Catena 167 (2018) 373–384

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Laboratory testing of Beerkan infiltration experiments for assessing the role of soil sealing on water infiltration

S. Di Prima[a,*], P. Concialdi[b], L. Lassabatere[c], R. Angulo-Jaramillo[c], M. Pirastru[a], A. Cerdà[d], S. Keesstra[e]

[a] *Agricultural Department, University of Sassari, Viale Italia, 39, 07100 Sassari, Italy*
[b] *Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy*
[c] *Université de Lyon, UMR5023 Ecologie des Hydrosystèmes Naturels et Anthropisés, CNRS, ENTPE, Université Lyon 1, 3 rue Maurice Audin, 69518 Vaulx-en-Velin, France*
[d] *Department of Geography, University of Valencia, Blasco Ibáñez, 28, 46010 València, Spain*
[e] *Team Soil Water and Land Use, Wageningen Environmental Research, Wageningen UR, Droevendaalsesteeg 3, 6700 AA Wageningen, The Netherlands*

ARTICLE INFO

Keywords:
Soil sealing
Rainfall simulation
Beerkan infiltration experiment
BEST algorithms
Saturated soil hydraulic conductivity

ABSTRACT

Soil surface sealing is a major cause of decreased infiltration rates and increased surface runoff and erosion during a rainstorm. The objective of this paper is to quantify the effect of surface sealing on infiltration for 3 layered soils with different textures for the upper layer and investigate the capability of BEST procedure to catch the formation of the seal and related consequences on water infiltration. Rainfall experiments were carried out to induce the formation of the seal. Meanwhile, Beerkan infiltration runs were carried out pouring water at different distances from the soil surface (BEST-H versus BEST-L runs, with a High and Low water pouring heights, respectively) for the same type of layered soils. Then, we determined saturated soil hydraulic conductivity, K_s, values from rainfall simulation and Beerkan infiltration experiments. Rainfall simulations carried out on soil layers having different depths allowed to demonstrate that infiltration processes were mainly driven by the seal and that K_s estimates were representative of the seal. Mean K_s values, estimated for the late-phase, ranged from 13.9 to 26.2 mm h^{-1}. Soil sealing induced an increase in soil bulk density by 38.7 to 42.1%, depending on the type of soil. Rainfall-deduced K_s data were used as target values and compared with those estimated by the Beerkan runs. BEST-H runs proved more appropriate than BEST-L runs, those last triggering no seal formation. The predictive potential of the three BEST algorithms (BEST-slope, BEST-intercept and BEST-steady) to yield a proper K_s estimate for the seal was also investigated. BEST-slope yielded negative K_s values in 87% of the cases for BEST-H runs. Positive values were obtained in 100% of the cases with BEST-steady and BEST-intercept. However, poorer fits were obtained with the latter algorithm. The comparison of K_s estimates with rainfall-deduced estimates allowed to identify BEST-steady algorithm with BEST-H run as the best combination. The method proposed in this study could be used to easily measure the seal's saturated hydraulic conductivity of an initially undisturbed bare soil directly impacted by water with minimal experimental efforts, using small volumes of water and easily transportable equipment.

1. Introduction

Droplet impact during a rainfall event can modify surface soil structure and determines the splash erosion (e.g., Assouline and Mualem, 2002; Fernández-Raga et al., 2017). The compaction of fine material from the disrupted and dispersed aggregates may form a thin and highly dense layer (Mualem and Assouline, 1989). This surface sealing is a major cause of decreased infiltration rates and increased surface runoff and erosion during a rainstorm (Moldenhauer and Long, 1964). The formation of seals is dominated by a wide variety of factors involving soil properties, rainfall characteristics, and flow conditions (Assouline, 2004). The determination of seal hydraulic properties, as well as their evolution over time, is one of the key issues in properly describing water flow in soils (Augeard et al., 2007).

