Geoderma 149 (2009) 355–366

Contents lists available at ScienceDirect

Geoderma

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

Temporal changes of soil hydraulic properties under different land uses

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ARTICLE INFO

Article history:
Received 18 February 2008
Received in revised form 23 November 2008
Accepted 23 December 2008
Available online 1 February 2009

Keywords:
Disc infiltrometer
Hydraulic conductivity
Land use
Temporal variability

ABSTRACT

Soil hydraulic properties impact the hydrologic cycle. Soil hydraulic conductivity (K) and the pore size distribution parameter, Gardner α, are important parameters for understanding some aspects of unsaturated soil water flow. They influence infiltration and runoff and the transport of nutrients in soils. K and Gardner α vary with time as well as with spatial position. The objective of this study was to identify whether K, Gardner α, and the contribution of pore size classes to flow varied through time under natural conditions in an Entisol in Shenmu County, China. Disc infiltration experiments at pressure heads of −15,−6,−3, and 0 cm were performed for four times from May to August in 2005 on four fields with different land uses (bunge needlegrass field, alfalfa field, soybean field, and korshinsk peashrub field). The sandy loam textured soil in all of the fields was classified as Ust-Sandic Entisol. The soybean field was moldboard plowed and seeded about 20 days before the commencement of the first set of infiltration measurements, but the other three fields were not subjected to recent human activities before or during the infiltration measurements. The results showed that K and Gardner α under the different land uses generally decreased from May to August, while no significant difference with respect to hydraulic properties was found between different land uses except for K at pressure head of −15 cm. The contribution of each pore fraction to flow also changed significantly with time, i.e., for macropores (>0.5 mm), mesopores1 (0.5–0.25 mm), and mesopores2 (0.25–0.1 mm) the contribution decreased, while it increased for micropores (<0.1 mm). Analysis of variance suggested that K and Gardner α were influenced more by a time factor than by land use. Our results will be helpful for describing hydraulic parameters with the aim of modeling soil water flow more accurately.

1. Introduction

Field measurement of the hydraulic conductivity (K) versus pressure head relationship is important for characterizing many aspects of unsaturated soil water flow such as rainfall infiltration and runoff, aquifer recharge, migration of nutrients, pesticides and contaminants through the soil profile, and design and monitoring of irrigation and drainage systems (Bagarello et al., 2005). Gardner α reflects the pore size distribution thus is a useful index for understanding soil water flow. Soil hydraulic properties vary spatially (Nielsen et al., 1973; Sisson and Wierenga, 1981; Byers and Stephens, 1983; Hopmans et al., 1988; Strock et al., 2001). Many water and solute transport models assume that soil surface characteristics are time constant, but in reality surface characteristics undergo temporal changes induced, for instance, by irrigation and tillage practices, rain and wind weathering and biological activity which can drastically modify soil structure (Imeson and Kwaad, 1990; Angulo-Jaramillo et al., 2000). Therefore, soil hydraulic properties are time-variant, and this fact should not be neglected in soil water flow modeling.

Compared with spatial variability studies, temporal variability of soil hydraulic properties has not been well studied. More recently, however, a number of studies have examined temporal changes in K for some soils and vegetation covers under different management (e.g., Logsdon and Jaynes, 1996; Azevedo et al., 1998; Zhang et al., 2006; Moret and Arrúe, 2007). According to the literature as summarized in Table 1, significant temporal change has been found for most conditions (Mapa et al., 1986; Starr, 1990; Somaratne and Smettem, 1993; Angulo-Jaramillo et al., 1997; Das Gupta et al., 2006; Genereux et al., 2008). However, Bormann and Klaassen (2008) found no significant seasonal variation for unsaturated hydraulic conductivity within a year at Lower Saxony, Germany, and Zhang et al. (2006) observed no seasonal variations except for the control treatment in the surface layer following two long-term fertilization regimes in

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doi:10.1016/j.geoderma.2008.12.016

Table 1
Summary of temporal changes of hydraulic conductivity

Site	Soil	Study depth	Sampling frequency	Surface cover/ land use	Management treatment[a]	Measurement technique[b]	Temporal change[b]	References
Oahu, HI	A typic torrox and a vertic haplustoll	Surface	Measurements made following successive wetting/drying cycle	Sugarcane	MP, Drip irrigation	Simplified drainage flux method	K near saturation decreased 100-fold with wetting and drying after tillage	Mapa et al. (1986)
Maryland, USA	A Delanco silt loam	Surface	Eight sets in a growing season	Corn, rye	CT and PT	Double-ring-type infiltrometer	Systematic changes (early season), constant (mid-season), increase(post-season)	Starr (1990)
South Dakota, USA	A well drained Beadle and a poorly drained Worthing	Surface	One sets for each of two years	Corn, soybean	MP,CP,RT1,NT continuous corn and corn/soybean rotations	Constant head	An increase in Ks of RT and NT systems in Beadle soil and an increase in Ks in the Worthing soil in year 3 compared with year 2	Khakural et al. (1992)
Kapunda, South Australia	Alfisol with sandy loam textured	Surface	Two sets at pre-seeding and post-harvest	Wheat	CT, DD	Tension infiltrometer	Significant drop of K at −20 rather than −40 mm under simulated raindrop impact	Somaratne and Smettem (1993)
South-eastern Australia	Red-brown earths (palexeralfs), a red earth (haploxeralf)	Surface	Four or five sets in each growing period of 3 years	Wheat, field peas	DD,CT	Tension infiltrometer	*K* varied significantly through the growing season, with general trend of decrease then increase with the turning point of tillering period	Murphy et al. (1993)
Iowa, USA	Canisteo silty clay loam	Surface	Seven sets in 1990,three and seven sets for NT and CP, respectively in 1991	Corn	CP, NT	Single-ring infiltrometer	Kept constant for NT and TRK and UNT positions for CP, infiltration rates increased steadily at BPIR and OPIR positions for CP	Prieksat et al. (1994)
Iowa, USA	Fine loam	Surface	Four sets during one and a half growing seasons	Corn-soybean rotation	Cultivation	Automated ponded and tension infiltrometer	Post-cultivation <late-season> pre-disk <post-disk except for *K* at −150 mm	Logsdon and Jaynes (1996)
Jokioinen and Mouhijärvi, Finland	A clay and an organic soil and a loam soil	0–0.21 m, 0.21–0.41 m, 0.41–0.55 m	One set made after 9 years of compaction	Spring cereals	Compaction with one or four pass or no compaction	Constant head	Ks decreased by 60–98% in 0.4–0.55 m under the effects of compaction after 9 years	Alakukku (1996)
Coria del Rio, Spain, Côte Saint André, France	A sandy soil (Xerochrept), a heterogeneous, stony, and sandy soil (Alfisol)	Surface	Two sets at plant emergence and prior to harvest	Maize	CT and irrigation (furrow and gun irrigation)	Tension infiltrometer	Significant decrease for sandy soil and no significant decrease for stony soil	Angulo-Jaramillo et al. (1997)
Iowa, USA	Nicollet loam, a fine-loamy, mixed, mesic Aquic Hapludoll	Surface and 0.15 m depth	Three sets during a growing season (7,8,9)	Corn	NT with and without cultivation	Tension infiltrometer	For cultivated: surface K kept constant then increased For uncultivated plots: surface *K* increased	Azevedo et al. (1998)

