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Temporal changes in soil hydraulic conductivity with different soil types and irrigation methods

Chen Zeng [a,b], Quanjiu Wang [b,c,*], Fan Zhang [a], Jun Zhang [d]

[a] Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institutes of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China
[b] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling 712100, China
[c] Institute of Water Resources, Xi'an University of Technology, Xi'an 710048, China
[d] Temple University, CORE 3223 N. Broad St., Philadelphia, PA 19140, USA

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ABSTRACT

The soil hydraulic conductivity (*K*) is an important parameter for understanding soil hydrologic processes. *K* varies with time, soil type, and irrigation method. Understanding and predicting the temporal variability of *K* are required for irrigation design and numerical analyses. The objective of this study was to investigate and evaluate the temporal variability in *K* from April to September of 2008 in two soils, clay loam (CLS) and sandy loam (SLS), and two irrigation methods, furrow irrigation (FIM) and drip irrigation (DIM). Five sets of infiltration measurements with five replications were taken in grape fields using a tension infiltrometer at supply *h* values of −15, −6, −3, and 0 cm. The results showed that *K* had significant temporal differences under all supply *h* values. Generally, *K* initially exhibited high values and decreased from April to September. *K* of SLS was always significantly higher than that of CLS. *K* values were lower and varied more for FIM than for DIM, but showed no statistically significant difference between the two irrigation methods. About 1.3 to 2.9 times differences existed between the maximum mean *K* (in April) and minimum mean *K* values (in July/September) through the whole growing period. However, the relative errors between the calculated *K* and measured *K* diminished within 10% when *K* was estimated using a regression to adjust *K* to the number of irrigation events. These results contribute to a more accurate description of *K* for irrigation design and water flow modeling.

1. Introduction

Hydraulic properties are key factors that control water flow and solute transport in soil. The hydraulic conductivity (*K*) is an important parameter for describing soil water flow, such as surface water infiltration and runoff, subsoil water recharge, and solution migration, as well as for designing and modeling field irrigation and drainage systems (Bagarello et al., 2005). Soil hydraulic properties are mainly influenced by the soil texture, bulk density, soil structure, and organic matter content (Bagarello and Sgroi, 2007; Petersen et al., 2008). The properties vary spatially as reported in previous studies (Coutadeur et al., 2002; Hopmans et al., 1998; Horn, 2004; Strock et al., 2001; Strudley et al., 2008; van Es et al., 1999).

Recent soil physics studies have focused on quantitative modeling to describe and predict soil water flow (Bormann et al., 1999; Herbst et al., 2006; Iqbal et al., 2005). In these studies, constant soil surface characteristics have been commonly assumed mainly because dynamic measurements are costly and time consuming (Angulo-Jaramillo et al., 1997). In reality, surface hydraulic properties undergo temporal changes (Das Gupta et al., 2006; Fuentes et al., 2004; Genereux et al., 2008; Hu et al., 2009) induced by tillage practices (Cameria et al., 2003), root activities (Iqbal et al., 2005), as well as wetting and drying cycles of climate and irrigation systems (Mubarak et al., 2009b), etc. Conflicting trends of hydraulic conductivities have been found in literature, such as increase (Ciollaro and Lamaddalena, 1998), decrease (Alakukku, 1996), no change (Bormann and Klaassen, 2008; Zhang et al., 2006), or irregular (Logsdon and Jaynes, 1996). Hence, the temporal patterns of soil hydraulic conductivities under different conditions need to be farther investigated.

Drip irrigation enhances the efficiency of irrigation and fertilization. Drip irrigation enables water and fertilizers to be applied exactly over a plant if the drip irrigation systems are properly designed (e.g., emitter discharge rate, emitter spacing, tape lateral spacing) and well managed (irrigation schedule) under given soil and climatic conditions (Mubarak et al., 2009b). Drip irrigation supplies smaller amounts of water to the soil at higher frequencies than traditional furrow irrigation (Mapa et al., 1986; Rawlins, 1973). Therefore, soil hydraulic properties such as *K* should be investigated more accurately for a drip irrigation design than for a furrow irrigation (Bresler, 1978; Revol

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* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling 712100, China. Tel./fax: +86 29 87012210.
E-mail addresses: zengchen@itpcas.ac.cn (C. Zeng), wquanjiu@163.com (Q. Wang).

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Table 1
The gravimetric percentage of gravel content in each soil layers of Shanshan.

Depth	Gravel size (%)				
cm	>50 mm	20–50 mm	10–20 mm	2–10 mm	≤2 mm[a]
0–50	0.0	7.2	13.6	25.0	54.2
50–120	7.6	19.3	16.8	22.0	34.3

[a] The size less than or equal to 2 mm is defined as the soil particle and the size greater than 2 mm is defined as the stone according to soil particle definition.

et al., 1997; Zur, 1996) to improve infiltration efficiency, reduce surface evaporation, as well as optimize the irrigation system and irrigation schedule, especially in extremely dry regions. Exact values of *K* are also essential for the development of mathematical modeling and analyses for water flow (Cook et al., 2003; Thorburn et al., 2003).

Different techniques have been applied for field measurements of *K*, such as Guelph permeameter (Elrick and Reynolds, 1992; Reynolds and Elrick, 1985; Xu and Mermoud, 2003), single-ring infiltrometer (Bagarello and Sgroi, 2004; van Es et al., 1999), double-ring infiltrometer (Starr, 1990), and inversed-auger-hole method (Messing and Jarvis, 1990). Furthermore, tension infiltrometers have been increasingly used to measure *K* at various supply pressure heads in the field (Angulo-Jaramillo et al., 2000; Perroux and White, 1988) and applied for example, to evaluate the influences of soil tillage (Ankeny et al., 1990), land uses (Hu et al., 2009), irrigation amount (Wienhold and Trooien, 1998), surface crusting (Vandervaere et al., 2000), as well as in studies on spatial and temporal changes (Hu et al., 2009). This technique is considered to be water saving, repeatable, and stable in space and time (Bagarello and Sgroi, 2007; Ventrella et al., 2005).

