LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. **25**: 163–172 (2014)

Published online 28 November 2011 in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ldr.1156

EFFECTS OF LAND USE ON SOIL MOISTURE VARIATIONS IN A SEMI-ARID CATCHMENT: IMPLICATIONS FOR LAND AND AGRICULTURAL WATER MANAGEMENT

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Received: 6 April 2011; Revised: 22 July 2011; Accepted: 28 September 2011

ABSTRACT

Knowledge of the effects of land use on soil moisture variations is necessary to improve land and agricultural water management in the semi-arid Chinese Loess Plateau. However, previous studies are insufficient to guide management practice in this area and improvement is needed to help with the development of the 'Grain for Green' programme. As part of the 'Grain for Green' programme, we examined the effects of five land uses (fallow, grassland, cropland, 3-year and 8-year jujube orchards) on soil water variations in a small catchment on the Loess Plateau. Soil moisture at 0–160 cm depth was monitored approximately weekly at 47 sites from 17 August to 19 October 2009 and from 4 April to 27 September 2010 using a portable time domain reflectometer. Results indicated that mean soil water profiles in different land uses varied with time, land use induced spatial variations of soil water but exerted negligible influence on soil water temporal patterns, and soil water content was of the greatest spatial variability with moderate means (approximately 20 per cent). Furthermore, the relationship between standard deviation and mean water content was dependent on soil depth, although it was negligibly affected by land use. Profile soil water for five land uses was different in various seasons, precipitation infiltration depth exhibited a positive correlation with precipitation, and the whole profile soil moisture (0–160 cm) was complemented following a 93·5-mm rainfall event. The findings presented here provide helpful information for land and agricultural water management in this area. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: soil water/soil moisture; variability; land use; Loess Plateau; jujube; precipitation infiltration; management; PR China

INTRODUCTION

Soil water (i.e. soil moisture) is a key factor affecting vegetation structure in water-limited environments (Rodriguez-Iturbe *et al*., 1999); in turn, vegetation exerts vital controls on the entire water balance (Rodriguez-Iturbe *et al*., 2001) via complex and mutually interacting hydrological processes (Porporato *et al*., 2002). Land use can significantly affect soil properties, such as bulk density, saturated hydraulic conductivity, infiltration rate, and available soil water (moisture) content (Haghighi *et al*., 2010). Because soil properties are the main factors controlling soil water variations (Vachaud *et al*., 1985; Famiglietti *et al*., 1998; Hu *et al*., 2010), land use could influence soil water variations by changing soil properties. Hence, land development featuring vegetation restoration in arid and semi-arid zones requires an understanding of soil-water variations, both in space and time (Wilcox and Newman, 2005; Chen *et al*., 2007).

Land use has been shown to be one of the main factors controlling soil water variability (Qiu *et al*., 2001, 2010; Pan and Wang, 2009). In recent studies, the effects of land use on soil water variations have been investigated via statistical analysis (Fu *et al*., 2003; Chen *et al*., 2007; Gross *et al*., 2008), or simulation of physical-based models (Li *et al*., 2009). The statistical models showed that temporal and vertical soil water variations behaved differently for seven land uses in the Chinese Loess Plateau (Fu *et al*., 2003; Chen *et al*., 2007). Li *et al*. (2009) showed that land use change from woodland to grassland decreased soil water by 18·8 per cent during 1981–2000 in an agricultural catchment of the Loess Plateau, established by simulation results using soil and water assessment tools. Clearly, it is necessary to study space–time soil water variations when ground cover evolves.

Understanding of the spatio-temporal field soil water process is important for agricultural water management and site-specific farming (Starr, 2005). Spatial variability of soil water varies with soil wetness and can be explained as a function of mean water content (Vereecken *et al*., 2007).

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Hitherto, studies have been performed to investigate the relationship between means and spatial variability of soil water. However, conflicting results were reported. Some field experiments have found increases in the standard deviation (SD) of soil water with reductions in mean water content (e.g. Hupet and Vanclooster, 2002; Brocca *et al.*, 2007), whereas others have found the opposite (e.g. Famiglietti *et al.*, 1998; Hu *et al.*, 2011). Whereas, numerical simulations and stochastic analysis indicate that SD and mean water content exhibit a convex upward relationship, i.e., SD initially increases with increasing mean water content, peaks and then declines (Teuling and Troch, 2005; Vereecken *et al.*, 2007; Lawrence and Hornberger, 2007; Pan and Peters-Lidard, 2008), which has been supported by recent experiments work (e.g., Famiglietti *et al.*, 2008; Brocca *et al.*, 2010). The relationship between SD and mean water content has also been examined in the Loess Plateau. For instances, Hu *et al.* (2011) observed a positive relationship between SD and mean water content for two different land uses (shrub and grass) in the Laoyemanqu watershed. The various relationships between SD and mean water content can be attributed to different climate zones (Lawrence and Hornberger, 2007) and/or soil texture (Vereecken *et al.*, 2007; Pan and Peters-Lidard, 2008). Using a modified soil water dynamic model, Lawrence and Hornberger (2007) observed that variance increased with mean water content in semi-arid regions, whereas it decreased with mean water content in humid regions, and variance peaked as mean water content was moderate in temperate regions. Moreover, Western *et al.* (2003) argued that the different behaviours of SD versus mean water content in humid and semi-arid environments could be attributed to the different patterns of controlling processes. Vereecken *et al.* (2007) obtained a variety of patterns on the relationship between SD and mean water content for different soil textural classes based on stochastic analysis. They found that SD increased with mean water content for sandy loam and loamy-sand soils, whereas peak values existed for silt-loam and clay-loam soils.