Southern Italy	Vertic soil with sandy clay textured	0.2 m and 0.4 m	Sampling monthly or longer interval during 2 years	Vegetable	Ploughed, untilled	Single ring infiltrometer	Ks increased after ploughing, such increment decreased with time	Ciollaro and Lamaddalena (1998)
New South Wales, Australia	Red Kandosol	Surface	Eight sets from June to October	Wheat, lupins, triticale	Main: CT, RT2, DD Sub: lime	CSIRO disc permeameter	Ks: decreased first and then increased *K* at −40 mm: decreased	Suwardji and Eberbach (1998)
Northwestern France	Loam	Surface	Three sets in a year	Maize	Cultivation, wheel compation	Tension infiltrometer	*K* decreased during a year at all tensions	Heddadj and Gascuel-Odoux (1999)
Shaanxi, China	Eumorthic Anthrosols with Siltloam textured	0–5 cm 10–15 cm	Four sets in one year	Winter wheat, summer maize	C, NPK, MNPK	Ks: Constant head Ku: Hot air	No seasonal variations except for the control treatment in the surface layer	Zhang et al. (2006)
Shaanxi, China	Calcareous loam	0–20 cm, 20–40 cm	One sets for each vegetation restoration stage	Different cover for different stages	NO	Constant head	Ks generally increased with vegetation recovery time	Li and Shao (2006)
Texas, USA	Clay-dominated biporous Vertisol	Surface	Twelve sets during a 21-mo period	Bermuda grass and bunchgrass	NO	Tension infiltrometer	Strong temporal variation, hydraulic conductivities close to saturation were positively correlated with antecedent moisture conditions	Das Gupta et al. (2006)
Zaragoza, NE Spain	Fine-loamy, mixed thermic Xerollic Calciorthid	1–10 cm	Four sets in one year	Long-fallow phase	CT, RT1, NT	Tension infiltrometer	Tillage significantly increased K, soil reconsolidation following post-tillage rains reduced K	Moret and Arrúe (2007)
Lower Saxony, Germany	Podzol and Stagnosol	Topsoil(15–25 cm) subsoil (40–60 cm)	Four sets within a year	Grassland, crops (maize) and forest	Grass cut, tillage	Ks: Constant head Ku: Ku-pF apparatus	No significant seasonal difference of Ks for topsoil at the 5% probability, no significant seasonal variation for Ku	Bormann and Klaassen (2008)
Denmark	Sandy loam soil	Four layer(0–60 cm)	Three sets corresponding to 1, 8, and 32 months after ploughing	Barley, wheat, grass	Cultivation	ICW Laboratory permeameter (constant and falling head combined)	Ks in the vertical and the horizontal directions generally decreased with time	Petersen et al. (2008)
North Carolina, USA	Ultisols (81%) and Inceptisols (13%) for that watershed	0–36 cm	Seven sets within one month	NO	NO	Field permeameter	Significant temporal change	Genereux et al. (2008)
Pennsylvania, USA	Glenelg, Hagerstown, Joanna, and Morrison	Surface	Four sets during May and October from 2004 to 2006	Woodland, cropland, pasture, urban	NO	Tension infiltrometer	A higher *K* in May than in October for cropland, pasture, and urban	Zhou et al. (2008)

[a] MP = moldboard plow; CT = conventional tillage; PT = plough tillage; CP = chisel plow; RT1 = ridge till; NT = no tillage; DD = direct drilling; RT2 = reduced tillage; C = control without any fertilizer; NPK = applications of chemical fertilizer; MNPK = application of chemical fertilizer plus dairy manure.

[b] *K* = hydraulic conductivity; Ks = saturated hydraulic conductivity; Ku = unsaturated hydraulic conductivity; TRK = center of a trafficked interrow; UNT = center of an untrafficked interrow; BPIR = between corn plants in a row; OPIR = directly over the base of a plant in a row.

China. Most previous studies focused on fields closely associated with human practices such as tillage, irrigation, and fertilization. The type of land use involved was generally farmland during one certain growing season. In addition, although significant temporal changes of hydraulic conductivities were found in many places, conflicting results were obtained. With time elapse, either decrease (Mapa et al., 1986; Alakukku, 1996), increase (Khakural et al., 1992; Ciollaro and Lamaddalena, 1998), no systematic change (Starr, 1990; Logsdon and Jaynes, 1996) or no changes (Zhang et al., 2006; Bormann and Klaassen, 2008) of K were reported. Therefore, more data are needed on the temporal change of K on soils with different environmental background, especially under natural conditions with different land uses.

On the Loess Plateau in China, hydrological and soil erosion modeling is very important because of the frequent occurrence of serious soil erosion. Therefore, soil hydraulic properties not only in space but also in time are necessary because of the sensitivity of soil erosion models to soil hydraulic properties (Merz and Plate, 1997; Herbst and Diekkrüger, 2002).

Field evidence identifies the existence of macropores hence preferential flow in soils (Larson and Jarvis, 1999). In a given soil, the temporal change of hydraulic conductivity tend to be followed mainly by the changes of soil structure as affected by biological activities (Suwardji and Eberbach, 1998), soil settlement (Petersen et al., 2008), soil and erosion processes (Genereux et al., 2008), and compaction (Alakukku, 1996). Simultaneously, the contribution of pore size classes to water flow may change accordingly. Obviously, knowledge of changing pore class contributions to water flow with time would better facilitate the understanding of underlying reasons for temporal changes in K. Unfortunately, most studies concerning temporal changes of K did not refer to the pore size contribution to water flow in soil when they presented explanations for the temporal changes of K.

Tension infiltrometers are widely used for measuring near-saturated K in the field (Perroux and White, 1988). Compared with other methods, the disc infiltrometer method is simple to use, and it consistently provides reliable values of K at known locations in order to characterize relatively larger areas (Reynolds, 1993). In addition, the tension infiltrometer technique holds considerable promise as a means of measuring K at various pressure heads near saturation hence characterizing water transmission in soil macropores and mesopores.

A large number of techniques are available for analyzing disc infiltration data (White and Sully, 1987; Ankeny et al., 1988; Smettem and Clothier, 1989; Ankeny et al., 1991). Each method has its own advantages and disadvantages. Logsdon and Jaynes (1993) and Hussen and Warrick (1993) suggested that multi-tensions with nonlinear regression based on the Wooding (1968) equation gave fast and stable results, and did not give any negative values compared to other methods. Furthermore, the nonlinear regression method does not require knowledge of soil moisture data. The method also determines the pore size distribution parameter. Therefore, multi-tension disc infiltration data analyzed with the nonlinear regression method are useful for characterizing spatial and temporal variability of soil hydraulic properties.

The objectives of this study were, (1) to analyze temporal changes of K and Gardner α for different types of land use, (2) to identify the possible concomitant change of relative contribution to flow for each class of pore size, including macropores (>0.5 mm in diameter), mesopores1 (0.5–0.25 mm), mesopores2 (0.25–0.1 mm), and micropores (<0.1 mm). The study focused on four land uses, needlegrass (*Stipa bungeana Trin.*), korshinsk peashrub (*Caragana Korshinskii kom.*), alfalfa (*Medicago sativa L.*), and soybean (*Glycine max*(*Linn.*) *Merr.*). In each field, disc infiltration measurements with multi-pressure heads of 0, −3, −6, and −15 cm were obtained at four times from May to August in 2005.

