*Pedosphere* **25**(4): 546–554, 2015
ISSN 1002-0160/CN 32-1315/P

Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

# Characteristics of Dried Soil Layers Under Apple Orchards of Different Ages and Their Applications in Soil Water Managements on the Loess Plateau of China

WANG Yunqiang[1,2,*], SHAO Mingan[3], LIU Zhipeng[2] and ZHANG Chencheng[2]

[1] *State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061 (China)*
[2] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling 712100 (China)*
[3] *Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101 (China)*

(Received August 18, 2014; revised March 20, 2015)

## ABSTRACT

Negative soil water balance (*i.e.*, water input < water output) can lead to soil desiccation and subsequently the occurrence of a dried soil layer (DSL). The DSLs are generally studied at a specific sampling depth (*e.g.*, 500 cm), and the actual extent of DSLs remains unknown due to the challenge of collecting deep soil samples. To investigate the characteristics of actual DSLs under different ages of apple orchards and ascertain the optimal age of apple orchards for avoiding/controlling the formation of DSLs, soil samples were collected to a depth of 1 800 cm under apple orchards of different ages in Changwu on the Loess Plateau of China. As the ages increased, soil water content (SWC) and mean SWC in DSLs showed an overall decreasing trend, whereas while DSL thickness and the quantity of water deficit (QWD) in DSLs demonstrated an increasing trend. The DSL was the thickest (1 600 cm) under the 17-year-old orchard, the forming velocity of DSL thickness was the highest at the apple tree growth stage of 9–17 years (168 cm year$^{-1}$), and the highest increasing velocity of QWD ($-181$ mm year$^{-1}$) was also observed at this stage. The thickness of DSL was significantly correlated with growth age and root depth of apple trees ($r > 0.88$), whereas the QWD and mean SWC in DSLs were found to have no correlation with them. The optimal age of apple orchards for avoiding/controlling the formation of DSLs was about 9 years. This information provided pertinent references for the management of deep water resources by controlling the growth age of plants.

*Key Words*: deep soil, growth age, plant roots, soil desiccation, soil water content, soil-plant water relation

**Citation:** Wang Y Q, Shao M A, Liu Z P, Zhang C C. 2015. Characteristics of dried soil layers under apple orchards of different ages and their applications in soil water managements on the Loess Plateau of China. *Pedosphere*. **25**(4): 546–554.

Global warming is generally projected to continue (Brown, 2002), which is expected to increase evapotranspiration and decrease soil moisture (Zavaleta *et al.*, 2003). Excessive extraction by plants and less rainfall also cause a further decline in soil moisture (Wang *et al.*, 2011). A serious decrease in soil moisture will lead to soil desiccation and ultimately to the formation of a dried soil layer (DSL) in soil profile (Li, 1983). The presence of DSLs negatively affect terrestrial ecosystems by 1) changing the processes of water cycles in the soil-vegetation-atmosphere transfer system and thus decreasing the grain yield of the following crops (Chen *et al.*, 2008a), 2) provoking regional carbon emissions, which stored in the biotic pool, by increasing forest flammability and tree mortality (Nepstad *et al.*, 2004), and 3) decreasing productivity of the second and later rotations of plantations (Bai *et al.*, 2006; Mendham *et al.*, 2011).

Because of the negative effects of DSLs, more and more attentions have been paid to the assessment of DSL formation, variation, and related factors at a series of spatial and temporal scales (Shangguan, 2007; Chen *et al.*, 2008a; Wang *et al.*, 2008a; Yang *et al.*, 2012). Some authors have further considered the possibility of recovering DSLs from different land-use types, such as orchards (Huang and Gallichand, 2006), farmland (Wang *et al.*, 2008b), and grassland (Liu *et al.*, 2010). Li and Huang (2008) investigated the dynamics and depletion of soil water at different stages of alfalfa (*Medicago sativa*) growth. Wang *et al.* (2012) studied the development and recovery of soil desiccation based on a set of long-term experimental data. These studies have enriched our understanding of the time dependence of DSLs.

*Corresponding author. E-mail: wangyunq04@163.com.

However, most of these achievements are based on specific sampling depths, which are generally < 500 cm (Schume *et al.*, 2004; Huang *et al.*, 2005; Li *et al.*, 2008; Yao *et al.*, 2012), because of the technological, methodological, and temporal challenges of collecting deep soil samples. The data obtained thus far does not fully represent the actual DSLs.

In practice, depending to a large extent on plant type and root characteristics, the depths of DSLs can extend to 1 000 cm or more (Li *et al.*, 2008; Li and Huang, 2008). Wang *et al.* (2009) reported that the depths of depletion of soil water by the root systems of planted alfalfa (*Medicago sativa*), caragana (*Caragana korshinskii*), and pine (*Pinus tabulaeformis*) on the Loess Plateau of China can reach 1 550, 2 240, and 2 150 cm, respectively. Wang *et al.* (2013) found that, in 21-m soil profiles, the distribution pattern and quantity of soil water content (SWC) in the root zone are significantly influenced by land use and plant characteristics, but that soil texture became a more important factor below the root zone. These studies of deep soil, however, still do not include calculations of actual DSL values. Information on actual DSLs is lacking, and is increasingly needed for a more integral understanding of DSL status and for practical eco-hydrological applications.

