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Dynamics of quasi-steady ponded infiltration under contrasting plant cover and management strategies

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Abstract

The runoff infiltration partitioning has direct consequences on preservation of water resources in rural territories, both in agricultural plots and uncultivated areas (e.g. ditches, channels, grass strips), and requires a better understanding of the variability of soil infiltration capacity by disentangling the complex links between soil, vegetation and management. The general objective of the study was to investigate the temporal variation in quasi-steady ponded infiltration rates of a fluvisol soil under bare and different cover crop type (a Malvaceae with a tap-root system and a Poaceae with a fibrous root system) and management conditions (burning, mowing, and chemical weeding) that are commonly found in the Mediterranean vineyards. A modified double-ring infiltration method was used to repeat measurement of the quasi-steady ponded infiltration, f_{cp} , on the same location over time. Placed on a 64 m² plot area with minimal distances between individual measurements of 30 cm, the setup allowed evaluation of variability among measurements that were conducted within the plot. The results showed a significantly lower f_{cp} for bare soil than covered soil, and a two-fold higher f_{cp} for soil covered by Malvaceae than Poaceae. A seasonal effect in f_{cp} was observed, with the highest f_{cp} in summer and the lowest in winter. The study revealed a strong spatial variability in f_{cp} along a transect of a few tens of centimeter, and showed no significant effect of management strategies compared to the vegetated control. The results revealed the importance of considering both plant traits and season rather than vegetation management strategies to explain quasi-steady ponded infiltration rates.

Keywords: double-ring infiltrometer, mixed effect model, root traits, mowing, burning, vegetation, soil hydrodynamics

1. Introduction

Services provided by wild vegetation in spaces between crops and at the border of fields have been widely studied in Mediterranean vineyards (Dollinger *et al.*, 2015; Garcia *et al.*, 2020; Rudi *et al.*, 2020). Managing this vegetation by relevant strategies with the objective of optimizing ecosystem services constitutes a means to foster agroecological transition and ensure the resilience of agrosystems to climate change. Due to the increase in extreme hydroclimatic events (e.g. droughts and floods), maximizing water infiltration by the plants is crucial for rainwater harvesting (Rockström et Falkenmark, 2015) and knowledge of the factors controlling soil water availability, especially during dry seasons, is necessary for selecting proper plant types that increase water infiltration. This is particularly relevant in ditches with intermittent functioning in Mediterranean areas because they are largely involved in groundwater recharge (Dagès *et al.*, 2009).

Infiltration properties are both governed by soil texture and pore size distribution and soil structure. It results also from the interrelations between soil, fauna, flora, and human practices (Cerdà, 1999; Meek *et al.*, 1992; Smith, 1949). It explains part of the separation of rainfall into infiltration and runoff at the soil surface (Chen *et al.*, 2006), especially in Mediterranean areas where Hortonian runoff dominates, i.e. when rainfall intensity exceeds infiltration and depression storage capacities.

Although mostly carried out in agricultural plots, specific studies of infiltration rate have focused on certain elements of the hydrographic network, such as ditches, and have considered the impact of the latter on groundwater recharge (Dagès *et al.*, 2009).

The interrelations between soil texture, structure, and agricultural management strategies on infiltration rate are well outlined in the literature (Coulouma *et al.*, 2006; Meek *et al.*, 1992; Smith, 1949). However, the effects of faunal and floral activities inside the soil matrix are still in need of full investigation. Among the biotic processes affecting infiltration rate, the plant root system seems to be a major driver of their variations over time. Plant roots act on soil infiltration capacity by creating macropores of different lengths, architectures, densities, connectivities and diameters (Doussan et Pagès, 2018). These macropores could be either filled through proliferation of roots, reducing infiltration rates, or emptied when dead roots started to decay, creating preferential flows of water (Bodner *et al.*, 2008).

Consequently, the links between root system and infiltration rates are complex and governed by either physiological and agronomic factors. This network of macropores has a high temporal variability explained by species-specific root decay rates (Strand *et al.*, 2008), micro-climate, seasonality (Bodner *et al.*, 2008), diurnal desiccation cycles (Huck *et al.*, 1970) and species interactions. The nature of the root system could have a great influence on infiltration rate, considering their general

shape (tap roots or rhizomatous, for example) and their depth. It seems that bulbous tussock root systems with fine roots, which are typical of some grass species, performed poorly in creating efficient macroporosity for water conductivity, or at least their effect was unclear (Ghestem *et al.*, 2011; Holden, 2005).

Agricultural practices could also affect infiltration rate through a modification of the root systems of plants. For example, chemical weeding can kill a living root system and induce macropore creation, whereas another practice, mowing, removes only the above ground parts of a plant. Indeed, the interactions between plant species, their root systems and management strategies remain unclear and need specific studies to be understood.

Considering the spatial aspects, infiltration rate can vary from several to many orders of magnitude at a fine scale (a few tens of cm), making it difficult to relate it to soil properties because they are almost impossible to measure at this scale in the field. Considering the temporal aspects, a small number of studies showed a seasonal effect in quasi-steady infiltration rate, but the amplitude and even the phasing of the variation varied according to previous studies (Cerdà, 1999; Meek *et al.*, 1992). These contrasting results call for a multi-date and multi-local measurement method and protocol capable of differentiating agronomical, ecological and pedological drivers of infiltration rate. The Müntz double ring method is a old procedure for the measurement of the quasi-steady infiltration rate at soil saturation (Boivin, 1990; Colombani *et al.*, 1973), which presents the limit of modifying the soil structure during settlement, like many other methods interested in measuring the hydrophysical properties of the soil (Lili2008). The fact of positioning a guard ring around the inner ring in which the measurement is carried out, with a constant water level in the two rings, allows measurements to be made in the inner ring by minimizing the lateral flow and the risks of leakage under the inner ring.

Considering the extreme variabilities of infiltration rate across spatial and temporal scales, the implementation of an in situ set-up able to monitor its dynamics subjected to different anthropogenic, climatic or ecological forces is necessary. To our knowledge, no study has been able to implement such a set-up. Multi-date or multi-site measurements have been always collected in different places (Cerdà, 1999).

