

the onset of wetting. Heterogeneity may influence the development of preferential flow pathways that may influence surface erosion, runoff, and the transport of contaminants through the vadose zone. Predictive models that describe infiltration and overland flow (Kamphorst et al., 2000) require knowledge of the various properties of soil that influence infiltration, particularly its spatial variability.

MATERIALS AND METHODS

Field Sampling

Soil was sampled from the surface of a perennial grassland site 10 km south of Edinburgh, Scotland. The soil was an imperfectly drained clay loam of the Winton Association (Ragg and Futty, 1967) (FAO taxonomy: Gleyic Luvisol) with a topsoil layer comprised of 21% clay, 45% silt, and 34% sand. At the 0- to 25-mm depth, the soil organic matter content was 7.5% and the pH was 5.6. The soil is not considered water repellent in the traditional sense as water readily infiltrates the surface, even when it is extremely dry. Using the excavation and laboratory set-up methods for runoff studies described in Douglas et al. (1999) and Douglas and O'Sullivan (2001) a soil slab (0.9 m wide, 1.3 m long, 0.25 m deep) was retained in a sealed steel-plate box. The soil was partially dried over a period of 8 wk in the lab at ambient temperature. Covering vegetation (predominantly grass) was regularly clipped by hand. After 8 wk the vegetation was removed by cutting it at the base of the stem, thereby not disturbing the surface soil. The porosity was 0.57 m^3 m^{-3} with ambient water content at testing of 0.22 m^3 m^{-3}, measured on five 50-mm diameter, 50-mm height soil cores taken after testing, resulting in an air-filled porosity of 0.35 m^3 m^{-3} for the infiltration tests. Sorptivity tests were performed at a water content typical of field conditions in the summer in Scotland.

Measurement of Water Transport at Different Scales

Water transport measurements were taken at the surface of the soil slab at different spatial resolutions controlled by the contact radii of the infiltrometer and the spacing distance between measurements.

Smaller-Scale Measurements at Millimeter Resolution

We used a miniaturized tension infiltrometer consisting of a 1.4-mm radius conductance tube with a sponge tip that enabled good soil contact and the establishment of a negative hydraulic head up to about −50 mm (Leeds-Harrison et al., 1994). Liquid was supplied to the conductance tube via a flexible pipe that connected to a reservoir on a recording balance accurate to 1 mg.

Sorptivity measurements were taken on a 50-mm square grid consisting of 205 sampling points. All measurements were done at −20 mm by adjusting the hydraulic head in the infiltrometer to take into account the surface elevation of the soil. This was achieved by altering the liquid level in the reservoir on the balance at each measurement where required. The rate of uptake of liquid, Q was recorded from the mass loss on the balance at 15-s intervals. Sorptivity, S was calculated using a formula presented by Leeds-Harrison et al. (1994) as

$$S = \sqrt{\frac{Qf}{4br}} \quad [1]$$

where b is a parameter dependent on the soil–water diffusivity function (taken as 0.55 after White and Sully, 1987), r is the radius of the infiltrometer tip (1.4 mm), and f is the fillable (air-filled) porosity. Typically, steady state for liquid transport was reached at 30 s. Each test lasted 3 min for each spatial location. Water sorptivity measurements were obtained at each sampling point.

The infiltrometer probe was attached to a fixed level gantry. There was a measuring tape adhered to the side of the probe to measure the distance between the gantry and the soil surface. The base elevation of 0 mm corresponded to the measurement with the greatest distance from gantry to soil (i.e., deepest depression). All surface elevation measurements are expressed as the distance above the base elevation.