The gully region of the Loess Plateau of China is well known for its deep loess-paleosol deposits and unique landscape (Li *et al.*, 2005). Prior to the 1980s, the favourable climate, soil, and topographic conditions in this region were found to be suitable for producing high-quality apples. The high income available from apple production leads to the conversion of at least 60% of all arable land in this area to apple orchards by local farmers (Huang and Gallichand, 2006). Compared with cropland having similar environmental conditions, apple orchards increase the evapotranspiration rates and decrease the available soil water. Ascertaining the relationship between actual DSLs and growth age is thus necessary not only for local farmers to improve land-use efficiency but also for understanding the dynamic evolutionary mechanisms of DSLs over time.

Therefore, the objectives of this study were to investigate the characteristics of actual DSLs under apple orchards of different ages by collecting soil samples to a depth of 1 800 cm on the Loess Plateau, and then ascertain the optimal age of apple orchards for avoiding/controlling the formation of DSLs. It was hypothesized that, with the increase of growth age, DSLs *i.e.*, became worse and worse, but an optimal age of apple orchards (*i.e.*, DSL is reclaimable) still existed.

## MATERIALS AND METHODS

### *Study area*

An experiment was performed at the Changwu Agro-ecological Experimental Station on the Loess Plateau, Chinese Academy of Sciences, in Wangdonggou Watershed, Shaanxi Province, China (Fig. 1). The station is located in the gully regions of the southern Loess Plateau of China and in the middle reaches of the Yellow River. The area is flat with an elevation of 1 200

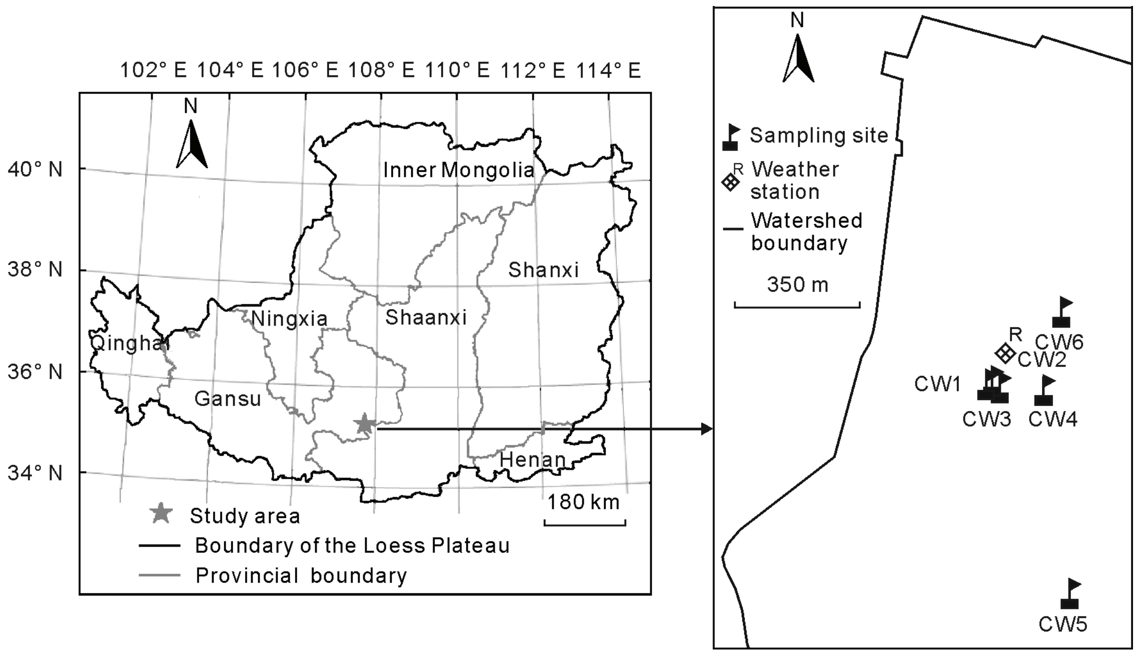


Fig. 1 Location of the study area, Wangdonggou Watershed on the Loess Plateau of China and distribution of the sampling sites. CW1–CW6 are the sampling site codes, corresponding to farmland, 5-, 9-, 17-, 22- and 26-year-old apple orchards, respectively.

m above mean sea level. The climate is semi-humid with an average annual precipitation of 560 mm (1985–2008), 70% of which falls in June–September. The average annual temperature is 9.1 °C, the average frost-free period is 194 $d^{-1}$ $year^{-1}$, and the average annual solar radiation is 5 266 MJ $m^{-2}$. The average annual pan evaporation is 1 358 mm (1985–2008), which is about two times higher than precipitation. The daily precipitation and temperature from 1985 (when the apple trees were first planted up) to 2011 are as shown in Fig. 2.

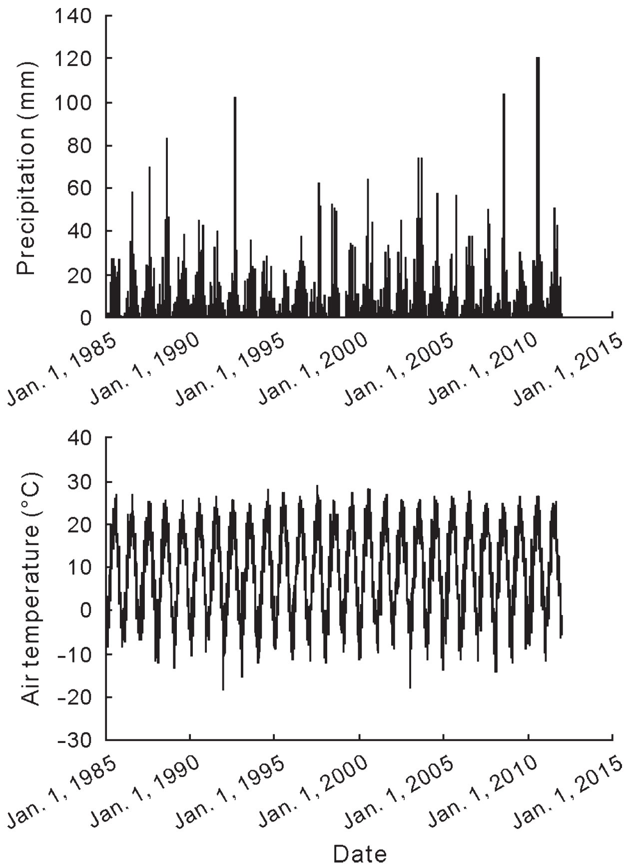


Fig. 2 Changes in daily precipitation and mean daily air temperature in Changwu on the Loess Plateau of China in 1985–2011.

