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Changes of deep soil desiccation with plant growth age in the Chinese Loess Plateau

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Abstract

Negative water balance in soil can lead to soil desiccation and subsequent the formation of a dried soil layer (DSL). Essential progress on DSL temporal change has been hampered by difficulty in collecting deep soil water samples (i.e. > 1000 cm), which are necessary to quantify the real extent of DSL. We collected soil samples up to a depth of 1800 cm and investigated the evolution of soil water content (SWC) and DSL under three vegetation types (*C. korshinskii*, *R. pseudoacacia*, apple) in three zones (Ansai, Luochuan, and Changwu) of the Chinese Loess Plateau. As plant growth age increased, SWC, available soil water (ASW), SWC within DSL (DSL-SWC), and quantity of water deficit for DSL (DSL-QWD) showed similar change trends of decreasing at first and then increasing, whereas DSL thickness (DSLT) showed an increasing trend over time. A turning point in soil water change was found for the three vegetation types. In Changwu zone, the turning point, both in and out of DSL, was corresponded to the 17-year-old apple orchard. The period from 9 to 17 yr was vital to maintain the buffering function of deep soil water pool and to avoid the deterioration of soil desiccation because the highest mean decline velocity of ASW and the maximum mean forming velocity of DSLT were 165 mm yr^{-1} and 168 cm yr^{-1}, respectively. Significant correlations were found between DSLT and growth age and root depth, and between DSL-QWD and root depth, whereas mean DSL-SWC had no significant correlation with either growth year or root depth. Soil water condition was highly dependent on the growth year of the plants. This information provides pertinent reference for water resource management in the Chinese Loess Plateau and possibly in other water-limited regions in the world.

1 Introduction

Global warming is projected to occur continually as global climate change progresses (Breshears et al., 2005; Brown, 2002), which increases evapotranspiration and decreases soil moisture that may lead to increased aridity in water-limited systems around the world (Zavaleta et al., 2003). Serious decline in soil moisture, which can also be attributed to the excessive extraction of plants and the decreasing input of rainfall, can lead to soil desiccation (Li, 1983; Yang et al., 1999). Severe soil desiccation combined with the profile distribution characteristics of plant roots can cause the formation of a dried soil layer (DSL) on the soil profile at a certain soil depth (which is generally below the annual average infiltration depth) (Li, 1983; Yang et al., 1999; Wang et al., 2010b; Chen et al., 2008a).

DSL is a hydrological phenomenon in water-limited ecosystems. The range of soil water content (SWC) in DSL is generally from permanent wilting point (lower limit) to stable field capacity (SFC) (upper limit) (L. Wang et al., 2008; Yang, 2001; Li, 1983). About 50 % to 75 % of the field capacity, depending on the soil texture on the site, is considered SFC, and a soil layer with SWC lower than SFC can be deemed as DSL (Wang et al., 2004; Yang and Tian, 2004). Four indices can be used to quantify the extent of DSL: (1) DSL thickness (DSLT), (2) depth where DSL begins to form (DSL forming depth, DSLFD), (3) mean SWC over DSLT within the soil profile (soil water content within DSL, DSL-SWC), and (4) Quantity of water deficit in the DSL (DSL-QWD) (Y. Q. Wang et al., 2011, 2012).

The presence of DSL has a series of negative effects in terrestrial ecosystems such as (1) changing water cycle processes in soil-plant-atmosphere system, (2) provoking regional carbon emissions by increasing forest flammability and tree mortality, (3) decreasing crop yields by suppressing plant growth, and (4) affecting productivity of second and later rotation of plantations (Breshears et al., 2005; Nepstad et al., 2004; Mendham et al., 2011). Consequently, the quantitative assessment of DSL at a series of spatial and temporal scales and its recover in soil moisture has attracted much research attention (Yao et al., 2012; L. Wang et al., 2008, Y. Q. Wang et al., 2011, 2012; Huang and Gallichand, 2006; Li, 2001; Yang, 1996, 2001; Han et al., 1990; Chen et al., 2008b; Shangguan, 2007; Liu et al., 2010).