The purpose of the study was to investigate the evolution of quasi-steady ponded infiltration rates of a fluvisol soil under bare and two types of cover crops (Poaceae and Malvaceae) with different rooting system and management conditions that are commonly found in the Mediterranean vineyards. This study is justified by the lack of experimental knowledge and the diverging results between studies on the interactions between time, species, and management strategies of infiltration rate. We focus on ponded infiltration rate, which is the most relevant for reproducing the infiltration conditions of agroecological infrastructures in or outside the field (such as vegetated vineyard inter-row, grass strips or ditches) during runoff or flooding.

A field experiment was conducted over two and a half years with the following objectives: (i) to investigate the temporal variation in quasi-steady ponded infiltration rate, (ii) to assess the effects of different plant species on the temporal variation

in quasi-steady ponded infiltration rate and (iii) to estimate the impact of management strategies on quasi-steady ponded infiltration rate.

2. Material and methods

2.1. Study site

The study site is located on the experimental site of Lavalette in Montpellier (43°38'49" N, 3°52'22" E) in the Lez River floodplain. The climate is Mediterranean, with an average monthly temperature ranging from 6°C in winter to 22°C in summer and scarce but heavy rainfall events (600 to 800 mm per year). Hourly and daily meteorological datasets are issued from a weather station located approximately 90 m from the study site—the INRAE CLIMATIK platform <https://intranet.inrae.fr/climatik/>, in French) managed by the AgroClim laboratory of Avignon, France. Soil water content has been measured by neutron thermalization method (Hignett et Evett, 2002) at approximately 50 m near the experiment and during the period 2017-2019. The soil water content data was provided by the INRAE team PRESTI (UMR GEAU, Montpellier, France).

The experiment took place on a recent fallow and the specific studied surface of approximately 64 m² was flattened and prepared using two successive grinder tracks separated by a sub-soiler track, followed by a rotary harrow in April 2017. A soil pit near the experiment was dug and morphological observations were done. The morphological descriptions were performed according to the Food and Agriculture Organization (FAO) guidelines for soil description (FAO, 2006).

Particle size distribution (texture), gravel and organic carbon (OC) content were measured at the French INRAE-ARRAS laboratory (Table 1). The mean bulk density of each horizon was measured following the classical core (100 cc) method (Blake1986). The soil corresponded to a homogeneous fluvisol (WRB), polyphasic, on old horizons of clayey alluvial soil of the Lez River. At the place of the final experiment, the variability of soil properties which may influence the comparisons between plots was low due to or because of: i) a low variability of soil texture, ii) a low standard error of the bulk density measurements, with the addition of any morphological observation of structure degradation (compacted features), iii) the same tillage preparation in dry conditions before the study.

2.2. Experimental set-up

In May, 2017, six rigid 150 cm by 150 cm square frames were installed to a depth of 15 cm in a 8 by 8 m² area. Nine 20 cm in diameter and 16 cm long plastic cylinder were then installed to a 10-cm depth in each of the six square areas (Figure 1). All the equipment (frame and cylinders) was Polyvinyl chloride (PVC) plastic except for the C square frame, which was aluminium to be protected from burning practice. In each frame except frame A, which was composed of bare soil (i.e., regularly weeded), 4 cylinders were planted with propagules from the Poaceae family (*Cynodon dactylon* L.) and 5 from the Malvaceae family (*Malva sylvestris* L.), which are able to be

Soil Horizon	Minimum-Maximum depth (cm)	Structure	Bulk density (s.e.)	Clay (%)	Silt (%)	Sand (%)	Organic carbon (g/kg)	Gravel content (%)
Ap1	0-18	Recently tilled surface horizon, granular with numerous roots	1.56 (0.04)	24	45	31	14.9	2
Ap2	18-45	Deep mouldboard tilled horizon, polyhedral subangular blocky, numerous roots and worm galleries	1.66 (0.04)	24	46	30	6.2	0

Table 1: Selected properties of top soil horizons.

propagated by cuttings. Three propagules of each plant were planted in each cylinder. Small fragments of each plant were chosen to limit soil disturbance. In accordance with the purpose of the study, we selected two species with contrasting root systems, the Malvaceae with a tap-root system and a Poaceae with a fibrous root system with rhizome, commonly found in Mediterranean field borders. The two species were chosen because of their perennial life cycle, their resistance to replanting, and their robustness.

It was impossible to distribute bare soil modalities in all frames because of the feasibility of the practices, with a risk of drift from the chemical treatments or fire inside a frame. Grouping plant species inside each frame was motivated by minimization of interactions between different plant species, given the robust and lateral root system of Poaceae, and the strong development of above ground parts of Malvaceae.

One year after the implementation of the set-up, we applied a given experimental treatment to each frame separately following the timeline presented in Table 2. This timeline was determined according to management practices observed in the area for non-cultivated vegetation maintenance (Levavasseur *et al.*, 2014). Burning in frame C occurred very early in October because of the local restriction of wildfire activities in 2018. The experimental practice consisted simply of igniting the vegetation, which then died and dried during the autumn period, and burning only superficially affected the soil. Mowing occurred in frames D and E when vegetation reached a significant height, depending on the number of degree-days since winter (Pare *et al.*, 2011). This experimental practice consisted of cutting all vegetation protruding from the cylinder with shears, at 5-6 cm from the ground. We proposed two strategies for mowing according to those occurring in Mediterranean cultivated landscapes (Biarnès *et al.*, 2009): autumn and summer mowing (frame D) or only summer mowing (frame E). Finally, chemical weeding was conducted in frames A and F in mid-April when living plant cover reached a mature height by applying glyphosate with a manual sprayer. During the study, undesirable species were manually weeded at the seedling stage inside the cylinders and chemically weeded outside the cylinders.

2.3. Infiltration measurements

In this study, quasi-steady ponded infiltration rate was measured at different dates from June 2017 to November 2019 (Table 2). The dates were chosen to ensure that there was at least one month between consecutive measurements, with a concentration of measurements in spring, when the plants were growing back, and in autumn, at the time of the Mediterranean rainy periods.

