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Investigation of spatial and temporal variability of saturated soil hydraulic conductivity at the field-scale

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ABSTRACT

Though soil hydrologists agree that field saturated conductivity (K_s) is a key parameter in modelling the dynamics of water flow and solute transport in soils, they also recognize that its variability in space and time is far from being completely understood. In order to highlight the variability of K_s at the plot scale we performed 10 measurement campaigns in three parcels within a 10 ha maize field during two subsequent crop seasons and in the fallow periods following them, in uniform conditions of crop, agricultural practices and, to a large extent, of pedological characteristics. This paper reports the outcomes of the measurements, conducted with the Guelph permeameter (GP) and with the tension infiltrometer (TI), along with detailed information on the data and a thorough description of the experimental field and of the measurement techniques. Based on a careful statistical analysis of the dataset and an extensive discussion of the results, the following conclusions were reached.

GP K_s show changes in time and space, both between and within the parcels, with a different temporal behaviour for the different parcels, and no evident seasonal cycle. Mean and standard deviation of the transformed GP data samples are shown to be linearly related. This allowed the definition of a model of K_s statistical distribution that elucidates the distinct contributions of soil matrix and macropores, and provides a validation of the Morales et al. (2010. J. Hydrol. 393, 29) concept of biologically-driven macropore dynamics.

TI estimations of K_s vary in space in agreement with the soil texture and show a stable seasonal pattern. However, in presence of macropores, they are not representative of the actual values of the saturated conductivity. On the other hand, TI K_s could provide an estimate of the conductivity of the soil matrix. The comparison with the soil matrix conductivity values deriving from the proposed model of K_s statistical distribution seem to support this possibility.

These results, that shall be corroborated by further experiments, support the importance of thoroughly investigating the interactions between soil biota, vegetation and the soil hydraulic properties.

1. Introduction

The saturated hydraulic conductivity (K_s) is a key parameter for describing water fluxes and solute transport within the soil. The importance of this parameter contrasts with the difficulties in its determination. Several authors (e.g. Shouse and Mohanty, 1998; Basile et al., 2003; Buczko et al., 2006; Kumar et al., 2010) believe that the value obtained through field measurements, due to the greater volume of soil explored, could produce more representative estimates of the K_s values, compared to laboratory measurements, performed on small core samples. Indeed, as the water potential gets close to zero, the conductivity may depend to a large extent on a small number of larger pores, particularly when the investigated soil is characterized by large macropores or cracks (see Bodhinayake and Si, 2004). Therefore, laboratory measurements performed on small soil samples, cutting through the macropore network, are often not representative of the main factor producing the actual K_s value.

Field K_s estimations can be performed with a variety of instruments and experimental setups. The most widely adopted instruments include: constant head ring or pressure infiltrometer (Angulo-Jaramillo et al., 2000; Dane and Topp, 2002; Bagarello et al., 2009), constant head double ring infiltrometer (Touma and

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Abbreviations: TI, tension infiltrometer; GP, Guelph permeameter; GM, geometric mean.

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Albergel, 1992; Dane and Topp, 2002; Lai and Ren, 2007), borehole constant head permeameter (Dane and Topp, 2002; Hinnell et al., 2009) – including the Guelph permeameter (GP, see Section 2.2) – falling head ring infiltrometer (Bagarello et al., 2004; Reynolds, 2008), and tension infiltrometer (TI, see Section 2.3).

The infiltration rates measured by all the instruments refer to saturated soils, except with the TI, whose measurements are taken under unsaturated soil conditions. Therefore, in the case of TI, K_s estimations are derived by extrapolation through an empirical curve (Gardner, 1958) calibrated with the collected unsaturated infiltration measurements. The TI estimation of K_s cannot account for the contribution of the larger macropores, which do not carry water under unsaturated conditions. There is increasing evidence that, at least in the case of macropores rich soils, a substantial underestimation of the overall (soil matrix and macropores) saturated conductivity can be expected, the values that are obtained being mostly representative of the soil matrix only (see, e.g. Fodor et al., 2011). On the contrary, there are several reasons to believe that the GP measurements – as for the borehole permeameters in general – are highly related with the development of macropores: they refer to saturated conditions; the infiltration flux is not confined by any physical barrier; the interested soil suffers minimal alterations; and the nearly undisturbed macropore network is directly involved in the infiltration experiment.

Irrespective of the instrument used, the field estimated value of K_s is fully representative only of the point and the time at which the measurement is taken. Indeed, the conductivity has been observed to vary considerably in space and time (e.g. Shouse and Mohanty, 1998; Gupta et al., 2006; Bormann and Klaassen, 2008; Alletto and Coquet, 2009) and it seems that the relationship between K_s and other soil characteristics (e.g. soil texture, organic matter and bulk density) is not strong enough to provide sufficiently accurate predictions of its value (see, e.g. the results of Chirico et al., 2007).