There are two main methodological approaches to measure the infiltration of the soil: rainfall simulations and water infiltration techniques using either ring or tension disk infiltrometers (Angulo-Jaramillo et al., 2016). Among the water infiltration techniques, the Beerkan

---

* Corresponding author.
E-mail address: sdiprima@uniss.it (S. Di Prima).

https://doi.org/10.1016/j.catena.2018.05.013
Received 16 October 2017; Received in revised form 11 May 2018; Accepted 14 May 2018
0341-8162/

method consists in infiltrating water through a ring under ponded conditions (Braud et al., 2005). Lassabatere et al. (2006) developed the BEST algorithm (Beerkan estimation of Soil pedoTransfer functions) to derive the whole set of soil hydraulic parameters related to water retention and unsaturated hydraulic conductivity curves from Beerkan experimental data. Ever since, three main algorithms were developed on the basis of this first version: BEST-slope (Lassabatere et al., 2006), BEST-intercept (Yilmaz et al., 2010) and BEST-steady (Bagarello et al., 2014a). The three algorithms make use of the same input data, but differ from the way they fit experimental data to the models for transient and steady states (Angulo-Jaramillo et al., 2016; Lassabatere et al., 2013). These differences allow one of the three methods to perform better according to the kind of soil. Beerkan runs and BEST calculations, also referred to as BEST procedure, are spread worldwide for the characterization of the hydraulic properties of uniform soils (Angulo-Jaramillo et al., 2016).

To study seal formation, most research studies in the last decades were performed with rainfall simulations, either during its dynamic stage or after it has already reached its final stage, when the seal layer is fully developed (e.g., Assouline, 2004; Baumhardt et al., 1990). Rainfall experiments are an attractive tool because the precision, accuracy and the possibility of high repetition rate offer a systematic approach to address the different factors that influence the studied processes (Iserloh et al., 2013). Besides, the use of water infiltration techniques for assessing soil sealing impacts on water infiltration is still largely unknown, notwithstanding that these methods have a noticeable practical interest (Bagarello et al., 2014b). Moreover, the use of ring or tension disk infiltrometers still presents a number of problems related both to theory and practice for data collected on heterogeneous layered soils (Angulo-Jaramillo et al., 2000); which is the case of sealed soils. Under such conditions, the steady-state water flow analysis based on usual analysis procedures are generally found to be inadequate (Logsdon and Jaynes, 1993). Besides, infiltrometer data are generally analyzed by assuming that the sampled porous medium is rigid, homogeneous, isotropic and uniformly unsaturated before the run (Alagna et al., 2013, 2017; Lassabatere et al., 2006, 2009; Reynolds and Elrick, 1990). However, when soil sealing occurs, the soil shifts from uniform to finely layered state. Lastly, the regular Beerkan runs that apply water at soil surface do not trigger any soil sealing; which fails to represent the real soil hydraulic behavior during intense rainfall events.

Recently, Di Prima et al. (2017) adapted the BEST infiltration procedure to mimic rainfall simulation experiments. These authors adapted the height of application of water (still maintaining ponding at surface) for mimicking the impacts of raindrops on soil surface. They demonstrated that both rainfall simulation experiments and modified Beerkan runs, carried out by applying water at a relatively large distance from the soil surface (BEST-H procedure), determine a similar degree of soil compaction and mechanical breakdown of aggregates, but the second ones are much easier to conduct. Moreover, the BEST-H procedure is easy to apply over large areas since the equipment to be transported is minimal and small volumes of water are enough to conduct an infiltration run. BEST-H runs can simply be replicated to develop a large number of sampling points, which means that intensive sampling over a large or relatively large areas is feasible (Gonzalez-Sosa et al., 2010). BEST procedures also allow to survey remote areas, which are difficult for other methods with heavy, expensive, time spending procedures and labor high costs (Bagarello et al., 2011). However, the comparison of BEST-H procedure with well tested methods for K_s estimation, such as rainfall simulation experiments, is necessary to experimentally assess the predictive performances of BEST for the case of soil sealing. Indeed, in the scientific literature there is no exhaustive testing of the relative performances of the BEST algorithms with regards to the specific case of layered and sealed soils.