*Experiment design and soil sampling*

In 2011, five representative apple orchards (the area of each orchard was greater than 50 m × 50 m) were chosen, in which apple trees were planted in 2006, 2002, 1994, 1989, and 1985, corresponding to 5, 9, 17, 22, and 26-year-old trees, respectively (Fig. 1). A region of permanent farmland cropped with wheat was also selected as a representative of the initial status of soil water. All the five apple orchards and the farmland were rainfed and managed by local farmers with conventional farming. The groundwater level is about 60 m below the soil surface, which precludes any upward capillary flow into the root zone. The distances between any two sites of apple trees were small (< 500 m), keeping comparable topographic conditions (*i.e.*, slope aspect, gradient, *etc.*).

At the center of each orchard, a sampling site was selected, which was 1 m away from the trunk of representative apple tree, and soil and root samples were both collected with soil auger (10 cm in diameter) at 10, 20, and 50 cm intervals from 0 to 20 cm, 20 to 600 cm, and 600 to 1 800 cm soil layers, respectively. The intervals were shortened to 25 cm for the 600–1 800 cm soil layer when measuring SWC, which was generally more vertically heterogeneous than other soil properties, *e.g.*, soil organic carbon (SOC) and soil texture.

*Laboratory analysis and data preparation*

Gravimetric SWC was determined from the loss in mass after oven drying to constant mass at 105 °C. Soil particle composition was measured by the laser diffraction method using a Master sizer 2000 (Malvern Instruments Ltd., Melvin, UK). The content of SOC was measured using the dichromate oxidation method.

Samples of plant roots were carefully washed to remove all soil attached to the roots. Roots were briefly dried on absorbent papers before weighing to determine the fresh root mass. The bulk density (BD) and the SWC at field capacity (FC, soil water content at −0.03 MPa) (Jipp *et al.*, 1998) along the soil profiles were not directly measured due to the practical challenge of collecting large numbers of undisturbed soil cores from deep soil profiles. Instead, the values for BD and FC were indirectly derived from the measured SOC and soil particle composition by introducing pedotransfer functions (PTFs). A representative PTF for predicting BD and FC was selected from a list of five established PTFs and validated with 382 local data sets from the Loess Plateau of China. The detailed processes of selecting a representative PTF are described in Wang *et al.* (2013). The SWC at stable field capacity (SFC) was calculated from FC (SFC = FC × 70%).

After the values of SWC, BD and FC were obtained, some evaluation indices of soil water condition were calculated. Thickness of DSLs (cm) at each sampling site was calculated using the following equations:

$$\text{Thickness of DSLs} = T_j \times \sum_{j=11}^{N} F(\text{SWC}_j - \text{SFC}_j) \quad (1)$$

$$F(\text{SWC}_j - \text{SFC}_j) = \begin{cases} 0, & \text{SWC}_j - \text{SFC}_j > 0 \\ 1, & \text{SWC}_j - \text{SFC}_j \leq 0 \end{cases} \quad (j = 11, 12, 13, \cdots, N) \quad (2)$$

where $T_j$ is the thickness of the $j$th soil sampling layer (cm); $SWC_j$ is the SWC of the $j$th layer at each site (g $kg^{-1}$); $SFC_j$ is the SFC of the $j$th layer at each site (g $kg^{-1}$); $N$ is the number of sampled soil layers or soil depths; and $F$ is the function of ($SWC_j - SFC_j$). The annual average infiltration depth of the study area is about 200 cm, which corresponds to $j = 10$; therefore, we only analysed the DSL for soil layers below 200 cm in Changwu.

Mean SWC and quantity of water deficit (QWD) in DSLs (g $kg^{-1}$) at each sampling site were calculated in Eqs. 3–4:

$$\text{Mean SWC in DSLs} = \frac{1}{n}\sum_{j=11}^{N} \text{SWC}_j \quad (\text{if } \text{SWC}_j - \text{SFC}_j \leq 0,\ \ j = 11, 12, 13, \cdots N) \tag{3}$$

$$\text{QWD in DSLs} = \sum_{j=1}^{N} (\text{SFC}_j - \text{SWC}_j) \times \text{BD}_j \times T_j \quad (\text{if } \text{SWC}_j - \text{SFC}_j \leq 0,\ \ j = 11, 12, 13, \cdots, N) \tag{4}$$

where $BD_j$ is the soil bulk density of the $j$th layer at each site (g $cm^{-3}$) and $n$ is the number of soil samples in the DSL ($n < N$).