Many studies have reported that DSL is frequently found in arid and semi-arid regions; in particular, in the Loess Plateau of China (Chen et al., 2008a; X. Y. Li et al., 2008; Wang et al., 2010a). Great progress has been achieved in research on DSL formation, variation, and its related factors at the plot, slope, and watershed scales (Li, 2001; Yang, 1996, 2001; Han et al., 1990; L. Wang et al., 2008; Chen et al., 2008b; Shangguan, 2007). Recently, Wang et al. (2010a) investigated the spatial variability and distribution pattern of DSL across the entire Loess Plateau; further, they evaluated the effects of land use and plant characteristics on DSL at different climatic regions across the Plateau (Y. Q. Wang et al., 2011) and then developed a regional DSL prediction model for forestland (Wang et al., 2012). Moreover, Yao et al. (2012) examined the spatial variance of deep soil moisture at multiple scales in the semi-arid region of the Loess Plateau, and then discussed the relative importance of related factors and the dominant driver of soil desiccation.

Because of the negative effects of DSL as described above, some authors have also paid attention on the topic that the possibility of recovering DSL from different land use types, such as orchards (Huang and Gallichand, 2006), farmlands (X. L. Wang et al., 2008; X. C. Wang et al., 2011), and grasslands (Liu et al., 2010; X. L. Wang et al., 2008; X. C. Wang et al., 2011). This highly relates with the temporal change of DSL. Li and Huang (2008) investigated soil water dynamic and depletion at the different periods of alfalfa (*Medicago sativa*) growth (3, 5, 12, 13, 16 yr). Wang et al. (2010b) conducted a preliminary investigation of DSL dynamics under alfalfa (1, 2, 3, 4, 31 yr) and *Caragana korshinskii* lands (1, 2, 3, 4, 31 yr), respectively. These studies have enriched our understanding on the time dependence of DSL. However, further studies are increasingly needed to explore the detailed information of DSL dynamics at longer time series and also for different vegetation types.

On the other hand, most research achievements on the topic of DSL were based on certain sampling depths which were generally < 5 m (Han et al., 1990; Wang et al., 2010a; Yao et al., 2012; J. Li et al., 2008), because of difficulty in collecting deep soil water samples in terms of technology, method, and time. Therefore, data obtained thus far do not reflect real DSL values. This may limit our understanding of DSL because information on DSL in deep layers (generally > 5 m) remains unknown. Depending, to a great extent, on plant type and its root characteristics, the depths of DSL can extend to 10 m or more (Li and Huang, 2008; J. Li et al., 2008). Wang et al. (2009) reported that the soil water depletion depths of the root systems of planted alfalfa, *Caragana k.*, and pine (*Pinus tabulaformis*) in a semi-arid area in the Loess Plateau can reach 15.5, 22.4, and 21.5 m, respectively.

The gully region of the Loess Plateau in China is well known for its deep loess-palaeosol deposits and unique landscape (Shi and Shao, 2000). Prior to the 1980s, the major crop in arable lands was winter wheat. The region was later found suitable to produce high-quality apples because of its favorable climatic and topographical conditions. Therefore, more and more agricultural lands have been converted to orchards by local farmers because of the high income from apple production (Zhai et al., 2008). Compared with cropland that has similar soil profile, apple orchards increase their evapotranspiration rates and decrease their available soil water (ASW) along with an increase in age because of their deep roots and extensive canopy, a condition which causes the formation of DSL (Huang and Gallichand, 2006). Meanwhile, the yield of apple orchards substantially depends on the dynamics of soil water profile because this dynamics is linearly related to the available soil water in the root zone (Sharma et al., 1986). Soil water deficit in the deep layer also directly contributes to groundwater recharge and base flow of the Yellow River (Li, 1983; Huang et al., 2001). Therefore, ascertaining the relationship between real DSL and plant growth age is necessary not only for local farmers to improve land use efficiency but also to understand the dynamic evolution mechanisms of DSL over time.