The measurements were conducted from a modified double-ring infiltrometer method adapted from the principle of Müntz's method (Colombani *et al.*, 1973). The device measures the change of infiltration over time at a constant water ponding depth that infiltrates vertically in the soil (Boivin, 1990). The presence of the guard ring forces water to move vertically down not only in the soil volume inside the cylinder but also below their bottom edges. A constant ponding depth was yet maintained inside a measuring cylinder sunk into the ground. The same ponding depth, a 5-cm depth of water, according to Lili *et al.* (2008), was held in a concentric guard ring whose role is to ensure the lateral moistening of the head of water. The ponding depth was kept constant during all infiltration rate measurements, which lasted several hours.

Müntz's method was automatized by Garnier and Elamri (2014). Both the measuring cylinders and the guard frame were filled from a water tank, and infiltrated volumes were measured using a Diver pressure sensor. Automatisations of the constant ponding depth in measuring and guard cylinders was insured by a capacitive sensor (ref: SCHXT230A1PAL2, Schneider Electric SE, Rueil Malmaison, France) able to detect 1-mm variation of water level connected to 12V-powered membrane solenoid valves for transferring water from transparent PVC pipe tanks. We slightly modified the method by replacing the concentric guard ring with a square frame surrounding 9 measuring cylinders (Figure 2) and using a larger measuring cylinder of 20 cm instead of 10 cm as in Garnier and Elamri (2014). The duration for measuring the 9 cylinders of one frame lasted approximately one and a half hours and consisted of a water immersion followed by a rough measure of infiltration rate until the steady

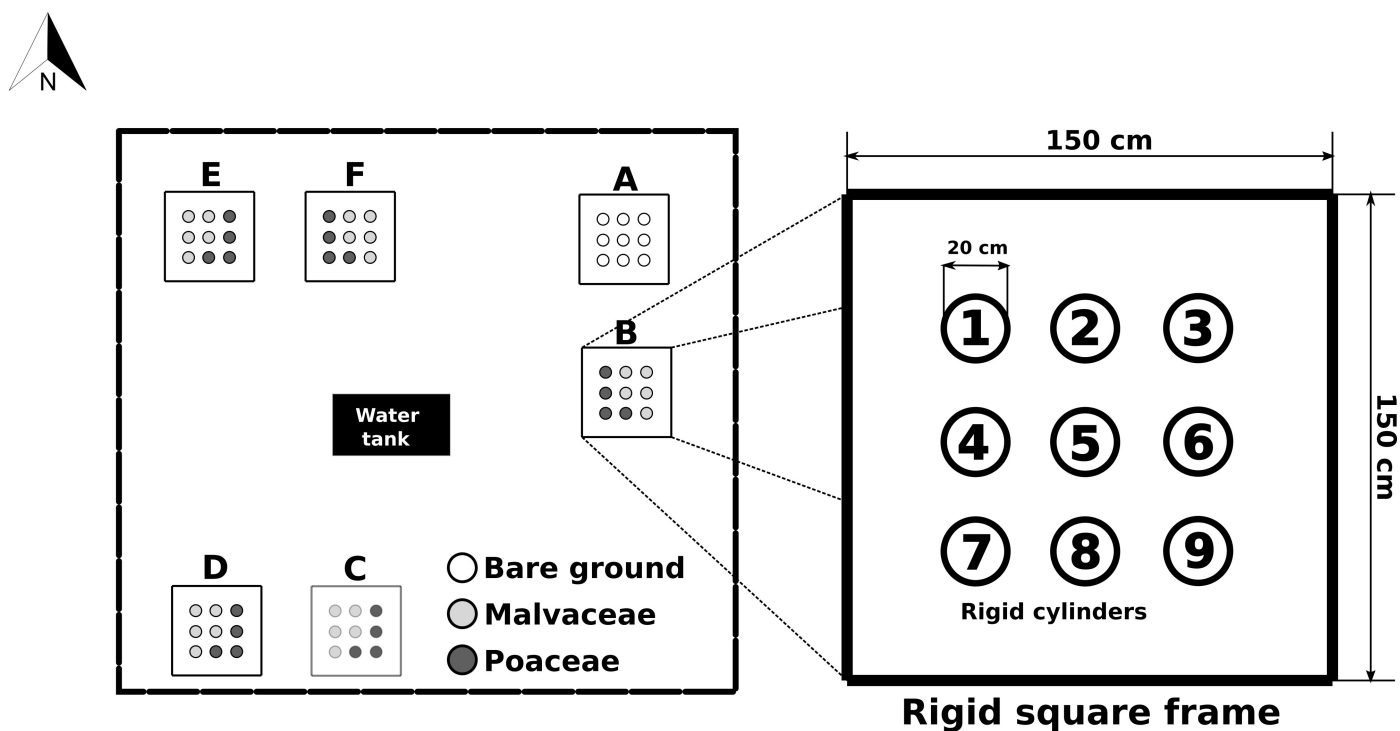


Figure 1: Schematic view of the experimental set-up showing the positions of the frame and cylinders.

Frame	Date	Practice
A	29/06/2017 – 07/08/2017 - 03/10/2018 - 27/02/2019 - 15/10/2019	chemical weeding *
B		control without practices
C	05/10/2018	burning
D	03/10/2018 - 26/06/2019	mowing (x2)
E	26/06/2019	mowing
F	16/04/2019	chemical weeding
All	02/06/2017 – 28/06/2017 – 02/08/2017 – 27/09/2017 – 16/01/2018 – 14/03/2018 – 24/04/2018 – 07/06/2018 – 02/10/2018 – 28/11/2018 – 10/04/2019 – 25/06/2019 – 27/11/2019	Infiltration campaigns

* All throughout the study when bare soil needed to be maintained.

Table 2: Timeline of experimental treatments and infiltration measurement.

state was reached. Then quasi-steady ponded infiltration rate, noted f_{cp} , was estimated considering a 30 min period, following the equation:

where ΔV is the difference in volume of water infiltrated within a given Δt , and the ponded surface of the measuring cylinder.