Land use can affect precipitation infiltration, which is of great importance to vegetation restoration and crop production in semi-arid areas (Li, 2001; Wang *et al.*, 2008). Liu *et al.* (2008) operated field infiltration experiments over different ground covers in the hilly area of the Loess Plateau. They found that the cumulative infiltration in forest land was significantly greater than that in farmland and grassland, whereas no significant difference existed between those in the latter land use types. Huang *et al.* (2010) reported that stable infiltration rate for grass cover was higher than that for wheat and bare soil control, based on artificial rainfall experiments in Yangling, Shaanxi Province, PR China. In addition to land use types, precipitation characteristics (Li and Shao, 2006; Wang *et al.*, 2008; Zhao *et al.*, 2010), antecedent soil water content (Phillip, 1957), and soil properties (Morin and Benyamini, 1977) also influence rainfall infiltration. However, most of the aforementioned studies examined rainfall infiltration characteristics based on artificial rainfall experiments. Furthermore, few of them recorded the precipitation infiltration depth.

The semi-arid Loess Plateau is one the frailest ecological systems and poorest economic zones in China due to frequent droughts and severe soil erosion (Wu *et al.*, 2002; Zhao *et al.*, 2009). The environment has to a large extent been improved since the implementation of the 'Grain for Green' programme in 1999, this project requires return of sloping cultivated land (>25 degrees) to forest and/or grass (Chen *et al.*, 2007; Zhao *et al.* 2009). However, in some areas of the Loess Plateau, 60–80 per cent of annual rainfall is concentrated between July and September, and much scarcer water resources exist in hillslope land than in river floodplain land (Zhao *et al.*, 2009). As a result, the forest plantations (e.g. *Pinus tabulaeformis* and *Populus canadensis*) grew well at first, but often become degraded once the initial water supply has been exploited (Chen *et al.*, 2007). This has resulted in many 'low-thin-old trees' on hillslope land and further land degradation (Zhao *et al.*, 2009). At present, the 'Grain for Green' programme has entered its second decade, and new ideas have emerged for converting degraded cultivated land into other land cover types that protect both the environment and farmers' income. For example, new-type jujube orchards have been established in the heart of the hilly area of the Loess Plateau since 2005. In these jujube orchards, planted at twice the density of traditional orchards, micro-irrigation equipment has been built to meet the water requirement of jujube in the dry seasons. The functions of this innovative approach in controlling soil erosion and raising economic benefits have been confirmed (Wu *et al.*, 2008; Zhao *et al.*, 2009), although it is just at a preliminary stage. However, the question 'how to manage the finite water resources reasonably in both space and time?' is still a big challenge in this area.

The objectives of the study presented here were (i) to characterise temporal variations of soil water profiles for five land uses including new-type jujube orchards and (ii) to analyse differences in vertical soil water distribution as well as the influence of precipitation on profile soil water for five land uses.

MATERIALS AND METHODS

Study Site

The experiment was conducted in the Yuanzegou catchment (37°15′N, 118°18′E) located in the north central part of the Loess Plateau, PR China (Figure 1). The catchment covers an area of $0{\cdot}58\,\mathrm{km}^2$ with a gully area of $0{\cdot}31\,\mathrm{km}^2$. On the basis of data from 1966–2006, this site has a semi-arid continental climate with a mean annual precipitation of 505 mm,

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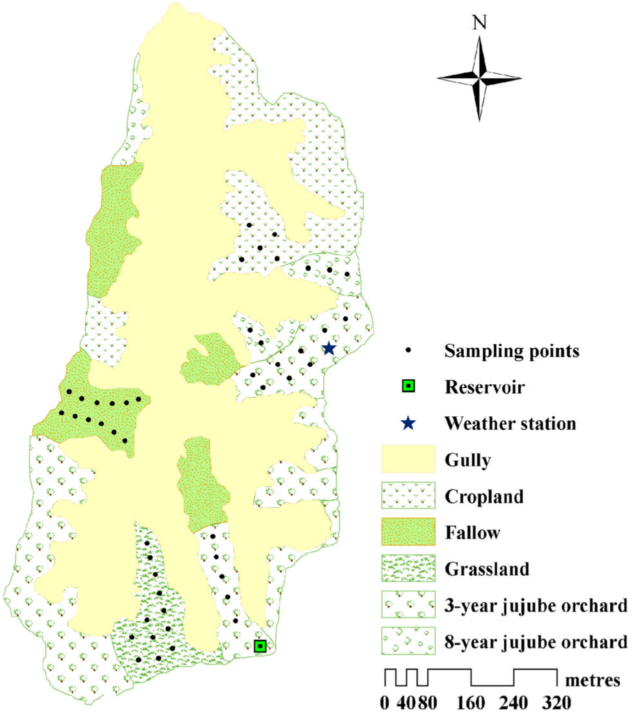

Figure 1. Land uses and soil water sampling points in Yuanzegou catchment. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

70 per cent of which falls during late summer and early autumn (August, September, and October); a mean annual temperature of 8·6°C, with mean monthly temperatures ranging from −6·5°C in January to 22·8°C in July; and 157 frost-free days and 2720 h of sunshine on average each year (Weather Bureau of Qingjian County, Shaanxi Province). The elevation of the Yuanzegou catchment ranges from 865 to 1105 m. The hillslope land has a relatively gentle slope (<35 °), whereas the inclinations of the gully walls range from 30 ° to 90 °. The whole catchment is covered by loess developed from wind-deposited loess parent material (Zhu *et al*., 1983).