The objectives of this study are (1) to investigate the soil water change with different growth ages for three vegetation types, (2) to evaluate the soil water conditions of apple trees with different growth ages up to a depth of 1800 cm in the Loess Plateau, and (3) to analyze the dynamics of real DSL (quantified by DSLT, DSL-SWC, DSL-QWD) along with an increase in apple growth age.

2 Materials and methods

2.1 Study area

The experiments were conducted at three different zones (Ansai, Luochuan, and Changwu) in the Loess Plateau of China (Fig. 1a). The Loess Plateau was described in detail in Shi and Shao (2000) and Chen et al. (2007), but it is briefly reiterated here. The Plateau is in the continental monsoon region, with annual precipitation ranging from 150 mm (northwest) to 800 mm (southeast), 55 %–78 % of the rain falls from June to September. The annual evaporation is 1400–2000 mm. The annual temperature ranges from 3.6 °C in the northwest to 14.3 °C in the southeast. The main geomorphic landforms on the Loess Plateau are large flat surfaces with little or no erosion, ridges, hills, and extensive steep gullies.

For the three zones, key location, climate and soil characteristics are shown in Table 1, and a map of their locations is shown in Fig. 1a.

In Ansai zone, we selected two typical vegetation types (*C. korshinskii* and *Robinia pseudoacacia*) which corresponding to a series of growth age as 10, 16, 26, 31, and 40 yr, and 9, 15, 29, and 34 yr, respectively. In addition, a permanent farmland was selected as the initial status of soil water in this zone. All the 10 sites are located in a small watershed (Zhifanggou watershed) and have a small spatial distance (Fig. 1b). In Luochuan zone, four orchards which planted apple trees with 5, 12, 18, and 30 yr respectively and one permanent farmland were selected as sampling sites (Fig. 1c). Similarly, in Changwu zone, six sites, including five orchards (5, 9, 17, 22, and 26 yr) and one permanent farmland were selected (Fig. 1d). Totally, we selected 21 representative sites (the area of each site > 50 m × 50 m) in the Loess Plateau and presented their site and environmental conditions in Table 2. The groundwater level for the three zones is about 60 m below the soil surface, which precludes upward capillary flow into the root zone.

In each zone, since the distances between any two sites of *C. korshinskii*, *R. pseudoacacia* and apple lands were small (Fig. 1b, c, d) and these sites were all located in the same slope position with comparable topographic conditions on similar soils, we considered that the SWC data may be representative of these sites corresponding to different growth ages. In this way, we can evaluate the effect of growth age on SWC and DSL dynamics reasonably.

2.2 Soil sampling

At each site, we collected soil samples by using traditional soil auger (5 cm in diameter) to determine SWC with different intervals and sampling depths in different zones. In Ansai zone, 0–6 m depth of soil samples were collected with an equal interval of 10 cm. In Luochuan zone, 0–10 m samples were collected at 10 and 20 cm intervals from the 0 to 2 m, and from 2 to 10 m soil layers, respectively.

In Changwu zone, we designed and developed a new soil auger (10 cm in diameter) to collect soil (which was used to determine soil properties such as soil organic carbon (SOC), soil particle composition) and plant root samples (which was used to determine root weight) at 10, 20, and 50 cm intervals from the 0 to 0.2 m, 0.2 m to 6 m, and 6 m to 18 m soil layers, respectively. The intervals were shortened to 25 cm for the 6 m to 18 m soil layers when soil samples were used to measure SWC which generally indicates higher heterogeneities in the vertical and horizontal directions than other soil properties (i.e. SOC). We used the new soil auger to replace the traditional auger just because the latter cannot be utilized to collect deep soil samples, especially below 10 m, with high efficiency.

The data of collected in Ansai and Luochuan zones was only used to investigate the change of SWC with growth age, while the data in Changwu zone was utilized to explore the dynamics of DSL since very deep soil samples were obtained and thus the calculation of real DSL indices was feasible.