2.4. Vegetation growth measurements

Vegetation growth, in terms of vegetation cover, i.e. the vegetation covering the surface of the ground, was measured in each cylinder during infiltration measurements. Vegetation cover was measured by photographing the frame vertically, orthorectifying the picture on the basis of the squared shape of the frame, and manually digitizing canopy growing out of each cylinder.

2.5. Statistical analyses

The variability of f_{cp} was analyzed using a linear mixed effect (LME) model fitted by using the restricted or residual maximum likelihood estimator for all parameters and the maximum likelihood estimator for the fixed effects. The use of a mixed effect model provides the best approach for enabling an explicit consideration of the spatial and temporal patterns of infiltration.

A logarithmic transformation of f_{cp} was done to ensure heteroscedasticity. Then, depending on the research question, we fixed some variables and considered others as random factors to account for the serial correlation of non-randomized repeated measurements.

For the LME model, we considered the dates of aggregated measurements at the month level (DATE) and the cover surface properties of each cylinder (PLANT): bare soil, Malvaceae, and Poaceae, as fixed factors. We considered the unique identifier of the cylinder (ID) as a random factor. For the last objective on the impact of management strategies on f_{cp} , we constructed 6 models corresponding to management strategies applied to each frame.

where ϵ is a random error term.

To address the first two objectives of the study, the dataset containing 9 values is a subset of all measurements before management strategies, whereas the last objective dealt with all dates before and after practices. A test for the significance of differences was performed using Tukey's honestly significant difference (HSD) test on the LME.

Quasi-steady ponded Infiltration rates were related to climatic variables, soil temperature, water content and vegetation growth parameters using Pearson product-moment correlation, noted ρ . All statistical tests were performed using R software (The R Core Team, 2022) with the lme4 package. Residual analyses of all models were conducted with a normal Q-Q plot to ensure normal distribution of the residuals.

3. Results

3.1. Distribution of infiltration rates and relations with environmental factors

During the first month of the experiment, the type of cover and the frames had no significant effect on f_{cp} (two-way

ANOVA, $df=2$ on 47, $p\text{-value}=0.07$ for cover; $df=4$ on 47, $p\text{-value}=0.12$ for frames). The coefficient of variation (CV) of mean f_{cp} ranged from 90 to 110 % per frame. These results validate the homogeneity of the experimental area and the absence of perturbation due to the planting of species.

Quasi-steady ponded infiltration rates ranged from 0.1 to 2370 mm h⁻¹, with 13 extreme values exceeding 1000 mm h⁻¹ (for a total of 702 values). As two cylinders (E1 and F2) concentrated the majority of the extreme values throughout the experiment (even before the installation of the cover crops), they were removed from the analysis dataset. The high values were due to formation of ant nests inside the cylinders E1 and F2, discovered at the end of the experiment. Values lower than 0.1 mm h⁻¹ correspond to non-detectable rates by our protocol. Values exhibited large variations from date to date, ranging from 50 mm h⁻¹ on average in winter to 260 mm h⁻¹ on average in June. Large variations were also recorded inside the same frame for cylinders having the same cover (Malvaceae, Poaceae or bare soil), with maximal values being 10-fold higher than minimal ones. In each frame, a group of two or three among the nine cylinders exhibited the highest values of infiltration rate more than 70% of the time (data not shown).

As shown in Figure 3, rainfall conditions were contrasted across years with a dry year in 2017 followed by a very wet year in 2018 and a year in the normal range in 2019 (the average annual rainfall was 450, 1200, and 600 mm, respectively). Intense rainfall occurred in June and October 2018 with an intensity of more than 30 mm.h⁻¹. The vegetation cover exhibited an important growth in the first year of implantation and was more limited in 2018 and 2019, although these were wet years. Vegetation cover was not correlated with infiltration rates ($|\rho| < 0.6$). Soil temperature at 10 cm below the surface ranged between 0 and 30°C during the period. Assuming that the temperature of the water during the experiment equilibrates with the temperature of the soil, the dynamic viscosity of the water ranged from 0.798 to 1.792 g m⁻¹ s⁻¹ and was not correlated with mean f_{cp} for all frames ($|\rho| < 0.6$). Soil water content was not correlated with f_{cp} for Frame B and F ($|\rho| < 0.6$), except a slight negative correlation for Frame A ($|\rho| = 0.64$).

3.2. Impact of the type of cover

The mean of all f_{cp} (whatever the date and cylinder) exhibited significant differences between bare soil and planted cylinders (Figure 4). Bare soil exhibited f_{cp} four times higher than those for cylinders planted with Malvaceae and two times higher for cylinders planted with Poaceae.

3.3. Temporal variation in quasi-steady ponded infiltration rates

Quasi-steady ponded infiltration rates of bare soil decreased significantly after 3 months (Tukey post hoc test on LME, $p\text{-value}<0.05$), whereas for the cylinders planted with Malvaceae and Poaceae they decreased significantly after 2 months (Tukey post hoc test on LME, $p\text{-value}<0.05$). After this period, f_{cp} exhibited different trends depending on the type of cover (Figure 5). In 2018, f_{cp} of bare soil was stable at approximately 8 mm