Field infiltration data from tension infiltrometers can be analyzed by various methods (Logsdon and Jaynes, 1993). Each method has its advantages and disadvantages. The present study employed multi-tensions with the non-linear regression method (Logsdon and Jaynes, 1993) based on Wooding's equation to calculate *K*. This method was verified to be better than others, yielding fast, stable, and non-negative results (Logsdon and Jaynes, 1993).

The objective of the current study was to investigate the temporal variability in *K* in two typical soil types and for two irrigation methods, drip and furrow irrigation. At each site, tension infiltration measurements with a range of supply pressure heads were performed throughout the grape-growing season from April to September of 2008. The results from the present study could be utilized to improve the optimization of the drip irrigation system and irrigation schedule for grape production in the studied region.

2. Material and methods

2.1. Site description

The study was conducted in the Turpan Grape countryside (42°52′ N, 89°12′ E; 33 m elevation) and Shanshan county (42°54′ N, 90°30′ E; 416 m elevation). Both the study sites belong to the Turpan Prefecture, Xinjiang Uygur Autonomous Region, China, and are famous for its grape production. The climate of the study region is extremely dry. For instance, the highest daily air temperature is 48.3 °C, the annual evaporation is about 2751 mm to 3500 mm, and the annual precipitation is below 25.3 mm. Due to the lack of surface freshwater, drip irrigation has been developed rapidly for grape irrigation in this region over the last 20 years. The soil at the two sites, the conventional agricultural soil of Turpan and the Gobi gravel soil of Shanshan, were two typical types in the grape production region of Xinjiang. The latter one was covered by exotic 50 cm sandy loam soil and mixed with some rock fragments (see Table 1) (Zeng et al., 2012) in the top 50 cm. Soil samples in the top 5 cm of the two sites were collected before the first experiment, and the soil particle size distribution was determined using a MasterSizer 2000 laser particle size analyzer (Malvern, UK). Soil organic matter content was determined using dichromate oxidation with an external heat source (Nelson and Sommers, 1996). The initial soil characteristics are given in Table 2. These two soils had the texture of clay loam (CLS) and sandy loam (SLS) (SI standard). The daily mean air temperatures and free water evaporations (Type E601B with 3000 cm^2 surface area) in the study sites during the experiment period are shown in Fig. 1.

Thompsons seedless grapes were planted in 1998 at the Turpan site and in 1980 at the Shanshan site. For the two study sites, the inter-row space was 3.6 m, which included a 0.9 m to 1.2 m wide furrow part and a 2.4 m to 2.7 m wide ridge part within each row (Figs. 2 and 3). The surface of the furrow part is considered as the reference level of 0 m. The ridge part is about 40 cm to 50 cm higher than the furrow. To avoid freezing injury, the grape vines were laid down in the furrow part and buried in soils from the ridge part during the winter dormant state. When the temperature increased, the grape vines were excavated and fastened to horizontal cultivated shelf wires at a height of 1.5 m before the bud burst in early spring until the end of autumn.

The two sites were always irrigated by furrow irrigation method before 2008. Parts of the study fields have been drip irrigated since 2008. The detailed phenological phases and irrigation schedule of the two study sites are shown in Table 3. For the furrow irrigation method (FIM), water coming from the supply system through the channel flowed directly into the cultivated furrow. The FIM quota was 1500 $m^3 \cdot ha^{-1}$ for Turpan and 1800 $m^3 \cdot ha^{-1}$ for Shanshan each irrigation event. For the drip irrigation method (DIM), three drip irrigation tapes were laid along the cultivated furrow: the first one at the bottom of the furrow, the second one on the furrow near the grapevine root, and the third one on the ridge about 50 cm apart from the second one (Fig. 2) (The annual excavation of grapevines caused furrow bottom was disturbed every year. So the top drip tape was placed on freshly disturbed soil in each year). The DIM flow for each emitter was 3.3 $L \cdot h^{-1}$ with 30 cm spacing. The irrigation quota for all the three tapes were 450 $m^3 \cdot ha^{-1}$ for Turpan and 525 $m^3 \cdot ha^{-1}$ for Shanshan at each irrigation event.

Table 2
General soil characteristics of the top 5 cm layer in the two study sites.

Site	Sampling time	Irrigation method	Particle size (%)			Organic matter content ($g \cdot kg^{-1}$)	Texture
			<0.002 mm	0.002 to 0.02 mm	>0.02 mm to 1 mm		
Turpan	Apr	FIM [a]	20.4	40.5	39.1	4.3	Clay loam
		DIM [a]	20.3	40.9	38.8	4.5	
	Sep	FIM [a]	20.0	40.2	39.8	4.2	
		DIM [a]	20.3	40.8	38.9	4.4	
Shanshan	Apr	FIM [a]	8.5	22.2	69.3	3.3	Sandy loam
		DIM [a]	8.2	22.7	69.1	3.4	
	Sep	FIM [a]	8.3	21.8	69.9	3.1	
		DIM [a]	8.0	22.3	69.7	3.2	

[a] FIM, furrow irrigation method; DIM, drip irrigation method.

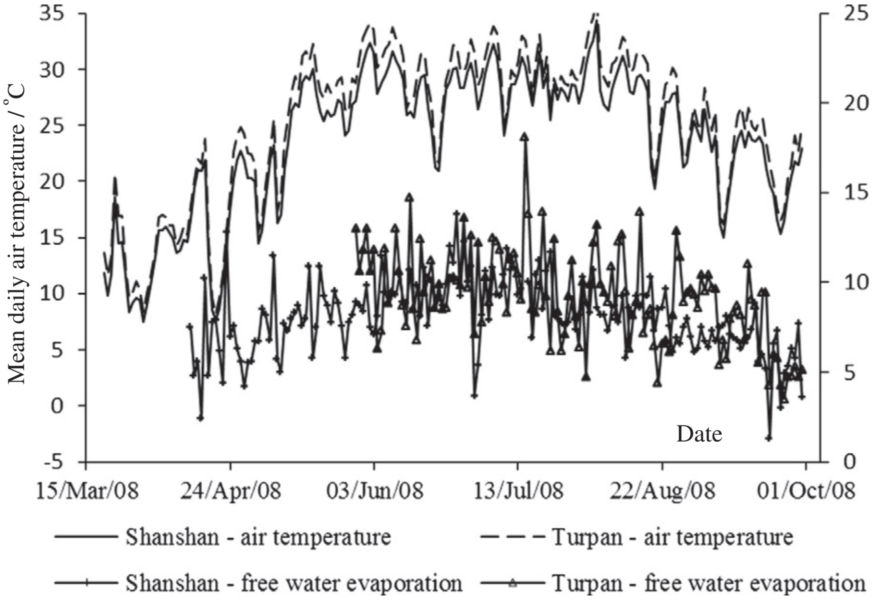

Fig. 1. Daily mean air temperatures and free water evaporations during the experimental period in the two study sites.