2. Materials and methods

2.1. Field site description

This study was conducted at Liudaogou watershed located in Shenmu County, Shaanxi Province, China (longitude 110°21′ to 110°23′ E and latitude 38°46′ to 38°51′ N). This area has a deep (up to 100 m) loess layer, which originated during the Quaternary period. The dominant soil (cultivated loessial soil), is a Ust-Sandic Entisol, which is loess-derived and therefore easily eroded (Tang et al., 1993). The soil particle size and organic matter content of the top 5 cm for the four land uses are given in Table 2. Particle size distributions for the fields of bunge needlegrass, alfalfa, soybean, and korshinsk peashrub were similar, with 3–6% of particles less than 0.002 mm, 16–21% of particles between 0.002 and 0.02 mm, and 73–81% of particles larger than 0.02 mm. Soil at these sites was classified as sandy loam according to the international standard. Soil organic matter content was 5.8 g kg^{-1} (bunge needlegrass field), 5.2 g kg^{-1} (alfalfa field), 4.2 g kg^{-1} (soybean field), and 4.7 g kg^{-1} (korshinsk peashrub field), respectively. Mean annual precipitation for Liudaogou watershed is 437 mm, nearly half of which is received from June to September. The potential evapotranspiration is 785 mm, with a mean aridity index of 1.8 and annual temperature of 8.4 °C, belonging to moderate–temperate and semi-arid zones. The rainfall and mean daily air temperature during the infiltration period are shown in Fig. 1.

On a hilltop with about 1° slope, disc infiltration measurements were made on fields with four different land uses. The area for each field was about 100 m^2. The criteria for selecting these four fields were the close spatial arrangement of the fields and the types of land uses represented in the fields. Therefore, all of the fields were closely spaced with the korshinsk peashrub, being the most distant, 30 m away from the others. Each field has its own dominant species as described above. Bunge needlegrass is a perennial herb, which can easily invade an alfalfa field after the aging and degradation of alfalfa. For this particular bunge needlegrass field, the alfalfa had a growth duration of 20 years and it had been totally replaced. Alfalfa is a perennial plant grown for livestock feed. For the alfalfa field, the alfalfa had a growth duration of 3 years, and it was the dominant species for this field. The soybean field had been moldboard plowed to a depth of about 20 cm just before being planted in early May 2005. During the disc infiltration measurement period, soybean underwent planting to fruit-bearing, with vegetation coverage ranging from 5%–70%. Korshinsk peashrub, being a dominant perennial shrub species in the ecosystem of the Korshinsk peashrub field, had a growth duration of 20 years. Vegetation coverage of bunge needlegrass, Korshinsk peashrub, and alfalfa for the infiltration period was about 45%, 60%, and 70%, respectively. It should be noted that for bunge needlegrass field, Korshinsk peashrub field, and alfalfa field, management activities were adopted only at the seeding (moldboard plow and alfalfa seeding)or planting (korshinsk peashrub planting with no tillage) period followed by alfalfa cutoff one or two times a year by a local farmer. In the year 2005, alfalfa was not cut until the completion of our infiltration measurement. Therefore, three of the fields were less affected by human activity than was the soybean field.

Table 2
General soil characteristics of the top 5 cm soil layer for four land use

Land use	Particle size (%)			Organic matter content (g kg^{-1})
	<0.002 mm	0.002–0.02 mm	0.02–1 mm	
Bunge needlegrass field	5	18	77	5.8
Alfalfa field	6	21	73	5.2
Soybean field	4	18	78	4.2
Korshinsk peashrub field	3	16	81	4.7

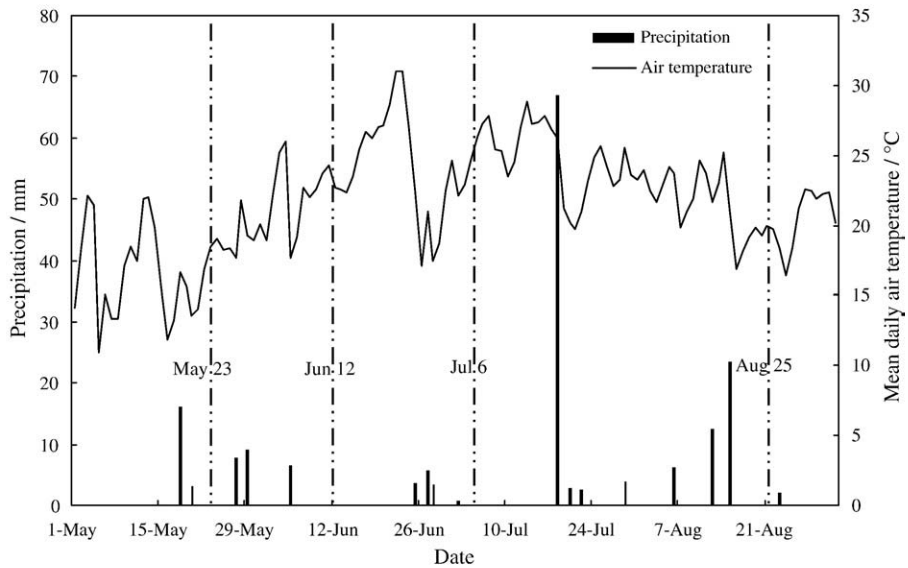

Fig. 1. Precipitation and mean daily air temperature during the infiltration measurement period. Also marked is the first date of each infiltration measurement set.

2.2. Sampling and measurements

Considering the possibility of hydraulic properties changing due to rainfall and plant development, four sets of disc infiltration measurements were made in each land use field during May to August 2005. Each measurement set was completed within four days, taking one day for each land use field. Measurement dates for the bunge needlegrass field were May 23, June 12, July 6, and August 25, respectively. Measurement dates for the other fields lagged orderly with the sequence of alfalfa, soybean, and korshinsk peashrub.

For each date and land use, six replicate sequences of infiltration rates were performed. At each infiltration location, a disc infiltrometer similar to those described by Ankeny et al. (1988) (50 mm radius with a reservoir tube radius of 1.7 cm) was used to determine infiltration under different applied pressure heads in the ascending sequence (−15, −6, −3, 0 cm).

The six measurement locations were spaced in a grid pattern, 2×3 with 5 m apart for each pair of neighboring points, within an area of 50 m^2, and the exact infiltration sites were located on bare soil surfaces between the associated dominant vegetation. For the first set of infiltration measurements, preparation of an unsmeared cleared soil surface was achieved by using a knife and removing the 1–2 mm depth of loose soil. The bare soil was covered with a cloth (with 20 um mesh), and a fine layer (about 1 mm) of sand (about 100 um grain size) was placed on the cloth to ensure good hydraulic contact between the disc and the soil. After the first infiltration set was completed, the sand layer and cloth were gently removed. Each infiltration site was surrounded by a top-open wire netting (a diameter of 40 cm and a height of 20 cm) by inserting it to a depth of 2 cm. The following infiltration measurements were made at the same locations to avoid spatial variability. The same infiltration procedure was repeated for each following set of infiltration measurements except there was no need again to prepare an unsmeared cleared soil surface. For each infiltration measurement, cumulative infiltration was recorded every one minute until steady infiltration occurred. The non-linear regression method (Logsdon and Jaynes, 1993) based upon the theoretical analysis of the 3D quasi-steady- state water flux under the infiltrometer (Wooding, 1968) was used to calculate soil K and Gardner α. The fitting equation can be written as:

$$\frac{Q_x(h_f)}{\pi R^2} = \mathrm{Ks}\exp(\alpha h) + \frac{[4Ks\exp(\alpha h)]}{\pi R\alpha} \tag{1}$$

where, $Q_x(h_f)$ is the steady infiltration rate (L^3 T^{-1}) under pressure head of h_f (-cm), R is the radius of the disc infiltrometer (L), α is the Gardner constant which characterizes soil pore size distribution (L^{-1}), and Ks is the saturated hydraulic conductivity (L T^{-1}).