The porous structure of dot-and-arris contacting of loess soil (Zhu, 1994) allows the storage of large amounts of water but the soil has a low water-holding capacity (Li *et al*., 1995). The field capacity and permanent wilting point of the loess at this study site is 24·3 per cent and 8·8 per cent (volumetric water content), respectively. The detailed information of soil texture and bulk density in the catchment is shown in Table I.

The current land uses in the hillslope land are 3-year and 8-year jujube orchards, cropland, grassland, and fallow land (Figure 1). Jujube trees were planted with a density of approximately 1650 trees per hectare and using cultivation. Cropland crops were mainly millet (*Panicum miliaceum*) and beans (*Phaseolus valgaris*). Grassland was dominated by *Artemisia gmelinii*, *Bothriochloa ischaemum*, and *Lespedeza davurica*. The two-year-old fallow land was mainly vegetated with *Artemisia scoparia*. According to field survey, the rooting depth of 8-year-old jujube exceeded 5 m, with more than 85 per cent of total root mass concentrating in the 0–80 cm horizon. The rooting depth of perennial grass was more than 1 m with approximately 92 per cent roots found at 0–60 cm. For annual grass and crops, main roots concentrated in the 0–40 cm horizon. Measured vegetation cover (canopy cover) for different land uses is also shown in Table I.

Jujube orchards were irrigated with micro-irrigation equipment in 2009. Surface run off, either originating from precipitation or spring water in gully bottoms, was collected in a reservoir near the outlet of the catchment. Then the accumulated water was pumped to a reservoir located on the top of the highest hill in the catchment (Figure 1).

A portable automatic weather station was located on the relatively level gully upland (Figure 1). In total, 524·8-mm precipitation was observed during the study period. The precipitation and potential evapotranspiration (ET_0) recorded for each month during the study period is shown in Figure 2.

Soil Water Measurements

The five land uses within the catchment were monitored using a total of 47 soil water sampling points, 5 in the 8-year jujube land, 13 in the 3-year-old jujube orchard, 5 in the cropland, 12 in the grassland, and 12 in the fallow land

Table I. Bulk density and soil texture at 0–20 cm and vegetation cover for five land uses

Land use	Bulk density (g/cm^3)	Soil texture			Canopy cover per cent
		Sand per cent (2 ~ 0·05 mm)	Silt per cent (0·05 ~ 0·002 mm)	Clay per cent (<0·002 mm)	
3-year jujube orchard	1·28	16·2	62·4	21·4	45[a]
8-year jujube orchard	1·33	15·2	63·1	21·7	70[a]
Grass	1·22	14·3	63·6	22·1	92[b]
Fallow	1·26	16·0	62·4	21·6	83[b]
Cropland	1·17	23·3	60·5	16·2	56[b]

[a] Estimated via visual observation.
[b] Measured by using cross-hair point frame.
Canopy cover was measured in 25 September 2010.

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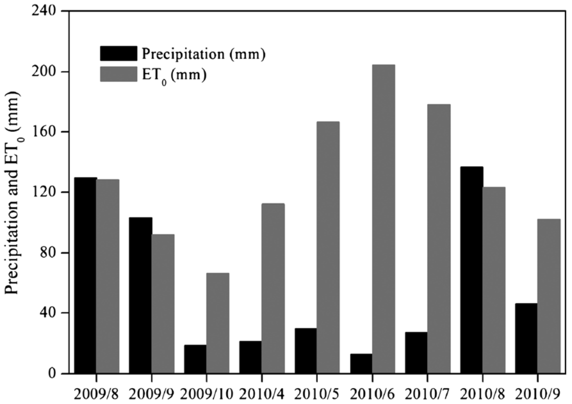

Figure 2. Monthly precipitation and potential evapotranspiration (ET_0) during study period.

(Figure 1). The spacing between sampling points within each land use category was approximately 20–35 m. Soil water was sampled at these points at depths of 0–160 cm at 20-cm increments from 17 August to 19 October 2009 and from 4 April to 27 September 2010, except for cropland that started measuring soil water in 13 July 2010. In general, soil water was sampled at weekly intervals. Moreover, soil water was also sampled before and after rain events as further described in the succeeding section (see section on Evaluation of Observed Vertical Soil Water Variations Derived from Precipitation). During the entire sampling periods, there were 38 sampling occasions (37 for deep horizon soil water) that were taken. On each sampling occasion, soil water was sampled within 4 min at each sampling point. In order to diminish the temporal variation of soil water as much as possible, all the soil water measurements were taken within 8 h during each sampling occasion.