2.2. Field measurements

Soil *K* was measured using a tension infiltrometer for the two soils and two irrigation methods at different times at consecutive irrigation events to determine whether time had a statistically significant temporal effect on *K*. All measurements were conducted in the bottom of the furrow part. The tension infiltrometer was similar to that described by Ankeny et al. (1988), with an infiltrometer base radius of 7.5 cm and a reservoir tube radius of 1.7 cm. Measurements were made in an ascending sequence of supply pressure heads at −15, −6, −3, and 0 cm (Adjusted the negative pressure head equal to the positive pressure head to make *K* at supply pressure head of 0 cm. The operations of the tension infiltrometer to measure *K* at 0 cm supply pressure head were similar as did under other supply pressure heads (−15, −6 and −3 cm) and the cylinder did not inserted in soil). Before each measurement, a relatively flat soil surface was chosen, using a knife blade to remove the loose surface soil (~2 mm) carefully at the higher positions (Try to avoid any disturbance of crust in the very top soil surface). Afterwards, a fine layer (about 1 mm) of sand (1–2 mm) was equally placed on the surface to ensure good contact between the infiltrometer base and soil surface. For each infiltration measurement, the cumulative infiltration was manually recorded at 5 min intervals until steady infiltration occurred (same results for three successive readings). Each sequence of supply pressure heads was repeated at the same location to reduce spatial variability. Each measurement was performed with five parallel repetitions on the last day of an irrigation interval (when the soil was driest) during each phenological phase (Table 3) to cope with the differences in the phenological phases at the two sites and the possibility of hydraulic property variations, such as possible differences in initial soil moisture before an irrigation event.

The bulk density undergoes temporal changes and influences the hydraulic conductivity (Horn, 2004) therefore was investigated in this study. After the infiltration, bulk densities for the surface 5 cm layer were investigated using cutting ring (5 cm long and 5 cm diameter) method. For each measurement location, 3 soil core samples

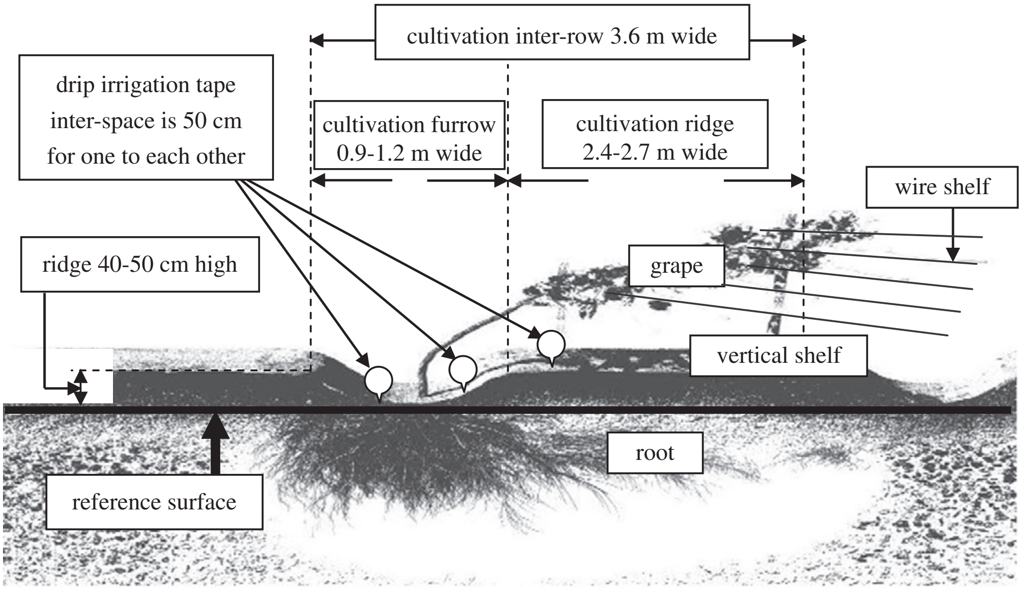

Fig. 2. Schematic diagram of the study sites.

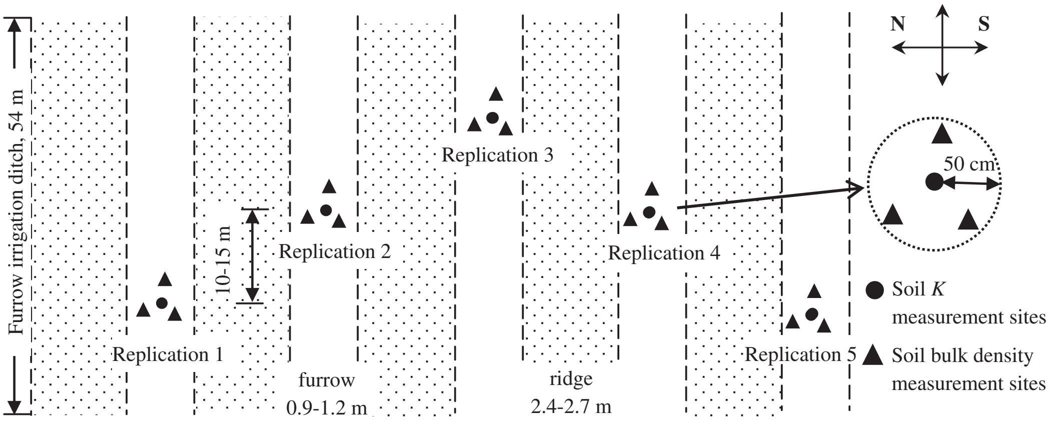

Fig. 3. Measurement plan of the study sites.

were collected within 50 cm away from the center of the tension infiltration position (Fig. 3) where they have no obvious disturbance. Afterwards, dry bulk densities were determined gravimetrically.

