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A modified hood infiltrometer to estimate the soil hydraulic properties from the transient water flow measurements

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Abstract

In-situ measurements of soil hydraulic properties on covered soil surfaces (i.e. vegetated or residue covered surfaces) are of paramount importance in many agronomic or hydrological researches. These soil parameters are commonly estimated with the tension infiltrometry technique. This paper presents a portable and modified design of the hood infiltrometer (MHI) that, unlike to the original hood infiltrometer, allows estimating the soil hydraulic properties from the transient cumulative infiltration curve. The MHI consists of a water-supply reservoir attaches to a hat-shaped base placed on the soil surface. The base of the hat is closed by a system of sticks and a malleable material ring. To test the viability of this new design, the hydraulic conductivity (K_s) estimated with MHI in a loam soil using the multiple head approach was compared to the corresponding values calculated from the transient infiltration curve analysis. Next, the MHI was tested on three different soils at saturated conditions, and the sorptivity (S) and K_s estimated by the transient infiltration curve analysis were compared to the corresponding values obtained with a disc infiltrometer (DI). An additional field experiment was performed to compare the hydraulic properties measured with MHI on a bare soil and a soil covered with plants. Results demonstrated that this design allows hermetically closing the base of the hat without disturbing the soil surface. The K_s estimated with the multiple head approach was not statistically different ($p = 0.61$) to that obtained with the transient infiltration curve analysis. No significant differences between the K_s ($p = 0.66$) and S ($p = 0.50$) values estimated with DI and MHI were observed. The S values measured with MHI on the covered soil surface were significantly higher than that measured on the adjacent bare soil. These results indicate that MHI can be a viable alternative to estimate the hydraulic properties of covered soils from the measured transient infiltration curve.

Keywords: Disc infiltrometer; Hydraulic conductivity; Sorptivity; Nonstationary water flow state.

1. Introduction

Measurements of the sorptivity (*S*) and hydraulic conductivity (*K*) on undisturbed soil surface is crucial to solve many hydrological engineering and environmental issues linked to soil water storage and transport in the vadose zone. The tension disc infiltrometer (Perroux and White, 1988) and later the hood infiltrometer (Schwärzel and Punzel, 2007) have become popular infiltration methods because of the relatively rapid and portable nature of this technique, its easy in-situ applicability, and its ability to measure at unsaturated soil conditions (Angulo-Jaramillo et al., 2000). The disc infiltrometer consists of a disc base attached to a graduated water-supply reservoir and a bubbling tower to impose a negative pressure head (h) at the disc base (Perroux and White, 1988). The hood infiltrometer, which can measure on covered soil surface, is a similar instrument where the disc base has been replace the by a side down hood.

The soil hydraulic properties are commonly calculated from the cumulative water-infiltration curves, which are measured from the drop in the water level of the reservoir tower. So far, several methods to estimate the soil hydraulic properties have been proposed: (i) methods based on the Wooding (1968) equation, which uses steady-state data (Ankeny et al., 1991; Reynolds and Elrick, 1991), (ii) methods based on the transient state data (Latorre et al., 2015) and (iii) methods which combine both transient and steady states, like BEST methods (Lassabatere et al., 2006; Yilmaz et al., 2010) The main advantages of the transient water flow procedure is that it requires shorter experiments, which involves smaller sampled soil volumes and more homogeneous initial water distribution (Angulo-Jaramillo et al., 2000).

The disc base of the infiltrometer, whose diameter ranges from 25 cm (Perroux and White, 1988) to 3.2 cm (Madsen and Chandler, 2007), is usually covered with a tightened nylon cloth of very small mesh. The base should be completely in contact with the soil surface to accomplish correct infiltration measurements. To achieve this contact, Perroux and White (1988) recommended trimming any vegetation within the sample to ground level and cover the soil with a material (i.e. sand layer) of high hydraulic conductivity. However, according to Reynolds (2006), the contact sand layer introduces an offset between the pressure head set on the bubbling tower and the pressure head applied to the soil surface. This offset should be corrected to prevent the introduction of systematic biases in infiltration results (Reynolds, 2006). These limitations were partially solved by Moret-Fernández et al. (2013), who developed an alternative disc base with a malleable membrane (MDB) that allowed excellent soil surface contact without using a contact sand layer. However, this membrane base prevents infiltration measurements on abrupt surfaces or soils covered with plants or crop residues. This problem was solved by UGT (Müncheberg, Germany), who developed a tension infiltrometer where the disc base was replaced by an acrylic (12.4 cm in diameter) hood. The hood is placed open side down onto the soil, within a retaining ring inserted into the soil, and the water-filled hood is directly in contact to the soil surface. Schwärzel and Punzel (2007) compared this new design with the conventional disc infiltrometer that uses a contact sand layer and observed that the hydraulic conductivities measured with this alternative design were 10 times higher than that measured with the disc infiltrometer. Although this system allows infiltration measurements on covered soils, the slow filling of the hood during the first infiltration times prevents estimating the soil hydraulic properties by using the transient water flow method. In this case, the multiple head approach, which is more time consuming, should be used. On the other hand, the retaining ring used to close the hood, which is slightly inserted into the soil, may create preferential infiltration channels that distort the infiltration measurements.