On a subset of 51 points, consisting of the first three rows of the spatial grid, ethanol sorptivity measurements were also obtained 24 h after the water sorptivity measurements. These were just adjacent to the location of the water measurements. It was assumed that the low volume of water infiltration, the soil (<0.0005 m^3) in the first test, water redistribution over time, and different sampling location would minimize the influence on the ethanol infiltration results. Ethanol readily infiltrates hydrophobic soil because of the solid–liquid contact properties. An index of water repellency, R, was evaluated as suggested by Tillman et al. (1989) from the sorptivity of water, S_{Water}, and ethanol, $S_{Ethanol}$ using the relationship,

$$R = 1.95\left(\frac{S_{Ethanol}}{S_{Water}}\right) \quad [2]$$

where the constant 1.95 accounts for differences in the surface tension and viscosity between ethanol and water. In a dry soil, R is directly proportional to the reduction in water sorptivity caused by repellency. An $R = 5$, for instance, would indicate a reduction in water sorptivity by a factor of five. Water present in the soil tested will affect the constant 1.95 and therefore R. Under a condition of complete ethanol dilution by water, $R = 1.95$, as differences in surface tension and viscosity no longer exist. In Tillman et al.'s (1989) original work on intrinsic sorptivity they determined that sand with $R = 1$ when dry increased to $R = 1.5$ when wet. They postulated that the reduction of ethanol sorptivity by water was probably offset by the higher surface tension of resident water pushed forward through miscible displacement (Tillman et al., 1989). It is therefore highly probable that a soil with $R > 1.95$ is affected by repellency. Equation [2] cancels out the influence of porosity used to evaluate S in Eq. [1], reducing any potential impact of spatial variability in porosity between water and ethanol sorptivity measurements. The short testing time of <3 min will minimize the time-dependent drop in repellency that has been noted by many researchers in water infiltration studies (Clothier et al., 2000)

Larger-Scale Measurements at Centimeter Resolution

The two techniques used to obtain larger scale water sorptivity measurements were the rapid infiltration method (Smith, 1999) and the tension infiltrometer (White et al., 1992). The technique of Smith (1999) involved infiltration of water from a small ring or cylinder inserted through the soil surface, and solution of Philip's (1957) equation. Measurements were made using two different ring sizes (37- and 55-mm radii) at 32 positions on a 4 by 8 grid. In each direction, ring size was alternated at successive positions. S was calculated by

$$S = D/\sqrt{t_a} \quad [3]$$

where D is the initial depth of water in the ring, and t_a is the time from application of the water to the instant at which half of the soil surface is observed to be no longer covered by water.

A tension infiltrometer with a base radius of 40 mm was used to measure infiltration at a −20-mm hydraulic head. A level contact area between the infiltrometer and the soil surface was obtained by application of a thin layer of fine sand. Measurements of infiltration, I, were made at the same locations as those for the 55-mm radius rings used in the Smith (1999) method. Sorptivity was calculated by Philip's equation, $I = S\sqrt{t}$. As with Eq. [1], hydraulic conductivity has negligible influence and can be ignored as sorptivity dominates infiltration at early time. S may be approximated by the slope of I vs. $\sqrt{t}$ for the first few minutes of testing. Surface elevation was determined by the distance between the infiltrometer surface and the fixed gantry used to support the infiltrometer in the smaller scale measurements described previously.

Spatial Analysis of Data

The spatial structure of soil properties was analyzed using Isatis 3.4 (Geovariances, Avon, France). In general, two neighboring samples are more likely to have similar properties than two samples further apart. Empirical semivariograms describing how data are related (correlated) with distance can be constructed. Semivariance values tend to increase as the distance between sample pairs increases until a plateau (sill) is reached, after which there are no further clear trends with distance. The distance at which the sill is reached is called the range, and is the average distance within which samples are spatially correlated. Semivariograms usually exhibit a discontinuity at the origin, called the nugget effect, because of small-scale variation not accounted for or because of measurement error. The spatially structured or spatially correlated part of the sample variance can be modeled and parameters (range, degree of spatial correlation) describing spatial patterns in the distribution of a variable obtained. Experimental semivariograms were computed for each data set with lags of 50 mm containing at least 731 pairs for both water sorptivity and elevation data and 52 pairs for ethanol sorptivity and water repellency. Spherical models were fitted to determine the range and degree of spatial autocorrelation where it was apparent. Models were adjusted to the experimental semivariograms by a method called multiscale principal components analysis.