2.3. Data analysis

Soil K obtained from the infiltrometer was based on Wooding's (1968) theory as follows:

$$Q_x(h) = \left(\pi R^2 + \frac{4R}{\alpha}\right)K(h) \tag{1}$$

where $Q_x(h)$ is the steady state infiltration rate ($\text{cm}^3\cdot\text{min}^{-1}$) under a pressure head $h(-\text{cm})$, R is the radius of the infiltrometer (cm), $K(h)$ is the hydraulic conductivity ($\text{cm}\cdot\text{min}^{-1}$) under a pressure head h, and α is the Gardner index that characterizes soil pore size distribution (cm^{-1}).

The non-linear regression method based on the analyses of the three-dimensional near-steady state water fluxes under the infiltrometer (Logsdon and Jaynes, 1993) was used to calculate soil K. The fitting equation was expressed as

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

where Ks is the saturated hydraulic conductivity ($\text{cm}\cdot\text{min}^{-1}$).

For the tension infiltrometer,

$$Q_x(h) = \frac{\pi r^2 H}{t} \tag{3}$$

where r is the radius of the reservoir tube (cm), H(cm) is the height of water drop in the reservoir tube at a time interval t (min).

Ks can be calculated by combining Eqs. (2) and (3) with the non-linear regression method. Consequently, K was calculated from the hydraulic conductivity curve function described by the exponential model of Gardner (1958) as

$$K(h) = Ks\exp(\alpha h). \tag{4}$$

A multivariate ANOVA (MANOVA) was employed to investigate the effects of the soil type, irrigation method, and time on K under the four supply pressure heads. Post hoc tests (using LSD when equal variance occurred and Tamhane's T2 when equal variance did not occur) were conducted to analyze the differences among $K(h)$ at different times. All analyses were performed using the SPSS13.0 software.

3. Results

3.1. Temporal changes in the soil bulk density

The soil gradually compacted from April to July and loosened in September (some soil cracking were observed in the field) for all measurements (Fig. 4). The dry bulk densities increased more rapidly and reached higher values for FIM than for DIM, and for CLS than for SLS. These results can be attributed to the influence of gravity and irrigation patterns, which caused the surface soil to be compacted and become less permeable under various irrigation effects.

3.2. Mean hydraulic conductivities in the study sites

Table 4 summarizes the basic statistical data for measured K values as related to soil types, irrigation methods and time. On average, the mean soil K was higher for SLS than for CLS, and for DIM than for FIM. Generally, K decreased with time under all conditions. A larger pressure head corresponded to a more significant change in

Table 3
Phenological phases and irrigation schedule of Thompson seedless grapes and field measuring dates for the two study sites.

Phenological phase (2008)			Excavation	Budburst	Bloom	Swell	Veraison	Harvest	Dormant
Beginning date	Shanshan		29-Mar	12-Apr	18-May	7-Jun	3-Jul	25-Aug	16-Oct
	Turpan		15-Mar	5-Apr	10-May	4-Jun	29-Jun	19-Aug	10-Oct
Irrigation interval (day)	Shanshan	FIM[a]	7	9	16	7	14	45	–
		DIM[a]	7	7	10	7	10	15	–
	Turpan	FIM[a]	20	20	20	20	15	30	–
		DIM[a]	9	9	9	9	9	20	–
Field measuring date	Shanshan	FIM[a]	–	18-Apr	23-May	9-Jun	20-Jul	5-Sep	–
		DIM[a]	–	22-Apr	22-May	11-Jun	11-Jul	4-Sep	–
	Turpan	FIM[a]	–	6-Apr	14-May	8-Jun	1-Jul	6-Sep	–
		DIM[a]	–	14-Apr	14-May	5-Jun	3-Jul	7-Sep	–

[a] FIM, furrow irrigation method; DIM, drip irrigation method.

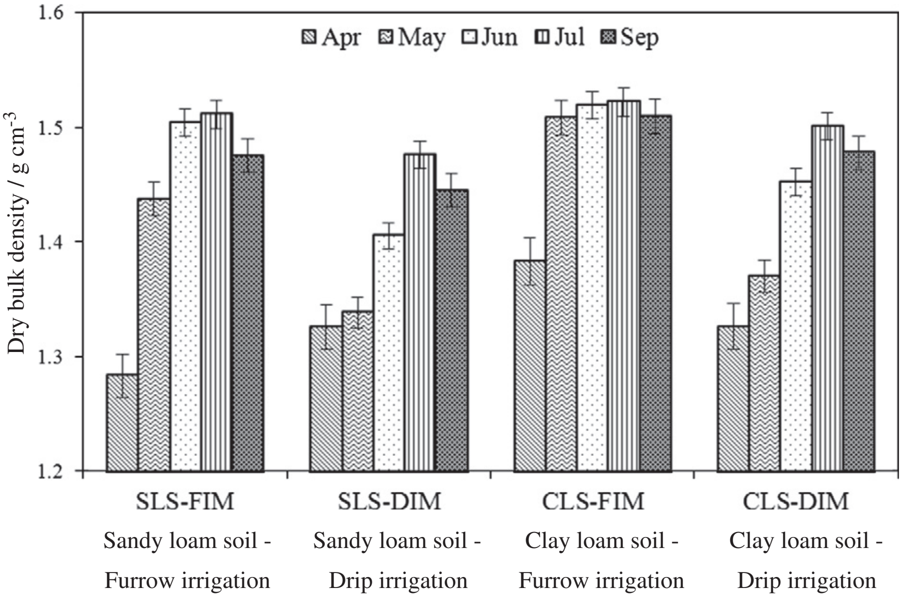

Fig. 4. Dry bulk density of the top 5 cm soil layer during the study period (standard errors are indicated).

K. For the two study soils, mean *K* values increased less than double when supply *h* increased from −3 to 0 cm indicated that the soil macropores for our study sites were very few or poorly connected (Hu et al., 2009) compared with those in other sites (Cameria et al., 2003; Mohanty et al., 1997).

Table 4
Descriptive statistical results of hydraulic conductivity (10^{-2} cm·min^{-1}) for different soil types, irrigation methods and times.