The objective of this paper is to present a modified hood infiltrometer, MHI, to estimate the soil sorptivity and hydraulic conductivity on covered soil surfaces. Unlike to the original hood infiltrometer, which employs the multiple head approach, this new prototype allows recording and using the transient infiltration curve to estimate the soil hydraulic properties. Because of the multiple head approach has been satisfactorily applied on the hood infiltrometer, this work will be mainly focused on the transient infiltration flow method. To validate this new prototype, the soil hydraulic properties estimated with the MHI in three different uncovered soil surfaces were compared with those estimated with a conventional disc infiltrometer, which, similarly to MHI, also allows estimating the soil hydraulic properties from transient water flow measurements. In a second step, the MHI was tested on a covered soil. To this end, the soil hydraulic properties measured on covered surfaces were compared with those obtained in the adjacent uncovered soil..

2. Material and methods

2.1. Infiltrometer design

Similar to the disc infiltrometer (DI), the modified hood infiltrometer (MHI) consists of a hat-shaped base attached at the top to a water-supply reservoir and a bubbling tower that imposes a negative pressure head (h) at the hat base (Fig. 1a and b). The hat base is a cylindrical acrylic tube (10 cm internal diameter –i.d-; 10 cm height) attached at the base to a metallic flat ring (3 mm thickness and 10 and 15 cm internal and external diameter, respectively), and closed at top by an acrylic lid. Three 1.5-mm deep holes are equidistantly made on the metallic ring, at 2.5 cm from the external diameter. The water reservoir consists of a 5 cm i.d. and 55 cm long acrylic tube. A vertical acrylic tube, that vertically traverses the hat, is connected to the water reservoir through a ball valve (Fig. 1). This vertical tube, which is placed at 1.5 cm from the soil surface, contents a 3 mm i.d. plastic pipe (*air inlet tube*) that is connected to a bubbling tower. A 8 mm i.d. silicone tube (*air flow tube*) connects the top of the water reservoir tube to the top of the hat (Fig. 1). This tube is closed by an air flow plastic stopcock. To check the pressure head on the soil surface a water manometer is inserted at the top of the hat. Finally, a ±0.5 psi differential pressure transducer (PT) (Microswitch, Honeywell), connected to a datalogger (CR1000, Campbell Scientist Inc.), is installed at the bottom of the water-supply reservoir (Casey and Derby, 2002). Previous laboratory experiments demonstrated the accuracy of PT for water level measurements was ±0.27 mm. The base of the hat is closed by compressing the MHI base against the soil surface. To this end, a three detachable sticks system is used (Fig. 1b).

2.2. Infiltrometer setup

Installation of modified hood infiltrometer needed the following steps. Firstly, a 10 cm diameter piece of cloth is placed on the soil surface to be measured. This prevents the soil surface disturbance during the hat water-filling. A malleable material (Plasticine®) ring (11-cm i.d and 1.5 cm thickness) is pasted under the hat, and the hat plus the malleable material ring are placed on the soil surface, making sure the 10-cm diameter cloth rested within the hat. Three arm-sticks (30-cm length and 2-cm thickness) (Fig. 1b), which are welded to a perforated iron metallic head, are equidistantly and perpendicularly placed against the metallic ring perimeter. A 25 cm long screw is screwed at the end of the arm, resting the ends of the screws on the corresponding metallic ring holes. Three sticks (40-cm length and 2-cm thick) are introduced in the corresponding perforated iron heads (Fig. 1) and subsequently are driven into the soil down to 30-cm depth. The iron heads are blocked and the hat base plus the malleable material is compressed against the soil surface by screwing the arm-stick screws against the hat base (Fig. 1). The strong pressure on the metallic ring, which squashes the malleable material against the soil surface, hermetically closes the base of the hat. In order to obtain sealing of the hat, the screws of the arm-sticks should be progressively and alternatively screwed.

Once the MHI base is installed, the bubbling tower is connected to the MHI *air inlet tube* (Fig. 1) and the water-supply reservoir is assembled on the hat. Next, the *air flow tube* is connected and the corresponding stopcock opened. The ball valve for water flow is turned off and the water reservoir is filled with water. Finally, the pressure transducer is connected to the data logger. Saturated infiltration measurements require that the pressure head inside the bubbling tower is equal to the distance between the soil surface and the end of the *air outlet tube* (Fig. 1). Thus, the pressure head measured with the water manometer (h_M) is

$$h_M = h_{BT} + h_{WL} \qquad (1)$$

where h_{BT} is the pressure head supplied by bubble tower and h_{WL} the water level inside the hat (Fig. 1). To start the infiltration measurements, the ball valve for water flow is turned on and the plastic stopcock for air flow is kept opened until the water level inside the hat reaches 2 to 4 cm height. This mechanism allows the air flows from the hat to the water reservoir, as the hat is filled with water. Once the plastic stopcock is closed, the air for water infiltration is immediately supplied from the bubble tower.