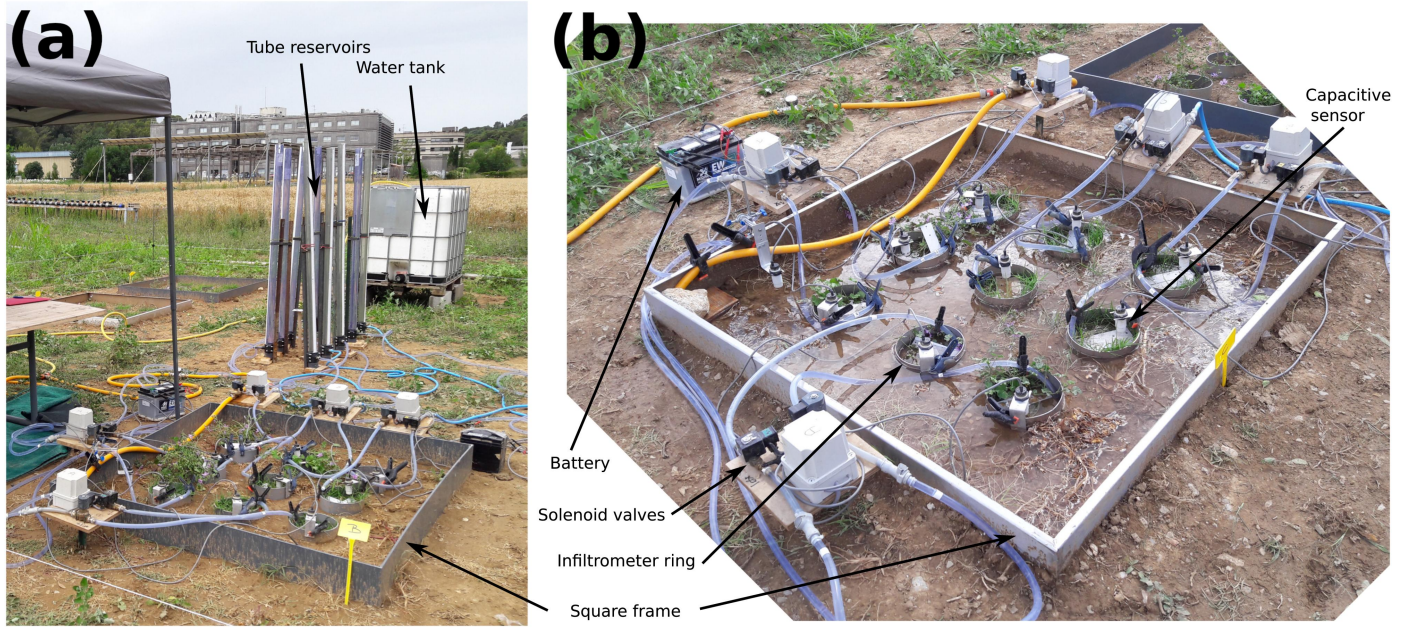


Figure 2: Photographs of the experimental set-up. (a) Water tank, transparent pipe reservoirs, and one of the frames with the ring infiltrometers. (b) A view of a frame during measurement with the 9 cylinders fitted with capacitive soil moisture sensors, the five squared boxes with 2 solenoid valves connecting the pipe reservoirs to the 9 cylinders and the outside frame.

h-1. For cylinders planted with Poaceae, f_{cp} increased gradually from 50 mm h⁻¹ in September 2017 to a non significant peak in June 2018 at 100 mm h⁻¹, and then a decrease. For cylinder planted with Malvaceae, f_{cp} exhibited the same trend as that of Poaceae, with an initial value at 80 mm h⁻¹ in September 2017, a significant peak of 500 mm h⁻¹ in June 2018 followed by a decrease to 200 mm h⁻¹ in October-November 2018.

3.4. Impact of management strategies

Figure 6 shows the impact of management strategies on all dates selected before and after treatment. We observed a reduction in f_{cp} in the spring period between 2018 and 2019, regardless of the studied frame.

Frame A, bare soil without vegetation, exhibited low f_{cp} ranging from 1 to 4 mm.h⁻¹, which were significantly different from frames B-F for all dates (Tukey post hoc test on LME, p-value < 0.05), except for June and September 2017 and June 2019 (Tukey post hoc test on LME, p-value > 0.05). There were no significant differences between f_{cp} for frames B, C, D, E, and F (Tukey post hoc test on LME, p-value > 0.05), except in October 2018 and April 2019 (Tukey post hoc test on LME, p-value < 0.05).

Frame B, vegetated without practices, exhibited a seasonal trend similar to that of the treated frames, with a non-significant difference due to the high heterogeneity of f_{cp} inside a given frame. Frames E and F exhibited higher values in 2018 but were never significant in comparison to frames B, C, and D, except in October 2018.

4. Discussion

This study highlighted a temporal variation in quasi-steady ponded infiltration rate during the year, with a 2- to 4-fold increase from the winter to summer periods. Cerdà Cerdà (1999) observed the same temporal variation in quasi-steady infiltration rate, with the highest values in summer and the lowest values in the rest of the year on a soil dominated by clay and silt. However, experimental results from Meek et al. Meek *et al.* (1992) on a sandy loam soil planted in alfalfa highlighted lower values of infiltration rate during summer. This seasonal variation could be only partially explained by the change in viscosity due to temperature, because variation in water viscosity due to different soil temperature did not affect infiltration rates significantly. The higher values of quasi-steady infiltration rates in summer could be due to swelling-shrinking phenomena and higher biological activity leading to a higher amount of biopores, results being observed on soil hydrologic properties as presented by Azevedo et al Azevedo *et al.* (1998).

As infiltration rates remained homogeneous between frames at the beginning of the experiment, we believe that divergence in infiltration rates between frames and plants could be due to preferential pathways through cracks or macropores (Cerdà, 1999), and the fact that some treatments exhibited the highest values during most of the experiment suggests a relative persistence of these preferential flows. Our results exhibited a CV between 100 and 300% at the scale of the frame. Interestingly, our study demonstrated that quasi-steady ponded infiltration rates exhibited very large variations at small distances, as the distance between cylinders inside each frame was 10 cm (border-to-border distance), even for cylinders planted with the same cover. Coulouma et al. Coulouma *et al.* (2006) also highlighted