With Ks and α, hydraulic conductivity $K(h_f)$ under another pressure head h_f can be derived by the Gardner exponential function written as:

$$K(h_f) = \mathrm{Ks}\exp(\alpha h) \tag{2}$$

For the purposes of this paper, K at applied pressure heads of −15, −6, −3, 0 cm are written as K15, K6, K3, Ks, and the dates for four measurement sets are expressed as May, June, July, and August.

According to capillary theory, infiltration at pressure heads of −3, −6, and −15 cm of water will exclude pores of equivalent radius greater than 0.5, 0.25 and 0.1 mm, respectively, from the flow process. Therefore, four classes of pore ranges were defined: pores with equivalent radius greater than 0.5 mm (macropores), between 0.5 and 0.25 mm (mesopores 1), between 0.25 and 0.1 mm (mesopores 2), and smaller than 0.1 mm (micropores).The contribution of each pore class to the total infiltration flow, φ(%)can be expressed as (Watson and Luxmoore, 1986):

$$\varphi_i(\%) = \frac{K(h_f)-K(h_{f-1})}{\mathrm{Ks}}\times 100, f = 1, \dots, n \tag{3}$$

where n is the number of measurements performed in a sequence, h the pressure head (L), $K(h_f)$ and $K(h_{f-1})$ the hydraulic conductivities (L T^{-1}) obtained for two consecutive pressure heads, and Ks the saturated hydraulic conductivity (L T^{-1}).

During the infiltration periods, bulk density and initial volumetric soil moisture for the surface 6 cm layer was determined for each measurement location, and the exact position for every measurement was selected within 50 cm away from the center of the disc infiltration position where no obvious disturbance occurred. Bulk density was determined gravimetrically for the top 5 cm layer, and initial volumetric soil moisture was measured by FDR with probe length of 6 cm (Frequency Domain Reflectometry, relative error was less than 5% with field calibration). Following infiltration measurements surface soil samples (5 cm long and 5 cm diameter) were collected from adjacent sites. Samples were air-dried before laboratory analysis. Soil particle size analysis was performed with a MasterSizer 2000 laser particle size analyzer produced by Malvern.

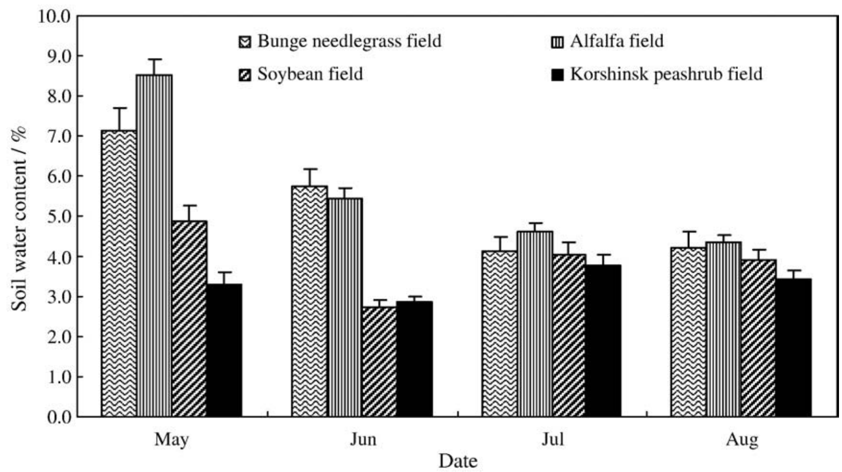

Fig. 2. Initial soil water content of the top 6 cm soil layer for each infiltration measurement set.

Soil organic matter content was determined using the potassium dichromate method.

For the present study, analysis of variance (ANOVA) and Post Hoc Tests (using LSD when equal variance occurred and Tamhane's T2 when equal variance did not occur) was used to analyze the difference of hydraulic properties among different land uses and times. Multivariate analysis was adopted to identify the relative contributions of land use and time to *K* and Gardner α. Statistical software used was SPSS 13.0.

3. Results

3.1. Temporal changes of basic soil properties

Initial soil moisture and bulk density may influence water infiltration rates, hence *K* and Gardner α. It is important to understand these basic properties within different land use areas and measurement dates. Figs. 2 and 3 show initial surface volumetric water content and soil dry bulk density, respectively. No obvious trends existed for water content. For the soybean field after tillage, the soil gradually compacted due to natural reconsolidation by gravity and raindrop impact. Thus, the soil bulk density of the soybean field increased during the study. The changes in bulk density during the infiltration period for the other three land uses may be attributed to the spatial variability between different sampling locations. For initial soil moisture, the differences among measurement dates can be attributed to the combined influence of spatial variability and rainfall.

3.2. Soil hydraulic conductivity and Gardner α for different types of land use

Q–*Q* plots indicated that normal distributions could describe data sets of *K* and Gardner α(data not shown). Therefore, no data transformations were necessary before performing statistical analyses. Table 3 summarizes the statistical parameters of the data sets of *K* and Gardner α for various land uses. For each land use, *K* decreased with decreasing pressure head. Average Ks, *K*3, *K*6, *K*15 of land use and time ranged from 1.7 to 9.9×10^{-2} cm min^{-1}, 1.6 to 7.8×10^{-2} cm min^{-1}, 1.4 to 6.2×10^{-2} cm min^{-1}, 1.0 to 3.6×10^{-2} cm min^{-1}, respectively. The coefficient of variation (CV) was related to the spatial variability of the hydraulic properties. For all of the hydraulic conductivities considered, the CV ranged from 8.5% to 55.4%, indicating weak to moderate variability at the field scale. For most of the measurement sets, the *K* variability tended to decrease with decreasing pressure heads. The Gardner α ranged from 3.0 to 7.7 cm^{-1}, and it showed weak to moderate variability (with CV of 11.1% to 59.0%). For all of the land uses, average K for all the measurement data sets

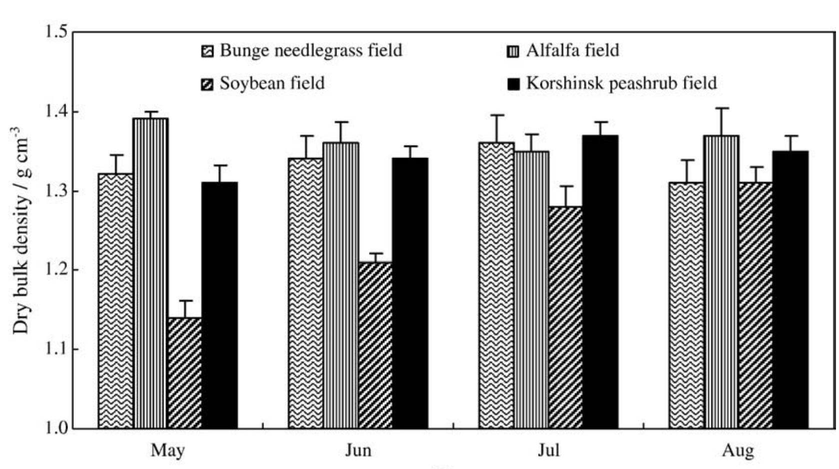

Fig. 3. Dry bulk density of top 5 cm soil layer for each infiltration measurement set.