Variable	Level	K	N	Min	Max	Mean	S.D.
Soil	CLS[a]	Ks	50	1.37	4.67	2.79	0.95
		K3	50	1.32	3.83	2.39	0.74
		K6	50	0.99	3.35	2.00	0.66
		K15	50	0.75	2.47	1.45	0.55
	SLS[a]	Ks	50	3.39	6.39	4.68	0.69
		K3	50	2.54	5.29	4.04	0.62
		K6	50	2.27	4.95	3.49	0.65
		K15	50	1.52	3.00	2.31	0.36
Method	FIM[b]	Ks	50	1.37	6.39	3.54	1.36
		K3	50	1.32	5.29	3.12	1.17
		K6	50	0.99	4.95	2.60	1.10
		K15	50	0.75	3.00	1.77	0.68
	DIM[b]	Ks	50	2.09	5.80	3.93	1.12
		K3	50	1.64	4.83	3.31	0.96
		K6	50	1.58	4.54	2.89	0.87
		K15	50	1.06	2.84	2.00	0.56
Time	Apr	Ks	20	3.81	6.39	4.96	0.78
		K3	20	3.31	5.29	4.08	0.66
		K6	20	2.79	4.95	3.71	0.75
		K15	20	2.01	3.00	2.53	0.30
	May	Ks	20	2.66	5.30	4.08	0.94
		K3	20	2.46	4.83	3.64	0.86
		K6	20	1.87	4.12	3.03	0.81
		K15	20	1.48	2.66	2.06	0.33
	Jun	Ks	20	2.06	5.01	3.50	1.11
		K3	20	1.87	4.46	3.17	0.97
		K6	20	1.46	3.68	2.55	0.76
		K15	20	0.96	2.70	1.78	0.61
	Jul	Ks	20	1.37	4.90	3.17	1.41
		K3	20	1.32	4.12	2.73	1.19
		K6	20	0.99	3.73	2.38	1.09
		K15	20	0.75	2.49	1.64	0.71
	Sep	Ks	20	1.76	4.27	2.97	0.90
		K3	20	1.57	3.73	2.45	0.78
		K6	20	1.18	2.96	2.06	0.64
		K15	20	0.81	2.13	1.41	0.47

[a] CLS, clay loam soil; SLS, sandy loam soil.
[b] FIM, furrow irrigation method; DIM, drip irrigation method.

Significant differences in *K* were observed under all supply *h* values for the different soil types and times ($P<0.001$) (Table 5). Their differences in *K* with the different irrigation methods were weaker (significances at $P<0.10$), but were not significant. Hence, the soil hydraulic conductivities in our study sites were more strongly influenced more by the soil type and time than by the irrigation method.

3.3. Hydraulic conductivities for the different soil types

The *K* values under all supply *h* values for CLS were lower than those for SLS (Fig. 5). The ratios were 1.59 to 1.75 on average. Significant differences ($P=0.05$) were found between the *K* values at all supply pressure heads of the two soils, with the *K* values for SLS always higher than for CLS. This may be explained by the differences of macropore flow (Bouwer and Rice, 1984; Peck and Watson, 1979) between the two study soils, that relatively coarse particles and rock fragments leading greater amounts of macropore for SLS than for CLS.

3.4. Hydraulic conductivities under the different irrigation methods

In the present study, some differences in *K* were observed between FIM and DIM, as shown in Fig. 6. For CLS, the *K* values under all supply *h* values for FIM were always lower than those for DIM. The ratios were 1.10 to 1.20 on average. There was a similar trend for SLS between FIM and DIM, but with smaller ratios of 1.03 to 1.09. The coefficient of variation (CV) for evaluating the variability of the hydraulic conductivities at different supply *h* values is plotted in Fig. 7. CV exhibited higher values under all supply *h* values for CLS than for SLS. Higher values were observed under all supply *h* values for FIM than for DIM.

3.5. Temporal changes in the hydraulic conductivity

Generally, *K* under all conditions exhibited the highest values at the beginning of the study period and decreased thereafter (Fig. 8). For CLS, *K* decreased from April to July but generally increased in September (except for *K*15 for DIM). For SLS, *K* continuously decreased from April to September for SLS. For CLS and FIM, the *K* values of *K*s, *K*3, *K*6, and *K*15 decreased from their maximum values

Table 5
Multivariate ANOVA results for the hydraulic conductivities of different soils under various irrigation methods and times (shown in part).

Source	Dependent variable	Type III sum of squares	*df*	Mean square	*F*	*P*
Time	Ks	0.005	4	0.001	349.686	0.000**
	K3	0.003	4	0.001	333.501	0.000**
	K6	0.003	4	0.001	332.555	0.000**
	K15	0.002	4	0.000	357.041	0.000**
Soil	Ks	0.009	1	0.009	2423.318	0.000**
	K3	0.007	1	0.007	2591.207	0.000**
	K6	0.006	1	0.006	2237.231	0.000**
	K15	0.002	1	0.002	1752.454	0.000**
Method	Ks	0.000	1	0.000	3.684	0.056
	K3	0.000	1	0.000	3.651	0.060
	K6	0.000	1	0.000	4.500	0.037*
	K15	0.000	1	0.000	3.019	0.086

** Correlation is significant at the 0.01 level (two-tailed).
* Correlation is significant at the 0.05 level (two-tailed).

in April to their minimum values in July/September with maximum ratios of 2.9, 2.5, 3.0, and 2.9, respectively. Similarly, *K*s, *K*3, *K*6, and *K*15 decreased with the maximum ratios of 1.9, 2.0, 1.7, and 2.0 for CLS and DIM, respectively; with the maximum ratios of 1.6, 1.9, 1.8, and 1.8 for SLS and FIM, respectively; with the maximum ratios of 1.4, 1.2, 1.5, and 1.3 for SLS and DIM, respectively. These analyses indicated that *K* decreased more evidently for FIM than for DIM, and more obviously for CLS than for SLS. These results conformed to the abovementioned temporal changes in the dry bulk density.

All *K* values under the same soil type measurement set were pooled together to analyze the temporal changes in *K* as shown in Fig. 9. For CLS, *K* under all supply *h* values significantly changed ($P=0.05$) from April to July and slightly varied from July to September. For SLS, *K* under all supply *h* values significantly changed ($P=0.05$) from April to May and from July to September, but varied weakly from May through June to July. Overall, the hydraulic conductivities had significant temporal variability cross the whole growth season of grapevine in this study.