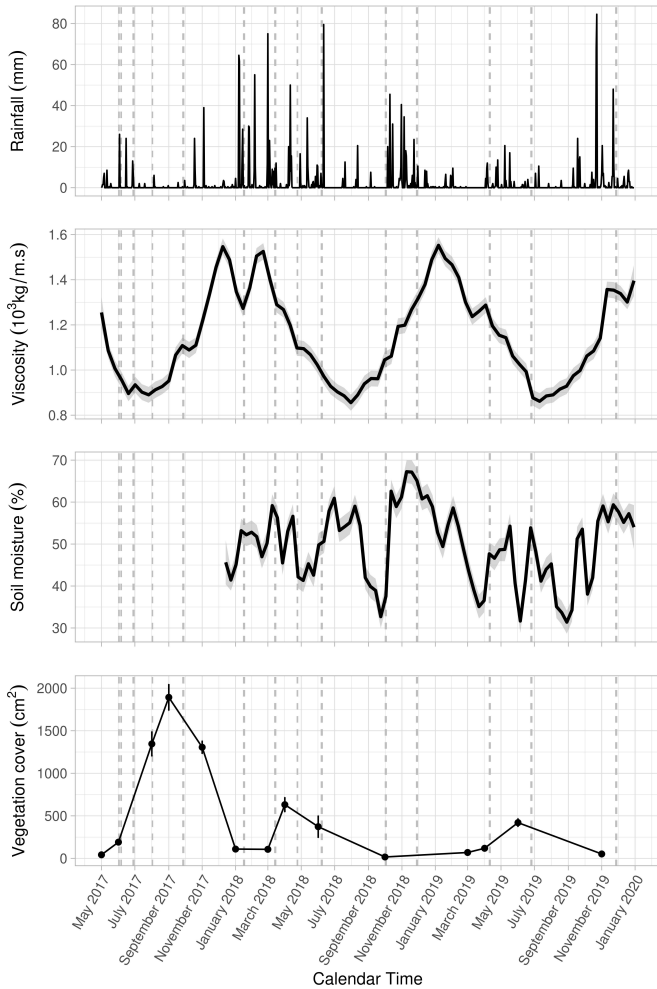


Figure 3: From top to bottom, chronicles of daily rainfall amount, water viscosity derived from soil temperature, soil moisture content and vegetation cover by cylinder during the period 2017-2019. Dashed vertical lines correspond to infiltration measurements. Confidence interval at 95% figured in grey for water viscosity and soil moisture. Vertical bars correspond to standard errors for vegetation cover.

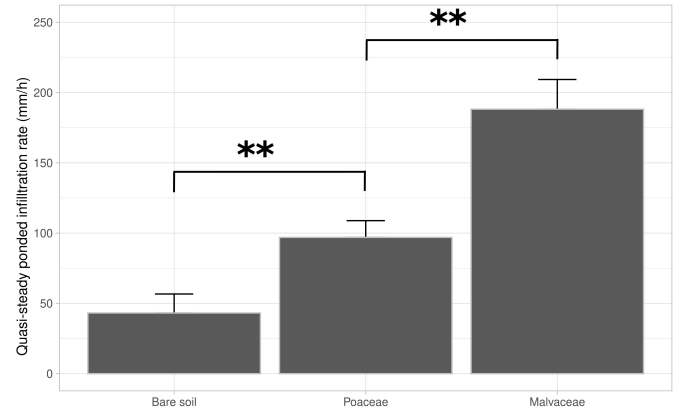


Figure 4: Quasi-steady ponded infiltration rates values according to the type of soil cover (bare soil, Poaceae, and Malvaceae). Analysis relied on a LME model with a log-transform of the explained variable. The model includes ID as a random effect. Vertical bars represent standard errors. The horizontal bars represent the results of the Tukey post hoc test on LME, with ** indicating significant at p-value < 0.05, and NS indicating p-value > 0.05 .

high variations in infiltration rates at distances of 20 cm, mainly because of structural soil variations due to tillage practices.

Our study demonstrated an overall increase in quasi-steady ponded infiltration rates from planted soil in comparison with bare soil, with a significant effect of Malvaceae compared to Poaceae. This was probably explained by the ability of tap-root systems to create larger biopores in the soils (Perkons *et al.*, 2014). Li *et al.* (2011) highlighted an infiltration rate 1.4-fold higher for vegetated plots than bare soil, but without statistically testing it. Leung *et al.* (2015) found the opposite result, with a lower infiltration rate for vegetated soil compared to bare soil and no effects from the type of cover, despite the authors comparing grass-covered to tree-covered soils.

In comparison to other experiments focusing on the influence of plant management strategies on infiltration rate (Ahuchaogu, 2016; Hussein *et al.*, 2019), our study did not involve agricultural machinery to investigate different treatments. We believe that our protocol prevents the modification of soil structure from gear passage to test the effects of only plant senescence or disappearance due to the practices. The similar effects of burning, mowing and chemical weeding on quasi-steady ponded infiltration rates could be explained by the disappearance of the crop cover that protects soil from crusting due to rainfall impacts. The effects of fire (Snyman, 2005), mowing (Cox, 1988) and chemical weeding (Saunders et Pezeshki, 2015) on root quantity and depth, are already highly variable according to studies on the subject and seemed to be of minor importance in explaining infiltration rates. The temporary effect of the practices on quasi-steady ponded infiltration rates could be linked to the quick increase in vegetation cover a few months after practice.

The overall reduction of quasi-steady ponded infiltration rates between 2018 and 2019 could be attributed to several factors. First, the formation of a surface crust (Leonard et Andrieux, 1998) for the frame consisting of bare soil, observed on

