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The Influence of Measurement Methodology on Soil Infiltration Rate

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ABSTRACT

The recorded rate at which water infiltrates into a soil is influenced by the physical condition of the soil, current and previous uses of the soil and the method and equipment used to record the infiltration rate. Soil's natural variability and the potential inaccuracy associated with particular methods can overestimate infiltration rate. To determine the most suitable apparatus for repeated use at a small-scale, a number of trials were conducted to investigate the influence of the method and moisture regime on the recorded infiltration rate. Trials were conducted on a medium clay-loam soil which has cropping history of maize-winter wheat-grass-grass-grass. It was observed that there was no significant difference in recorded infiltration rates which could be attributed to the practice of pre-saturating the soil prior to measuring infiltration rate. Furthermore, there was no significant difference between the rates recorded using a single ring infiltrometer and a double ring infiltrometer, indicating that these methods are equally suitable for infiltration rate determination when working at this scale which facilitates multiple replications in the same location or within a short timeframe.

Key words: Soil infiltration rate, double ring infiltrometer, single ring infiltrometer, agricultural soil

INTRODUCTION

The rate at which water enters and moves through the soil profile is influenced by the physical conditioning of the soil (Hemmat *et al*., 2007). The type, texture, structure, in particular the bulk density and degree of porosity and the moisture content of the soil all influence the infiltration capacity of a soil at any time (Millar *et al*., 1990; Lowery *et al*., 1996; Parr and Bertrand, 1960). Agricultural management practices, both current and previous, also affect a soil's capacity for water infiltration (Boyle *et al*., 1989; Parr and Bertrand, 1960), for example tillage practices have been shown to reduce the degree of porosity within the soil (Emadi *et al*., 2008), restricting air and water movement as well as restricting root proliferation (Avnimelech, 1986). The incorporation of organic material can increase infiltration of water into soil (Boyle *et al*., 1989) by reducing bulk density and increasing porosity (Sylvia *et al*., 1999) and drainage (Yusuf and Yusuf, 2008).

The organic fraction of the soil skeleton has a significant impact on the rate of water infiltration both through its influence on the soil physical environment and through its effect on soil moisture content (Millar *et al*., 1990); organic matter actively adsorbs water particles, holding them in the soil profile. The application of organic material has an effect on the infiltration rate of a soil through its influence on porosity, aggregation and bulk density (Babalola *et al*., 2012) if organic cover is maintained on the soil surface (Gulser, 2004). Millar *et al.* (1990) reported high infiltration rates after application of crop residues to the soil surface, which decreased rapidly when crop residues were removed.

The moisture content of a soil has a significant effect on the infiltration capacity of soil (Aronovici, 1955; Slater, 1957); the higher the soil moisture content at the time of assessing infiltration rate, the lower the observed infiltration rate (Lowery *et al.*, 1996). Chowdary *et al.* (2006) described the moisture content of soil as being the dominant factor influencing the infiltration rate of a soil in the first hours of assessment, however the influence of moisture content decreases as infiltration rate determination continues (Brady and Weil, 2008). Lai and Ren (2007) noted that the high soil water content at the time of conducting their trials abated capillary effect, reducing the contribution of lateral flow to the recorded infiltration rate. Burgy and Luthin (1956) observed no significant difference between the infiltration rates recorded using a single ring infiltrometer and a double ring infiltrometer when working at a high initial soil moisture content, indicating the high moisture content effectively eliminated lateral flow (Chowdary *et al.*, 2006; Lai and Ren, 2007).

Obtaining an accurate measure of the rate at which water infiltrates into soil has proven difficult as the rate is variable (Mahdian *et al.*, 2009) both temporally and spatially as a result of being dependent on multiple variable attributes of soil (Chowdary *et al.*, 2006). The method used to record infiltration rate also has an effect on the observed rate. An ideal infiltrometer measures the mean infiltration rate taking into account the shortcomings of the infiltrometer itself, without affecting the actual infiltration rate (Shouse *et al.*, 1994). It has been suggested that a single ring infiltrometer is the simplest technique for measuring infiltration, however the total flow observed from a single ring infiltrometer has been described as being a result of both horizontal and vertical flow (Tricker, 1978). Lateral flow of water can contribute to overestimating the true infiltration rate of a soil, thus it is generally accepted that an equipment modification should be implemented such that an accurate assessment of the infiltration rate of a soil can be obtained (Landon, 1984; Swartzendruber and Olson, 1961).