The objectives of this research were to: (i) measure the effect of surface sealing on infiltration at the surface of three bare soils with different textures exposed to the direct impact of raindrops, (ii) evaluate the influence of the thickness of the upper layer of soil on seal formation and related impacts on water infiltration, (iii) compare ponded infiltrometer runs (Beerkan runs) with rainfall simulation experiments in terms of saturated soil hydraulic conductivity for the case of soil sealing, and (iv) investigate which BEST algorithm can be satisfactorily adopted to properly estimate K_s of the seal.

2. Material and methods

2.1. Soil sampling

Soil materials used in this study were taken from Ap horizons of three Sicilian sites with different physical properties (Bagarello et al., 2014a). According to the USDA classification, a sandy-loam (SL) soil and a clay-loam (CL) soil were sampled at the Department of Agricultural, Food and Forest Sciences of the Palermo University. A clay (C) soil was sampled at the experimental station for soil erosion measurement at Sparacia (University of Palermo), approximately 100 km south of Palermo. Particle size distribution (PSD) was determined following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium hexametaphosphate and mechanical agitation (Gee and Bauder, 1986). In particular, fine size fractions were determined by the hydrometer method, whereas the coarse fractions were obtained by mechanical dry sieving. The soil organic carbon content, OC (%), was determined by the Walkley–Black method (Nelson and Sommers, 1996). Then, the soil organic matter content, OM (%), was estimated using the van Bemmelen conversion factor of 1.724 (Van Bemmelen, 1890). Each soil was air-dried, ground to an aggregate or particle diameter slightly larger than 2 mm, and sieved through a 2-mm mesh (Bradford et al., 1987). The measured soil physical properties are summarized in Table 1.

2.2. Rainfall simulation experiments

Many laboratory as well as field studies have been conducted over more than five decades on the formation of seals at the surface of bare soils exposed to the direct impact of raindrops (e.g., Bradford et al., 1987; Lado et al., 2004; Tackett and Pearson, 1965; Touma et al., 2011). Laboratory experiments carried out on packed samples have the clear advantage to overcome the effects of soil heterogeneities and spatial variability on K_s measurements (Liu et al., 2011). In this investigation, we used the rainfall simulator of the Kraijenhoff van de Leur Laboratory for Water and Sediment Dynamics at Wageningen University, the Netherlands. A detailed description of the rainfall simulator is given in Lassu et al. (2015). A Lechler nozzle (nr. 460.788) was used to apply water from a 3.85-m height. In this study, a total of thirty storms were simulated at rainfall intensity $R = 60\ \mathrm{mm\ h^{-1}}$. The experiments were carried out on small rectangular soil plots encased in a transparent plexiglass box. The box set-up had two compartments: a soil compartment ($1.3 \times 10^{-2}\ \mathrm{m^2}$ plot area), and a runoff collection

Table 1

Coordinates, soil textural classification, clay (0–2 μm), silt (2–50 μm), and sand (50–2000 μm) content (in %) (USDA classification system) in the 0–10 cm depth range, soil organic matter (*OM* in %) content, dry soil bulk density (ρ_b in $\mathrm{g\ cm^{-3}}$), and initial volumetric soil water content (θ_0 in $\mathrm{cm^3\ cm^{-3}}$), for the three sampled soils. Standard deviations are indicated in parentheses.

Coordinates	33S 355,511 E 4,218,990 N	33S 355,341 E 4,219,012 N	33S 391,172 E 4,166,165 N
Textural classification	Sandy-loam	Clay-loam	Clay
Clay	17.6 (1.9)	29.9(2.8)	71.5 (1.8)
Silt	29.8 (2.8)	34.1(1.8)	23.6 (1.4)
Sand	52.6 (4.7)	36.0(1.2)	4.9 (0.8)
OM	3.9(0.7)	2.3(0.1)	1.1(0.6)
ρ_b	0.936 (0.008)	0.984 (0.018)	1.065 (0.029)
θ_0	0.062 (0.001)	0.039 (0.001)	0.059 (0.002)