Seasonal variation of soil physical properties under different water managements in irrigated rice

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Title: SEASONAL VARIATION OF SOIL PHYSICAL PROPERTIES UNDER DIFFERENT WATER MANAGEMENTS IN IRRIGATED RICE

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Abstract

While soil porosity and soil hydrological properties are key characteristics that define different soil types, they are influenced by many factors: land use, tillage management, and agricultural practices such as irrigation. As expected, water management impacts the physical properties of soil in irrigated rice significantly; however, the importance of seasonal variation on those soil properties requires further consideration, especially given the period of continuous submersion. In this paper, the different soil physical properties have been studied with two goals in mind: 1) to compare the bulk densities, cumulative pore size distribution curves, and near-saturated hydraulic conductivity values associated with seasonal variation induced by submerging water or rainfall on irrigated rice cultivated under two different water managements and in one rain-fed crop, and 2) to describe and parameterize the relationship that links near-saturated hydraulic conductivity to soil porosity in a generic semi-empirical model independent of treatment differences and seasonal variability.

The experiment was conducted in the Piedmont Region (NW Italy) in sandy loam soil on three contiguous fields cultivated as follows: (i) continuous rice in submersion, (ii) continuous rice seeded in dry soil submerged one month after the first field, and (iii) maize in rotation with rice (rain-fed treatment). The physical properties of the soil were measured five times over the year at depths of 0-12 cm and 12-25 cm.

Results showed a progressive compaction of the soil and a consequent reduction of the near-saturated hydraulic conductivity due to submersion. Macro- and meso-porosity decreased while micro-porosity increased. At the end of submersion, new large porosity was created and the situation reverted to that noted at the start of the year. The non-submerged field showed a different behaviour; in the absence of submersion, bulk density reduced as a result of rainfall but the effect on the different classes of pores was reversed.

Finally, a new semi-empirical model is presented that describes near-saturated hydraulic conductivity as a function of soil porosity.

Key words: rice; irrigation; soil porosity; soil physical properties; semi-empirical model.

1 Introduction

The relationship between soil physical properties and soil structure and porosity has been widely explained by Kutilek (2004). The author classified soil pores according to their hydrological functionality: (i) submicroscopic pores are considered non-active; (ii) micro-pores (capillary pores) are those where the unsaturated flow of water occurs; (iii) macro-pores (non-capillary pores) are those where capillary menisci are not formed across the pore and water flow is driven by gravity alone. Other authors have introduced the concept of meso-porosity (Luxmoore, 1981) as pores having an intermediate functionality between macro- and micro-porosity.

Other than hydrology, soil porosity influences biogeochemical processes and soil fertility. For example, pore size distribution, together with pore shape and connectivity, influences the transport of dissolved and non-dissolved chemicals and gases. It also acts upon plant rooting and on the conditions for the life of all soil biota (Kutilek et al., 2006). Furthermore, it helps explain the dynamics of soil C and N cycles (Juma, 1993) and is positively correlated with root growth and soil enzyme activity (Pagliai and De Nobili, 1993). Clearly its description is of primary import in agricultural systems.

Soil porosity can be described using direct methods based on microscopic techniques and image analyses (Pagliai and Vignozzi, 2002) or it can be described functionally using indirect methods based on the measurement of soil physical properties. A functional description of porosity requires the estimation of total soil porosity by pairing bulk densities with particle densities, the distribution of pore size in the soil by utilizing the water retention curve, and the identification of those soil pores that are highly active in water and solute transmission by measuring the near-saturated hydraulic conductivity (Ankeny et al., 1991).

Soil porosity and soil hydrological properties characterize the different types of soils, but are also largely influenced by land use (Bormann and Klaassen, 2008), tillage management, (Moret and Arrùe, 2007a) and other agricultural practices. Moreover, they change over time due to anthropic soil perturbation and environmental forces. For example, as reported by Cameira et al., (2003) in a maize cultivation experiment, irrigation affected the macro-porosity and meso-porosity of the ploughed layer as evidenced by a decrease of 65% and 50%, respectively. This was attributed to the breakdown of fragile pores created by tillage. Furthermore, in the same experiment, seven irrigation events were found to effect a continuous reduction in macro-porosity until harvest when it increased, probably due to root development.

Many have described the effect of wet–dry cycles on soil porosity and consequently, on soil physical properties (Petersen et al., 2004; Schwartz et al., 2003). Additionally, many have focused on describing the soil physical property dynamics of irrigated rice under different puddling intensities and depths compared to unpuddled fields (Kukal and Aggarwal, 2002; Mohanty et al., 2004). They have demonstrated that the continuous presence of submerging water destroys porosity and reduces water percolation in treatments where puddling is not applied. However, description of the effect of submerging water on different soil physical properties as opposed to rainfall on rain-fed crops remains unexplored.

The description of the dynamics of the different soil hydrological properties can be simplified by the fact that some of them vary together. In particular, authors have related the near-saturated hydraulic conductivity to the amount of pores hydraulically active (Kozeny, 1927, Carman, 1937 and 1956, Aimrun et al., 2004). Consequently, the near-saturated hydraulic conductivity dynamic—a time consuming measurement—can be described using other easier-to-measure variables, such as the dynamic of total soil porosity.

The different soil physical properties considered in this paper have been studied with two goals: 1) to compare the bulk densities, cumulative pore size distribution curves, and near-saturated hydraulic conductivity values associated with seasonal variation induced by submerging water or rainfall on irrigated rice cultivated under two different water regimens and in one rain-fed crop, and 2) to describe and parameterize the relationship that links near-saturated hydraulic conductivity to soil porosity in a generic semi-empirical model independent of treatment differences and seasonal variability.

2 Materials and methods

The experiment was carried out in 2005 in the Piedmont Region (NW Italy, lat. 45° 17’, long. 8° 25’) in the widest European paddy area on a Typic Endoaquept, coarse-silty, mixed, non-acidic, mesic soil (USDA, 1977). The explored horizon (0-25 cm) was classified as sandy loam according to USDA texture classification. The average soil organic carbon content was 9.8 g kg^{-1} dry soil.