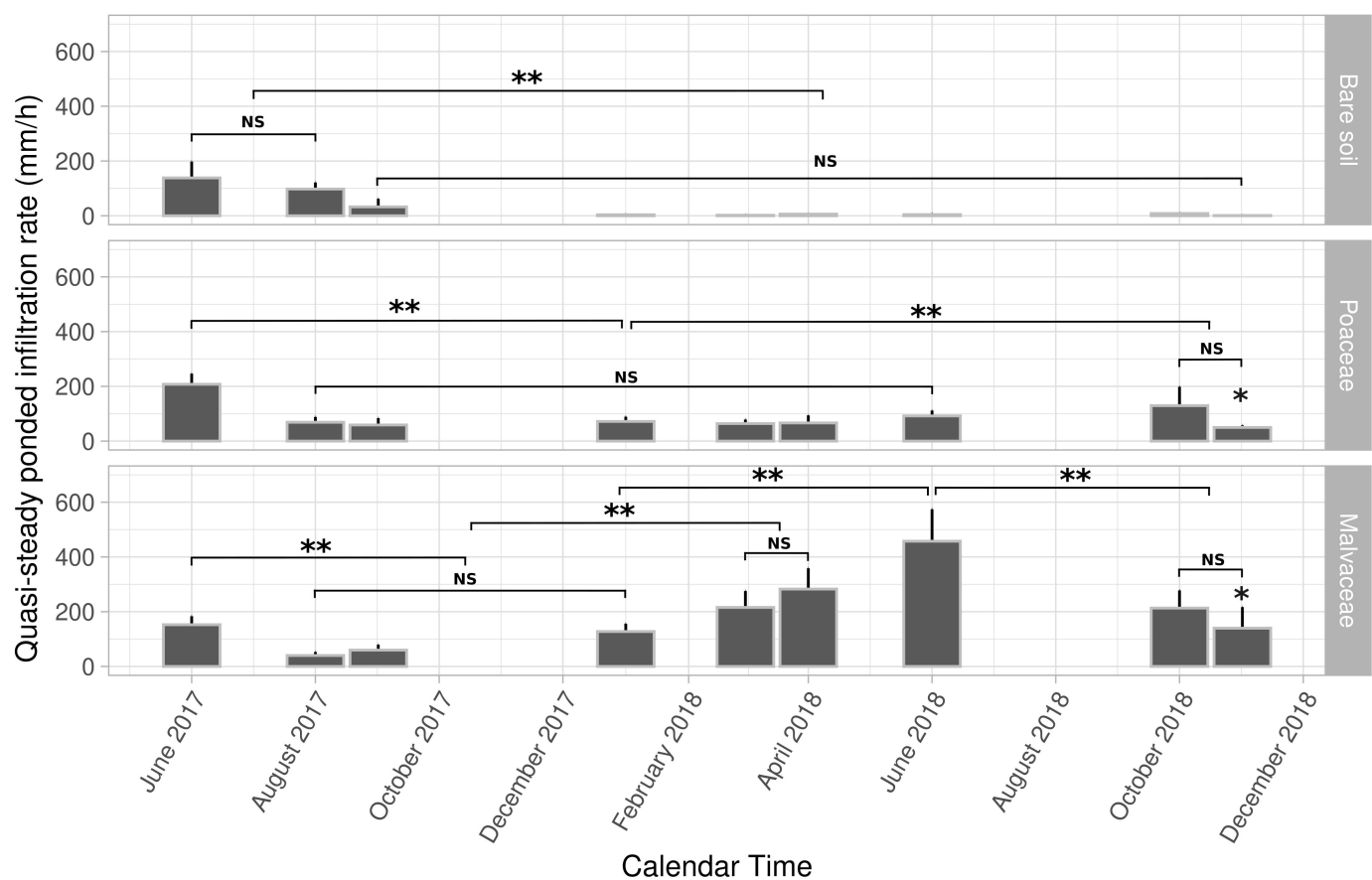


Figure 5: Change of the quasi-steady ponded infiltration rate versus time and type of soil cover (bare soil, Poaceae, and Malvaceae). Analyses relied on LME models with a log-transform of the explained variable. All models include ID as a random effect. Vertical bars represent standard errors. The horizontal bars represent the results of the Tukey post hoc test on LME, with ** indicating significant at p-value < 0.05, and NS indicating p-value > 0.05, and * indicating that values from frames C and D were excluded from the analyses for December 2018, as they were already affected by maintenance practices.

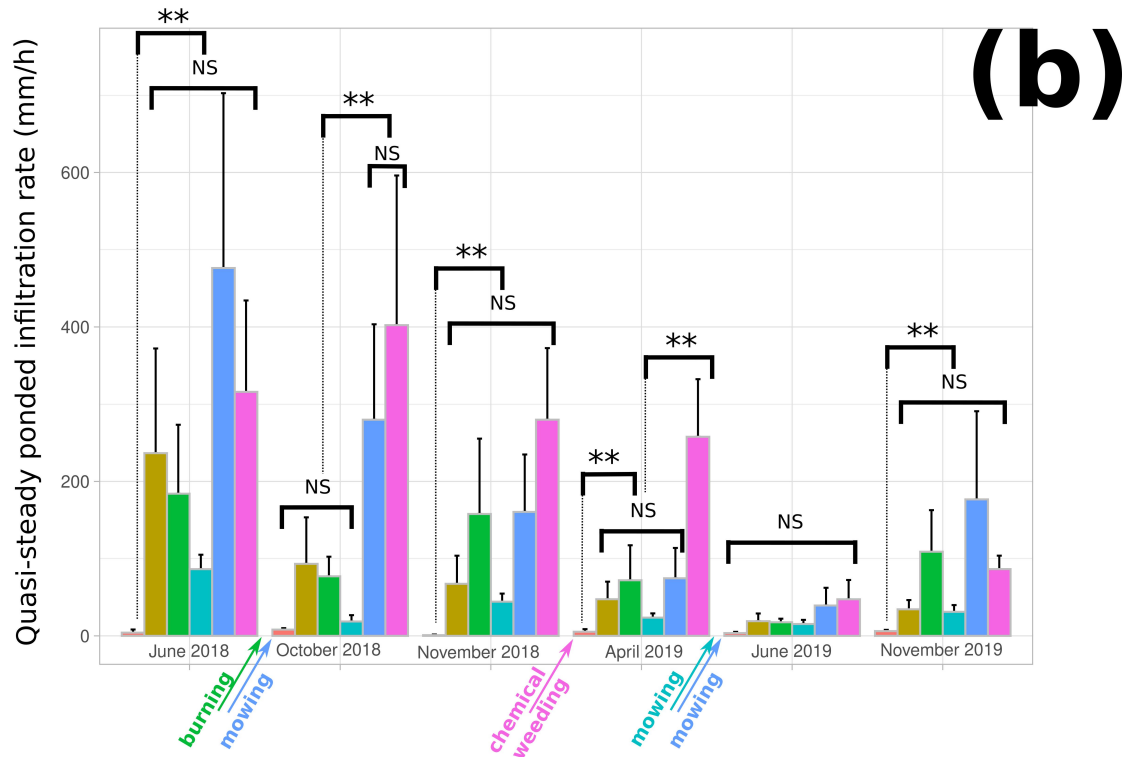
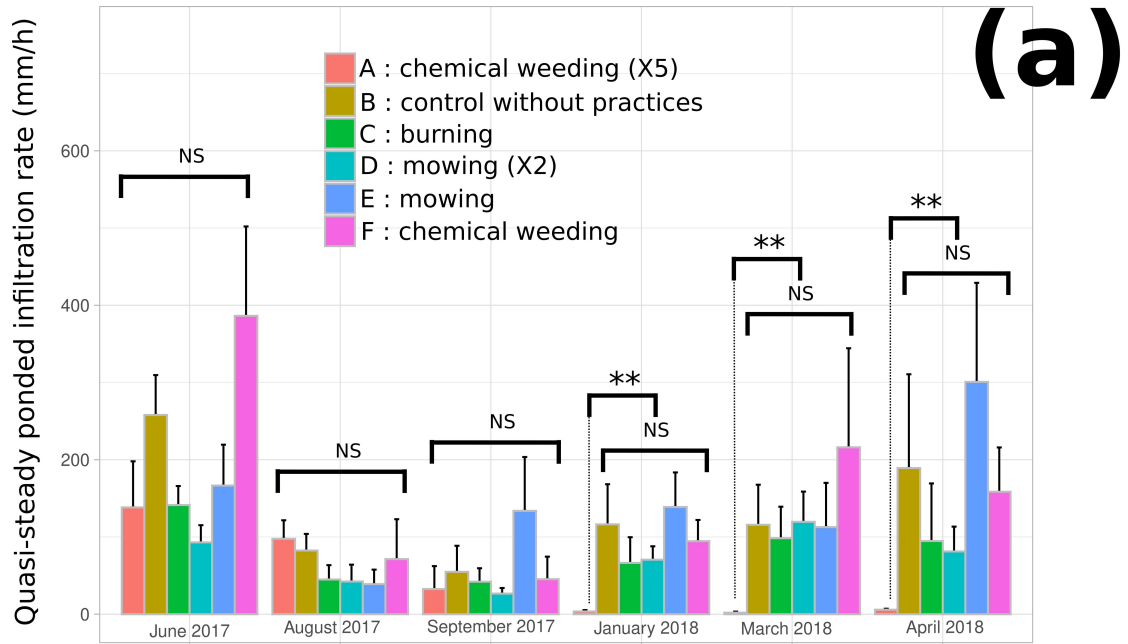