Soil water values for all depths were sampled using a portable time domain reflectometry (TDR) system (TRIME-PICO IPH/T3; IMKO, Germany), consisting of a TRIME-IPH probe, a TRIME-DataPilot data-logger and fibreglass access tubes ($\phi = 40$ mm). A hand-auger ($\phi = 45$ mm) was used to install fibreglass access tubes instead of the equipment-supplied accessories for installing tubes, because the original tools are difficult to operate in hillslope land. The ground space between the tube and soil was filled with diluted mud consisting of water and loess soil. Tubes installation was finished in 15 July 2009. A total of 25 sites (5 for each land use) were used to gravimetrically calibrate the system as follows. Soil water at these sites was measured using the TDR tool at 0–20, 20–40, 40–60, 60–80, and 80–100 cm depths. Meanwhile, a 1-m-deep pit was excavated 0·5 m from the access tubes to collect undisturbed soil samples from the corresponding depths in order to obtain measurements of the dry soil bulk density and gravimetrical soil water content (θ). Values of θ were then transformed to volumetric water contents (Hu *et al*., 2009), and a calibration curve was generated by plotting the measured TDR-derived soil water values against the volumetric water contents and fitting a regression equation (Equation 1).

$$y = 0.9471x - 4.3796, \quad R^2 = 0.904 \qquad (1)$$

Definition of Soil Water Profiles

In arid and semi-arid environments, plant-root accessible zones of soil water are generally deeper because of the hydrotropism of roots and usually low soil water contents in their shallow soil layers. In the Loess Plateau in particular, the depth of active zones often exceeds 1 m because of the thick loess (Yang and Shao, 2000). On the basis of the root surveys, we defined soil layers of 0–20, 0–80, and 80–160 cm as surface horizon, root zone, and deep soil horizon, respectively, in this study. For any sampling point, surface soil water was the soil water at 0–20 cm; root zone soil water was the mean of that at 0–20, 20–40, 40–60, and 60–80 cm; and deep horizon soil water was the mean of that at 80–100, 100–120, 120–140, and 140–160 cm.

Evaluation of Observed Vertical Soil Water Variations Derived from Precipitation

To indicate the infiltration depth of rainfall, we measured soil water at the day before rainfall events, after rainfall events, and before the next ones, respectively, according to local weather information from Weather China (www.weather.com.cn). Considering the hysteresis of rainfall-infiltration process, soil water was measured at two occasions with an interval of days after rainfall events. The lengths of time intervals between two occasions were dependent on the precipitation; in general, the larger the amount of precipitation, the longer the time interval. Four scenarios were designed to evaluate observed vertical soil water changes derived from precipitation.

Scenario 1 Low precipitation. The rainfall event on 4 May 2010 with a total of 3·3-mm precipitation was selected as the low precipitation scenario. Soil water readings from 0–160 cm on 3, 5, and 6 May 2010 were used to show profile soil water variations for four land uses excluding cropland.

Scenario 2 Medium precipitation. The rainfall event between 26 and 27 May 2010 with a total of 16·7-mm precipitation was selected as the medium precipitation scenario. Soil water measured between 0–160 cm on 25, 28, and 29 May 2010 was used to indicate profile soil water changes for four land uses in addition to cropland.

Scenario 3 High precipitation. The rainfall event between 10 and 13 August 2010 with total 51·7-mm

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precipitation was selected as the high precipitation scenario. Soil water recorded for 0–160 cm on 10, 13, and 16 August 2010 was utilised to explore profile changes for all five land uses.

Scenario 4 Extreme-high precipitation. The rainfall event between 3 and 10 September 2009 with total 93·5-mm precipitation was selected as the extreme-high precipitation scenario. Soil water readings between 0–160 cm on 2, 11, and 18 September 2009 was employed to explore profile variations for four land uses excluding cropland.

To distinguish the effect of precipitation on soil water, we calculated the absolute differences between measured soil water at all depth intervals before precipitation and that after precipitation for each land use. We hypothesised that the absolute difference was defined as a stochastic change if it was not more than 0·5 per cent, or else, was defined as a significant change resulting from precipitation infiltration if the difference is positive.

Statistical Analysis

One-way analysis of variance was employed to determine the effect of land use on soil water profiles and the least significant difference method was used to show the difference between mean water content in different land uses. All the analysis was performed with SPSS 16.0® (SPSS Inc., Chicago, USA).

RESULTS AND DISCUSSION

Temporal Variations of Soil Water Profiles in Different Land Uses

There were differences of soil water for the different land uses. These changed with time and were dependent on soil depth (Figure 3a–c). In general, surface soil water for all different land uses correlated positively with precipitation events, increasing rapidly after rainfall and decreasing during the dry periods (Figure 3a). Comparing surface soil water with that in the root zones, there was a clear lag in response to precipitation, although both surface and root zone soil water had similar temporal variations (Figure 3b). An even greater lag could be observed for deep layer soil water measurements. These were less influenced by precipitation, resulting in gradual and relatively smooth temporal changes (Figure 3c).