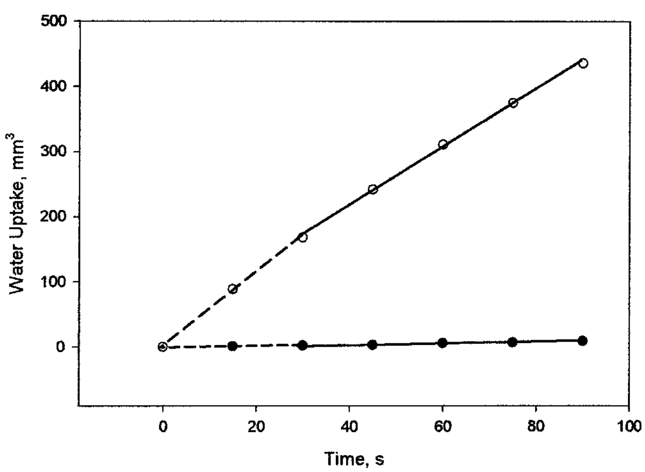

Fig. 1. Water uptake with time at two locations on the test slab that illustrate the extreme range of transport properties examined. The solid line indicates steady-state conditions from which Q was evaluated.

RESULTS

Smaller-Scale Measurements at Millimeter Resolution

The miniaturized infiltrometer provided a sensitive measurement of infiltration rates at millimeter resolution (Fig. 1) and permitted sampling on a 50-mm spatial grid. Flow reached a steady state after about 30 s, thereby permitting an evaluation of Q from the linear slope indicated by the solid line after this time. Water sorptivity, evaluated from Q (Eq. [1]), varied by 800% across the surface of the intact slab of soil (Fig. 2a). Ethanol sorptivity, which provides a measurement of the influence of pore structure on infiltration without most of the effects of repellency, also varied but less than for water (Fig. 2b).

Geostatistical analyses indicated a high level of heterogeneity for all measurements. Two of the data sets were positively skewed (Fig 2); water sorptivity (skewness −2.90) and ethanol sorptivity (skewness −0.61). When data are strongly skewed, (skewness >1) the confidence limits on the semivariogram are wider than they would otherwise be and the semivariances are less reliable (Webster and Oliver, 2001). Therefore, water sorptivity data were natural log-transformed, resulting in a near normal distribution. Ethanol sorptivity data were analyzed after transformation to square roots to obtain a near normal distribution. Surface elevation and water repellency data were near normal (Fig. 2c,d) and were analyzed untransformed. Water sorptivity and repellency variability had no spatial component at the scale of measurement, as the random fluctuations of the semivariogram with distance indicate (Fig. 2a,d). The horizontal or near horizontal semivariograms suggest that much of the variability associated with both of these properties was present at scales below the scale of measurement (<50 mm).

Spatial structure was found for ethanol sorptivity and elevation (Fig. 2b,c). The range of spatial dependence for elevation (275 mm) was longer than that for ethanol sorptivity (258 mm). The spatially correlated part of the variance accounted for more of the total sample variance for elevation (60%) than for ethanol sorptivity (50%). Plots of the spatial distribution of water sorptivity and elevation are presented in Fig. 3. The figures of the spatial distribution of ethanol sorptivity and water repellency, R are for a subset of points from the sampling grid.

A poor relationship was found between sorptivity and surface elevation (Fig. 4a). Water and ethanol sorptivity were not related, indicating the early phase of wetting was influenced by more than just pore structure (Fig. 4b).