2.3. Field testing

A first field experiment to measure the maximum tension that can be maintained inside the hood infiltrometer before the air starts to enter by the base of the hat was performed. To this end, two infiltration experiments at saturation conditions were performed in a compacted soil located in an olive tree field in the campus of the Estación Experimental de Aula Dei (EEAD-Oli). The soil is loam and selected physical and chemical properties are summarized in Table

1. To monitor the pressure head changes in the hat, the water manometer was replaced by a ±0.5 psi PT connected to the data logger. Ten minutes after the start of the infiltration, the bubbling tower was blocked out and the infiltration continued until the pressure head in the hat was stabilized. This indicates that the vacuum into the hat was broken. According to Eq. (1), the maximum pressure head inside the hat ($h_{\max}$) measured during the hat vacuum experiment was calculated according to

$$h_{\max} = h_{M_{Final}} - \left(h_{BT_{Sat}} + h_{WL}\right) \qquad (2)$$

where $h_{M_{Final}}$ is the final hat pressure head vacuum into the hat was broken (Fig. 2). Although it is not the main objective of this paper, an additional experiment was performed in the same field to test the viability of the MHI to estimate the hydraulic conductivity with the multiple head approach. Three infiltration measurements at three consecutive soil tensions, 0, 2 and 5 cm, for 14, 20 and 25 minutes, respectively, were concluded. The pressure head inside in the hat was monitored with a ±0.5 psi PT connected to the datalogger. Flow readings were automatically recorded every second from the drop in water level of the water supply reservoir. The K_s estimated from transient cumulative infiltration curve was next compared to the corresponding values estimated with the multiple head approach (Ankeny et al., 1991).

The soil hydraulic properties estimated with this new prototype were subsequently compared with those estimated with a disc infiltrometer (DI) in three experimental fields with different soil conditions (Table 1). The first field was the EEAD-Oli above described. The infiltration measurements were randomly distributed within a 25 m^2 surface. The second field (EEAD-NT) was located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (41°44′N, 0°46′W, altitude 270 m). Soil at the research site is a loam (fine-loamy, mixed, thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Selected physical and chemical properties of the soil

(Table 1) were given in López et al. (1996) and Blanco-Moure et al. (2012). The infiltration measurements were conducted on a rectangular plot (30 x 10 m^2) under no tillage treatment (NT), set up on a nearly level area (slope 0–2%). The experimental field corresponds to a long-term conservation tillage experiment started in 1991. The field was in the fallow period of 18 months-long winter barley (Hordeum vulgare L.)–fallow rotation. The third field (CODO) was located in the Codo municipality (NE Spain; 41º30'N, 0º15'W). The land use in the area is based on a traditional agro-pastoral system involving dry cereal croplands and extensive sheep production. Soil at the research site is loam (Calcic Petrogypsids) according to the USDA classification (Soil Survey Staff, 2010). More details of chemical analysis of the soil (Table 1) were given Moret-Fernández et al. (2011). The infiltration measurements were randomly distributed within a 20 m^2 surface.

The DI employed in the experiment was a conventional Perroux and White (1988) infiltrometer with a base radius of 50 mm. To install the DI a circular thin layer of commercial sand (80–160 μm grain size), with the same diameter as the disc base, was layered on the soil surface. This allowed a good hydraulic contact between the base of the disc (covered with a 20 μm mesh nylon cloth) and the soil surface. Similarly to the HI, the water level in the water reservoir was recorded with a ±0.5 psi PT, which connected to a datalogger (CR1000, Campbell Sci.) was installed at the bottom of the water supply reservoir.

All infiltration measurements were done on a nearly levelled and bare soil surfaces. The infiltration sites of DI were separated about 30-50 cm from MHI measurements. In all cases, only infiltration measurements at soil saturation conditions were conducted. Flow readings, which last up to 10 min, were automatically recorded every 5 s from the drop in water level of the water supply reservoir. The final soil water content, needed to calculate the hydraulic conductivity, was sampled from the upper centimetres of the soil just after removing the disc infiltrometer from the soil surface. The soil dry bulk density (ρ_b), also used to determine the initial volumetric water content of the soil, was determined by the core method with core dimensions of 50 mm diameter and 50 mm height. The core samples were taken near the measurement locations, the same day as infiltration measurements. Ten and four ρ_b samplings were taken in CODO and EEAD (EEAD-NT and EEAD-Oli), respectively. A total of 39 soil infiltration measurements for each infiltrometer type, 20 in CODO, 10 in EEAD-NT and 9 in EEAD-Oli, were completed. The K_s and S values were calculated from the cumulative infiltration curve using the Latorre et al. (2015) procedure, which analyses the transient cumulative infiltration curve using the cuasi-analytical solution of the Richards equation for a disc water source (Haverkamp et al., 1994). This procedure automatically omits the jump in the cumulative infiltration curve produced by contact sand layer, if used, and directly estimates both K_s and S. The K_s and S values estimated with DI were compared to the corresponding values measured with MHI. To this end an ANOVA test was used.

In order to check the viability of MHI on covered soils, an additional field experiment was done in the CODO field (Table 1). The hydraulic properties measured with MHI on soil covered with a plant of *Salsola Kali* were compared with the corresponding measurements obtained on the bare soil. Nine replications were performed in both covered and bare soils, and the distance between the pair of infiltration points was around 30-40 cm.