Table 3
Hydraulic conductivity and Gardner α for different land uses at different times

	Bunge needlegrass field				Alfalfa field				Soybean field				Korshinsk peashrub field			
	Ave	Max	Min	CV%	Ave	Max	Min	CV%	Ave	Max	Min	CV%	Ave	Max	Min	CV%
May																
Ks	6.2	6.8	5.3	9.9	6.6	11.1	2.3	55.4	6.8	8.9	4.6	31.9	6.5	8.0	4.8	24.3
*K*3	5.4	6.1	4.8	9.8	5.5	8.7	2.2	50.3	5.7	7.3	4.0	29.6	5.6	6.5	4.3	20.3
*K*6	3.3	5.6	4.6	8.6	4.6	6.4	1.9	45.0	4.4	5.9	3.0	29.8	4.3	5.2	3.1	25.4
*K*15	3.6	4.1	3.3	10.7	2.8	4.4	1.4	43.7	2.4	3.2	1.6	28.0	2.3	2.8	1.6	27.2
α	3.8	4.5	3.3	13.5	5.3	7.9	2.4	43.0	5.7	6.9	5.0	15.2	5.1	6.6	3.7	28.8
June																
Ks	6.0	7.9	4.1	24.3	7.3	10.0	4.7	27.5	6.5	7.5	5.8	9.1	9.9	12.9	6.3	22.6
*K*3	5.3	6.7	3.8	22.5	6.3	7.9	4.2	22.6	5.3	6.0	4.8	8.6	7.8	9.7	5.1	20.4
*K*6	4.7	5.8	3.5	20.9	5.4	6.9	3.9	19.5	4.3	4.9	3.9	8.5	6.2	7.3	4.1	18.8
*K*15	3.4	4.1	2.5	18.3	3.6	4.5	2.5	21.0	2.3	2.6	1.9	11.3	3.1	3.7	2.2	17.5
α	3.8	5.3	2.5	25.8	4.7	9.2	3.1	47.5	5.3	8.0	5.9	11.1	7.7	9.5	6.7	14.2
July																
Ks	5.1	6.5	2.9	27.4	5.2	8.1	2.7	37.6	3.5	5.4	1.7	36.8	5.5	7.2	3.9	21.8
*K*3	4.5	5.6	2.6	25.4	4.6	7.1	2.5	34.4	3.1	4.7	1.6	35.3	4.7	6.1	3.4	20.1
*K*6	3.9	4.9	2.4	23.7	4.1	6.3	2.4	31.9	2.8	4.2	1.5	33.8	4.1	5.2	2.9	18.6
*K*15	2.7	3.3	1.8	20.3	2.9	4.3	2.0	28.7	2.0	2.9	1.2	29.2	2.6	3.2	1.9	16.3
α	3.1	6.0	3.1	27.2	3.7	7.3	2.1	52.4	3.4	4.1	2.2	20.6	4.9	6.2	3.8	18.3
Aug																
Ks	2.4	4.0	1.3	44.6	3.4	4.1	2.6	16.2	3.1	4.6	1.6	36.1	1.7	3.5	0.9	52.1
*K*3	2.1	3.3	1.2	42.0	3.1	3.6	2.4	17.4	2.8	4.1	1.5	33.3	1.6	3.0	0.9	47.1
*K*6	1.9	2.8	1.1	39.5	2.8	3.3	2.1	20.0	2.5	3.6	1.5	30.5	1.4	2.6	0.9	42.1
*K*15	1.4	1.7	0.8	32.6	2.0	2.6	1.0	30.2	1.9	2.5	1.3	22.6	1.0	1.6	0.8	28.7
α	3.0	6.1	3.1	22.7	3.7	7.8	2.1	59.0	3.1	4.7	1.6	35.7	3.0	5.2	1.3	47.9

increased by no more than 2 times as pressure heads increased from −3 to 0 cm. This increase was much less than the increases previously reported by others (e.g., Clothier and Smettem, 1990; Mohanty et al., 1997; Cameria et al., 2003). This relatively small increase suggested that soil macropores were few in number or were poorly connected in our study areas.

In order to explore the possible impacts of land use on *K* and Gardner α, all four measurement sets were pooled together for each land use, and then a one way ANOVA was performed. Fig. 4 shows mean *K* and Gardner α for the different land uses. Visually, some differences in *K* and Gardner α existed among the different land uses. However, ANOVA analysis showed that statistically significant differences only existed for *K*15 (significance level was 0.034). Results of Post Hoc Tests showed that significant differences only existed between the alfalfa field and the soybean field for *K*15 (significance level was 0.024). These analyses indicate that land use did not have significant impact on *K* and Gardner α in this study area.

3.3. Temporal changes of soil hydraulic conductivity and Gardner α for different land uses

Fig. 5 presents measured *K* and Gardner α values with time for the different land uses. Except for the phenomenon that *K* was larger in June than May for the alfalfa field and the korshinsk peashrub field, the trend of *K* was a general decrease from May to August. The larger the pressure head, the more significant the trend for *K*. Generally, from May to August, *K* decreased with a factor of 1.3 to 2.2 for the soybean field, a factor of 1.4 to 1.9 for the alfalfa field, a factor of 2.3 to 2.6 for the bunge needlegrass field, and a factor of 2.3 to 3.8 for the korshinsk peashrub field. A one way ANOVA showed that time had a statistically significant impact on *K* at a level <0.001 for all of the land uses except *K*15 of the soybean field.

Except in the korshinsk peashrub field from May to June, Gardner α showed a slight decrease from May to August for the land uses. An

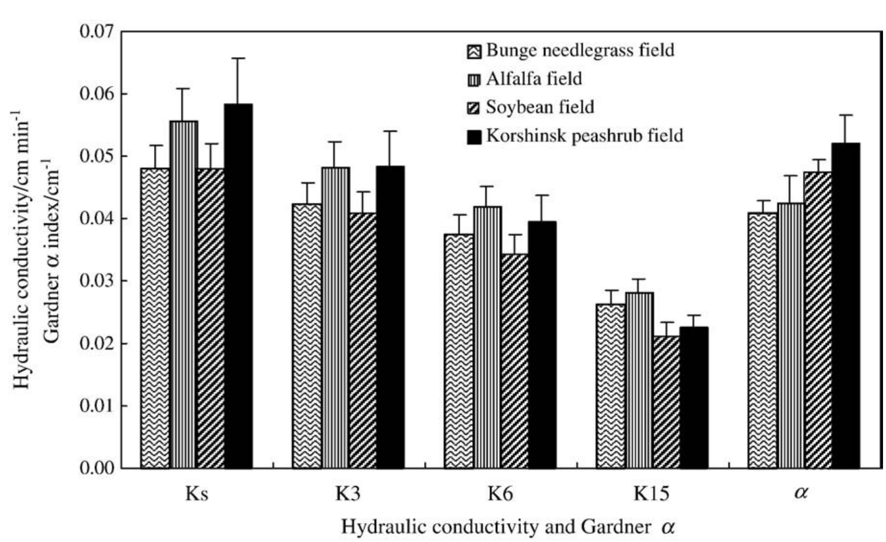

Fig. 4. Comparison of soil hydraulic conductivity and Gardner α under different types of land use (standard error is indicated).