No significant difference in surface soil water was observed for five land uses (Table II). This is consistent with Chen *et al*. (2007) who observed low variations of soil water at 0–20 cm among five land uses (cropland, alfalfa, shrub land, woodland, and grassland) in the western Loess Plateau over either dry (May and June) or wet (July and August) seasons. Meanwhile, Qiu *et al*. (2001) found that soil water at 0–5 cm in woodland was significantly higher ($p < 0{\cdot}05$) than that in other land uses in a small watershed of the Loess Plateau. However, soil water in both root zone and deep soil layer indicated statistical difference ($p < 0{\cdot}05$) for different

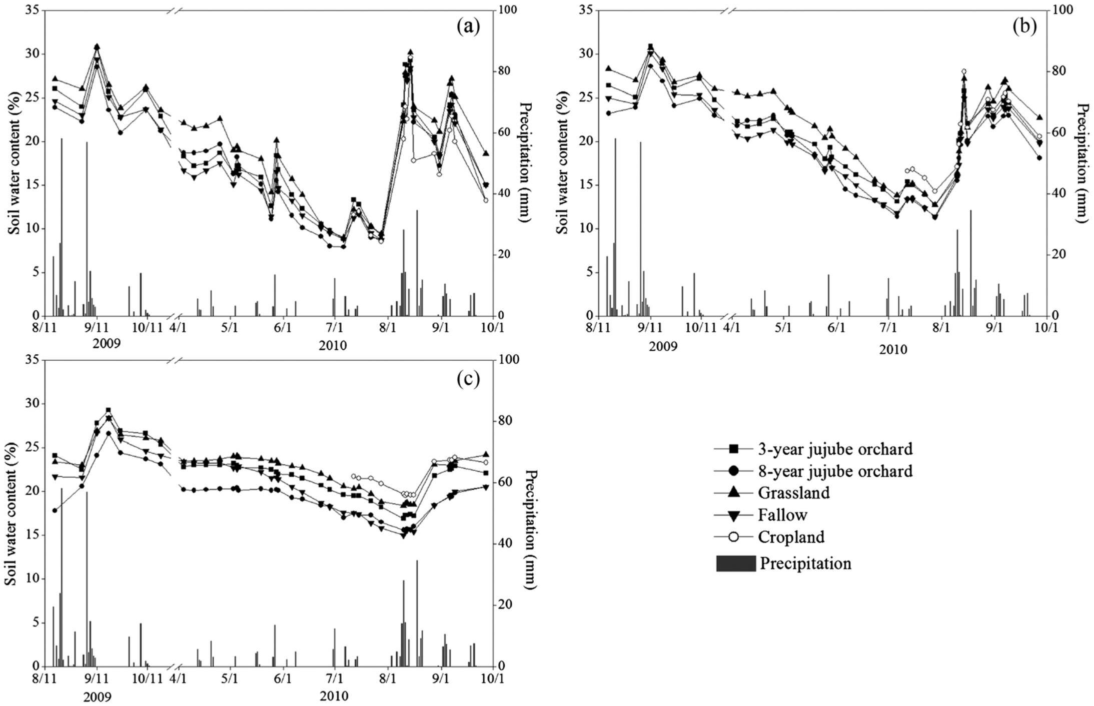

Figure 3. Temporal variations of soil water content for surface horizon (a), root zone (b), and deep soil horizon (c) under different land uses.

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Table II. Multiple comparisons for mean water content of four land uses during study period

Land use	Soil water content (per cent) Surface horizon	Root zone	Deep horizon
3-year jujube orchard	19·1 a	20·9 ab	21·9 a
8-year jujube orchard	18·1 a	19·6 b	19·4 b
Grassland	20·4 a	22·4 a	22·7 a
Fallow	18·1 a	19·8 b	20·5 b
p-value	0·313	0·042	<0·001

p-value refers to the probability of same soil water values of analysis of variance in the 95 per cent significance level.

Values in each column with the same lower-case letter are not significantly ($p < 0{\cdot}05$, least significant difference) different among land uses.

land covers (Table II), which can be ascribed to various evapotranspiration activities resulting from different root distribution under different land uses (Yang and Shao, 2000). This corroborates the findings of Qiu *et al.* (2001) and Fu *et al.* (2003) in the Loess Plateau. The relatively high surface soil water in grassland was probably because of the higher clay content (Table I) and the north-facing spatial location (Figure 1). Although the significant differences of soil water in root zone and deep soil layer were observed for different land uses, similar temporal evolutions of soil water at all depths existed among them (Figure 3). This implies that land use induced spatial variations of soil water but exerted negligible influence on soil water temporal patterns.

Scatter plots of SD versus mean water content for three soil horizons are depicted in Figure 4(a). For data sets of all soil horizons, SD increase with decreasing mean water content and a transition to an adverse trend was observed within drier conditions. SD peaked when mean water content was approximately 20 per cent. This is consistent with recent findings (Vereecken *et al.*, 2007; Brocca *et al.*, 2010). However, Hu *et al.* (2011) found SD positively correlated with mean water content in a small watershed of the Loess Plateau, which may be due to the semi-arid environments in their study (Lawrence and Hornberger, 2007) with mean annual precipitation of 437 mm. The convex relationship between SD and mean water content in this study is probably because of the silt-loam soils (Vereecken *et al.*, 2007) and the measurement period covering both the wet and dry soil conditions. Moreover, it was found that similar patterns of SD versus mean water contents existed in surface horizon and root zone. Whereas the relationship in deep horizon was apparently different from that in the other two soil horizons; that is SD decreased with increasing mean water content. However, Western *et al.* (2003) found that the influence of soil depth on this relationship was not significant. The distinctive relation of SD to mean water content at deep soil horizon in our study is probably because of the relatively high mean water content (>15 per cent) over the whole study period (Figure 3c).