4. Discussion and conclusions

4.1. Temporal variability in the soil hydraulic conductivity

Various factors have significant temporal impacts on *K*, including field management, temperature, initial soil moisture, and irrigation (Alletto and Coquet, 2009; Das Gupta et al., 2006; Mubarak et al., 2009b; Petersen et al., 2008; Zhou et al., 2008).

For the present study, field management of the excavation of grapevines should be considered because this activity was performed 30 days before the first infiltration measurements. The excavation of grapevines resulting in low dry bulk densities and high *K* values in initial (Due to same filed managements, the disturbance of excavation to surface soil was assumed the same in different years). Afterwards, the soil was gradually compacted by irrigation and became less permeable, leading to increased dry bulk densities and decreased *K* values. However, according to the work of Azevedo et al. (1998) as well as Ciollaro and Lamaddalena (1998), the influence of cultivation decreases or disappears with time during the growing season and could be ignored in long-term observations.

Increased temperature can influence *K* by decreasing the water viscosity (Suwardji and Eberbach, 1998). In this study, the field irrigation, overshadow effect, and strong evaporation by grapevines induced a relatively humid microenvironment, leading to a general increase in soil temperature. Therefore, soil temperature is unlikely to be the main reason of decrease in *K* with time for present study.

The initial soil moisture linked to temporal changes in *K* may not be the main reason for the present study. All the measurements were made at the last day of an irrigation interval, when the soil was driest during an irrigation interval, to diminish the possible impact of initial soil moisture on *K*. The surface soil was very dry on the measurement day (60% to 75% of the field capacity) due to the combined effects of evapotranspiration and vertical infiltration.

Irrigation is closely associated with the changes in soil *K* by influencing soil physical properties of particle size distribution, pore structure, and bulk density (Mubarak et al., 2009a, 2009b). The increases of soil dry bulk densities after the first infiltration can explain the decrease in *K* for the present study. Besides, soil surface crust could be another possible reason resulting to the decrease of *K*. The impact of crust was more obvious for DIM than FIM that larger and larger puddles can be observed below the dripper in the field. The increased *K* in September can be explained by soil cracking induced by the extension of irrigation interval after the harvest on August (see Table 3) and high daily air temperature (Fig. 1). The high frequency irrigation caused surface soil to crust and easily crack while soils become dry (Davidson and Pay, 1956; Hussain et al., 1986; Logsdon and Cambered, 2000). Besides, dry surface soil requires more time to reach the steady state (On average, 25 and 40 min for SLS and CLS in April, and 35 and 65 min for SLS and CLS in September) using a tension infiltrometer which results in higher *K* values than in reality.

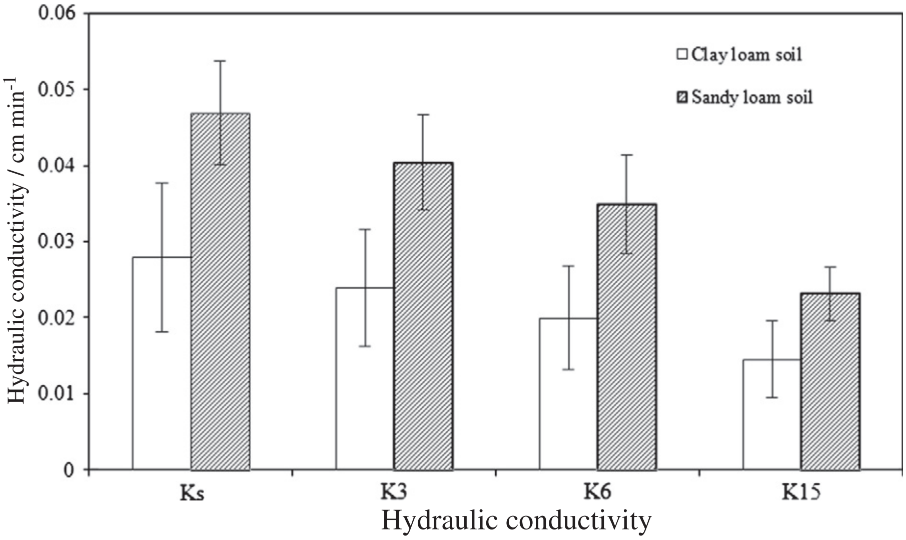

Fig. 5. Comparison of soil hydraulic conductivities for different soil types (standard errors are indicated).

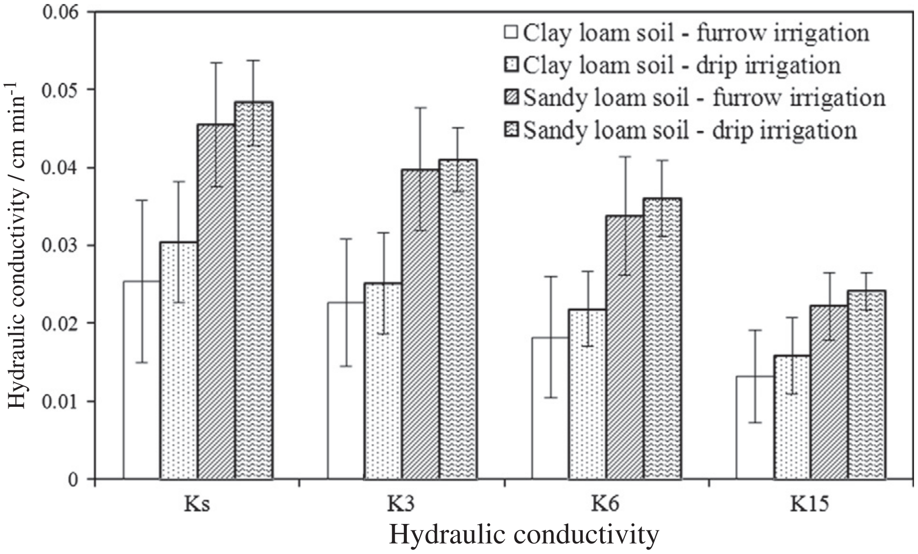

Fig. 6. Comparison of soil hydraulic conductivities for different irrigation methods (standard errors are indicated).