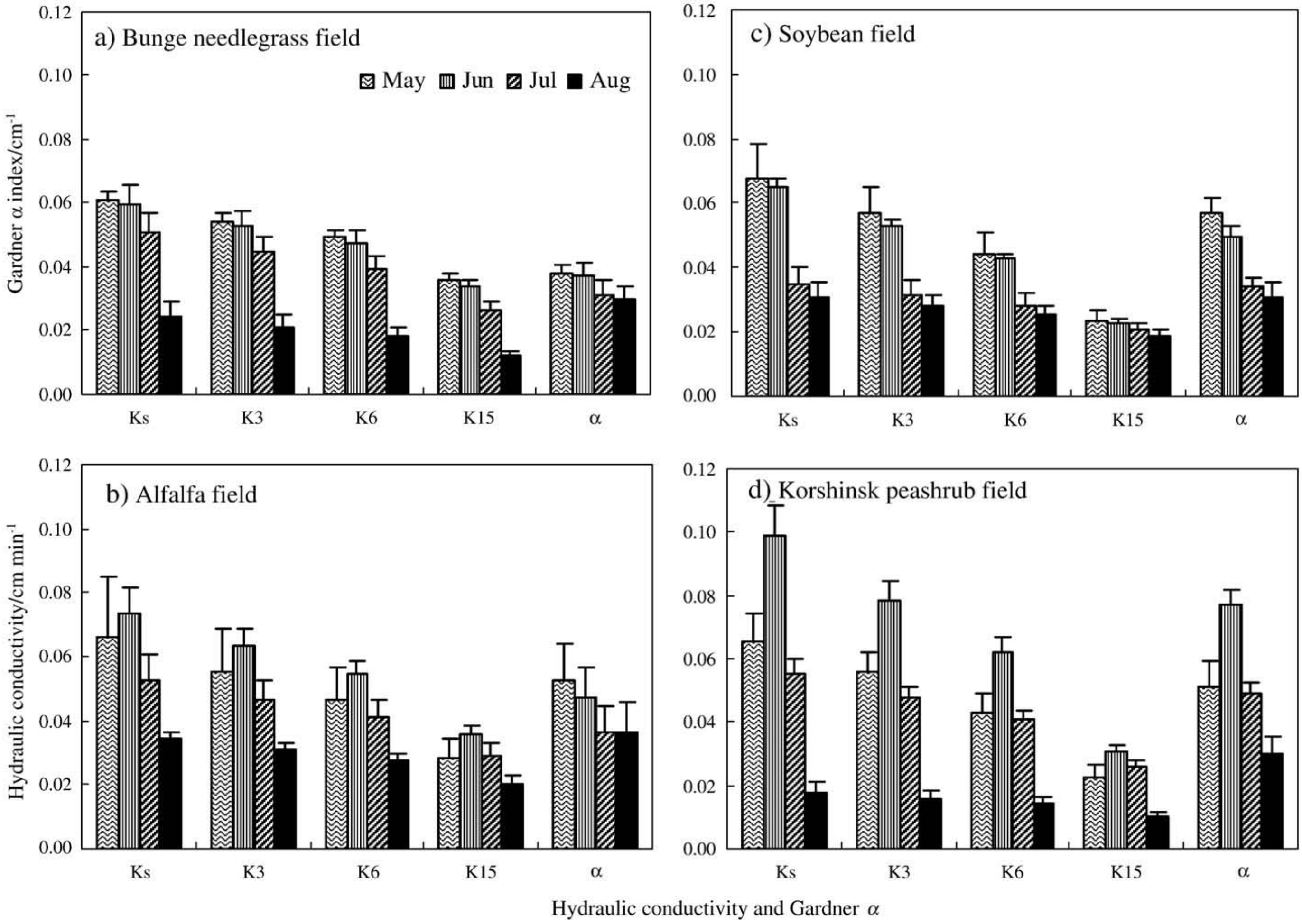

Fig. 5. Temporal changes of soil hydraulic conductivity and Gardner α under different land uses (vertical bars represent standard error).

ANOVA showed that this change was also significant (significant level = 0.001), indicating that the differences in K between larger and smaller pressure heads lessened with a decrease in macropores. The decrease of Gardner α with time was in accord with the finding that the decrease in saturated hydraulic conductivity was more marked than the decrease for unsaturated hydraulic conductivity.

Because no significant difference in Gardner α and hydraulic conductivity except $K15$ existed among the different land uses, each K

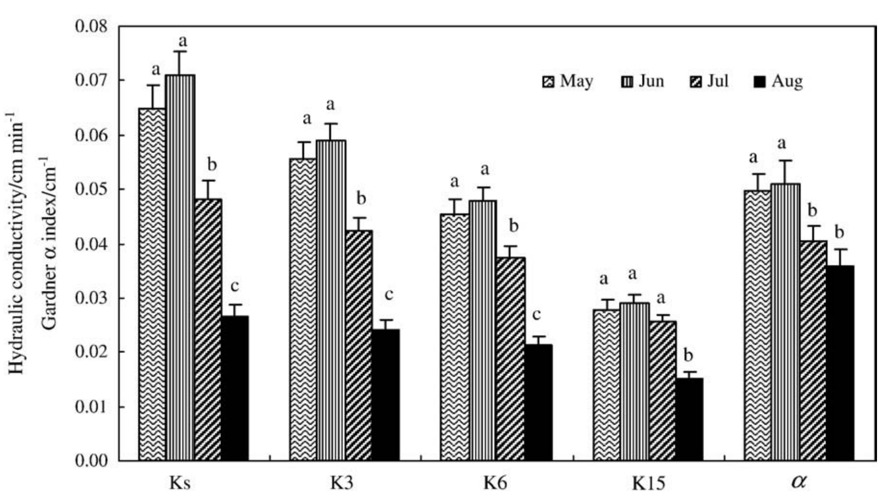

Fig. 6. Temporal changes of soil hydraulic conductivity and Gardner α when the data of all of the land uses were pooled together. Vertical bars represent standard error. For each hydraulic property bars with the same letter do not show significant differences for $P<0.05$.

Table 4
Tests of between-subjects effects with two factors of land use and time (shown in part)

Source	Dependent variable	Type III sum of squares	*df*	Mean square	*F*	Sig.
Time	Ks	0.03	3	0.010	33.407	0.000
	*K*3	0.019	3	0.006	36.359	0.000
	*K*6	0.012	3	0.004	36.280	0.000
	*K*15	0.003	3	0.001	23.575	0.000
	α	0.007	3	0.002	9.099	0.000
Land use	Ks	0.002	3	0.001	2.200	0.095
	*K*3	0.001	3	0.000	2.008	0.119
	*K*6	0.001	3	0.000	2.141	0.102
	*K*15	0.001	3	0.000	5.391	0.002
	α	0.002	3	0.001	2.104	0.106

and Gardner α was pooled together for each measurement set to analyze the temporal changes of them. The mean values and their Post Hoc Tests are shown in Fig. 6. For the hydraulic conductivities, except for May to June for all tensions considered and June to July for the −15 cm pressure head, they all showed significant differences. For the Gardner α, except for May to June and July to August, significant differences could also be found for all other pairs in the data set.

3.4. Relative influence of space and time on soil hydraulic conductivity and Gardner α

We have analyzed the effects of land use and time on *K* and Gardner α. In order to evaluate the relative contributions of these two factors on them, a multivariate analysis was performed. Significant differences only existed for *K*15 with respect to land use (Table 4). However, time significantly affected all of the hydraulic conductivities and Gardner α. This indicated that soil hydraulic conductivities and Gardner α at the study location were more influenced by time than by land use.