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2.3 Laboratory analysis and data preparation

Gravimetric soil water content (g H_2O/100 g dry soil, %) was determined from the loss in mass during oven drying at 105 °C to constant mass. Plant root samples were carefully washed to remove all of the soil attached to the roots. The roots were separated from the soil using a combination of sieving of the soil in suspension through a 0.5-mm mesh and visual inspection of the soil slurry after sieving. Roots were allowed to dry for a short time on absorbent paper before weighing to determine the fresh root mass. Live root biomass was calculated based on the fresh root mass per unit volume of soil.

Based on the measured SWC data and combined with the published values of FC and PWP (Li, 1983; Wu et al., 2011). Eight evaluation indices of soil water condition were calculated as follows:

1. Mean soil water content at ith site ($\overline{\mathrm{SWC}_i}$):

$$\overline{\mathrm{SWC}_i} = \frac{1}{N_j}\sum_{j=1}^{N_j} \mathrm{SWC}_{i,j} \tag{1}$$

2. ASW content of the jth layer at ith site ($\mathrm{ASWC}_{i,j}$):

$$\mathrm{ASWC}_{i,j} = (\mathrm{SWC}_{i,j} - \mathrm{PWP}_{i,j}) \times \mathrm{BD}_{i,j} \times T_j \tag{2}$$

3. Capacity of available soil water content of the jth layer at ith site ($\mathrm{CASW}_{i,j}$):

$$\mathrm{CASWC}_{i,j} = (\mathrm{FC}_{i,j} - \mathrm{PWP}_{i,j}) \times \mathrm{BD}_{i,j} \times T_j \tag{3}$$

4. DSL thickness at ith site (DSLT_i):

$$\mathrm{DSLT}_i = T_i \times \sum_{i=11}^{N_l} S(\mathrm{SWC}_{i,j} - \mathrm{SFC}_{i,j}), \tag{4}$$

and $S(\mathrm{SWC}_{i,j} - \mathrm{SFC}_{i,j}) = \begin{matrix} 0, \mathrm{SWC}_{i,j} - \mathrm{SFC}_{i,j} > 0 \\ 1, \mathrm{SWC}_{i,j} - \mathrm{SFC}_{i,j} \leq 0 \end{matrix}, (j = 11, 12, 13, \cdots, N_j)$

where the annual average infiltration depth of the study area is about 200 cm, which corresponds to $j = 10$; therefore, we only considered soils below 200 cm in calculating the DSL in Changwu zone.

5. Mean SWC within the DSL at ith site ($\overline{\mathrm{DSL\text{-}SWC}_i}$):

$$\overline{\mathrm{DSL\text{-}SWC}_i} = \frac{1}{n}\sum_{j=11}^{n} \mathrm{SWC}_{i,j}, \quad \text{if } \mathrm{SWC}_{i,j} - \mathrm{SFC}_{i,j} \leq 0, (j = 11, 12, 13, \cdots, n) \tag{5}$$

6. Quantity of water deficit in the DSL at ith site ($\mathrm{DSL\text{-}QWD}_i$):

$$\mathrm{DSL\text{-}QWD}_i = \sum_{j=1}^{n} (\mathrm{SFC}_{i,j} - \mathrm{SWC}_{i,j}) \times \mathrm{BD}_{i,j} \times T_j, \\ \text{if } \mathrm{SWC}_{i,j} - \mathrm{SFC}_{i,j} \leq 0, (j = 11, 12, 13, \cdots, n) \tag{6}$$

7. Total of $\mathrm{ASW}_{i,j}$ (ASW_i) and $\mathrm{CASW}_{i,j}$ (CASW_i) at ith site:

$$\mathrm{ASW}_i = \sum_{j=1}^{N_j} \mathrm{ASWC}_{i,j} \tag{7}$$

$$\mathrm{CASW}_i = \sum_{j=1}^{N_j} \mathrm{CASWC}_{i,j} \tag{8}$$

where $\mathrm{SWC}_{i,j}$ is the SWC of the jth layer at ith site, N_i is the number of sites in each zone; N_j is the number of sampling soil layers or soil depths; $\mathrm{BD}_{i,j}$, $\mathrm{FC}_{i,j}$,