Figure 6: Change of the quasi-steady ponded infiltration rate in each quadrat (managed with different practices) (a) before and (b) during management practices. Analyses of the quasi-steady ponded infiltration rate, f_{cp} , versus management strategies relied on LME models with a log-transform of the explained variable. The model includes ID as a random effect. Coloured bars correspond to the timing of each practice. Black vertical bars represent standard errors. The horizontal bars represent the results of the Tukey post hoc test on LME, with ** indicating significant at p-value < 0.05, and NS indicating p-value > 0.05.

the images taken initially to observe the vegetation cover of the cylinders, and probably caused by intense rainfall occurring in 2018 could explain the decrease. Secondly, a possible explanation for the overall reduction in quasi-steady ponded infiltration rates for planted frames is a progressive filling of all macropores by plant roots, the latter prevented from developing on the surface because of the cylinder walls. Finally, the recurrent ponding infiltration tests with large amounts of water will lead to change in soil structure. This last point is a limitation of our method.

The absence of relationships between vegetation cover and quasi-steady infiltration rates reported in our study differed from Thompson *et al.* Thompson *et al.* (2010) and Li *et al.* Li *et al.* (2011) who found a positive relationship between above ground biomass and infiltration rates. However, they studied a diversity of pedoclimatic contexts that encompass the strict link between vegetation and infiltration rate.

We highlighted a significant difference in quasi-steady ponded infiltration rates between plant species having contrasting root systems. The plants with tap-root, i.e. stronger root systems than plants with fibrous ones, could create higher channels around roots. This could suggest that the presence of service crops with tap-root systems should be favored in vineyard inter-rows for increasing or maintaining infiltration capacity of the soil. However, the question arises on how to extrapolate our experimental results to the diversity of service crops that encompass a wider variety of root systems in terms of density and structure. In addition, the experiment shows no effect of common plant management strategies (mowing, chemical weeding and burning) on quasi-steady ponded infiltration rates, despite the potential role of chemical weeding inducing macropore creation due to root decay after vegetation death. This lack of effect could be due to the study conditions, which reduced the time required for root decay. This suggests that the role of management strategies to control biodiversity (tap-root or fibrous systems), instead of directly controlling the infiltration rates, should be explored.

The high variability, even over a few cm, calls for updating the infiltration measurement protocols to be carried out in the field, either by refining sampling protocols to increase the density of measuring positions or by considering methods able to follow infiltration rates over larger areas, such as the linear source method presented by Lili *et al.* Lili *et al.* (2008). Combining experiments with inverse modeling is also an interesting way to assess the infiltration capacities of landscape elements, such as ditches (Dagès *et al.*, 2009). Finally, an improvement of the method by an automatized single-ring could be mentioned, as it prevents preferential flows between guarding and inner rings and water saving supposing that the effect of ponding depth and depth of ring insertion should be corrected (Jačka *et al.*, 2016).

This study is a first step for the implementation of nature-based solutions to store rainwater to mitigate detrimental effects of climate change (Rockström *et al.* Falkenmark, 2015). It shows the necessity to increase soil infiltration during summer to enhance the water available for plants or groundwater recharge and at the beginning of autumn to limit the effects of intense

rainfall due to the poor infiltration capacities of soils.

5. Conclusion

This experiment explored the influence of cover (bare soil, Malvaceae, and Poaceae), time, and management strategies on quasi-steady ponded infiltration rate in a Mediterranean agricultural area. An original protocol based on an automatized infiltrometer allowed taking nine measurements of infiltration rates simultaneously. The results showed a strong variability in quasi-steady ponded infiltration rates according to the seasons (higher values in summer than in winter) and at short spatial scales. An effect of the cover was highlighted, with a higher infiltration rate for Malvaceae than Poaceae and a higher one for both types of plants than for bare soil. There was no significant effect of management strategies applied to the plant cover on the quasi-steady ponded infiltration rates. The study calls for a better consideration of both seasonal and functional traits of plants to maximize infiltration.

Data availability statement

The data that support the findings of the study are available at 10.5281/zenodo.5013558 as of the date of publication.

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