3. Results and discussion

Field experiments demonstrated that the system used to fix the hat of the infiltrometer on the soil surface is portable and easy to install. This also was an efficient system to hermetically close the base of the hat without disturbing the soil surface and without preventing the lateral water flow by capillarity. The time needed to install the MHI was less than 6 minutes. On average, the time to fill the hat up to 3.5 cm height sheet of water and the time to start the bubbling in the bubbling tower was about 2-3 seconds and 6 seconds, respectively. The hat vacuum experiment showed that the average maximum pressure head allowed inside the hat was -12.1 cm (Fig. 2). Infiltration experiments under unsaturated infiltration conditions demonstrated that MHI can infiltrate at negative pressure heads (Fig. 3). The non-significant differences between the K_s estimated with the MHI using the multiple head approach and that using the transient cumulative infiltration analysis demonstrated that MHI can satisfactorily run with both methods (Tabla 2). However, while the multiple head approach needed about 1 hour to estimate K_s, less than 15 minutes were needed with the transient infiltration method.

The cumulative infiltration curve obtained with MHI showed a large jump in the first seconds of the infiltration measurements (Fig. 4). This corresponds with the filling of the hat once the ball valve is opened. Despite this irregular shape, the K_s and S were successfully estimated with the Latorre et al. (2015) numerical procedure which, similarly to DI with contact sand layer, allowed correcting the infiltration jump. This method also allowed estimating the time needed to start the bubbling (Fig. 4). Overall, the deep well observed in the K_s and S error distribution (Fig. 4), calculated by the numerical optimization of the Haverkamp et al. (1994) model (Latorre et al., 2015), indicates the infiltration curves recorded with MHI allows accurate estimates of the soil hydraulic properties.

No significant differences between the K_s and S calculated in the three fields with the DI and the corresponding values estimated with the MHI were observed (Table 3). The standard deviation and the dispersion of the K_s and S values, due to the soil surface hydraulic properties variability, was similar in the two infiltrometers (Fig. 5). The estimated hydraulic parameters were within the same order of magnitude than those obtained by Moret and Arrúe (2007) and Moret-Fernández et al. (2013) in the same field, or Lampurlanés and Cantero-Martínez (2006) in a similar semiarid dry-land region. These results indicate that the MHI can be an alternative instrument to estimate the soil hydraulic parameters from the transient infiltration curve.

Comparison between the hydraulic properties measured in the CODO field on bare and covered soil showed that S under *Salsola* (0.303 mm $s^{-0.5}$) was significantly higher ($p = 0.015$) than the measured in bare soil (0.184 mm $s^{-0.5}$). These differences can be attributed to the higher organic matter content accumulated on the soil surface, under the *Salsola* plant, which may increase the water absorption capabilities during the first infiltration stages. No significant differences in K_s were observed between the different soil surfaces, which values were 0.064 and 0.068 mm s^{-1} for the bare and covered soil, respectively.

4. Conclusions

This paper presents a modified design of the tension hood infiltrometer (MHI), that allow estimating the sorptivity (S) and hydraulic conductivity (K) on covered soils using the transient cumulative infiltration curve. Field tests demonstrated that MHI can estimate the soil hydraulic conductivity using both the multiple head approach and the transient infiltration curve analysis. The new prototype was validated by comparing the soil hydraulic properties estimated with this technique on three different uncovered soil surfaces with those measured with a conventional disc infiltrometer. The results demonstrate that this technique allowed accurate estimates of both sorptivity and hydraulic conductivity. Finally, this work demonstrates that this prototype also allows satisfactory estimations of the soil hydraulic properties on covered soil surfaces. Compared to the hood infiltrometer (Schwärzel and Punzel, 2007), the MHI allows using the transient cumulative infiltration curve to estimate the soil hydraulic properties, which substantially reduces the length of the experiment. These results show that the MHI can be an alternative to the DI when infiltration measurements are required on covered soils. However, caution should be taken when using this instrument, since erratic results can be obtained if: (i) the hat of the infiltrometer is not hermetically closed against the soil surface, for which lateral bubbling will be observed in the hat; or (ii) a bubbling is observed from the wetted soil surface inside the hat. In these cases, similarly to the original hood infiltrometer, the experiment should be stopped and repeated in other place.