Comparing the differences of irrigation impact on different soil types, the compacting and cracking effects are more significant in the one that contains more clay as reported by Davidson and Pay (1956) as well as Hussain et al. (1986). This phenomenon was in accordance with our study, that *K* of CLS decreases faster (compaction) and increases more obviously (crack) than that of SLS. Therefore, considering that the temporal changes in *K* corresponded with the effect of irrigation in the present study is reasonable.

4.2. Evaluation and estimation of the temporal changes in the hydraulic conductivity

Soil *K* is strongly related to the infiltration and water flow model, unsaturated hydraulic conductivity calculation, soil water distribution, and falling rate stage of soil evaporation, etc. Soil *K* was verified sensitively in soil lateral flow, groundwater recharge modeling (Zhang, 2011) and runoff simulation (Blanco-Canqui et al., 2002). Temporal changes should be considered in irrigation design or water flow modeling and analyses based on irrigation conditions. Otherwise, great errors are incurred. In our study, through the whole growing period, 2.9 times difference existed between the maximum mean *K* (in April) and minimum mean *K* values (in July/September) for CLS under FIM, 1.9 times for CLS under DIM, 1.8 times for SLS under FIM, and 1.3 times for SLS under DIM (Fig. 8). The significant differences in soil *K* at different times may partly explain the different values of *K* between the model inverse solution result with field observation and the direct field measurement in study sites (Chen et al., 2011).

Theoretically, soil *K* should be investigated throughout the entire growing season. However, this task is costly and time-consuming. The relationships between the relative change rates of the mean *K* values and number of irrigation events under four supply *h* values are shown in Fig. 10. Negative linear correlations generally exist between the mean *K* values and accumulative irrigation times

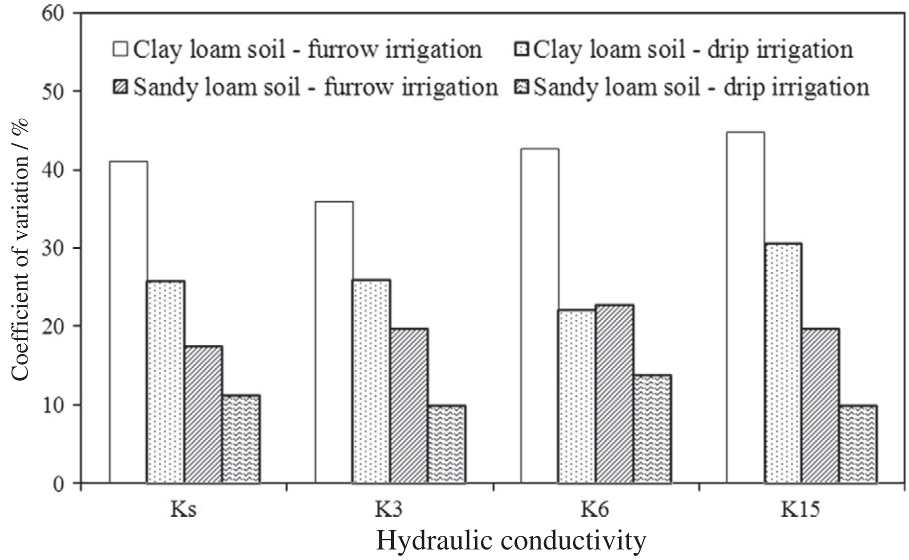

Fig. 7. Comparison of coefficients of variation for different irrigation methods.

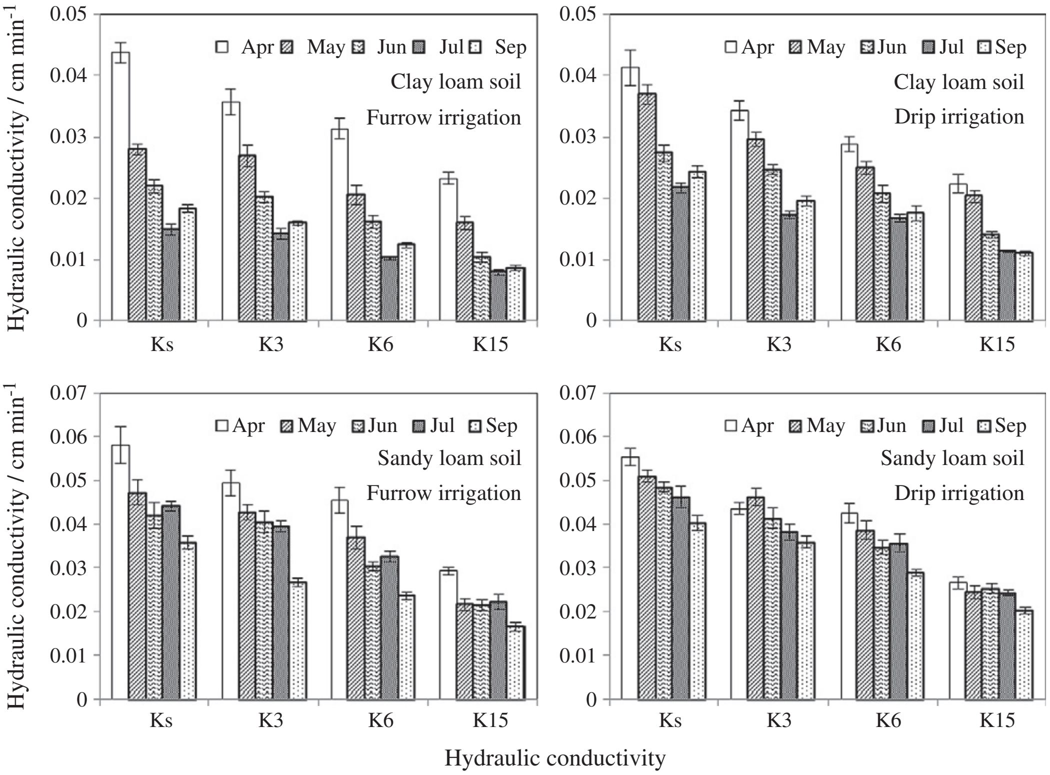

Fig. 8. Temporal changes in soil hydraulic conductivity under different soil types and irrigation methods (standard errors are indicated).