One of the most widely applied equipment modifications to reduce the influence of lateral flow on the observed infiltration rate is the use of an outer buffer ring (Bouwer, 1963; Landon, 1984); a double ring infiltrometer is the most commonly used apparatus for determining infiltration rate (Sidiras and Roth, 1987). The buffer ring is employed to reduce the influence of lateral flow by flooding the soil surrounding the inner cylinder, forcing the water in the inner cylinder to move vertically through the soil (Gregory *et al.*, 2005). The efficacy of using a buffer ring can be observed from trials conducted by Chowdary *et al.* (2006), who reported the lateral flow element of cumulative infiltration associated with single ring infiltrometers ranged from 31.8-67.9%, while it ranged from 11.7-11.9% for double ring infiltrometers. Although, lateral flow was still evident when a double ring infiltrometer was used the extent of lateral flow was significantly reduced (Chowdary *et al.*, 2006). Bouwer (1986) found no benefit of using a buffer ring where infiltrometer diameter is small but rather recommended using as large a diameter single ring infiltrometer as practicable to reduce the influence of lateral flow.

It has been suggested that using a larger diameter infiltrometer can compensate somewhat for the heterogeneity of soil and a more accurate and true reading of the infiltration rate of soil can be obtained. Lai and Ren (2007) reported that the representativeness of the soil sampled in the ring infiltrometer increased as the infiltrometer diameter increased. When determining the most suitable equipment for a field study the perceived loss of accuracy associated with using smaller scale infiltrometers must be weighed up against the cumbersome nature of an infiltrometer with a large diameter (Tricker, 1978) and the potentially excessive water requirement (Landon, 1984) associated with a larger instrument, particularly if multiple replications are required. Land managers intent on improving and maintaining the quality of their agricultural holdings can use infiltration rate as a representative of the overall physical conditioning of the soil as it is related to and associated with, numerous other physical parameters, as outlined earlier. Measuring the infiltration rate should, therefore, be a user-friendly, easily repeatable and efficient process. The objective of this research was to investigate the effect that different methodologies and instruments had on the recorded soil infiltration rate to determine the most suitable equipment and method for repetitive measurements.

MATERIALS AND METHODS

Experimental set-up: The influence of the method used to determine infiltration rate was evaluated on a medium clay-loam soil (43% sand, 27% silt, 30% clay) which had been in maize-winter wheat-grass-grass-grass rotation. This soil has an organic matter content of 4.64%, determined using a Skalar Primacs^{SLR} total organic carbon analyser (Skalar Analytical B.V., Breda, The Netherlands). Soil was translocated from its field location at University College Dublin's research farm at Lyons Estate, Newcastle, Co. Dublin, Ireland into purpose-built boxes of size 0.6×0.6×0.45 m. The boxes were designed to minimise edge effects from the box walls during infiltration rate determination. To simulate the presence of crop material post-harvest in a min-till scenario, chopped barley straw was incorporated into the uppermost 75 mm of the soil profile at a rate of 3000 kg ha^{-1} (Fig. 1). The boxes were completely filled with soil and allowed to settle for a number of weeks before organic material was incorporated to ensure there were no air pockets in the soil which could bias water infiltration. The soil was compacted in the boxes to the original in-situ bulk density to reduce the disturbance of the soil. The boxes were located in an area which receives an average of 711 mm of rainfall annually (Fitzgerald and Forrestal, 1996); the total rainfall recorded over the duration of the trial was 108.3 mm.

Measurement of infiltration rate: The infiltration rate of soil was determined once a week for a period of eight weeks using each of three methods; each method was replicated three times

Fig. 1: Soil boxes used to determine the influence of measurement methodology on the recorded infiltration rate of a medium clay-loam soil

(n = 3) per week. The average infiltration rate of the three replicates was used to reduce the effect of soil heterogeneity on the observed infiltration rate as suggested by Chowdary *et al.* (2006). Prior to each infiltration rate investigation, samples of soil were collected from each soil box for moisture content determination. Moisture content was determined gravimetrically (Gardner, 1986).

Method 1: It employed an infiltrometer and methodology outlined by the United States Department of Agriculture (USDA, 1999). This method uses a single ring infiltrometer with a diameter of 152 mm. The time required for a known volume of water, equivalent to a 25.4 mm head, to infiltrate into the soil is recorded. At the measurement scale in question a head of 25.4 mm is equal to 444 mL of water. The soil boxes used in this analysis were saturated 48 hr prior to infiltration rate determination and allowed to return to field capacity prior to infiltration rate being measured, as recommended by Lowery *et al.* (1996). The water used to pre-saturate the soil was the same quality as that used in the determination of infiltration rate.

Method 2: It is based on the falling head method described by Landon (1984) and Gregory *et al.* (2005). Method 2 involves filling a double ring infiltrometer with irrigation water; the initial infiltration rate is determined by recording the fall in the water level in the inner cylinder of the infiltrometer during the first 15 min of the trial. This timeframe was chosen based on trials conducted by Slater (1957) (time taken for 25.4 mm to infiltrate, or 30 min) and Gregory *et al.* (2005) (20-30 min) while bearing in mind the number of replicates that had to be assessed in a single day; it was necessary that the infiltration rate of each soil box be recorded on the same day to minimise variation in the initial soil moisture content caused by changing weather conditions. A double ring infiltrometer of a similar scale to the single ring infiltrometer used in method 1 was used in this method; the diameter of the inner ring was 100 mm and the diameter of the outer ring was 200 mm.