Acknowledgements

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Figures captions

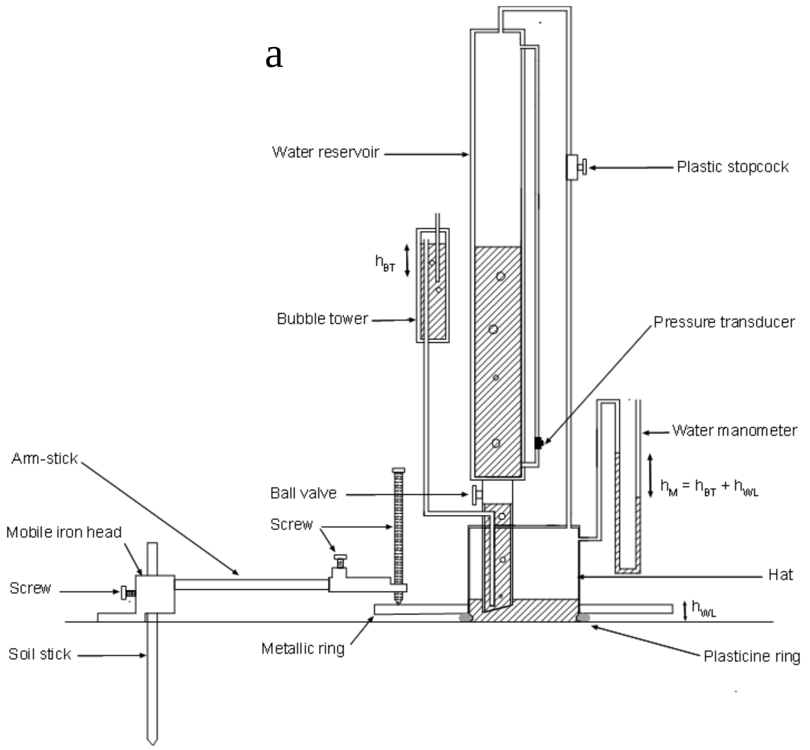
Figure 1. Diagram (a) and picture measuring in the NT field (b) of the modified hood infiltrometer.

Figure 2. Cumulative infiltration (I) and hat pressure head (h) curves measured with the modified hood infiltrometer during the hat vacuum capability experiment. White and grey colours indicate the first and second replication of infiltration measurements

Figure 3. First replication of the multiple head infiltration measurement (a) and the corresponding pressure head inside the infiltrometer hat (b) recorded with the MHI in the EEAD-Oli field

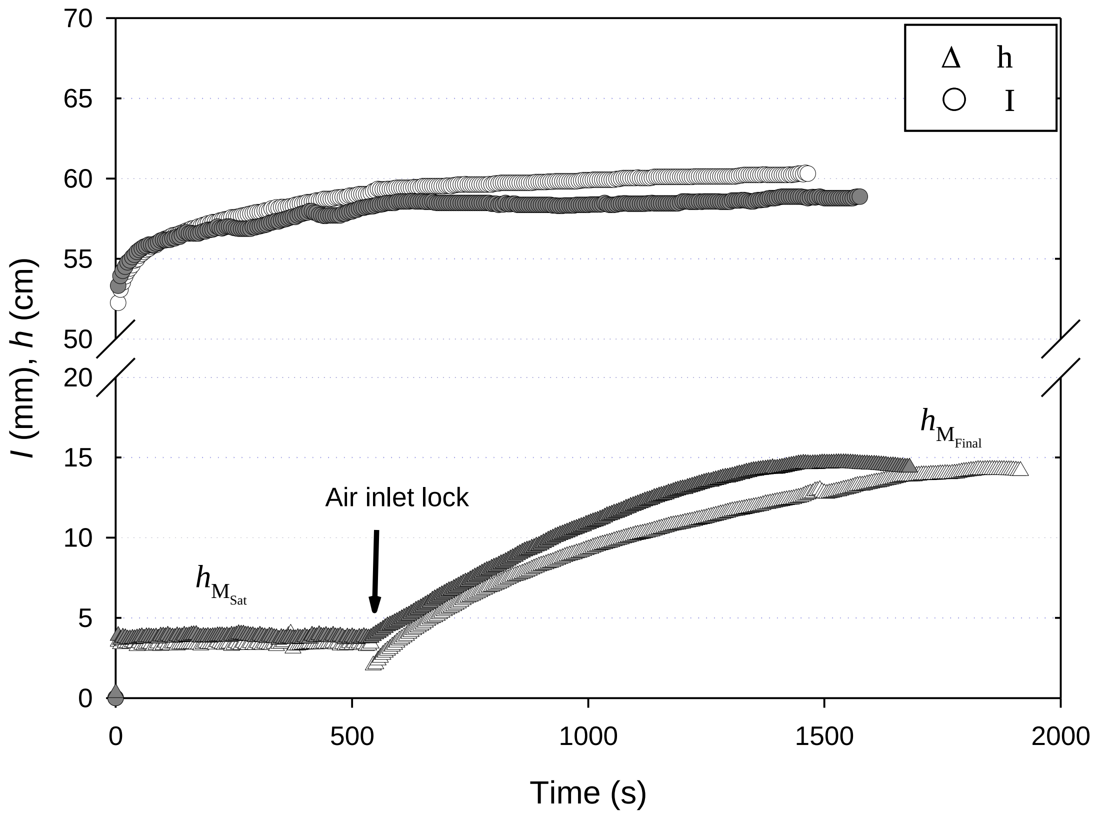
Figure 4. Measured (circles) and modelled (line) cumulative infiltration curves measured with the modified hood infiltrometer in the bare soil surface of the CODO field (a), and error distribution functions estimated for the sorptivity ,S, (b) and hydraulic conductivity , K_s (c) according to the Latorre et al. (2015) procedure.