We analysed the physical properties of the soil in three contiguous fields totalling about 1840 m^2, hydraulically separated by 80 cm large embankments, and supplied with water derived from the same channel.

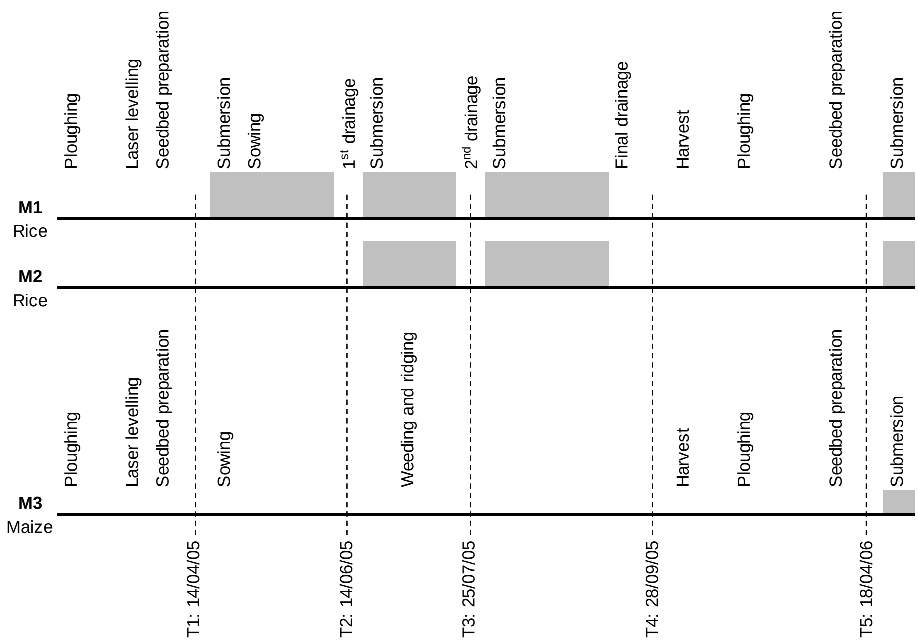


Fig. 1: Samplings and managements of the three fields in the experiment.

The three fields differed in that each underwent a unique water management described in Figure 1. The first management (M1) was based on continuous rice (*Oryza sativa* L.) submerged from before seeding up to one month before harvest with two drainages of about five days each; it represented the traditional management of the area. In the second (M2), rice was seeded in dry soil and irrigation was delayed for one month later than in the M1 field. The third (M3) field was cultivated with maize (*Zea mays* L.) after two years of continuous rice; it served as the experimental control as it never received irrigation during the studied year.

All three fields were ploughed in spring with a moldboard plough and laser levelled. The seedbeds were prepared using a rotovator. Additionally, the maize crop was weeded and ridged two months after sowing. Although puddling is a common practice in paddy areas around the world, it is not done in the Italian paddy area and consequently, not in our fields.

In each field, measurements were taken from two different holes dug about 5 m apart and placed in the centre of the field.

The three fields were physically characterised at the start of the experiment from soil texture and particle density measurements. Soil texture was measured using the pipette method according to SIA (2000) on 25g samples. Measurements were replicated six times for each field. Particle density (PD) was measured using 20g samples for six replications on each field via the picnometer method (Blake and Hartge, 1986a) utilising ethylic alcohol as the displaced fluid (EMBRAPA, 1997).

The resulting measurements showed that the different fields were generally homogeneous (Table 1). Differences appeared in the coarse sand of the first layer (5%) and in the clay of the second layer (1.7%). However, as they were not too large, we considered that they would not influence hydrological properties.

Table 1: Average values and 95% confidence intervals of the physical parameters of the soil.

Parameter	MU	T1		T2		T3	
		0-12 cm	12-25 cm	0-12 cm	12-25 cm	0-12 cm	12-25 cm
Clay	%	6.5 ± 1.8	6.9 ± 1.1	6.3 ± 1.1	6.6 ± 1.0	5.0 ± 1.0	5.2 ± 0.6
Fine silt	%	20.0 ± 2.3	19.7 ± 2.5	21.5 ± 0.8	21.6 ± 1.7	20.3 ± 0.8	19.7 ± 1.9
Coarse silt	%	22.1 ± 2.5	25.0 ± 2.6	24.5 ± 1.1	24.8 ± 2.5	24.8 ± 3.0	24.8 ± 2.8
Fine sand	%	26.9 ± 2.0	27.7 ± 2.4	27.6 ± 1.2	27.5 ± 3.8	28.6 ± 3.5	31.0 ± 4.6
Coarse sand	%	24.5 ± 2.4	20.8 ± 2.5	20.1 ± 0.4	19.5 ± 0.8	21.2 ± 1.0	19.3 ± 2.4
Particle density	Mg m^{-3}	2.57 ± 0.07	2.59 ± 0.09	2.62 ± 0.04	2.60 ± 0.07	2.59 ± 0.06	2.58 ± 0.08

2.1 Repeated soil physical measurements

We repeated the following soil measurements at different times during the experiment: soil dry bulk density, water retention curve, and near-saturated hydraulic conductivity curve.