Larger-Scale Measurements at Centimeter Resolution

Surface elevation and water sorptivity results for standard scale ponded infiltration tests are listed in Table 1. The difference between measured surface elevations for all tests was insignificant ($P > 0.05$; P indicates the level of significance evaluated from an ANOVA test). Water sorptivity measured using Smith's (1999) approach, was not affected significantly by the size of the infiltrometer ring ($P > 0.05$). In comparison, water sorptivity was much lower for the tension infiltrometer (Table 1) and the small-scale measurements (Fig. 2a) because of the imposed negative hydraulic head. Although water sorptivity was significantly different between the standard tension infiltrometer and smaller scale measurements ($P < 0.001$), it was of the same order of magnitude. The CV was much lower for the larger scale tension infiltrometer results than for the small-scale infiltration measurements, indicating less heterogeneity between measurements.

Elevation and water sorptivity were positively correlated for both ring sizes in the ponded tests (Fig. 5a,b) indicating a contrast in early time infiltration rates between depressions and peaks on the soil surface. No relationship was found between these parameters, however, for the tension infiltrometer test (Fig. 5c).

DISCUSSION

The spatial variability of water sorptivity was high for all types of infiltration measurements at different scales. This is commonplace in soil, primarily because of pore structure heterogeneity (Youngs, 1995) and, in some cases, water storage in topographical depressions (Kamphorst et al., 2000). The high spatial variability in the larger scale-ponded infiltration measurements were probably caused by macropores influencing transport (Smettem, 1987; Lin et al., 1998). At the onset of wetting, such as for the first few minutes of rainfall, infiltration under tension will be prominent so it is very important to also determine water flow without macropore flow dominating the measurements (Smith, 1999). Reducing the influence of macropores, by using a tension infiltrometer, resulted in much lower variability at a similar scale of measurement. Variability in these measurements may have also been reduced slightly by the sand layer used to provide better contact with the rough soil surface.

Reducing the scale of observation in the tension infiltrometer measurements from a 40- to 1.4-mm radius ring size resulted in a large increase in the spatial variability of water sorptivity, to higher levels than was found with the ponded tests discussed previously. A decrease in radius would be expected to increase variability because of the smaller zone of influence (Smettem and Collis-George, 1985; Sisson and Wierenga, 1981). However, the observed increase in water sorptivity with decreasing tension infiltrometer size was unexpected. A variety of factors could affect calculated sorptivity values, however, including soil heterogeneity and assumptions about water flow used in infiltration theory (Youngs, 1995).

As tension infiltration measurements were influenced less by macropore flow, other soil properties must be causing spatial variability. We hypothesized that low levels of water repellency would be responsible for high spatial variability in water transport, particularly under conditions of tension infiltration when macropores are inactive. Repellency is caused by organic matter, waxes from plant leaves, and microbial exudates (DeBano, 2000). Nunan et al. (2002) and Grundmann and Debouzie (2000) have reported high variability and spatial