## RESULTS AND DISCUSSION

### *Overall characteristics of soil properties along the soil profile*

Mean SWCs under the five apple orchards decreased in the following order: 5 years (186 g $kg^{-1}$) > 9 years (173 g $kg^{-1}$) > 22 years (140 g $kg^{-1}$) > 26 years (132 g $kg^{-1}$) > 17 years (122 g $kg^{-1}$) (Table I). The mean SWC (163 g $kg^{-1}$) under farmland was lower than that under apple orchards of 5 and 9 years, which might be caused by the relative higher evapotranspiration in farmland than that at the initial growth stage of apple orchards and other factors except for land use, for instance, the distance of the locations to the gully. The coefficients of variation (CVs) of SWCs at the five sites had small ranges, varying from 11% to 14%, indicating a weak variation of soil water along the soil profiles. The SWCs at different growth ages of apple orchards differed both in the vertical distribution patterns and in the quantity of soil water though the vertical distributions of soil particle composition demonstrated a similar pattern (Fig. 3).

Overall, with increasing growth age, mean SWC firstly decreased and then increased. The lowest value of mean SWC in the apple orchards were 122 g $kg^{-1}$, corresponding to the 17-year-old orchard. After that, the SWC slightly increased but was still smaller than its initial status (permanent farmland). Meanwhile, the greatest difference in SWC between the 5- and 17-year-old apple orchards was also observed at depths from 250 to 1 100 cm (Fig. 3), which might be attributed to the depth and capacity of plant water uptake. Root analysis showed that the root depths of the 5- and 17-year-old apple trees had reached 580 and 1 550 cm, respectively, implying that deep soil water (*i.e.*, below 1 000 cm) could also be extracted and utilized by deep-rooted plants; this process may shape the pattern of deep SWC distribution.

The selected sampling sites with different growth ages had similar natural elements (*e.g.*, topography and climate), farm management (*e.g.*, fertilization and branching), close proximity (Fig. 1), and vertical patterns of soil particle composition (Fig. 3). The differences in plant growth ages, leading to different capabilities in the uptake water by roots, photosynthesis, and yield of apples, can thus be deemed as the dominant driving force for the different patterns of soil water in deep profiles. Meanwhile, it should be noted that the distance of the 6 sites to the gully may be a possible factor affecting the soil water balance and thus may change, to some extent, the regime of SWC in deep profile.

TABLE I

Basic statistics of soil water content at the 6 soil sampling sites under apple orchards of different growth ages and a permanent farmland cropped with wheat in Changwu on the Loess Plateau of China

| Site code | Growth age | Vegetative type | Land use | Sampling depth | Sampling date | $n$ | Minimum | Maximum | Mean | CV[a)] | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Years | | | m | | | g $kg^{-1}$ | | | % | | |
| CW1 | | Wheat | Farmland | 18 | Aug. 9, 2011 | 79 | 91 | 221 | 163 | 17 | −0.479 | −0.224 |
| CW2 | 5 | Apple | Orchard | 18 | Aug. 10, 2011 | 79 | 118 | 231 | 186 | 12 | −0.410 | 0.000 |
| CW3 | 9 | Apple | Orchard | 18 | Aug. 11, 2011 | 79 | 142 | 233 | 173 | 11 | 0.884 | 1.004 |
| CW4 | 17 | Apple | Orchard | 18 | Aug. 17, 2011 | 79 | 88 | 160 | 122 | 14 | 0.470 | −0.311 |
| CW5 | 22 | Apple | Orchard | 18 | Aug. 15, 2011 | 79 | 111 | 193 | 140 | 14 | 0.704 | −0.193 |
| CW6 | 26 | Apple | Orchard | 18 | Aug. 13, 2011 | 79 | 107 | 172 | 132 | 12 | 0.573 | −0.174 |

[a)] Coefficient of variation.