$PWP_{i,j}$, and $SFC_{i,j}$ are the bulk density, field capacity, permanent wilting point, and the stable field capacity of the jth layer at ith site, respectively; T_j is the thickness of the jth soil sampling layer; and n is the number of soil samples within the DSL ($n < N_j$).

2.4 Statistical method

We calculated the descriptive statistical parameters (i.e. mean, maximum, and minimum standard deviations and coefficient of variation) and tested the normal distribution properties of the data using skewness, kurtosis, and Kolmogorov–Smirnov tests. Pearson correlation coefficients were used to determine the strength of correlations among SWCs at different soil depths, as well as the possible relation between DSL indices and root depths. Analysis of variance (ANOVA) was performed to evaluate the differences in mean SWCs of the different growth ages. All statistical analyses were performed with Microsoft Excel (version 2010), SPSS (version 13.0), and SigmaPlot (version 10.0). The map of the study area in the Loess Plateau was developed with GIS software (version: ESRI® ArcMap™ 9.3).

3 Results

3.1 Characteristics of soil water content in the three zones

3.1.1 Summary statistics

Basic statistics of the SWCs of the three zones are presented in Table 3. In Ansai zone, the highest mean SWC (8.1 %) under the two vegetation types with different ages was smaller than that of permanent farmland (13.5 %), and also smaller than the criteria of a DSL (SFC = 11.4 %, Table 1) at the level of 0.01, indicating a series soil desiccation occurred in this zone for *C. korshinskii* and *R. pseudoacacia* land. Observed several values of SWC (i.e. 3.6 % in *C. korshinskii* and 3.7 % in *R. pseudoacacia* land) were smaller than the value of PWP (= 4.3 %), which further demonstrates a great extent of soil desiccation.

In Luochuan and Changwu zone, the phenomenon of soil desiccation was also detected for some orchard with longer growth age, although the mean SWCs for different sites were generally higher than that in Ansai zone.

The CV value of SWC for the soil profile reflected the variation of SWC within the profile. For the 21 sites, CVs had small range varied from 11 % to 26 %, indicating a weak variation of SWC along soil profile. This can also be seen from the vertical distribution of SWC in Fig. 2. Relative high variation was further found in Ansai zone (mean CV = 18 %), compared to the CV value in Luochuan zone (15 %) and Changwu zone (13 %) (Table 3). It is expected that the data of SWCs for each site was generally normally distributed since a weak vertical variation was detected. The values of skewness and kurtosis in Table 3, and Kolmogorov-Smirnov tests (data not listed) justified this distribution of the data.

3.1.2 Overall trend of soil water content

The mean SWC for each site under each vegetation type in each zone showed a similar trend that decreased with increasing growth ages firstly and then increased gradually (Table 3). One-way ANOVA (Fig. 3) showed that these mean SWCs generally differed significantly ($P < 0.05$). Therefore, we can infer that, with the increasing of plant growth age, a turning point (= the lowest value of mean SWC) of soil water condition exists. For *C. korshinskii* and *R. pseudoacacia* in Ansai, and apple orchards in Luochuan and Changwu, the turning points were 5.3 %, 5.2 %, 11.2 %, and 12.2 %, respectively, corresponding to the plant age of 26, 15, 18, and 17 yr (Tables 2 and 3, and Fig. 3).

The vertical distribution of SWC depicted in Fig. 2 visibly shows the dynamic patterns of SWC for different growth ages, which are in accordance to the trends of mean SWCs listed in Table 3.