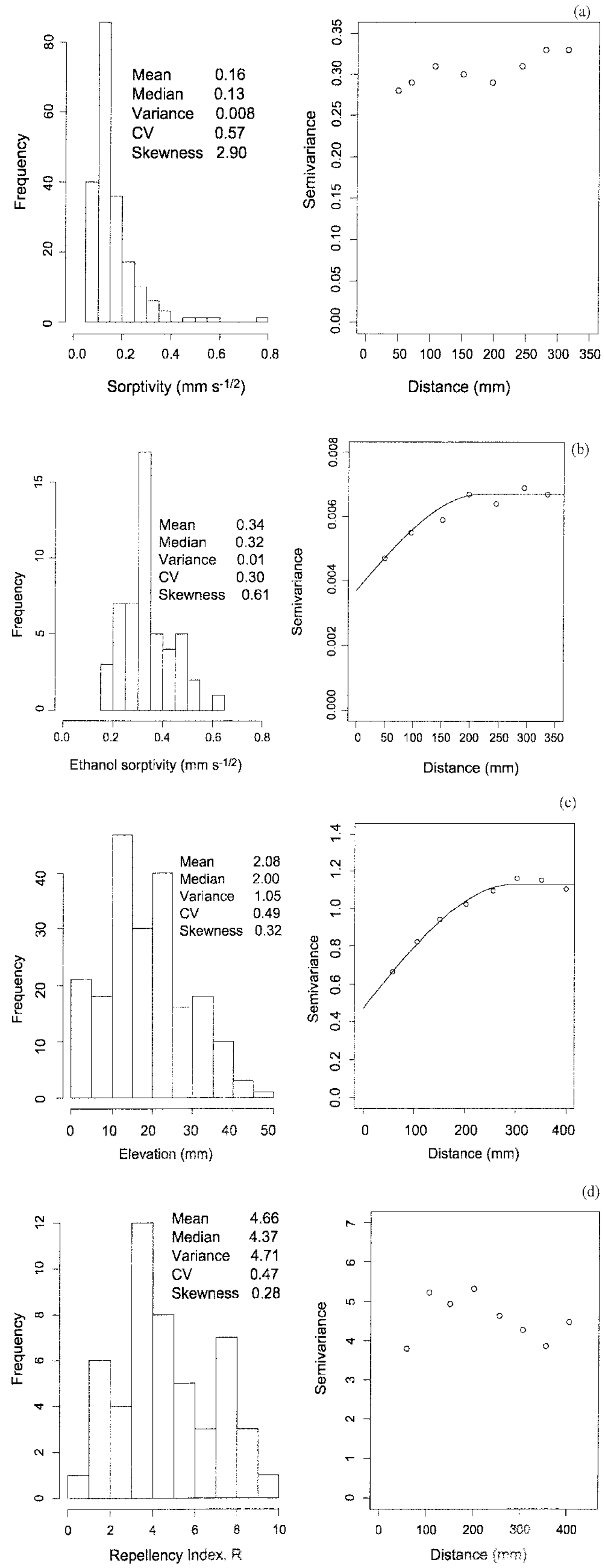

Fig. 2. Frequency distribution and semivariograms for (a) water sorptivity, (b) ethanol sorptivity, (c) surface elevation, and (d) water repellency.

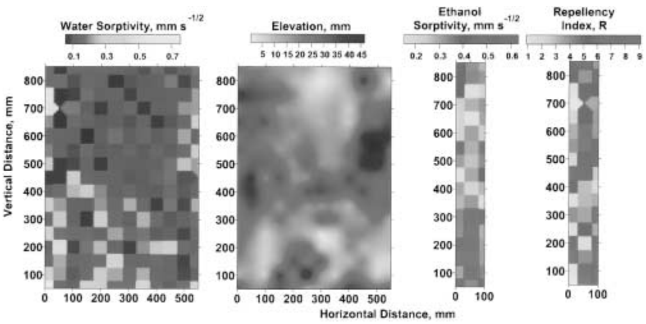

Fig. 3. Spatial plots of transport properties and elevation on the test slab. The elevation data has been kriged using the conditions defined by the geostatical analysis. Both ethanol sorptivity and repellency are for a subset of points with the *x*-*y* coordinates identifying their location in the larger sampling area plotted for the other variables. The sampling interval is 50 mm using a 1.4-mm radius infiltrometer.

correlation in measurements of microbial abundance and microbial activity at scales below 2 mm. Variability in water sorptivity measurements caused by repellency would therefore be masked in the larger scale tension infiltration measurements made with conventional sized infiltrometers, as used in this study, because of averaging over the scales at which the spatial distribution of repellent substances on soil surfaces occurred. Reducing the