Method 3: It employs the same double ring infiltrometer as method 2 and is again based on the falling head method described by Landon (1984) and Gregory *et al.* (2005). In this case, however, the rate at which rate of fall of the water level is monitored such that a cumulative infiltration rate is determined after 120 min. This time period was chosen keeping in mind the number of replicates that had to be assessed in a single day. It is the same timeframe used by Smith *et al.* (1937) and Tricker (1978) and was considered to be a mid-range duration, with a 90 min duration used by Hemmat *et al.* (2007) and Lai and Ren (2007), a three hour duration used by Bagarello and Sgroi (2004) and a four h duration used by Martens and Frankenberger (1992).

Methods 2 and 3 were investigated both on soils which had and had not been saturated 48 h prior to infiltration rate determination to investigate the effect of pre-saturation on the recorded infiltration rate. The water used to pre-saturate the soil was the same quality as that used in the determination of infiltration rate. The soils which were not pre-saturated received irrigation in the form of natural precipitation only. The soils which were pre-saturated were sheltered such that the pre-saturation water was the only form of irrigation received. This step was included to optimise the potential of achieving field capacity prior to infiltration rate determination. Thus, there were a total of five variable combinations investigated; single ring infiltrometer (with pre-saturation); 15 min initial infiltration rate using double ring infiltrometer (with pre-saturation); 15 min initial infiltration rate using double ring infiltrometer (without pre-saturation); 120 min cumulative infiltration rate using double ring infiltrometer (with pre-saturation) and 120 min cumulative infiltration rate using double ring infiltrometer (without pre-saturation).

Statistical analysis: Differences in the infiltration rates recorded using each of the methods were analysed for significance using SPSS 18.0 statistical package (SPSS Inc., 2009) with method used as between-subjects factor. Differences were separated using *post hoc* tests with a Bonferroni correction and a significance level of $p<0.05$ used to determine significance.

RESULTS

Effect of method used to record infiltration rate: There was no significant difference observed between the infiltration rates recorded using a single ring infiltrometer and those recorded using a double ring infiltrometer. Although the infiltration rates recorded using the single ring infiltrometer were generally higher than those recorded using the double ring infiltrometer (Table 1), this difference was not significant ($F(2,30) = 0.721$).

Similarly, there was no significant difference in the infiltration rates which could be attributed to the duration of measurement. Although the infiltration rates recorded over 15 min were generally higher than those recorded over 120 min (e.g., mean difference: 4.617), this difference was not significant (Table 2).

Effect of moisture regime on infiltration rate: Figure 2 shows the average infiltration rate recorded weekly using each method. The infiltration rates recorded under each of the five measurement variations were analysed to determine whether a significant difference existed in the infiltration rates recorded using different measurement techniques. Included in this analysis was a comparison between pre-saturating soil prior to infiltration rate determination as suggested by Lowery *et al*. (1996) and exposing the soil to naturally-occurring precipitation only. The significance of each of these parameters on the recorded infiltration rate is shown in Table 1.

It was observed that a significant correlation exists between the practice of pre-saturating soil prior to infiltration rate determination and the recorded infiltration rates and between the moisture

Table 1: Significance of pre-saturation of soil, equipment used and moisture regime on recorded infiltration rate of a medium clay-loam soil

Condition investigated	Statistical output
Correlation between moisture regime and soil moisture content	$r_s = 0.161^{ns}$
Correlation between moisture regime and recorded infiltration rate	$r_s = -0.264^{**}$
Correlation between soil moisture content and recorded infiltration rate	$r_s = -0.212^{**}$
Effect of pre-saturation of soil on recorded infiltration rate	$F(1,19) = 2.886^{ns}$
Effect of equipment used on recorded infiltration rate	$F(2,30) = 0.721^{ns}$

r_s: Spearman's rho statistic, F = ANOVA F statistic, ns: Non significant, **Highly significant at ($p<0.01$)

Table 2: Significance of the method used on recorded infiltration rate of a medium clay-loam soil

Condition investigated	Mean difference[a]	Significance
Single ring vs. double ring (initial)	1.541	ns
Single ring vs. double ring (cumulative)	6.158	ns
Double ring (initial) vs. double ring (cumulative)	4.617	ns

[a]A positive mean difference indicates a higher infiltration rate recorded for the first method than for the second method in the comparison, ns: Non significant