The cylindrical sampler method (Blake and Hartge, 1986b) was used to measure soil dry bulk density (BD) with six replicates for each field measurement. The cores were 50.4 mm in diameter and 50.0 mm high (100 cm^3). The total porosity (Φ) was derived from the BD and PD through the known function:

$$\Phi = 1 - \frac{BD}{PD} \qquad [1]$$

The water retention curve was derived in the laboratory from undisturbed samples. Laboratory analyses were conducted in desorption, with both tension chamber and pressure plate apparatuses, following the methodology proposed by Klute (1986). Three cylindrical soil samples (58 mm in diameter and 30 mm in height) were extracted, weighed at saturation and after equilibration at various pressures, and then oven-dried (105 °C, 24 hours) to determine their dry weight. Water tensions of 0.2, 0.5, 1, 2, 5, 6, and 10 kPa were achieved in a tension chamber while water tension of 33 kPa was achieved in the pressure plate apparatus. The soil samples used for determining the water retention curve were thinner and larger than those used for determining soil bulk density. The thinner samples accelerate attaining equilibrium *versus* the hydrological equipment as water has a shorter pathway to leave the sample. Since thinner soil samples cause the volume determination to be less precise because of the roughness of the two surfaces, we expressed the water content first as water content relative to saturation of each sample, then converted it to absolute water content via the soil total porosity calculated using equation [1]. The results of the water retention curve were converted to a cumulative pore size distribution. The equation reported by Gardner et al. (1991) was used to calculate the equivalent pore radius of the pores corresponding to the different water tension values. The measured water content was considered to be the total volume of pores occupied by water at each tension and represents the sum of the volume of all pores filled with water at a given tension.

The near-saturated hydraulic conductivity was measured in four replicates for each field measurement using tension infiltrometers (White, 1992) with 148 mm diameter bottoms. The steady-state infiltration rate was measured at each location manually at three different water tensions (0.05, 0.1 and 0.2 kPa). The measurements started at the highest water tension and ended with the lowest (i.e., closest to saturation) in order to avoid problems due to hysteresis (Zavattaro et al., 1999). The infiltrometers were directly placed over the soil without any interposed material. The steady-state infiltration rate was converted from three-dimensional hydraulic conductivity into one-dimensional hydraulic conductivity following the method proposed by Ankeny *et al.* (1991). With this procedure, involving linear interpolation between measurements, four pairs of hydraulic conductivity at water tensions of 0.05, 0.075, 0.15, and 0.2 kPa were calculated and the value corresponding to the mid water tensions was removed (0.1 kPa). This procedure, based on a stepwise interpolation, has been widely applied by other authors (Messing and Jarvis, 1993; Zavattaro et al., 2001; Daraghmeh et al., 2008).

Following this set of measurements and according to the literature, macro-porosity was defined as pores with an equivalent radius of greater than 745 μm applying a water tension equivalent to 0.2 kPa (adapted from Cameira et al., 2003) while the upper limit of micro-porosity was chosen as 30 μm per Kutilek (2004), which corresponds to a water tension equivalent to 2 kPa. Consequently, meso-porosity was defined in the range of 0.2-2 kPa.

2.2 Measurements times and depths

The bulk density, cumulative pore size distribution, and near-saturated hydraulic conductivity were each measured in the three fields at five different times corresponding to the rice management operations reported in Figure 1:

1) after seedbed preparation and before the first submersion of M1 (T1 = 14/04/2005);

2) upon initial drainage of M1 and immediately before the first submersion of M2 (T2 = 14/06/2005);

3) at the second drainage of M1 corresponding to the first drainage of M2 (T3 = 25/07/2005);

4) after the final and complete drainage of M1 and M2 (T4 = 28/09/2005);

5) at seedbed preparation during the following year, (T5 = 18/04/2006).

In M3, weeding and ridging occurred between T2 and T3.

The measurements were conducted in the ploughed layer at 0-12 cm and 12-25 cm which allowed for evaluation of the effect of the submerging water on the two depths. The cumulative pore size distribution curve was not measured in the first layer at T1 and T5 as the soil was too incoherent to allow undisturbed sampling. Moreover, measurements were not performed in the second layer at T2 and T3 because it was impossible to dig holes in the fields during short-term drainage due to the high water content. Details of the measurements are reported in Table 2.

Table 2: Measurements performed at different times and in different soil layers for each attribute analysed on the three fields.

Measurement	Time		Depth	
			0 - 12 cm	12 - 25 cm
Bulk Density	Start	T1	X	X
	1st drying	T2	X	
	2nd drying	T3	X	
	Final	T4	X	X
	2nd year	T5	X	X
Water Retention Curve	Start	T1		X
	1st drying	T2	X	
	2nd drying	T3	X	
	Final	T4	X	X
	2nd year	T5		X
Near-saturated hydraulic conductivity	Start	T1	X	X
	1st drying	T2	X	
	2nd drying	T3	X	
	Final	T4	X	X
	2nd year	T5	X	X

2.3 Data analysis

2.3.1 Seasonal variations

The seasonal variation in the bulk density, cumulative pore size distribution, and near-saturated hydraulic conductivity at different water tensions were analysed to compare the effect of the different water managements. Data on the near-saturated hydraulic conductivity at different water tensions showed a log-normal distribution as reported by other authors (Petersen et al., 2004); afterwhich, they were presented as log-transformed data. As variances were not homogeneous between different water managements, the 95% confidence intervals were chosen to allow the independent comparison between treatments. Only means showing significant differences are discussed here.

2.3.2 Porosity—near-saturated hydraulic conductivity relationship

The relationship between saturated hydraulic conductivity and soil porosity is largely known (Ahuja et al., 1984; Messing, 1989; Rawls et al., 1998; Aimrun et al., 2004; Han et al., 2008) and described through a power function parameterised with two empirical constants that are site specific. The simplified formulation of this equation is reported here:

$$K = B * \Phi_{eff}^{n} \quad [2]$$

Where:

K = saturated hydraulic conductivity

B, n = fitting parameters

Φ_{eff} = effective soil porosity hydraulically active at saturation

Jarvis et al. (2002) extended the application of the equation [2] to the near-saturated hydraulic conductivity. According to these applications, equation [2] has been applied here to the different values of near-saturated hydraulic conductivity measured at different tensions separately. The equation has been applied in the form:

$$K(h) = B_h * \Phi_{eff}^{n_h} \quad [3]$$

h = water tension at which K(h) has been referred (kPa)

K(h) = near-saturated hydraulic conductivity (cm s^{-1}) referred at h

B_h, n_h = fitting parameters

Φ_{eff} = effective soil porosity hydraulically active at saturation

Effective porosity is described using different limits of water tensions by different authors (Ahuja et al., 1984; Messing, 1989; Rawls et al., 1998; Poulsen et al., 1999; Han et al., 2008) as pore-size distributions and water retention curves vary across soils and over time. We decided to fit the total porosity in equation [3] instead of effective porosity, assuming that the reduction of porosity between total and effective will be expressed by an average proportion that will be included in the B_h fitted parameter. This decision was justified by the fact that we worked on only one type of soil and was also supported by the good curve fitting we obtained that is presented later.

$$K(h) = B_h * \Phi^{n_h} \quad [4]$$

According to Aimrun et al. (2004), equation [4] also bears similarities to expressions relating unsaturated hydraulic conductivity to the degree of saturation as presented by Averjanov

(1950), Wyllie and Spangler (1952), and Brooks and Corey (1964). Consequently, the four regressions, each applied to a different water tension, could be combined into one as long as the reduction of water-filled pore space at those different water tensions is taken into account.