Based on the vertical line of SFC distribution, we further explored the change of DSL although the real values of DSL indices (especially for DSLT) can not be calculated due to the limited sampling depths (i.e. Fig. 2a, b, c). The DSL-SWC and DSL-QWD in Ansai (Fig. 2a, b) and Luochuan zone (Fig. 2c) visibly demonstrated a trend of decreasing and then increasing, with the increasing of growth ages, thus we can also infer that a turning point exists for DSL-SWC and DSL-QWD change.

In Changwu zone, we can effectively ascertain the dynamics of soil water condition (i.e. ASW) and DSL indices, since the sampling depth (18 m) was proved to be enough to determine the lower boundary of DSL.

3.2 Change of available soil water with increase of growth age in Changwu

Available soil water is more useful than SWC in evaluating soil water condition because it can effectively indicate how much water can be utilized by plants. Figure 4 shows that the five apple sites in Changwu zone had approximate ASW capacities (CASW, ∼ 3200 mm, Eq. 8) at the 0 to 18 m soil layer; the ASW value (Eq. 7), which changed with plant growth age, gradually decreased from 5 yr (∼ 2380 mm) to 9 yr (2066 mm) and to 17 yr (747 mm), and then gradually increased to 22 yr (988 mm) and to 26 yr (1022 mm). The ratios between ASW and CASW also showed a similar trend (Fig. 4). The 17-year-old orchard had the lowest ASW value (747 mm), a result that agrees with the finding deduced from SWC that the 17-year-old orchard had the worst soil water condition (Table 3). Similar to the differences in SWCs (Fig. 3), the wide ASW range between the 5- and 17-year-old orchards contributed to a large extent to the water uptake of the apple trees because the study area has high homogeneities in topography, climate, and soil conditions.

Using the data on growth age, ASW, and CASW, we calculated the velocity of ASW as it changed across growth ages along the 0 cm to 1800 cm profile. From 5 to 9 yr and from 9 to 17 yr, ASW decreased at the ratio of 78 and 165 mm yr^{-1}, respectively, whereas from 17 to 22 yr and then to 26 yr, ASW was replenished at ratios of 48 and 9 mm yr^{-1}, respectively. The velocity of ASW change further justifies that the 17-year-orchard is the turning point of soil water condition. This finding is understandable because deep soil water loss can be mainly attributed to the extraction of plant roots in the study area where ground water is very deep (generally > 60 m).

Moreover, the SWC of the 22-year-old orchard was higher than that of the 26-year-old orchard (Table 3), whereas the opposite was true with their ASW data (Fig. 4), a result that can be mainly ascribed to the difference in soil textures along loess–paleosol sequences between the two sites (Fig. 5).

3.3 Changes in the dried soil layer with growth age

3.3.1 DSLT and DSL-SWC

Figure 5 shows the profile distribution of SWC and SFC and the plant root at the five sampling sites. DSL was not found in the 5-year-old orchard because of the small evapotranspiration of this young apple tree. With an increase in growth age, however, the DSL of the 9-year-old orchard was DSLT = 80 cm, and it gradually extended below and reached the maximum thickness of 1600 cm, which corresponds to the 26-year-old orchard.

The data on the forming velocity for DSLT showed that from 5 to 9 yr, 17 to 22 yr, and to 26 yr of apple growth, the highest forming velocity of DSL (168 cm yr^{-1}) was found for the period from 9 to 17 yr. The lowest forming velocity was 5 cm yr^{-1} for the period from 17 to 22 yr. These results indicate that the DSLT forming velocity varies with the growth stage of the plant.

From Fig. 5, we further calculated the mean DSL-SWC (Eq. 5) for each site, which was in the following order: 9 yr (14.67 %) > 22 yr (13.55 %) > 26 yr (12.98 %) > 17 yr (11.83 %). One-way ANOVA showed that the DSL-SWC data differed significantly ($P < 0.01$) across the different ages of the orchards, except those of the 22- and 26-yr old orchards ($P = 0.140$).