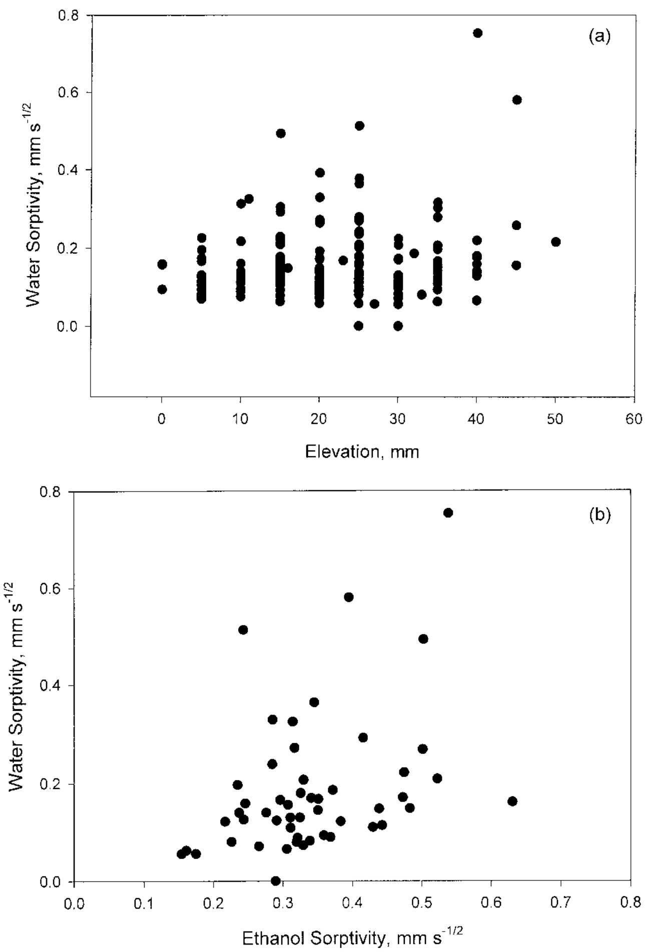

Fig. 4. Relationships between water sorptivity and (a) elevation and (b) ethanol sorptivity, at a sampling interval of 50 mm and an infiltrometer size of a 1.4-mm radius.

Table 1. Sorptivity and elevation results obtained by the method of Smith (1999) for small (37 mm) and large (55 mm) radius rings, and by a large (40 mm) radius tension infiltrometer (−20 mm head) by the method of White et al. (1992). The large radius measurements were taken at the same location for both types of tests.

	Small ring-ponded		Large ring-ponded		Tension infiltrometer
	Sorptivity	Elevation	Sorptivity	Elevation	Sorptivity
	mm $s^{-1/2}$	mm	mm $s^{-1/2}$	mm	mm $s^{-1/2}$
Mean	2.16	19.99	2.62	15.11	0.097
Median	2.15	21.15	2.19	16.60	0.095
Variance	1.32	78.44	1.87	47.36	0.000
CV	0.53	0.44	0.52	0.46	0.22
Skewness	0.13	−0.76	0.49	−0.62	1.283

size of the infiltrometer to millimeter resolution helped to reveal this variability, as the higher variability found at the small scale when compared with the larger scale water sorptivity measurements suggest (Fig. 2a and Table 1). No spatial correlation was evident in the small-scale water sorptivity measurements, suggesting that the factors influencing water sorptivity operate at scales below the minimum lag of the semivariogram, that is, 5 cm (Fig. 2a). Although no other conclusion can be drawn as to the scale of organization of factors affecting water sorptivity, the lack of spatial correlation at the scale of measurement and the highly skewed nature of the water sorptivity frequency distribution (Fig. 2a) are consistent with what has been found for microbial abundance measurements (Nunan et al., 2002).

If water sorptivity measurements were influenced primarily by the pore structure and slight differences in water content, then a significant relationship with ethanol sorptivity would be expected. This was clearly not the case (Fig. 4b). There may be potential error due to slight differences in the spatial location of sampling between water and ethanol measurements, surface contact with the sponge tip of the probe, the influence of ethanol mixing with water during infiltration, and residual water from the first measurements of water sorptivity (Tillman et al., 1989). Moreover, the small size of the probe and −20-mm tension may have masked the influence of macropore flow that would be observed in larger scale measurements. However, if these two variables were closely related, one would also expect them to have similar spatial patterns (i.e., in the case of a positive relationship, regions of high water sorptivity would be expected to also have high ethanol sorptivity) regardless of the slight differences in sample location. Here, the spatial patterns of water and ethanol sorptivity were different, as the semivariograms and frequency distributions indicate (Fig. 2a,b). These suggest that high water sorptivity values are relatively rare and randomly distributed (no spatial correlation), while high ethanol sorptivity values tend to be spatially aggregated or spatially correlated (Fig. 3). The different spatial distributions further emphasize the lack of relationship between the two variables and suggest that different factors are important