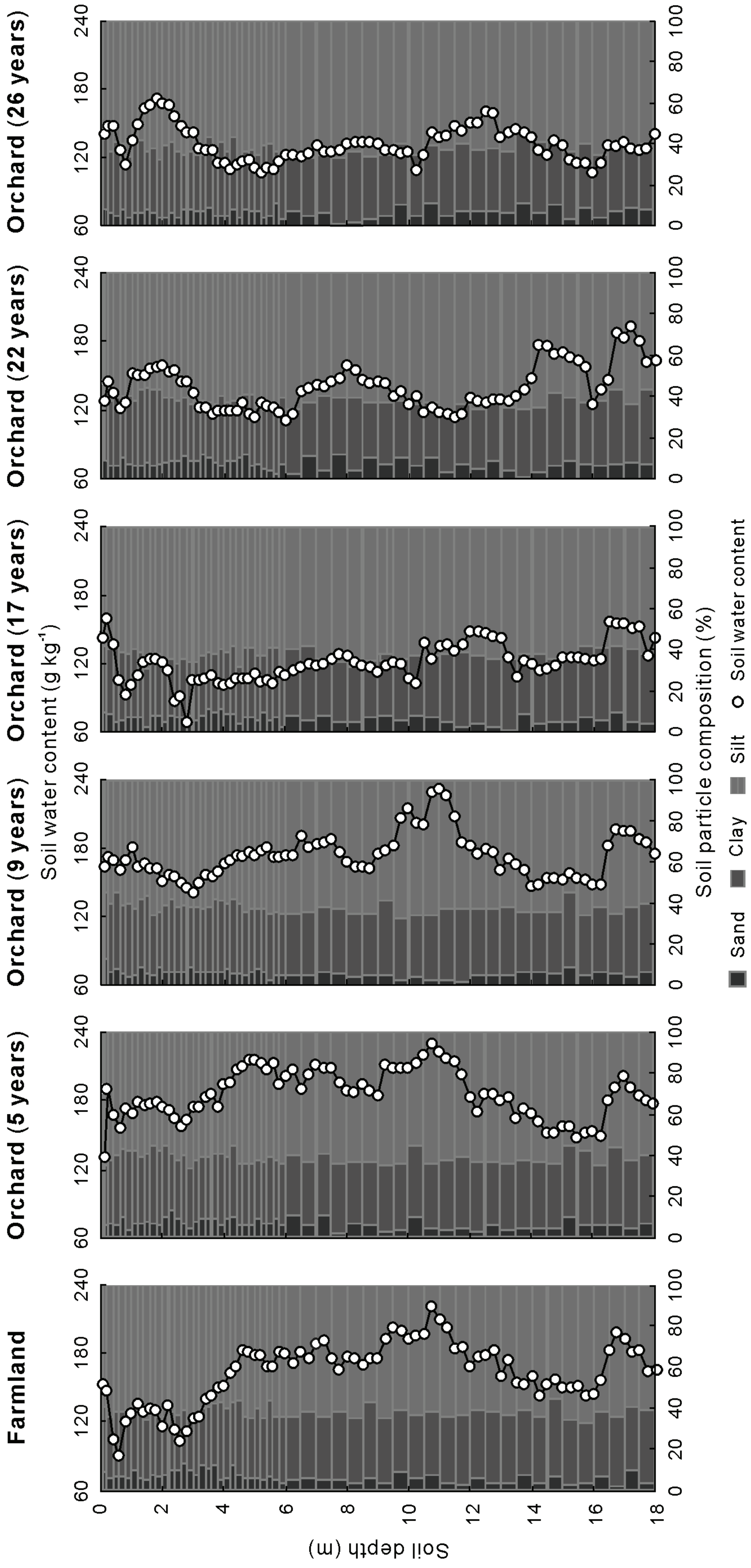


Fig. 3 Vertical distribution of soil water content and particle composition along the 0–18 m soil profile in the apple orchards of different growth ages and farmland in Changwu on the Loess Plateau of China.

*Changes in dried soil layers with growth ages*

After calculating BD and FC for each soil sample by using the corresponding PTFs (Wang *et al.* 2013), the vertical distributions of SFC were obtained (Fig. 4). The characteristics of actual DSLs could be quantitatively evaluated since the sampling depths (1 800 cm) were generally sufficient (based on the distribution of root depths) to determine the lower boundary of the DSL.

Fig. 4 shows the vertical distributions of SWC, S-FC and plant root weights at the 6 sampling sites in Changwu. The thickness of DSLs was very thin under the 5-year-old orchard because of the low evapotranspiration in these young apple trees. With an increase of growth age, the DSL under the 9-year-old orchard increased to a thickness of 260 cm and then rapidly extended downward to a maximum thickness of 1 600 cm, which corresponded to the 17-year-old orchard (Table II). A DSL had also notably formed in the farmland due to the high yield of wheat, in accordance with the results of Chen *et al.* (2008b).

TABLE II

Some indices[a)] of dried soil layers (DSLs) in the apple orchards of different growth ages in Changwu on the Loess Plateau of China

| Site code | Growth age | Root depth | DSL | | | |
|---|---|---|---|---|---|---|
| | | | Thickness | QWD | Mean SWC | $V$ |
| | years | ——— cm ——— | | mm | g kg$^{-1}$ | cm year$^{-1}$ |
| CW2 | 5 | 580 | 170 | 33 | 146 | – |
| CW3 | 9 | 850 | 260 | 26 | 153 | 23 |
| CW4 | 17 | 1 550 | 1 600 | 906 | 118 | 168 |
| CW5 | 22 | 1 700 | 1 210 | 464 | 132 | – |
| CW6 | 26 | 1 800 | 1 510 | 656 | 128 | 75 |

a) QWD = quantity of water deficit; SWC = soil water content; $V$ = forming velocity.

The data on the forming velocity ($V$) of DSL showed that at the apple tree growth stages of 5–9, 9–17, 17–22, and 22–26 years, the forming velocity of DSL was the highest for the period from 9 to 17 years (168 cm year$^{-1}$) and the lowest for the period from 5 to 9 years (23 cm year$^{-1}$) (Table II), indicating that the forming velocity of DSL varied with the growth stage of apple trees.

The lowest value of mean SWC in DSLs was 118 g kg$^{-1}$ in the 17-year-old orchard. Meanwhile, the QWD in DSLs data indicated that the most deficit quantity of soil water in the DSLs was 906 mm in the 17-year-old orchard, and the highest increasing velocity of QWD occurred at the growth stage of 9–17 years (181 mm year$^{-1}$), implying that the 17-year-old apple tree required more water and time than the other apple trees to restore moisture to the DSL.

According to the forming velocity of DSL and the increasing velocity of QWD, we can infer that the optimal age of apple orchards for avoiding/controlling the formation of DSLs is about 9 years. Overall, Fig. 5 further demonstrated a trend of worsening DSLs (represented by the DSL thickness, mean SWC and QWD in DSLs) with increasing growth ages.

As ages increased, SWC in soil and mean SWC in dried soil layers showed an overall decreasing trend while the DSL thickness and QWD demonstrated an increasing trend, which verified our hypothesis that with the increasing of growth age, DSLs became worse and worse. The growth of the plants and the related ecohydrological processes substantially affect the severity of the DSLs.

Long-term climatic change, indicated by lower rainfall and higher air temperatures on the Loess Plateau of China, strongly aggravates the scarcity of soil water (Wang *et al.*, 2011). Seasonal droughts may lead to temporary DSLs, but this type of DSL can generally be restored by rainfall in the rainy season (Li, 1983). Temporary DSLs may also occur in regions with deep soil and be characterized by large seasonal variations in rainfall, such as in the Brazilian Amazon (Markewitz *et al.*, 2010) and in southern Australia (Mendham *et al.*, 2011), but these DSLs require further study.