3.5. Temporal changes of contribution of each pore class to flow

Temporal changes of *K* may be mainly related to the changes in soil pore volume and geometry. Correspondingly, the contribution of each pore class to flow may also change with time. Fig. 7 shows the temporal changes of the contribution of four pore classes, including macropores (>0.5 mm), mesopores 1 (0.5–0.25 mm), mesopores2 (0.25–0.1 mm), and micropores (<0.1 mm), to soil water flow for the four land uses. For all of the land uses, the average relative proportion of the four pore classes to flow was 1(macropores): 1(mesopores1): 2 (mesopores2): 4(micropores). This means that for our study area, the total water flow in macropores and mesopores was relatively small, accounting for only half of the total flow. With elapse of time, the trend of proportional pore class contributions behaved similarly for all of the land uses, i.e., the contribution of macropores and mesopores generally decreased, while the contribution of micropores generally increased. Fig. 8 shows the changes of contribution of pore sizes when the data for different land uses were pooled together for each measurement date. On average, during the measurement period, the contribution of macropores, mesopores1, mesopores2 monotonously decreased from 14.7% to 9.3%, 16.0% to 8.9%, and 28.0% to 19.9%, respectively, with the exception that the contribution of macropores increased slightly form May to June. The contribution of micropores to flow monotonously increased from 41.3% to 61.9%. Post Hoc Tests showed that except for two pairs of neighbor measurement dates, May

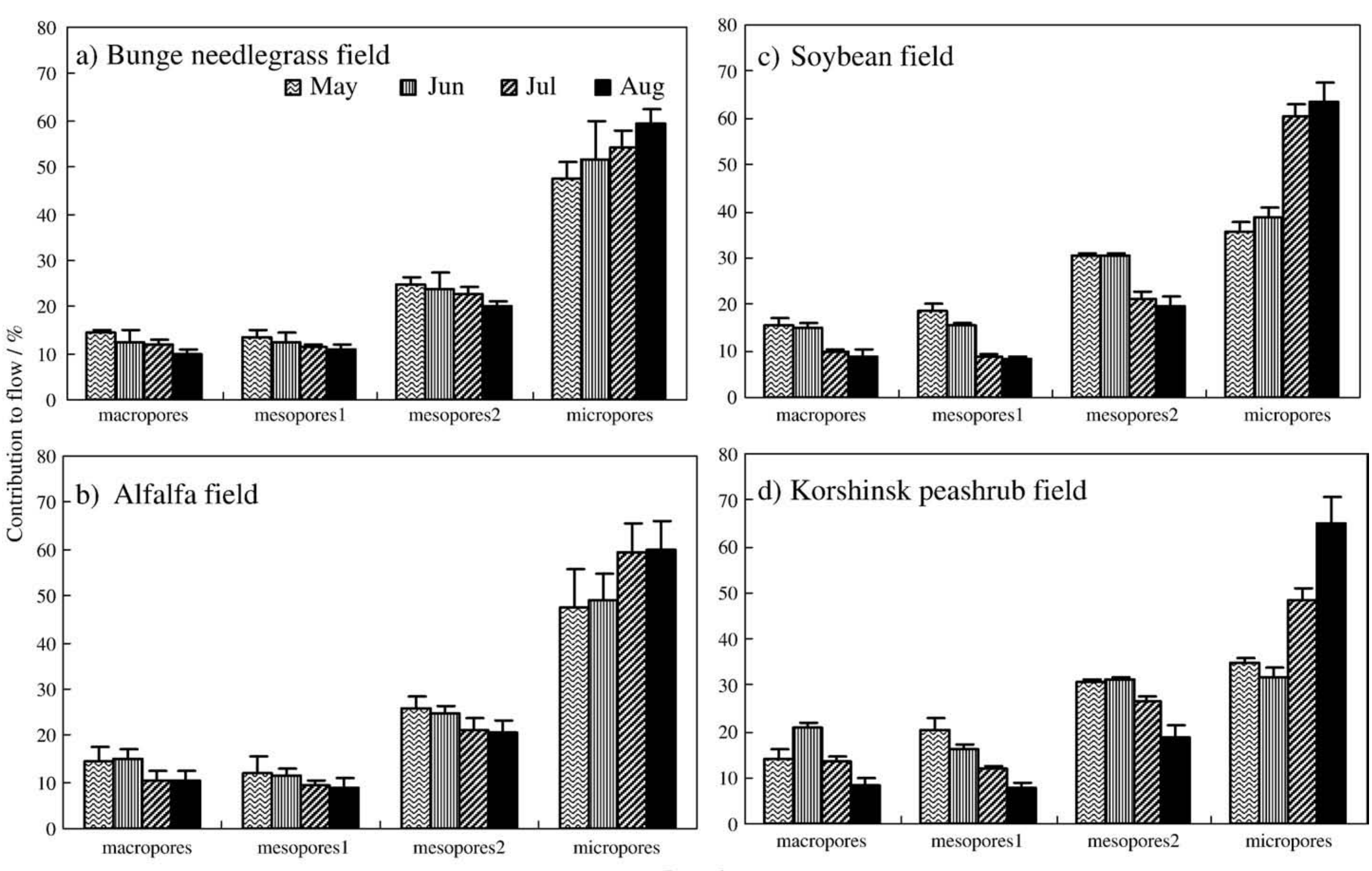

Fig. 7. Temporal changes of contribution of each pore class to flow for different land uses (vertical bars represent standard error).

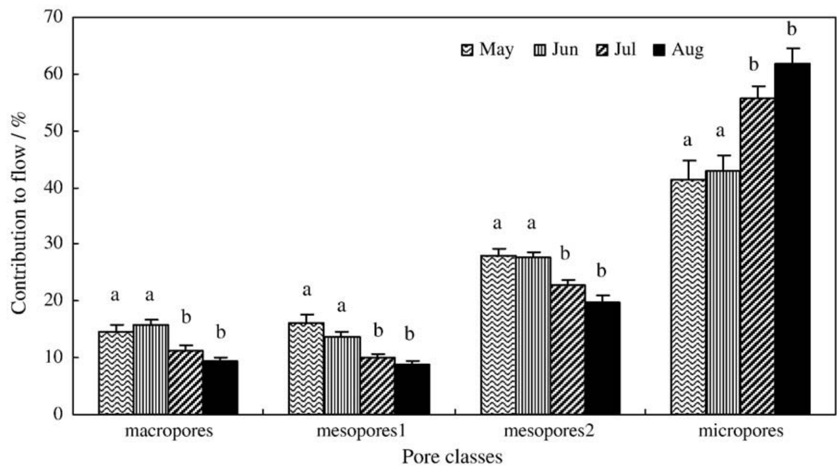

Fig. 8. Temporal changes of contribution of each pore class to flow when the data of all of the land uses were pooled together. Vertical bars represent standard error. For each pore class bars with the same letter do not show significant differences for $P<0.05$.

to June and July to August, all the contribution changes were statistically significant.

4. Discussion

4.1. Land use effects on soil hydraulic properties

Significant effects of certain land uses on *K* are described in the literature (Stolte et al., 2003; Fuentes et al., 2004; Bormann and Klaassen, 2008; Zhou et al., 2008). The reported land use-induced differences in *K* may be reasonable because many previous data had verified the changes of soil properties such as soil chemical properties and bulk density (Neill et al., 1997; Franzluebbers et al., 2000; Murty et al., 2002; Bewket and Stroosnijder, 2003; Bronson et al., 2004; Braimoh and Vlek, 2004) as well as pore volume (Neves et al., 2003) as influenced by land use. Probably, these changes reflect a change in soil structure which directly influences *K*.