Differences in both parameters B_h and n_h at each water tension were tested at a 95% confidence interval of probability; at significant differences, non-linear regression was applied to express the variation as a function of the water tension.

The goodness of fit between estimated and measured values of near-saturated hydraulic conductivity was checked through the coefficient of determination R^2, the NRMSE (Loague and Green, 1991), and by regression analysis between fitted and measured values. The null hypothesis tested was that the linear regression did not significantly deviate from the 1:1 line. These statistics were applied to log transformed near-saturated hydraulic conductivity data as previously specified.

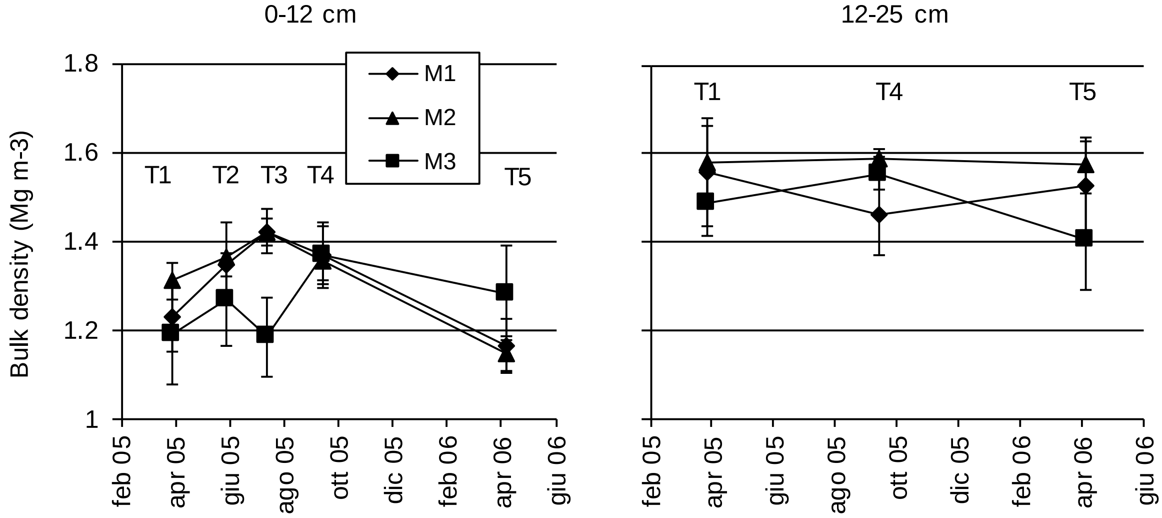
3 Results

3.1 Seasonal variations

3.1.1 Bulk density

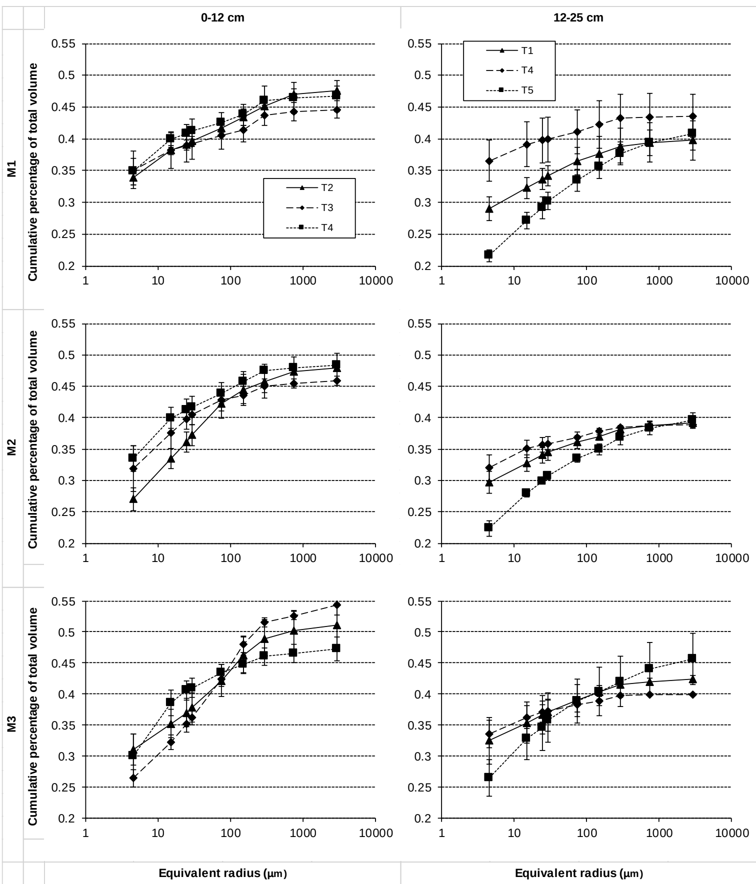
In the first layer, the general trend of the bulk density is to increase from T1 to T3 and then decreases from T3 to T5 (Figure 2). In the interval between T1 and T2, the average bulk density values increased in M1 to a greater extent than compared to the other two treatments; they increased to the same extent. In the T2-T3 interval, bulk density increased in both of the submerged treatments to the same extent while it decreased in M3 due to the weeding and ridging performed. During the last part of the cropping season, bulk density decreased in M1 and in M2 due to submerging water removal while it increased in never-submerged M3. At this point in the process, the three treatments showed the same value of bulk density. At T5 bulk density values were equal for M1 and M2 and greater for M3.