The longevity of apple trees able to sustain a certain yield is usually about 30 years (trees older than 30 years are often cut), whereas the distribution of the formed DSLs may endure longer, generally exceeding 40 years (including recovery time). Using a one-dimensional simulation model known as simultaneous heat and water transfer, Huang and Gallichand (2006) reported that after the conversion of orchards to winter wheat, the recovery time of the soil water required 6.5–19.5 years, with an average of 13.7 years for the 0–1 000 cm soil profile. If apple orchards are not converted to cropland but are replanted with young apple trees, the DSL will never be reclaimed, and the yield of the "new orchard" will fluctuate closely with the annual rainfall.

*Relationships between DSL indices and growth age*

Pearson correlation analysis showed that the DSL thickness was positively correlated with growth age ($r$ = 0.882, $P < 0.05$) and root depth ($r$ = 0.945, $P < 0.05$) of apple trees, whereas the QWD and mean SWC in DSLs were not significantly correlated with either growth age or root depth (Table III). Growth age and root depth were positively correlated ($r$ = 0.978, $P < 0.01$), which could be expected because the roots

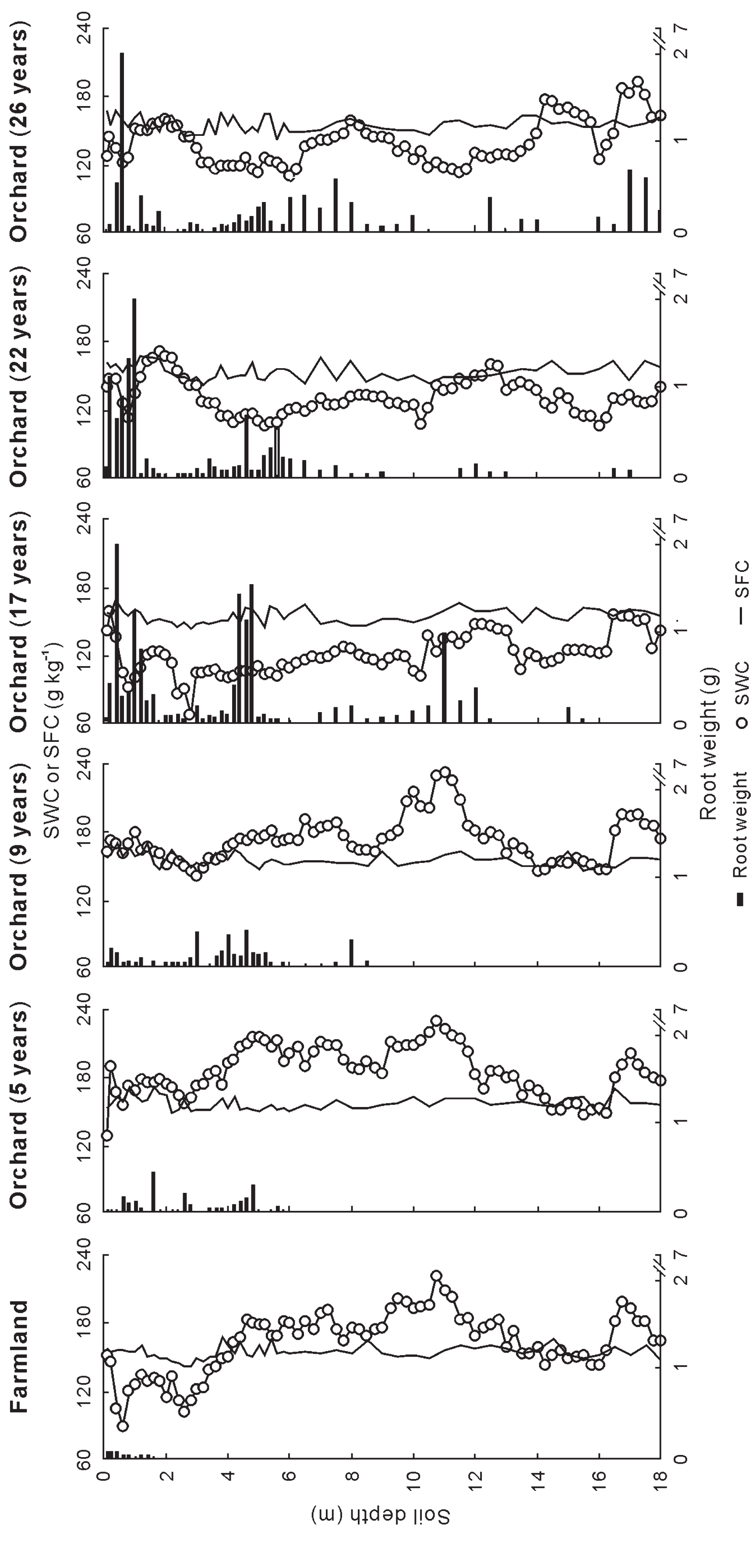


Fig. 4 Vertical distribution of soil water content (SWC), stable field capacity (SFC), and plant root weight along the 0–18 m soil profile in the apple orchards of different growth ages and farmland in Changwu on the Loess Plateau of China.