The relationship between SD and mean water content in various land uses is shown in Figure 4(b). Overall, SD behaved similarly with increasing moisture content for different land uses, and SD peaked as mean water content was approximately 20 per cent, which was in accordance with the results when data sets for all land uses were taken into consideration. Hu *et al.* (2011) also reported a similar finding in two land uses (shrub and grass) of the northern Loess Plateau. This suggests that land use may be not the main factor affecting the relationship between SD and mean water content.

Profile Soil Water Variations in Different Land Uses

Seasonal patterns of vertical soil water

Figure 5(a–c) shows the seasonal patterns of vertical soil water over 0–160 cm for different land uses. Overall, profile soil water indicated distinct vertical patterns for various seasons. In spring, soil water in different land uses, except for that in fallow land, exhibited increase-then-decrease variations with depths over 0–80 cm, reaching the highest values at 40–60 cm. However, weak variations of soil water existed over 80–160 cm for all land uses, creating a moisture-stability layer (Yang and Shao, 2000). Soil water decayed unanimously with depth independent on land uses in summer, which may be a result of strong evapotranspiration. In autumn, soil water at 0–40 cm, except for that in cropland, exhibited higher values than that in deeper depths. Moreover, a water stability layer (80–160 cm) existed for different land uses in autumn. Surface soil water in cropland was low in summer and in autumn, but it was the highest at deeper depths (40–160 cm). A possible explanation is that greater evaporation existed in the surface horizon of cropland than that in the other land uses due to ploughing, which diminishes soil water evaporation in deeper layers by creating a capillary barrier at the surface horizon.

Observed profile soil water changes derived from precipitation

Table III shows the magnitude of soil water changes in the whole soil profile for various land use excluding cropland. Irrespective of ground cover, only the first 20-cm horizon responded with increased soil water levels significantly after low (3 mm) and medium (16·7 mm) rainfall, when measured 1 day later after the precipitation event. However, the significant increase of surface water disappeared at the second measurement for 3-year-old jujube orchard and grassland. Note that the precipitation in medium precipitation was 5·06 times of that in low precipitation, but the averaged increase in soil water content was only 1·7-times of that in low precipitation. This can be ascribed partly to the fact that

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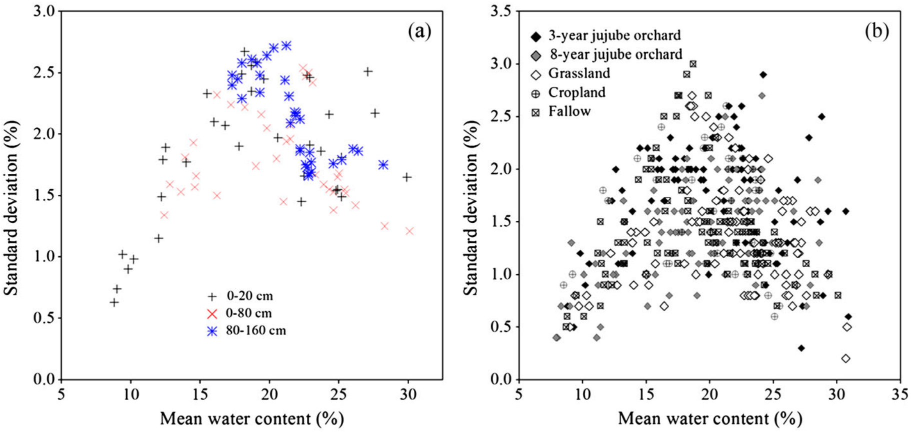

Figure 4. Relationship between standard deviation and mean water content for different soil horizons (a) and for various land uses (b). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

vegetation in different land uses just began to shoot up in early-May (low precipitation), whereas plants have taken on exuberance of foliage, which is expected to intercept part of precipitation in late-May (medium precipitation).

After a high rainfall event (42·5 mm), a significant increase in soil water could be determined at the 60-cm horizon for the first measurement after rainfall for all land uses, while it was also observed at the 80 cm horizon for the second measurement in addition to for 8-year-old jujube orchard. Strikingly, the whole profile soil water (0–160 cm) was supplied by precipitation following a 7-day continuous rainfall event (93·5 mm) for both measurements after precipitation. For this extreme-high precipitation, the infiltration depth is expected to be more than 160 cm on the basis of the increased soil water content in Table III. The observed result is consistent with Li (2001) who reported that the maximum infiltration depth of precipitation was 100–300 cm.

Although a positive correlation was observed between precipitation and infiltration depth derived from precipitation, it is difficult to quantify the relationship between them because of the varying antecedent soil water contents, rainfall intensity, vegetation cover, and meteorological conditions among the four scenarios. For the effects of precipitation on profile soil water to be quantified, more intensive observation experiments are necessary.