Fig. 2: Bulk density of the three managements measured at different times in the two layers. Error bars refer to 95% confidence interval.



Second layer values showed greater pattern variability; however, the values at the beginning of the second year were close to those at the beginning of the first year, except for M3.

Fig. 3: Cumulative pore size distribution curves of the three different managements measured at different times. Larger values are referred to an arbitrary pore radius as they represent the saturation. Error bars refer to 95% confidence interval.

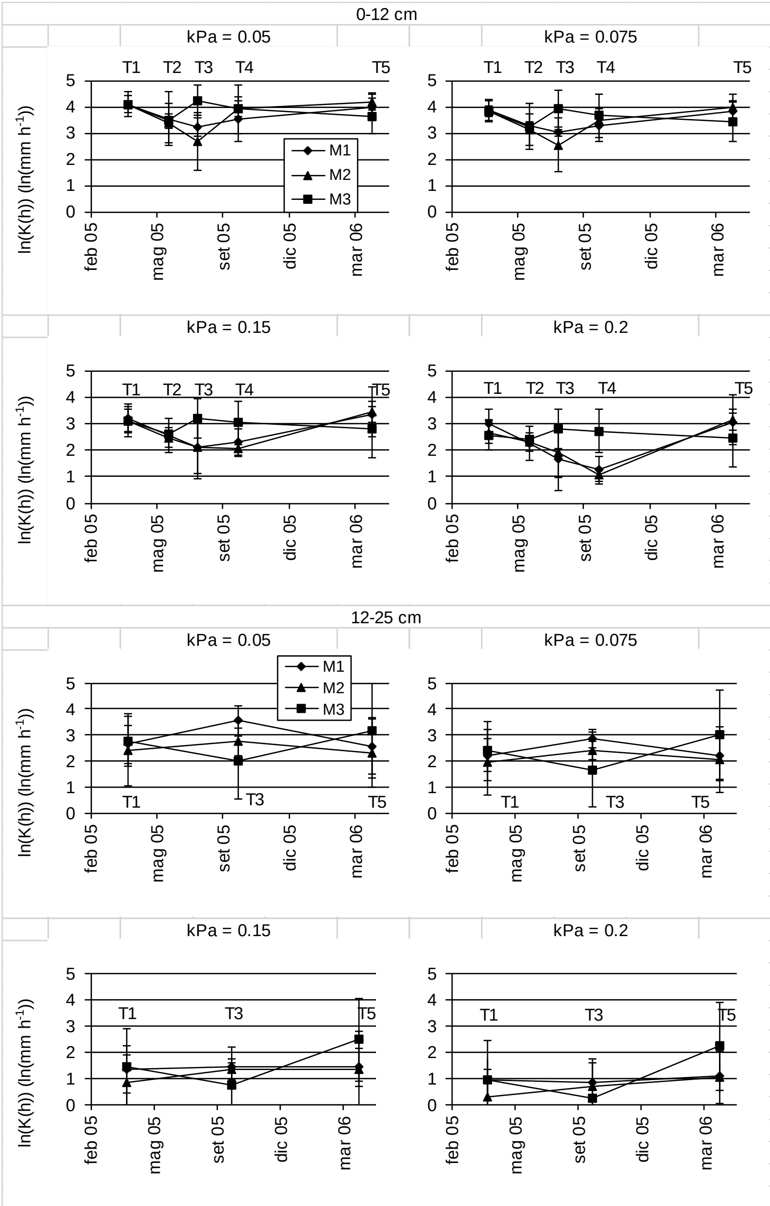


3.1.2 Cumulative pore size distribution curve

Figure 3 shows the cumulative pore size distribution curve of the three treatments at different sampling times of the two layers. Larger values are referred to an arbitrary pore radius as they represent the saturation. In the first layer of the submerged treatments (M1, M2) from T2 to T3, the cumulative pore size distribution curve decreased in macro- and meso-porosity volume and increased in micro-porosity volume. The increase is more evident in M2 than in M1. During the T3 - T4 interval, the porosity increased in all the explored ranges. In the case of M3, the behaviour of the ranges of porosity was different. Macro- and meso-porosity increased from T2 to T3 due to the effect of ridging and weeding while micro-porosity decreased. In the later interval, the opposite occurred.

In the second layer of the submerged treatments, the porosity increased from T1 to T4. Later, during T5, it decreased. The same result occurred in M3 for micro-porosity, but the behaviour was reversed for macro- and meso-porosity.

Fig. 4: Near-saturated hydraulic conductivity of the three different managements measured at different times. Error bars refer to 95% confidence interval.