Figure 5. Soil sorptivity (S) and hydraulic conductivity (K) values measured with the disc and modified hood infiltrometers (MHI) in the CODO and EEAD (EEAD-NT and EEAD-Oli) experimental fields.


a
Water reservoir
Plastic stopcock
h_{BT}
Bubble tower
Pressure transducer
Water manometer
Arm-stick
$h_M = h_{BT} + h_{WL}$
Ball valve
Screw
Mobile iron head
Hat
Screw
h_{WL}
Soil stick
Metallic ring
Plasticine ring


b

Fig. 1.


70
65
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20
15
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5
0
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○ I
Air inlet lock
$h_{M_{Sat}}$
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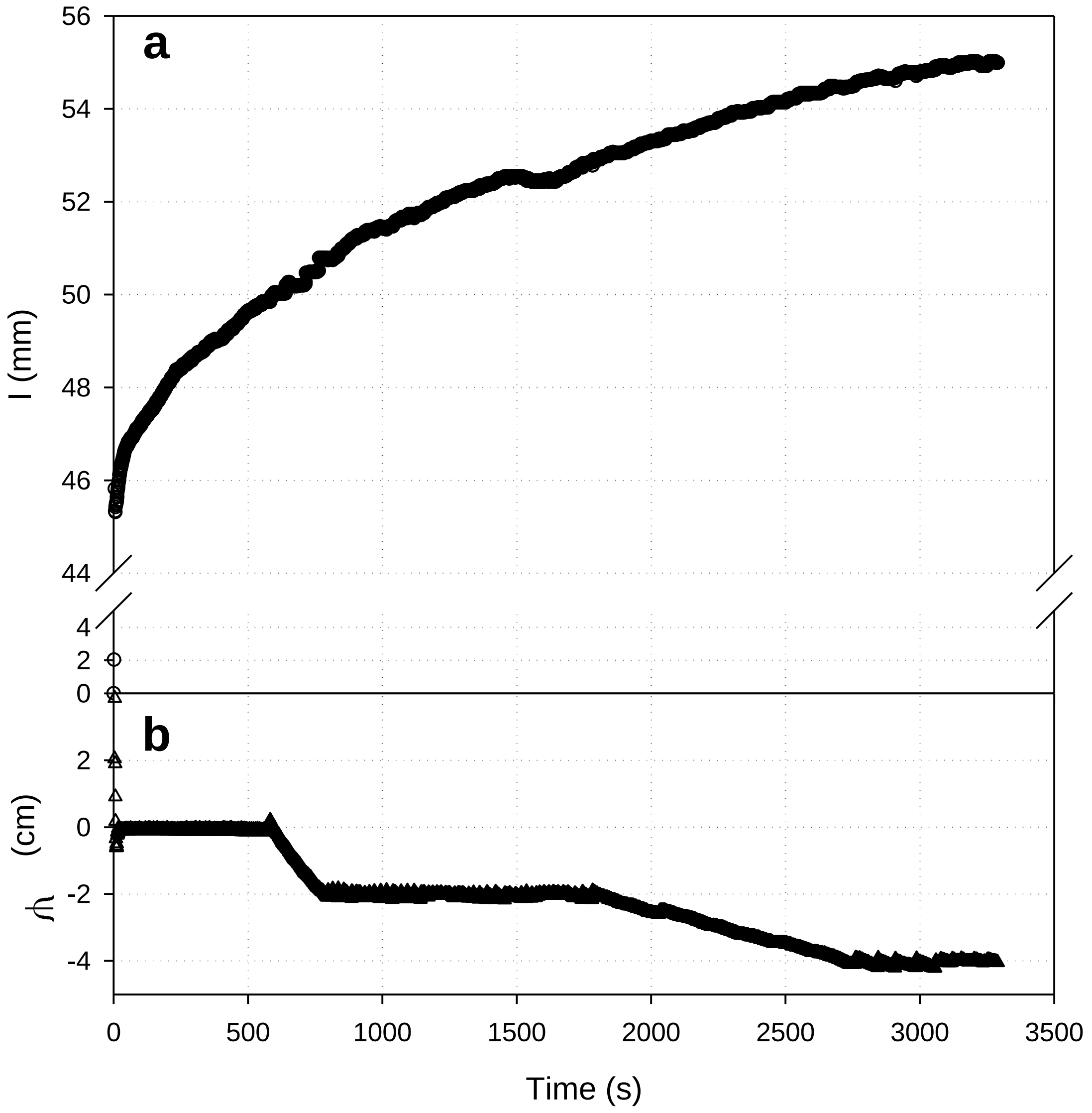
I (mm), *h* (cm)
0
500
1000
1500
2000
Time (s)

Fig. 2.


a
b
l (mm)
h (cm)
Time (s)
56
54
52
50
48
46
44
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0
2
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-2
-4
0
500
1000
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2000
2500
3000
3500

Fig. 3.