Many authors agree that, in agricultural soils, K_s changes following a seasonal pattern, and a decreasing tendency is expected from tillage to crop harvest due to soil compaction, and progressive pore clogging (e.g. Angulo-Jaramillo et al., 2000; Laloy and Bielders, 2008; Alletto and Coquet, 2009). Some of the studies aiming at the definition of the seasonal behaviour of K_s are based on measurements taken over a single year (e.g. Bormann and Klaassen, 2008; Alletto and Coquet, 2009), implicitly assuming that K_s follows a cyclostationary pattern, as the factors affecting this parameter are generally expected to do. However, when the conductivity measurements are taken over multiple years, a periodic behaviour emerges only in some cases (e.g. Olyphant, 2003; Bagarello and Sgroi, 2004), while more frequently a clear and stable periodicity is missing (e.g. Fuentes et al., 2004; Gupta et al., 2006; Bagarello and Sgroi, 2007).

Strudley et al. (2008) reviewed 80 papers concerning the effects of selected factors affecting the soil hydraulic properties in agricultural fields (tillage, soil compaction, irrigation, residuals management, crop type, climate, soil texture and organic content, topography). They concluded that the results of the studies are so contradictory that no general rule can be found. Therefore, to improve our knowledge, Strudley et al. (2008) recommends to enhance the data collection in order to elucidate spatial and temporal trends and to perform seasonal/annual measurement campaigns to clarify short-term responses, reporting also ancillary factors potentially influencing the measurements.

Among these, there are relatively unexplored factors related to biotical activity, which could explain at least part of the observed time variability of K_s. Indeed, root development, dead roots decomposition, and earthworms burrows produce a physical effect on the soil, creating interconnected macropore networks that can greatly enhance soil saturated conductivity (Chan, 2001; Wuest, 2001; Lichner et al., 2011). Using a tracer, Nielsen et al. (2010) investigated the effect of the biopores as preferential flow pathways, assessing the relevance of their contribution up to 2 m in depth. Among others, Chan (2001) and Willoughby et al. (1997) investigated specifically the activity of earthworms, underlining that they are able to dig continuous pores with diameters of some millimetres, concurring significantly to the observed value of K_s. The same conclusion was reached by other authors (e.g. Bodhinayake and Si, 2004; Alletto and Coquet, 2009) in their analysis of the factors that determine the variability of their datasets of K_s measurements.

Finally, there is evidence that the bio-chemical action, due for example to bacteria, roots and fungi, can significantly influence the soil hydraulic behaviour (e.g. Rillig, 2005; Buczko et al., 2006; Hallett, 2007; Lichner et al., 2011) through water resistance, or subcritical water repellency, that could be more common than what usually thought (DeBano, 2000; Hallett, 2007). This is one of the actions considered by Morales et al. (2010), who provide an interesting conceptual interpretation of the biophysical processes that enhance and sustain the spatial differentiation of the soil state and characteristics. Because of this process, the soil is split in wetter preferential flow zones and dryer bulk soil zones: while the former will tend to rise in organic carbon content and nutrients, enhancing root growth and biological activity, the latter are more likely prone to the development of some degree of water repellence.

In order to investigate the relevance of some of these less explored factors on the soil saturated conductivity we designed a monitoring activity aimed at highlighting the variability of K_s at the spatial scale of an agricultural field and at the time scale of an agricultural season, considering uniform conditions of crop, agricultural practices and, to a large extent, of pedological characteristics. Ten campaigns were conducted in three parcels in a maize field (see also Gandolfi et al., 2012) located in the Lombardy alluvial plane (northern Italy) during two crop seasons (2010 and 2011) and during the following fallow seasons. The measurements of the soil hydraulic conductivity were performed with two of the more widely adopted in-field instruments: the Guelph permeameter (GP) and the tension infiltrometer (TI).

The objectives of this paper are to present the results of the K_s measurement campaigns, providing a dataset of 152 GP values (single head) and 33 TI values (triple head), along with detailed ancillary information, and to illustrate and discuss the results of an extensive statistical analysis of the collected data.

2. Material and methods

2.1. Field description, measurement campaigns and ancillary information

Ten campaigns of K_s measurements were conducted from June 2010 to October 2011 in a uniform maize field where the same crop and agricultural practices had been applied for more than 10 years. The experimental field has an area of 10 ha with slope 0.1% and is located at Lat 45,3232°N, Long 9,2695°E, elevation 88 m a.s.l., in the alluvial Po valley (Lombardy region, northern Italy). The local climate is humid subtropical following the Koppen classification and humid continental following the Stralher classification. In the cropping season (April–September) the average temperature is around 19 °C, while rainfall is 250–300 mm (Table 1).

The field had been cropped with maize since year 2000 (*Zea mais* with inter-row spacing of 70 cm and intra-row spacing of 20 cm) and surface irrigation has been applied usually one or two times per season except for year 2011. A shallow groundwater table is present beneath the field and its upward level was within 90 and 120 cm from the soil surface during the cropping seasons