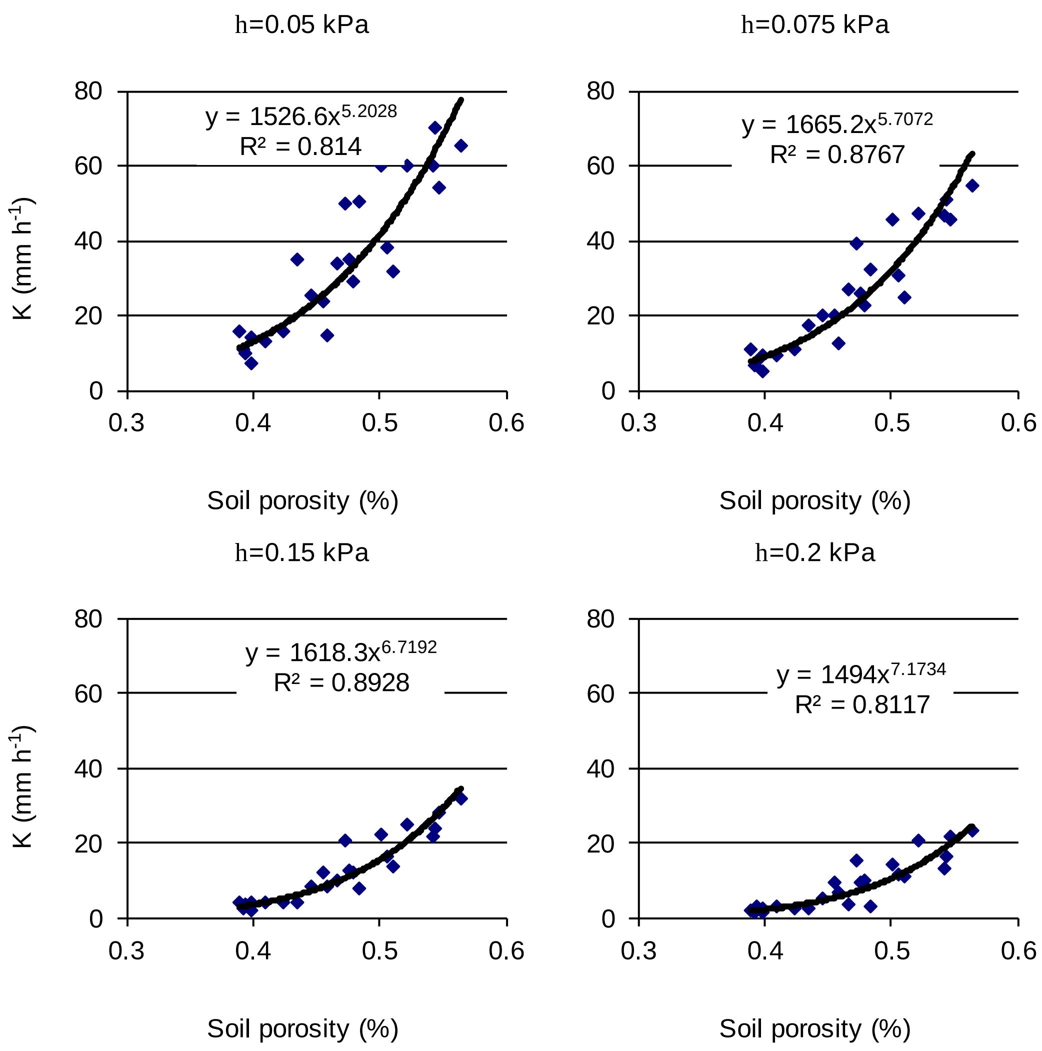


3.1.3 Near-saturated hydraulic conductivity

Figure 4 reports near-saturated hydraulic conductivity. The results partly confirmed the trend shown for bulk density; that is, all values in the first layer at T1 were similar for all treatments save for M2 that instead showed some bulk density differences. Between T3 and T4, as a consequence of drainage, the near-saturated hydraulic conductivity increased at the two greater tensions while it decreased at the lower tension. During this interval the increase in soil porosity has increased the near-saturated hydraulic conductivity only at tensions closer to saturation showing a different behaviour than at the other times of measurements. At T5, values were equal to those at T1 for M1 and M2, and in agreement with bulk density measurements. Among them, the value for M3 was the greatest.

In the second layer, trends in M1 and M2 were quite homogeneous as opposed to the increase in near-saturated hydraulic conductivity at the greater tensions seen in M3 at T3.

Fig. 5: Relationship between near-saturated hydraulic conductivity measured at different water tensions and total porosity (n = 24). All treatments x dates x depth are pooled together.



3.2 Porosity—near-saturated hydraulic conductivity relationship

Equation [4] has been applied to near-saturated hydraulic conductivity, measured at different water potentials, and total porosity (Figure 5) using the dataset obtained by pooling together times, managements, and depths. It shows good coefficients of determination ranging from 0.812 to 0.893.

Fig. 6: Values of the fitted parameter B_h of equation [4] at different water tensions (h). Error bars represent standard error.

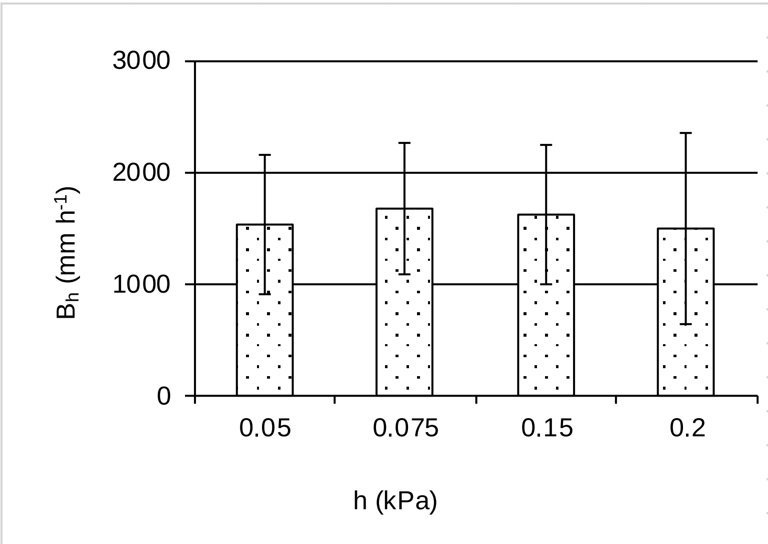
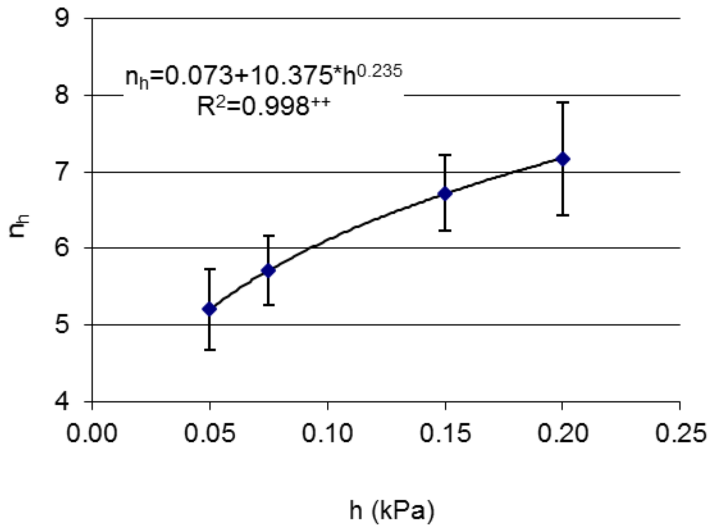


Figure 6 represents the B_h fit parameter of equation [4] reported in Figure 5 at water tensions 0.05, 0.075, 0.15, and 0.2 kPa. The B_h values showed little variability and no statistical differences between different water tensions. This confirms what Ahuja (1984) reported—that B is a specific parameter of the soil.