Implications for Land and Agricultural Water Management

Climate change affects the hydrological cycle (Syed *et al.*, 2010; Parry *et al.*, 2007) and is likely to reduce summer precipitation over the central parts of arid and semi-arid Asia. This in turn will lead to an expansion of deserts and will cause periodic severe water stress conditions (Parry *et al.*, 2007). Thus, improving land and agricultural water management is vitally important to make efficient use of

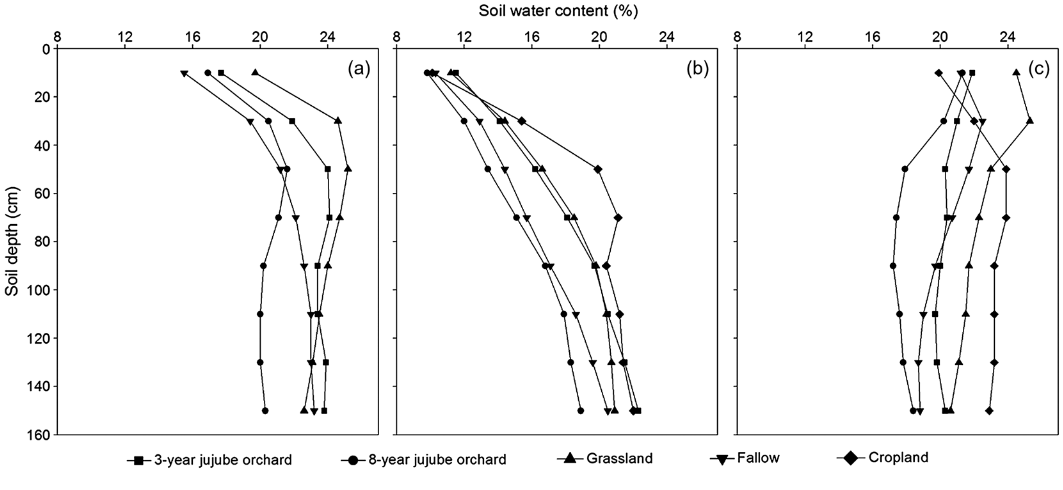

Figure 5. Seasonal patterns of vertical soil water variations for different land uses: spring (a), summer (b), and autumn (c).

Table III. Magnitude of soil water changes (per cent) for different depth intervals over 0–160 cm for various scenarios

Soil depth (cm)	Scenario 1				Scenario 2			
	3-year JO	8-year JO	Grass	Fallow	3-year JO	8-year JO	Grass	Fallow
0–20	**3·8**(0·4)	**3·1(1·0)**	**2·6**(0·1)	**3·8(1·1)**	**5·6(4·2)**	**4·9(3·1)**	**6·4(4·1)**	**5·7(3·3)**
20–40	−0·1(−0·2)	−0·5(−0·5)	−0·1(−0·3)	−0·4(−0·5)	−0·1(−0·4)	−0·4(−0·6)	0·3(−0·1)	0·3(0·1)
40–60	−0·2(−0·2)	0·1(0·0)	−0·1(−0·4)	0·0(−0·3)	−0·4(−0·6)	−0·1(−0·5)	−0·2(−0·5)	0·1(−0·1)
60–80	−0·2(0·1)	−0·3(0·2)	0·1(−0·2)	−0·1(−0·2)	−0·1(0·0)	−0·2(−0·1)	−0·3(−0·4)	0·0(0·3)
80–100	0·0(0·2)	0·0(0·1)	−0·1(−0·1)	0·1(0·2)	−0·1(−0·3)	−0·3(−0·4)	−0·1(−0·5)	0·1(0·2)
100–120	−0·2(0·0)	0·2(−0·1)	0·1(0·3)	−0·1(0·1)	0·1(0·3)	0·0(0·1)	−0·4(−0·1)	0·0(−0·2)
120–140	0·1(−0·4)	0·1(0·1)	0·0(0·2)	0·0(0·1)	0·0(−0·2)	−0·1(0·2)	0·2(0·2)	0·1(−0·3)
140–160	0·0(−0·2)	−0·4(−0·2)	−0·1(0·1)	−0·1(0·1)	−0·1(0·1)	−0·2(0·1)	0·1(0·0)	0·1(0·1)

Significant changes are bold, and negative values represent soil water content decreases. Values out of parenthesis are the differences between soil water at the first measurement after precipitation and that before precipitation, and the ones in parenthesis are the differences between soil water at the second measurement after precipitation and that before precipitation.
JO: jujube orchard.

Table III. (Continued)

Soil depth (cm)	Scenario 3				Scenario 4			
	3-year JO	8-year JO	Grass	Fallow	3-year JO	8-year JO	Grass	Fallow
0–20	**5·1(1·0)**	**5·1**(−0·8)	**7·9(1·7)**	**5·7**(0·1)	**6·6(2·5)**	**7·6(2·4)**	**5·9(0·6)**	**6·2(1·9)**
20–40	**4·1(8·9)**	**4·4(10·9)**	**5·6(12·2)**	**3·9(9·2)**	**4·7(2·7)**	**5·6(3·4)**	**2·7(1·4)**	**5·0(2·1)**
40–60	**2·0(6·6)**	**1·6(4·8)**	**2·6(7·5)**	**2·9(5·7)**	**4·1(3·3)**	**4·1(4·3)**	**3·9(3·0)**	**5·2(4·6)**
60–80	0·4(**2·1**)	0·1(0·2)	0·2(**0·5**)	0·1(**0·6**)	**5·1(4·9)**	**4·8(6·7)**	**3·6(4·1)**	**5·8(6·3)**
80–100	0·3(−0·1)	−0·1(0·0)	0·0(0·2)	0·1(−0·1)	**5·4(5·8)**	**4·4(6·6)**	**3·2(4·6)**	**6·2(7·2)**
100–120	**0·5**(0·1)	0·0(−0·3)	0·1(−0·1)	0·3(0·1)	**5·4(6·0)**	**3·8(6·4)**	**4·1(5·6)**	**6·1(7·3)**
120–140	0·1(−0·2)	0·1(−0·1)	0·2(0·1)	0·1(0·1)	**5·4(6·2)**	**2·0(6·1)**	**4·2(5·6)**	**4·8(6·5)**
140–160	0·1(−0·4)	−0·2(−0·3)	0·3(−0·1)	0·2(−0·3)	**3·9(5·2)**	**1·1(5·6)**	**3·9(5·4)**	**2·7(5·4)**