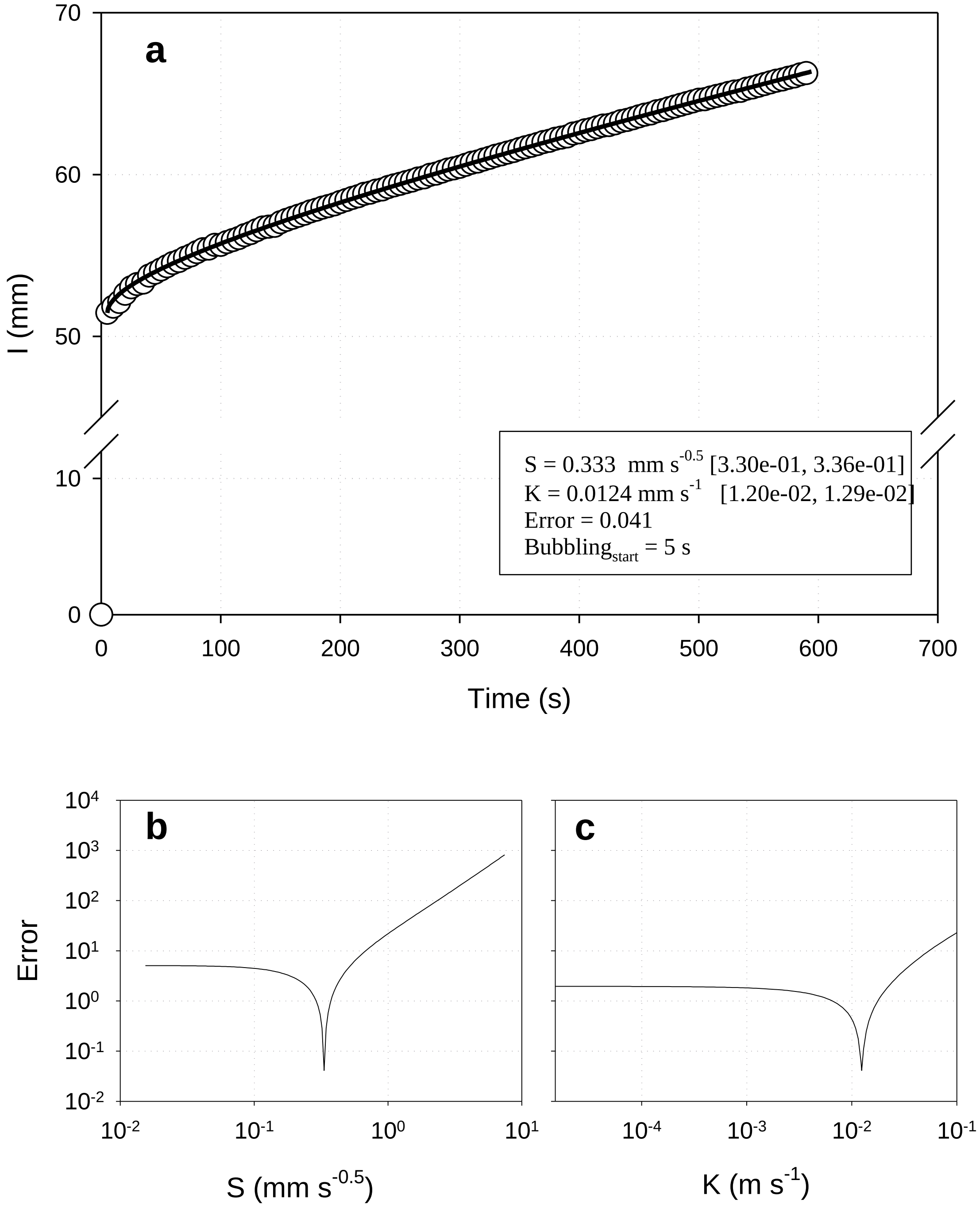
a
70
60
50
10
0
I (mm)
0
100
200
300
400
500
600
700
Time (s)
S = 0.333 mm s-0.5 [3.30e-01, 3.36e-01]
K = 0.0124 mm s-1 [1.20e-02, 1.29e-02]
Error = 0.041
Bubblingstart = 5 s
b
c
Error
10-2
10-1
100
101
S (mm s-0.5)
10-4
10-3
10-2
10-1
K (m s-1)

Fig. 4.