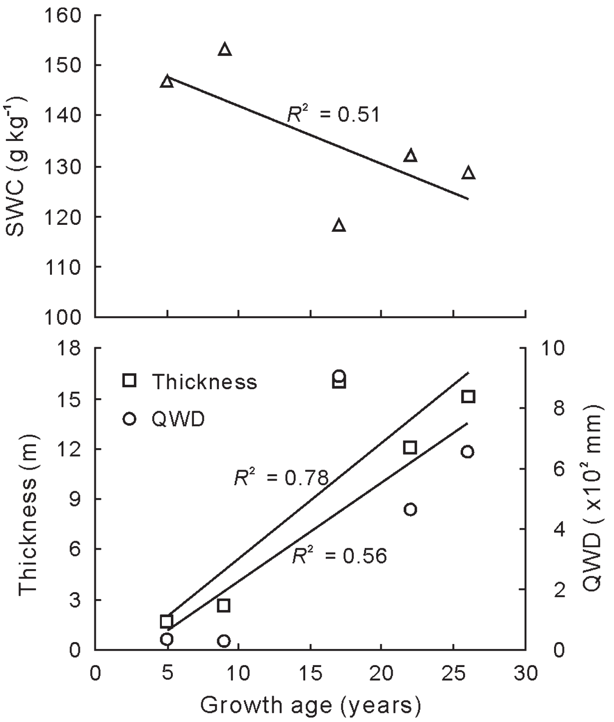


Fig. 5 Changes in the dried soil layer thickness, mean soil water content (SWC), and quantity of water deficit (QWD) along the 0–18 m soil profile with increasing growth ages of apple orchards in Changwu on the Loess Plateau of China.

continue to search for water stored in deep soil in water-limited regions under the driving force of plant growth and, originally, solar radiation.

Plant roots play a key role in the development of DSLs. Their distribution depths and patterns effectively determined the thickness of DSLs and the SWCs in the profile (Table III). The extent of DSLs was closely associated with the distribution of plant roots and varied with the type and age of the vegetation. Formed DSLs, though, can in turn affect the uptake of water by roots and thus the growth of the plants and the yields (Yan *et al.*, 2007). An awareness of the depth of roots is very important for understanding the relationship between plant growth and DSL dynamics.

In summary, the plant-soil-environment is a mutually interacting system with interfaces at the plant roots and the land surface. The occurrence of DSLs is a comprehensive phenomenon caused by the negative water balance between decreasing inputs and increasing outputs (Li, 1983; Wang *et al.*, 2008a; Wang *et al.*, 2011). The nature and extent of DSLs can serve as indicators for evaluating the processes of soil desiccation and the status of soil water and can reflect the dynamics of plant growth and the functional status of roots near DSLs for different ages of plants (Figs. 4 and 5). DSLs have yet to be systematically studied at a necessary level (Shangguan, 2007; Chen *et al.*, 2008b), but our results provide an evidence for relationships among DSL indices, plant roots, and growth ages of plants, and also provide new information and implications for the restoration and management of soil water and DSLs at different stages of plant growth on the Loess Plateau of China, and possibly in other arid and semiarid regions around the world. Adequate attention should be paid to the mechanisms of formation, restoration, and eco-hydrological effects of actual DSLs because they may directly or indirectly affect related physical, chemical, and biological processes in terrestrial ecosystems at both site and regional scales.

## CONCLUSIONS

The characteristics of dried soil layers under apple orchards of different growth ages showed that the changes in mean water content in the soil and dried soil layer with growth age generally showed a similar decreasing trend, while the thickness and the quantity of water deficit in dried soil layers indicated a similar increasing trend. The dried soil layer under the 17-year-old orchard was the thickest and was positively correlated with the growth age and root depth of apple trees, whereas the quantity of water deficit and mean

TABLE III

Pearson correlation coefficients between some indices[a)] of the dried soil layer (DSL) and the growth ages and root depths of apple trees in Changwu on the Loess Plateau of China.

| Item | Index | DSL | | | Apple tree | |
|---|---|---|---|---|---|---|
| | | Thickness | QWD | Mean SWC | Growth age | Root depth |
| DSL | Thickness | 1.000 | | | | |
| | QWD | 0.972** | 1.000 | | | |
| | SWC | −0.953* | −0.984** | 1.000 | | |
| Apple tree | Growth age | 0.882* | 0.747 | −0.715 | 1.000 | |
| | Root depth | 0.945* | 0.843 | −0.816 | 0.978** | 1.000 |

*, ** Significant at $P < 0.05$ and $P < 0.01$, respectively.
[a)]QWD = quantity of water deficit; SWC = soil water content.

soil water content in dried soil layers had no significant correlation with either the growth age or the root depth of apple trees. The 9- to 17-year-old appleorchards had both the highest forming velocity of dried soil layers and the largest increasing velocity of quantity of water deficit in the dried soil layers; so this period was vital for maintaining the buffering capacity of the pool of deep soil water and for avoiding the deterioration of soil through desiccation. The optimal age of apple orchards for avoiding/controlling the formation of dried soil layers was about 9 years.

## ACKNOWLEDGEMENTS

This study was supported by the National Natural Science Foundation of China (No. 41471189), the Youth Science and Technology New Star Foundation of Shaanxi Province, China (No. 2013KJXX-09), the CAS "Light of West China" Program, and the Youth Innovation Promotion Association CAS. We thank the Changwu Agro-ecological Experimental Station on the Loess Plateau, Chinese Academy of Sciences, for providing help in soil sampling, and the Ecological Environmental Database of Loess Plateau of China for providing topographic data. Thanks also to Mrs. LIU Yong-Gang, LU Xiao-Hui, and LU Run-An, Yangling, China for their field assistance.