Figure 7 represents the n_h parameter of the equation. In contrast to B_h, n_h shows important differences relative to the water tensions and an increasing trend as the soil gets drier. The data represented on the graph correspond to the four values of water tension and were fitted with an empirical function in the same mathematical form as that of the Kozeny Carman equation, albeit with the addition of a constant to maintain proportionality between K and Φ even when h was equal to zero.

Fig. 7: Values of the fitted parameter n_h of equation [4] at different water tensions (h). Error bars represent standard error.



The fitted equation for n is reported below:

$$n_h = m + C \cdot h^d \qquad [5]$$

The fitting of the power function equation [5] resulted in a highly significant non-linear regression and a coefficient of determination very close to 1 (Figure 7). We are aware that only four points (one for each tension) have been fitted, however the n_h parameter follows very well the equation that is expected to describe the progressive reduction of conductive porosity as water tension increases.

When equations [4] and [5] are joined, we obtain equation [6]:

$$K(h) = \mathrm{B_h} * \Phi^{m + C*h^d} \qquad [6]$$

that can also be expressed in the more simple logarithmic form used for the fitting:

$$\ln(K(h)) = \ln(\mathrm{B_h}) + \left(\mathrm{m} + C * \mathrm{h}^{\mathrm{d}}\right) * \ln(\Phi) \qquad [7]$$

Where:

h = water tension at which K(h) has been referred (kPa),

K(h) = near-saturated hydraulic conductivity referred at h (cm s^{-1}),

B_h, C, m, d = fitting parameters, and

Φ = total soil porosity.

Equation [7] lets us summarize the four equations [4] into only one, and consequently reduce the total number of parameters from eight (two for each of the four tension-specific equations [4]) to four, and increase the number of cases to 96 (pooled dataset).

Equation [6] is a new semi-empirical description of the relationship that relates near-saturated hydraulic conductivity to total porosity.

Fig. 8: Predicted values of the logarithm of the near-saturated hydraulic conductivity versus measured values with (a) or without (b) values measured in T4 as specified in the text.

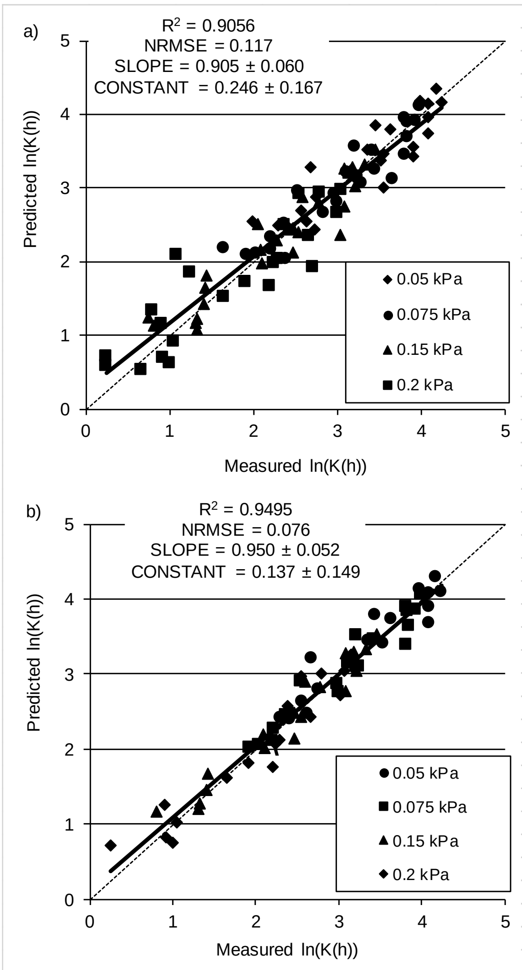


Figure 8a shows the final results of the fitting. The relationship between measured and predicted values of the logarithm of the near-saturated hydraulic conductivity is very good with a coefficient of determination greater than 0.9 and a RMRSE equal to 11%, but with a significant deviation with respect to a 1:1 line that led to a slight overestimation close to the saturation.

4 Discussion

4.1 Seasonal variations

Most treatments, if submerged the year before the measurements, showed a value of bulk density close to 1.18 Mg m^{-3}. Also the treatment cultivated with maize, but submerged during the previous year, showed the same value in T1 as well as after weeding and ridging. Consequently it can be assumed that this soil, if submerged during the previous year, tends to reach a constant value of BD after secondary tilling. Moret and Arrùe (2007b) have also described this very low variability in bulk density measured under the same conditions but in different years or at different points in time, albeit for a different soil type.

After tilling, the physical properties of soil start their dynamics. The effect of the water on the soil from irrigation or water submersion tends to decrease the porosity and the water permeability (Kukal and Aggarwal, 2002; Cameira et al., 2003). The results of this experiment allowed us to quantify the effect of the rainfall and the effect of the submerging water.

During the interval T1-T3, M1 was constantly submerged and the bulk density increased for 97 days (not accounting for 5 days when the soil was drained). Assuming a constant rate, this corresponds to approximately 2 kg m^{-3} d^{-1}. Obviously, it is expected that the process reaches a plateau, but the measured data do not permit us to define when this occurs. The M2 treatment was submerged during the T2-T3 interval as well, and the measured rate of increase in bulk density confirmed the rate calculated in M1.