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the finite water resources in these areas, to respond effectively to existing and new emerging challenges.

Because cropland could induce severer soil erosion and land degradation, other land uses in terms of artificial forest (e.g. jujube orchards in our site) and natural rehabilitation (e.g. fallow and grassland in our site) have been suggested to replace cultivated land in the Loess Plateau (Tang, 2004). However, artificial forest (3-year-old and 8-year-old jujube) could cause soil drying (Table II) when no other water resources than precipitation is supplied. If this situation continues, 'low-thin-old trees' and further land degradation will probably occur. To be contrasted, soil water increased in natural rehabilitation land (fallow and grass land; Table III), which was good for sustainable development. This is probably because of the deposition of fine soil particles during vegetation restoration (Table I), which leads to an increase of the water-holding capability of soils. For most areas of the Loess Plateau, natural rehabilitation may be the best avenue to improve the degraded ecology of the Loess Plateau because of the relatively high cost of micro-irrigation over hillslopes. On the other hand, for our study site, irrigation at the key seasons of water requirement of jujube is expected to avoid vegetation and soil degradation. In particular, soil water has been shown as a reasonable indicator for regulated deficit irrigation in pear/jujube orchards (Cui *et al*., 2008). Our findings indicated that surface soil water and profile soil water exhibited relatively low values ($<$15 per cent) in different land uses from middle June to late July (Figure 3a, b) over the study period. During this period, the availability of soil water content was low. Meanwhile, a large amount of evapotranspiration existed in June and July in this area (Wu *et al*., 2008). Thus, an irrigation scheme must be worked out to meet water requirement of jujube based on soil water content and evapotranspiration. Moreover, a detailed irrigation scheme should be based on detailed information of soil water distribution (Starr *et al*., 2008). Because intensive soil water measurements are time-consuming and laborious, a better soil water monitoring scheme could be achieved via examining the relationship between spatial variability and spatial means of soil water content (Pan and Peters-Lidard, 2008). Our findings showed that the spatial distribution of soil water was most variable when mean water content was intermediate (approximately 20 per cent; Figure 4). This implies that we should increase the intensity of soil water samplings to acquire a good knowledge of soil water distributions during mean soil water was moderate (e.g. from 1 May to 1 June 2011 for surface soil water in Figure 3a). In addition, detailed knowledge of spatial soil water variability is also necessary for precision irrigation due to finite water resources in hillslope land. Effective site-specific management of soil water through irrigation is possible, provided an adequate yield response can be demonstrated and the zones of management are comparable in size to the correlation distance of soil water variability (Starr, 2005). Hence, the relationship between jujube yields and soil water as well as irrigation and soil water variability in jujube orchards should be investigated to determine whether or not to perform precision irrigation in this area. In any case, the economic cost of land and agricultural water management should be taken into consideration to make an advisable decision.

CONCLUSIONS

We have studied temporal and vertical variations of soil water profiles for different land uses in a small catchment of the Chinese Loess Plateau based on intensive soil water measurements from 17 August to 19 October 2009 and from 4 April to 27 September 2010. Soil water profiles under different land use that changed with precipitation, soil water in surface, and root zone horizons were driest during summer (from late June to late July 2010), and soil water lag was observed in the root zone and deep soil horizon. In particular, land use can lead to spatial variations of soil water but has negligible effect on soil water temporal patterns. An upward convex relationship existed between mean water content and SD, and soil water was most variable at approximately 20 per cent. Furthermore, the relation of SD to mean water content was dependent on soil depth, whereas land use showed negligible effects on this relationship. Vertical soil water profiles showed seasonal patterns for different land uses. Cropland vertical moisture profiles behaved differently to that of the other land uses, with relatively low soil water in the surface but high in the deep horizon. Moreover, a positive correlation exists between precipitation and infiltration depth for all land uses, and vertical soil water changes over 0–160 cm were observed following an extreme-high rainfall event (93·5 mm). The results presented here can provide insight into land and agricultural water management.

ACKNOWLEDGEMENTS

We would like to thank Heping Liu for his assistance with daily routines and experiments during the study period. We also would like to thank Dr Liusan Cheng for help with soil water measurements. Special thanks to Dr Monika Walter for her generous work to improve the manuscript. This work was jointly supported by the Special Foundation of National Science & Technology Supporting Plan (grant No. 2011BAD29B09), the National Natural Science Foundation of China (31172039), the Supporting Project for Young Technology Nova of Shaanxi Province (grant No. 2010KJXX-04), and the Supporting Plan for Young Elites of Northwest A & F University.

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