For the present study, however, no significant differences in hydraulic conductivity were found among land use types except for *K*15. Some of the soil physical properties we measured such as particle size distribution, organic matter content, initial soil moisture, and bulk density were generally believed to influence soil *K*. However, we did not find any systematical relationships between soil *K* and these four soil physical properties. Finding no significant differences in these soil properties among the different land uses may explain in part why there was little significant difference in soil hydraulic properties. Generally, well-structured soils tend to more easily drain than do soils with poor structure. For the sandy loam in our fields, the relatively coarse particle size and relatively low organic matter did not facilitate the development of soil structure. Therefore, this makes it more difficult for land management systems to influence soil macropore networks in these soils. The poorly structured soils had relatively small increases in *K* as pressure heads increased from −3 to 0 cm for all of the measured data sets. In addition, because of the close spatial alignment of our fields, the fields all experienced similar hydrological processes and weather conditions, which also contributed to the relatively homogeneous hydraulic conductivities and Gardner α among the different land uses. Lastly, the six replicated tension infiltrometer measurements within the small area still displayed spatial variation to some extent (Table 3). Therefore, the relatively small sampling numbers may also be a reason for the lack of significance from the statistical tests. Consequently, even with tillage in the soybean field prior to the first infiltration measurements, there was no significant difference in hydraulic conductivity between the four land uses. Similar results can be found in Sauer et al. (1990) who reported no differences in *K* between a no-tillage treatment and tilled treatments.

4.2. Time effects on soil hydraulic properties

From May to August, *K* and Gardner α generally decreased for all the land uses. An ANOVA indicated that *K* and Gardner α were significantly influenced by time. Significant time effects on hydraulic conductivity have also been observed in other places, and various factors identified to explain the temporal changes. These factors mainly consisted of management practices (Starr, 1990; Somaratne and Smettem, 1993; Logsdon and Jaynes, 1996; Alakukku, 1996; Ciollaro and Lamaddalena, 1998), biological activity (Khakural et al., 1992; Somaratne and Smettem, 1993; Azevedo et al., 1998; Das Gupta et al., 2006; Petersen et al., 2008), rainfall (Somaratne and Smettem, 1993; Das Gupta et al., 2006), soil consolidation or settlement (Somaratne and Smettem, 1993; Angulo-Jaramillo et al., 1997; Moret and Arrúe, 2007; Petersen et al., 2008), soil disaggregation (Suwardji and Eberbach, 1998; Heddadj and Gascuel-Odoux, 1999; Bormann and Klaassen, 2008), drying/wetting processes (Mapa et al., 1986; Petersen et al., 2008), initial soil moisture (Zhou et al., 2008), and erosion and deposition processes (Genereux et al., 2008).

For the present study, except for the soybean field, where tillage occurred just 20 days before the first infiltration measurements, the history of obvious management practices for the other three types of land use was relatively long. Therefore, the influence of management practices for the bunge needlegrass field, the alfalfa field, and the korshinsk peashrub field on the present short-term hydraulic properties trend with time may not be very important. Such small influence was also demonstrated by the work of Azevedo et al. (1998) and Ciollaro and Lamaddalena (1998) who observed that the effect of cultivation disappeared or decreased with time during the growing season. For the soybean field, however, the effects of tillage practice could not be ignored because of the short time (about 20 days) after plowing. At the first infiltration time, soil was relatively loose due to the recent tillage, later the soil gradually compacted due to natural causes. The soil bulk density increased from 1.14 to 1.31 (Fig. 3). Therefore, increased bulk density reasonably explained some of the decrease in *K* for the soybean field. Still, we did not believe that tillage was the main reason for the decrease of hydraulic conductivity in the soybean field because overall there were no significant land use effects. For the other three land uses, however, the changes of bulk density did not explain the decrease of hydraulic conductivity because they showed no systematic changes with time.

Initial soil moisture has been linked to temporal changes in *K* (Zhou et al., 2008). For this study, soil moisture could not be the main reason for the decrease of hydraulic conductivity since no significant correlation existed for soil moisture and hydraulic conductivity. However, the larger *K* in June compared with May for the soybean field and the korshinsk peashrub field may have been due to some extent to the drier initial soil moisture in June.

The viscosity of water decreases as temperature increases (Suwardji and Eberbach, 1998). It is unlikely that the significant decrease in *K* with time as observed in the present study is due to the change of soil temperature, because the mean daily air temperature during our infiltration except for July to August generally increased, 18.5 °C, 22.8 °C, 26.5 °C, and 21.1 °C for May, June, July, and August, respectively (Fig. 1).

The fields were little affected by human activities, especially during the infiltration period. Therefore, changes in arrangement of soil particles and pore structure caused by natural rainfall may be the main reason for the decreasing values of hydraulic properties. Under natural rainfall events, surface soil can seal due to raindrop impact. Fine soil particles tend to be easily scattered by rain drop splash because of poor structure and aggregate instability, and the particles can be transported by infiltrating water and clog some soil macropores or mesopores. Such changes were reported by Moret and Arrúe (2007). This effect can be demonstrated well by a decreasing of contribution of macropores and mesopores to flow with time (Figs. 7 and 8).

Some differences in the magnitude of decrease in hydraulic conductivity existed for the four land uses (with a factor of 1.3 to 2.2 for the soybean field, a factor of 1.4 to 1.9 for the alfalfa field, a factor of 2.3 to 2.6 for the bunge needlegrass field, and a factor of 2.3 to 3.8 for the korshinsk peashrub field), This seemed to contrast with the finding that there were no land use effects on hydraulic conductivity. However, this may really relate to the different magnitude of decrease for different stages. As can be seen from Figs. 5 and 6, all of the decrease for various land uses were non-linear with time, and for a given land use, the numerical value of K cannot be the largest or smallest for all the measurement sets. This may also reflect that the land use effect was time-dependent. Therefore, the seeming paradoxical results of having no significant land use effects, and having some differences in the magnitude of hydraulic conductivity decrease over time for the different land uses are reasonable.

5. Conclusions

Soil hydraulic properties are important for many aspects of unsaturated soil water flow. They vary with space and time, and are expected to differ between land uses due to differences in soil structure. In this paper, four types of land use (bunge needlegrass field, alfalfa field, soybean field, and korshinsk peashrub field) were studied. Four sets of disc infiltration measurements were obtained in order to examine the temporal changes of *K*, Gardner α, and the contribution of pore size classes to flow.

The results showed that land use only significantly influenced *K* at a pressure head of −15 cm. From May to August, *K* generally decreased by a factor of 1.3 to 2.2 for the soybean field, a factor of 1.4 to 1.9 for the alfalfa field, a factor of 2.3 to 2.6 for bunge needlegrass field, and a factor of 2.3 to3.8 for the korshinsk peashrub field. The larger the pressure head, the more significant the trend for *K*, which corresponded well with the decrease of Gardner α with time. Compared with land use, *K* and Gardner α were influenced much more by time.

Generally, the contribution of macropores (>0.5 mm), mesopores1 (0.5–0.25 mm), and mesopores2 (0.25–0.1 mm) to flow decreased, while that of micropores (<0.1 mm) increased from May to August.

The general monotonic decrease of *K* observed for this time period is not sustainable and should not be extrapolated to a relatively long time period. Our observational period was during the rainy season, and surface soil structure was affected by the raindrops. Over a long time period, soil may undergo processes favorable to the development of soil structure. In this situation, *K* should increase. In addition, six replicates may be a limitation to the present study. Therefore, data with more replicates are needed to focus on the temporal changes of soil hydraulic properties at a longer time scale.

Acknowledgements

The study was financially supported by the “Innovative Team” program of Chinese Academy of Sciences, the “Hundred Talents Program ” of the Chinese Academy of Sciences, and the National Natural Sciences Foundation of China (Grant numbers of 90502006 and 50479063). The comments from the two anonymous reviewers were greatly appreciated.

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