The increase of bulk density in M2 and M3 during the T1-T2 interval and in M3 during the T3-T4 interval was mainly driven by rainfall between other processes. During the second interval, total rainfall was equal to 454.8 mm which led to a greater rate of compaction when compared with those calculated in the first period for both treatments when only 135.4 mm of rain fell. The effect of the almost-permanent submerging water on soil compaction was greater than the effect exerted by 135.4 mm of rainfall and comparable to the effect of 454.8 mm.

After the removal of the submerging water in M1 and M2, the soil drainage and root turnover (Cameira et al., 2003) created a new porosity and a decrease in bulk density.

The water retention curve allows us to better understand which pore dimensions contribute most to total porosity at different times. The effect exerted by water trough submersion or rainfall tends to disrupt macro- and meso-porosity and this is evident either in the treatment submerged or not submerged during the first interval.

The second effect exerted by the water is the increase in micro-porosity that can be noted in M2 during the T2-T3 interval (T2: beginning of submersion). In M1 it seems that the increase happened before T2 as at this time, micro-porosity values were almost equal to those of T3. As M2 was submerged only after T2, and M1 was already submerged before T2, the comparison of these two different situations reveals that whereas the process of reduction in macro- and meso-porosity due to water submersion continues for a long time, the process of creation of micro-porosity after laser levelling is very fast and is shorter than the interval T1-T2 or T2-T3.

In T4 water drainage and root turnover caused an increase in porosity in all explored ranges of pores.

In M3, the effect of tillage between T2 and T3 increased the macro- and meso-porosity as expected, but also reduced the micro-porosity. After T3 the soil was not disturbed other than by rainfall that resulted in the same effect as that produced by irrigation of the submerged treatment during the T2-T3 interval (macro- and meso-porosity decreased and micro-porosity increased).

Hu et al. (2009) analysed the trend of the different pore classes over time in relation to different rainfed crops, and expressed results in terms of contribution to water flow. They described trends similar to those described in this work between T1 and T3, with a progressive reduction of the role of the macro- and meso-porosity during the growing season and an increase of the role of the micro-porosity. However, they failed to note any new increase of macro- and meso-porosity at the end of the growing season, nor any reduction in bulk density. In contrast, Cameira et al., (2003) reported an increase of macro- and meso-porosity at the end of the growing season. Consequently, it is clear that different soils behave differently in this respect.

The results seen in the near-saturated hydraulic conductivity of the first layer confirmed the trend shown in bulk density. The three treatments at the onset of the experiment and M1 and M2 at the beginning of the second year showed very similar values due to a common history.

M3 instead demonstrated different values due to a different history of submersion.

It is interesting to note that at T4, the near-saturated hydraulic conductivity at water tensions greater than 0.15 kPa followed a different pattern when compared to the other tensions and to the trend measured in bulk density. The interruption of the submersion, with a consequent drying of the soil, changed the near-saturated hydraulic conductivity curve and its relationship to bulk density.

The increase in macro- and meso-porosity measured in the T3-T4 interval led to a greater near-saturated hydraulic conductivity only at water tensions greater than 0.15 kPa. In fact, near-saturated hydraulic conductivity at 0.15 kPa remained almost constant while it decreased at 0.20 kPa. This confirms that, as expected, the near-saturated hydraulic conductivity is dominated by the larger pore classes.

In the second layer, the most interesting aspect is related to the effect of the laser levelling. It was performed before T1 but not before T5. As shown by the water retention curves, macro- and meso-porosity is similar in the two situations, which reveals the minor effect laser levelling plays on this porosity range. Moreover, micro-porosity is greater at T1 than in T5, showing that many other environmental effects can influence micro-porosity more than laser levelling can.

The very similar pattern observed over time between macro- and meso-porosity and near-saturated hydraulic conductivity measured at water tensions greater than 0.15 kPa also confirmed the simple relationship that exists between these two soil physical characteristics.

4.2 Porosity —near-saturated hydraulic conductivity relationship

The relationship between the near-saturated hydraulic conductivity measured to 0.2 kPa of water tension and total porosity explained most of the combined seasonal variation of the two parameters. It showed that near-saturated hydraulic conductivity could be derived from total porosity after the equation was parameterised. The unique equation showed that the relative distribution of different pore classes is quite constant in the soil despite different depths, treatments, and situations during the year.

The overestimation of the near-saturated hydraulic conductivity that we obtained close to saturation from fitting equation [6] derived from the different behaviour of near saturated hydraulic conductivity measured at water tensions greater than 0.15 kPa in T4 as previously underlined. Removing the values measured in T4 from the regression, the new coefficients of determination for the regressions (shown in figure 5) would increase to about 90%, which would allow them to still be fitted by equation [4] with similar results. B_h values would still not be statistically different between water tensions. A new fitting performed on equation [6] would yield a final coefficient of determination increased to 95%, the NRMSE would decrease to 7.6%, and the regression would became statistically not different from the 1:1 line (Figure 8b) perfectly describing the relationship to all the other times of measurement.

5 Conclusions

The total amount and the relative distribution of the different pore classes in the ploughed layer show an important dynamic over the cropping season that leads to quite different values of bulk density, water retention curves, and near-saturated hydraulic conductivity. Hydrological and biochemical processes that depend on these parameters require a characterization over time of the soil physical properties that must take seasonal variation into account. Submerging water and rainfall both destroy macro- and meso-porosity while on the other hand, micro-pores are formed.

The strict relationship between near-saturated hydraulic conductivity and bulk density described in this soil led to development of a semi-empirical model that could describe the near-saturated hydraulic conductivity *versus* total porosity dynamic at any time interval. This let measure the latter soil physical property with a lower intensity of bulk density.

Coupled measurements of near-saturated hydraulic conductivity and bulk density performed after the final soil drainage showed a behaviour different from the rest of the dataset and should be further investigated. Also the equation relating porosity to near-saturated hydraulic conductivity should be tested and validated over a wider range of soils.

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