No relationship between water sorptivity and elevation was found for tension infiltration measurements (Fig. 4a, 5c), presumably because other properties of soil were more dominant in the variability of water

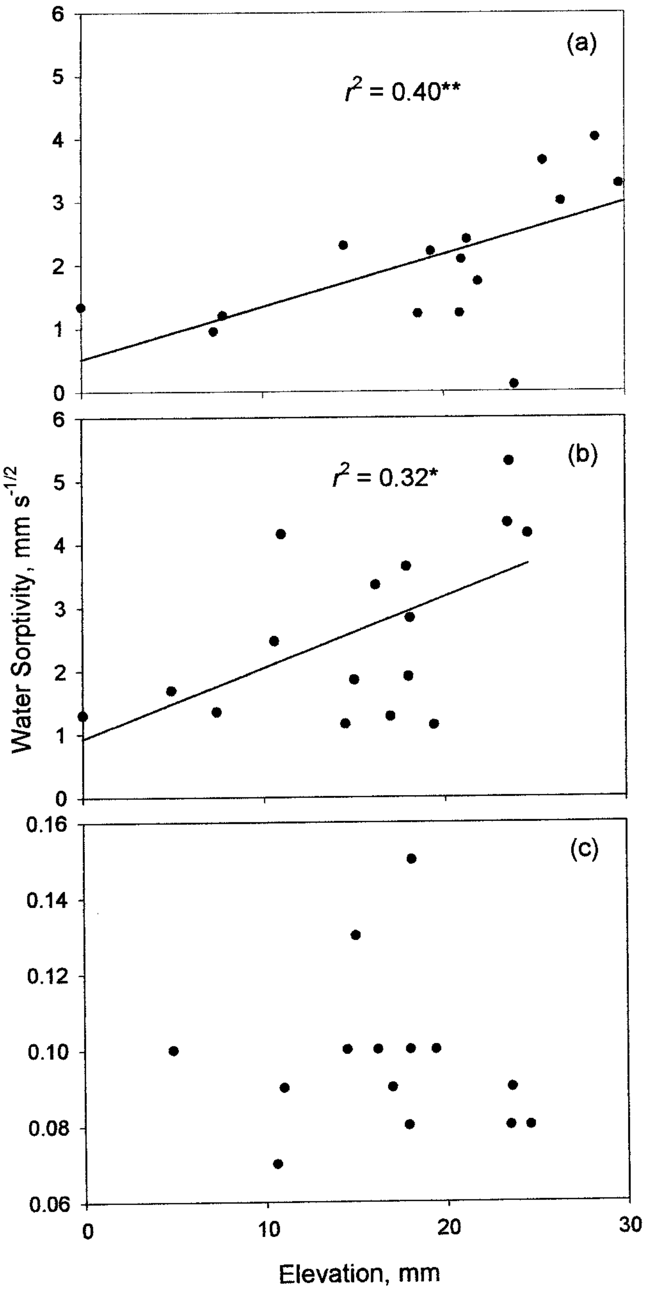

Fig. 5. Relationship between water sorptivity and elevation for measurements obtained using Smith's (1999) ponded method with (a) small and (b) large rings, and for (c) a tension infiltrometer.

sorptivity. This also suggests that depressional storage and deposition had minimal influence on the results. Water repellency is probably the major property of the soil that leads to a high level of variability under tension wetting. Under ponded conditions, the relationship between surface elevation and water sorptivity may have been influenced by extra water storage and the deposition of finer particles in depressions (Fig. 5a,b). Furthermore, Douglas et al. (1992) reported a concentration of soil macropores around the elevated crownal area of grass plants, in contrast with lower areas, on the same grassland soil.