## REFERENCES

Bai L P, Sui F G, Ge T D, Sun Z H, Lu Y Y, Zhou G S. 2006. Effect of soil drought stress on leaf water status, membrane permeability and enzymatic antioxidant system of maize. *Pedosphere*. **16**: 326–332.

Brown K. 2002. Environmental data. Water scarcity: Forecasting the future with spotty data. *Science*. **297**: 926–927.

Chen H S, Shao M A, Li Y Y. 2008a. The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. *J Hydrol*. **360**: 242–251.

Chen H S, Shao M A, Li Y Y. 2008b. Soil desiccation in the Loess Plateau of China. *Geoderma*. **143**: 91–100.

Huang Y L, Chen L D, Fu B J, Zhang L P, Wang Y L. 2005. Evapotranspiration and soil moisture balance for vegetative restoration in a gully catchment on the Loess Plateau, China. *Pedosphere*. **15**: 509–517.

Huang M B, Gallichand J. 2006. Use of the SHAW model to assess soil water recovery after apple trees in the gully region of the Loess Plateau, China. *Agr Water Manage*. **85**: 67–76.

Jipp P H, Nepstad D C, Cassel D K, De Carvalho C R. 1998. Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry amazonia. *Climatic Change*. **39**: 395–412.

Li Y S. 1983. The properties of water cycle in soil and their effect on water cycle for land in the Loess Plateau. *Acta Ecol Sin* (in Chinese). **3**: 91–101.

Li J, Chen B, Li X F, Zhao Y J, Ciren Y J, Jiang B, Hu W, Cheng J M, Shao M A. 2008. Effects of deep soil desiccation on artificial forestlands in different vegetation zones on the Loess Plateau of China. *Acta Ecol Sin*. **28**: 1429–1445.

Li Y S, Huang M B. 2008. Pasture yield and soil water depletion of continuous growing alfalfa in the Loess Plateau of China. *Agr Ecosyst Environ*. **124**: 24–32.

Li Y Y, Shao M A, Zheng J Y, Zhang X C. 2005. Spatial-temporal changes of soil organic carbon during vegetation recovery at Ziwuling, China. *Pedosphere*. **15**: 601–610.

Liu W Z, Zhang X C, Dang T H, Ouyang Z, Li Z, Wang J, Wang R, Gao C Q. 2010. Soil water dynamics and deep soil recharge in a record wet year in the southern Loess Plateau of China. *Agr Water Manage*. **97**: 1133–1138.

Markewitz D, Devine S, Davidson E A, Brando P, Nepstad D C. 2010. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. *New Phytol*. **187**: 592–607.

Mendham D S, White D A, Battaglia M, McGrath J F, Short T M, Ogden G N, Kinal J. 2011. Soil water depletion and replenishment during first- and early second-rotation *Eucalyptus globulus* plantations with deep soil profiles. *Agr Forest Meteorol*. **151**: 1568–1579.

Nepstad D, Lefebvre P, Da Silva U L, Tomasella J, Schlesinger P, Solórzano L, Moutinho P, Ray D, Benito J G. 2004. Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. *Glob Change Biol*. **10**: 704–717.

Schume H, Jost G., Hager H. 2004. Soil water depletion and recharge patterns in mixed and pure forest stands of European beech and Norway spruce. *J Hydrol*. **289**: 258–274.

Shangguan Z P. 2007. Soil desiccation occurrence and its impact on forest vegetation in the Loess Plateau of China. *Int J Sust Dev World*. **14**: 299–306.

Wang L, Wang Q J, Wei S P, Shao M A, Li Y. 2008a. Soil desiccation for Loess soils on natural and regrown areas. *Forest Ecol Manag*. **255**: 2467–2477.

Wang X C, Li J, Tahir M N, Fang X Y. 2012. Validation of the EPIC model and its utilization to research the sustainable recovery of soil desiccation after alfalfa (*Medicago sativa* L.) by grain crop rotation system in the semi-humid region of the Loess Plateau. *Agr Ecosyst Environ*. **161**: 152–160.

Wang X L, Sun G J, Jia Y, Li F M, Xu J Z. 2008b. Crop yield and soil water restoration on 9-year-old alfalfa pasture in the semiarid Loess Plateau of China. *Agr Water Manage*. **95**: 190–198.

Wang Y Q, Shao M A, Liu Z P. 2013. Vertical distribution and influencing factors of soil water content within 21-m profile on the Chinese Loess Plateau. *Geoderma*. **193–194**: 300–310.

Wang Y Q, Shao M A, Zhu Y J, Liu Z P. 2011. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. *Agr Forest Meteorol*. **151**: 437–448.

Wang Z Q, Liu B Y, Liu G, Zhang Y X. 2009. Soil water depletion depth by planted vegetation on the Loess Plateau. *Sci China Ser D*. **52**: 835–842.

Yan J H, Zhou G Y, Zhang D Q, Chu G W. 2007. Changes of soil water, organic matter, and exchangeable cations along a forest successional gradient in southern China. *Pedosphere*. **17**: 397–405.

Yang L, Wei W, Chen L D, Mo B R. 2012. Response of deep soil moisture to land use and afforestation in the semi-arid Loess Plateau, China. *J Hydrol*. **475**: 111–122.

Yao X L, Fu B J, Lü Y H, Chang R Y, Wang S, Wang Y F, Su C H. 2012. The multi-scale spatial variance of soil moisture in the semi-arid Loess Plateau of China. *J Soil Sediment*. **12**: 694–703.

Zavaleta E S, Thomas B D, Chiariello N R, Asner G P, Shaw M R, Field C B. 2003. Plants reverse warming effect on ecosystem water balance. *P Natl Acad Sci USA*. **100**: 9892–9893.