throughout the entire growing season for SLS and CLS, and can be expressed as follows:

For SLS,

$$K_{\text{cal}} = K_0 - N_{\text{cal}} \cdot \alpha \cdot K_0. \tag{5}$$

For CLS,

$$\begin{array}{ll} K_{\text{cal}} = K_0 - N_{\text{cal}} \cdot \alpha \cdot K_0 & K_{\text{cal}} \text{ for the initial irrigation interval} \\ K_{\text{cal}} = K_{\text{m}} & K_{\text{cal}} \text{ for the second irrigation interval} \end{array} \tag{6}$$

where K_{cal} is the calculated K value (cm·min^{-1}), K_0 is the initial K value (cm·min^{-1}), N_{cal} is the number of irrigation events from K_0 to K_{cal}, K_{m} is the K value investigated at the second irrigation interval (cm·min^{-1}), α is a parameter equal to the slope of the straight line.

According to the results in Fig. 10, soil K should be measured at least twice to estimate α during the growing season, the first irrigation event, and the last irrigation event under the same irrigation interval were recommended.

$$\alpha = \frac{K_{\text{i}} - K_{\text{i+n}}}{N_{\text{n}}} \tag{7}$$

where K_{i} is the K value for the first field investigation (cm·min^{-1}), $K_{\text{i+n}}$ is the K value for the second field investigation (cm·min^{-1}), N_{n} is number of irrigation events from K_{i} to $K_{\text{i+n}}$. K_{i} and $K_{\text{i+n}}$ both should be investigated within the first irrigation interval. Other K values can be estimated by combining Eqs. (5), (6) and (7).

This method which results in relative errors between the calculated K and measured K are less than 5% for CLS-FIM, CLS-DIM, SLS-DIM, and within 10% under the SLS-FIM condition. If soil K is only measured once, it could be estimated by the given α values of 1.35, 1.25, 1.15 and 1.10 for CLS-FIM, CLS-DIM, SLS-FIM and SLS-DIM, respectively, according to

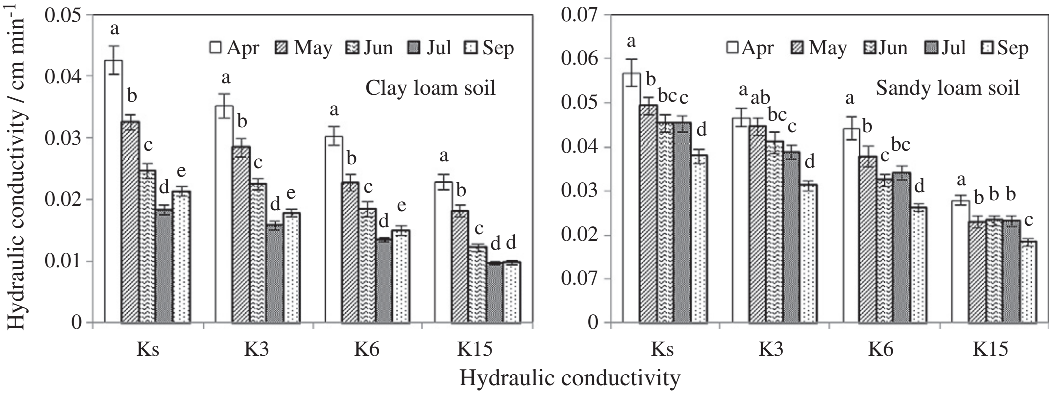

Fig. 9. Temporal changes in soil hydraulic conductivity. Vertical bars represent the standard error. Bars with the same letter indicate no significant difference for $P<0.05$.

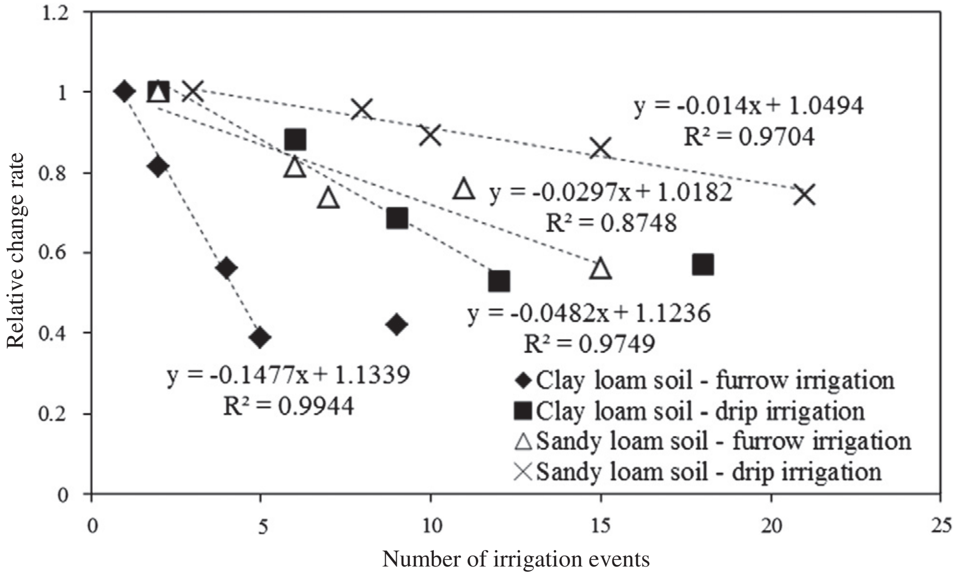

Fig. 10. Relative change rates of mean *K* values with different number of irrigation events. Mean *K* values measured in the second irrigation interval for CLS-FIM and CLS-DIM were not considered in linear regression.

our study. Results by the given α values yield relative errors that are less than 10% between the calculated *K* and measured *K*, except for 20% under the SLS-FIM condition.

Our observation period spanned an entire growing season. However, observations for one growing season may not be sufficient to draw a conclusion on the impact of irrigation on surface soil properties. The value of parameter α relates to a certain soil, irrigation method and years that need to be tested in future study. Besides, the reason for increasing soil *K* under longer irrigation interval condition also needs further investigation. Therefore, a sustained observation is recommended to investigate the temporal change in *K* under various irrigation methods at a longer time scale.

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