Most soil transport studies ignore repellency, unless it completely impedes water infiltration, because its influence is assumed insignificant. The sensitive testing approach of Tillman et al. (1989), adapted for this study to allow for very small-scale measurements, suggested that repellency is commonplace in soil. Subsequent studies by Wallis et al. (1991) and Hallett et al. (2001) have confirmed this finding for a wide range of soils and have shown that undisturbed pasture soils tend to have higher repellency levels than similar soils under intensive cultivation. The perennial grassland soil we studied had R values > 8, suggesting that water sorptivity at the onset of wetting can be reduced to 1/8 its expected value without the presence of hydrophobic pore surfaces. Even if the constant 1.95 in Eq. [2] is inaccurate due to interactions between invading ethanol and resident water with miscible displacement (Tillman et al., 1989), there is still a significant reduction in water sorptivity due to repellency. This soil was dried in the laboratory from a wet winter condition to a level similar to those found in the summer so the results are applicable to natural conditions. Similar studies on other soils internationally are needed to determine the extent of subcritical water repellency inducing small-scale variability.

The small-scale spatial variability in water repellency will influence the development of overland flow pathways at larger scales (Shakesby et al., 2000). Moreover, the causal agents of repellency tend to be more abundant on the soil surface and along macropore walls because of oxygen availability (Rappoldt and Crawford, 1999), dissolved organic matter eluviation (Gerke and Kohne, 2002), and the deposition of organic matter by soil fauna and plant roots (Young and Ritz, 2000). This will enhance overland and macropore flow in comparison with the bulk soil potentially causing greater erosion and solute transport to ground water. Data on water infiltration, repellency, and surface elevation, similar to that obtained in this study, could be used to extend overland flow and erosion simulation models if the resolution was sufficient to detect areas of spatial contiguity. This may be possible with conventional techniques by reducing the size of infiltrometer used for this study to <0.5 mm in radius (Czarnes et al., 2000), thereby allowing for spatial sampling on a grid finer than 50 mm.

Our study is the first to show that subcritical repellency is a biophysical property of soil that may cause a high spatial variability in water sorptivity at millimeter resolution. Studies on other soils (Hallett et al., 2001; Wallis et al., 1991) suggested a wider range of soil types than first thought, could be affected by repellency, albeit at low levels. Future research on overland flow and water infiltration should consider and potentially measure its influence, particularly how small-scale variability in repellency may influence flow patterns that develop at the onset of wetting and the resulting impact on field scale processes. The data on elevation and water sorptivity collected in this study could potentially be used to extend existing models, although spatial variability below the observation scale would prohibit its application to predicting field scale behavior.

CONCLUSIONS

Subcritical water repellency appears to have a large influence on the spatial distribution of water sorptivity in soil, potentially causing very high levels of spatial variability. Despite using a miniaturized infiltrometer that provided far greater spatial resolution than any previous study, it was too large to detect the spatial dependence of water sorptivity using geostatistics. This complicates our understanding of surface run-off generation and potential erosion since no contiguous surface distribution of water sorptivity levels was detected. The results also demonstrated that repellency, caused by organic matter and biota, could induce very high levels of spatial variability in water transport at small scales. This basic property of soil can therefore have a major influence and needs to be considered when examining water transport heterogeneity.

Although it has been accepted for several decades that repellency influences overland flow patterns and erosion (Osborn et al., 1964), limited research has been conducted in this area. The recent development of more sensitive testing approaches (Tillman et al., 1989; Hallett and Young, 1999) shows most soils to possess a low level of repellency. Consequently, the influence of repellency may be more widespread than was previously believed. A 50% drop in water sorptivity caused by repellency is not uncommon, and it is highly probable that a change of that magnitude would influence the initiation and spatial patterns of overland flow. To effectively predict water sorptivity heterogeneity, finer scale infiltration measurements are needed to detect the scale of spatial dependence. There is scope to integrate the identified small-scale variability of sorptivity with larger-scale phenomena such as overland flow, erosion, and preferential flow.

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