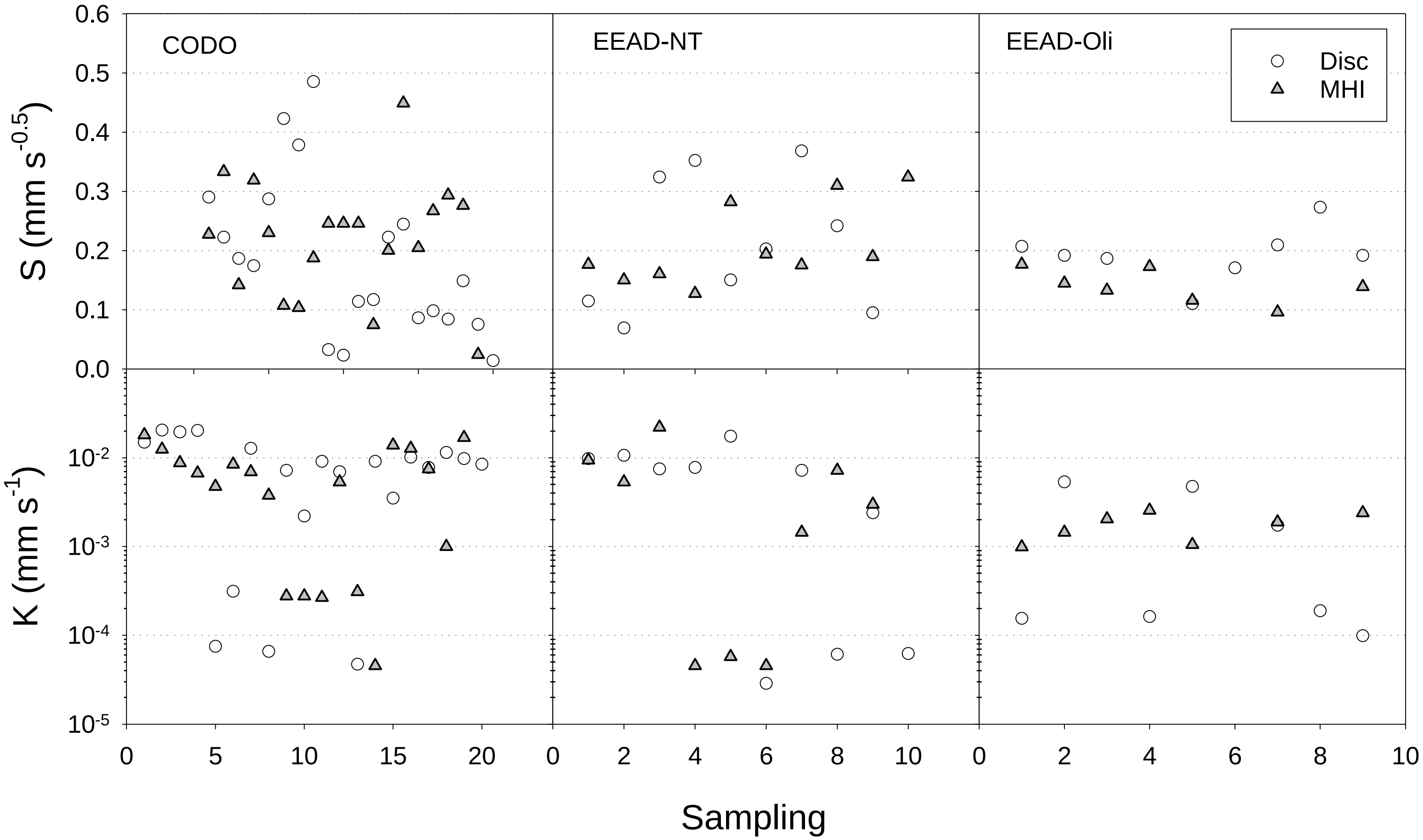

Figure 5.

Table 1. Altitude, average annual, precipitation (P), temperature (T), and average soil dry bulk density (ρ_b) of the experimental plots located in the no-tillage (NT) and olive tree (Oli) farms of the Estación Experimental de Aula Dei (EEAD) and in the Codo municipality (CODO)

Soil	Altitude (m)	P (mm)	T (ºC)	ρ_b ($Mg\ m^{-3}$)	pH (H_2O, 1:2.5)	EC (1:5) [a] $dS\ m^{-1}$	Sand	Silt	Clay	$CaCO_3$	Gypsum	Organic carbon
							$g\ kg^{-1}$					
EEAD-Oli	260	390	14.5	1.61	7.7	0.24	366	404	230	353	-	15.3
EEAD-NT	270	390	14.5	1.52	8.3	0.31	313	451	236	473	-	13.3
CODO	400	313.7	14.5	1.34	7.5	1.96	422	409	169	923	402	2.5

[a] EC, electrical conductivity.

Table 2. Average and standard deviation (parenthesis) values for the K and S parameters estimated in the EEAD-Oli field with the modified hood infiltrometer using the transient flow (TF) and multiple head (MH) methods. K_S, K_2 and K_4 are the soil hydraulic conductivity at saturation and -2 and -4 cm of pressure head, respectively.

	K_s	K_2	K_4
		mm s^{-1}	
TF	2.09×10^{-3} (9.0×10^{-4})	-	-
MH	1.85×10^{-3} (6.0×10^{-4})	9.00×10^{-4} (4.0×10^{-4})	5.00×10^{-4} (1.0×10^{-4})
Sig [1]	0.68	-	-

[1] denotes the significance value for the ANOVA analysis

Table 3. Average and standard deviation (parenthesis) values for the *K* estimated with the disc and modified hood infiltrometer in the CODO and EEAD experimental fields.

	CODO	EEAD-NT	EEAD-Oli	CODO	EEAD-NT	EEAD-Oli
		S (mm $s^{-0.5}$)			K (mm s^{-1})	
Disc	0.18 (0.13)	0.21 (0.07)	0.19 (0.06)	6.2×10^{-3} (5.0×10^{-3})	8.7×10^{-3} (6.0×10^{-3})	1.7×10^{-3} (2.0×10^{-3})
Hood	0.22 (0.09)	0.21 (0.11)	0.14 (0.11)	5.3×10^{-3} (7.0×10^{-3})	6.7×10^{-3} (6.0×10^{-3})	1.7×10^{-3} (1.0×10^{-3})
Sig [1]	0.37	0.93	0.19	0.34	0.76	0.87

[1] denotes the significance value for the ANOVA analysis