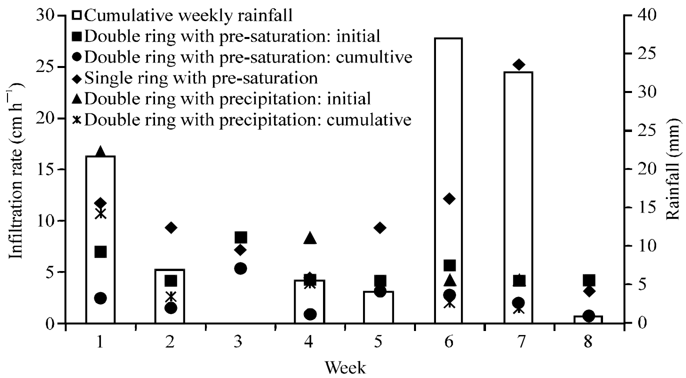

Fig. 2: Average infiltration rate recorded weekly for eight weeks (June to August 2010) under each of the five assessment conditions

content of the soil at the time of measuring infiltration rate and the infiltration rates recorded. Despite these correlations the infiltration rates recorded for soils which had been pre-saturated were not significantly different from those recorded for soils which were exposed to precipitation only. No correlation exists between the pre-infiltration moisture regime and the moisture content at the time of recording infiltration rate (Table 1). This indicates that pre-saturating the soil did not influence the moisture content at the time of infiltration rate determination.

DISCUSSION

Effect of method used to record infiltration rate: No significant differences were observed between the infiltration rates recorded using a single ring infiltrometer and a double ring infiltrometer. This suggests that these methods are equally suitable for the determination of the infiltration rate of soil when working at this scale. This result is in keeping with that of Bouwer (1986) who reported no benefit of using a buffer ring when working at a small scale. The infiltration rates recorded using the single ring infiltrometer were generally higher than those recorded with the double ring infiltrometer, which is contrary to the findings of Chowdary *et al.* (2006) who recorded infiltration rates using infiltrometers ranging in diameter from 0.1-0.35 m and observed higher infiltration rates when using infiltrometers at the lower end of the size range.

No significant differences were observed between the initial infiltration rates and the cumulative infiltrations rates recorded over this trial. Chowdary *et al.* (2006) reported that infiltration rates recorded using single and double ring infiltrometers were similar up to a point (approx. 50 min) after which the rates diverged. This is contrary to the rates recorded during this research which indicates that under the conditions investigated there was no significant difference between the infiltration rates recorded using single and double ring infiltrometers up to 120 min. This suggests that lengthy measurement duration is not required for the determination of infiltration rate when working at this scale as steady-state infiltration had been reached. This measurement duration is in keeping with that used by Gregory *et al.* (2005), as is the diameter of the infiltrometer used.

Effect of moisture regime on infiltration rate: It was observed that the infiltration rate of a soil is affected by the moisture content at the time of determination, as reported by Lowery *et al.* (1996) and Chowdary *et al.* (2006). Soils which had been exposed to precipitation exhibited more variable moisture contents than soils which were pre-saturated. Precipitation-exposed soils exhibited moisture contents ranging from 1.56% in incidents of low rainfall to 40.22% in incidents of high rainfall, whereas pre-saturated soils' moisture contents ranged from 7.91-24.62%. As this trial was conducted outdoors the soil boxes were exposed to all environmental conditions of heat, wind and humidity which may explain the variation in the recorded moisture contents. There was no significant difference between the infiltration rates recorded for soils which had been pre-saturated compared to those that were exposed to naturally-occurring precipitation, despite the recommendation by Lowery *et al.* (1996) to pre-saturate the soil before allowing it to return to field capacity.

CONCLUSIONS

The infiltration rates recorded using a single ring infiltrometer did not differ significantly from those recorded using a double ring infiltrometer; this suggests that either method is suitable when working at this scale. From a land owner's perspective the ease of handling of a single ring may be the deciding factor in choosing this method without having to sacrifice the accuracy associated with using a double ring infiltrometer. In addition, there was no significant difference observed between measuring infiltration rate after 15 min and after 120 min.

There was no significant effect of pre-saturation of soil prior to determining infiltration rate. This result suggests that under Irish conditions of rainfall the infiltration rate of a soil can be determined without the need to saturate the soil and allow it to return to field capacity prior to assessment. This result has the potential to minimise delays and bias introduced by changing weather conditions which may be important where multiple replications are required.

The water savings associated with using a single ring infiltrometer over a double ring infiltrometer as well as not having to pre-saturate soil prior to infiltration rate determination may make the single ring method more favourable both from an environmental and a labour point of view. The time saving from conducting infiltration measurements over a shorter duration is in the double ring infiltrometer's favour, however. Given the time savings and the accuracy associated with the equipment, it is considered that the double ring infiltrometer should be the default instrumentation choice when working at this scale.

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