3.3.2 Quantity of water deficit within the dried soil layer

DSLT and DSL-SWC cannot effectively express the relationship between DSL and growth age because DSLT increased with growth age, and DSL-SWC showed a decreasing to increasing trend. Therefore, we further calculated another evaluation index for DSL, the quantity of water deficit in DSL (DSL-QWD) (Eq. 6), which combines the advantages of DSLT and DSL-SWC.

The deficit quantity of soil water was in the following order: 9 yr (–8 mm) > 26 yr (–555 mm) > 22 yr (–576 mm) > 17 yr (–755 mm). This sequence indicates that the 17-year-old orchard, followed by the 22-year-old orchard, and then by the 26-year-old orchard need more water and time than the other orchards to restore the DSL soil profile. Similar to the results on ASW content (see Sect. 3.2), the deep soil water in the upper profile (about 200 cm, see Fig. 5) began to recover after the turning point of the 17-year-old orchard, and this recovery can be attributed to the processes of positive water cycle-input (rainfall) > output (evapotranspiration).

Consequently, as the apple orchards aged from 5 to 26 yr in Changwu zone, (1) the DSLT gradually increased, (2) the mean DSL-SWC decreased from 5 to 17 yr and then increased, and (3) the DSL-QWD increased from 5 to 17 yr before it gradually decreased from 17 to 26 yr. Therefore, we can infer that (1) soil desiccation becomes worst when the planted apple trees reach 17 yr old, and (2) the optimal planting year for apple orchards is about 9 yr to avoid/control the formation of DSL; the 9-year-old apple orchard has not formed serious DSL that can be recharged on a rainy year.

3.4 Relationships between DSL and growth age and root depth

Pearson correlation analysis showed that DSLT was positively correlated with growth age ($r = 0.947$, $P < 0.05$) and root depth of the apple trees ($r = 0.985$, $P < 0.01$), whereas DSL-QWD was only significantly correlated with root depth ($r = -0.914$, $P < 0.05$) (Table 4). The mean DSL-SWC had no significant correlation with either growth age or root depth.

The positive correlation between growth age and root depth, which was also observed at 0.01 level, was expected because the roots keep on searching for water stored in deep soil in water-limited regions under the driving force of plant growth and, originally, solar radiation.

Furthermore, among the evaluation indices of dried soil layers, a significant correlation was found only between DSLT and DSL-QWD ($r = -0.959$) under different growth ages (Table 4). The mean DSL-SWC was highly correlated with DSL-QWD ($r = 0.918$) and DSLT ($r = -0.772$), but these relationships were insignificant at 0.05 level.

4 Discussion

4.1 Dependence of dried soil layer on the growth age

In each zone, the selected sampling sites but different growth ages in current study had similar natural elements (i.e. topography, climate, soil properties, and loess-paleosol sequences), farmer management measures (i.e. fertilizing and branching) as well as small spatial distances between any two sites (Fig. 1b, c, d). Therefore, differences in plant growth ages, which refer to different capabilities in root water uptake, photosynthesis, and apple yield, can be deemed as the dominant driving force for the deep-profile soil water patterns.

As plant growth age increased, the SWC (Table 3 and Fig. 3) in the three zones, and ASW (Fig. 4), DSL-SWC, and the DSL-QWD along the 1800 cm profiles in Changwu zone indicated a similar trend of soil water dynamic (a turning point) with the increase of plant growth ages. The following five stages can be used to describe the relationships between soil water and plant growth: (1) in the initial stage, which is after the young apple trees are planted, the water supply from both rainfall and water stored in deep soil is enough, and the plants growth well with abundant water supply; (2) in the second stage, the growth of plants needs more and more water under the drive of increasing transpiration ability, so the water stored in deep soil is extracted and utilized by the roots. Simultaneously, DSL begins to develop in the soil profile. (3) In the third stage, plant roots keep extending below to absorb soil water and thus maintain the exuberant growth of the plants. The extent of DSL becomes worse at this point compared with that in the preceding stage. (4) In the fourth stage, the growth of plant becomes relative stable at a certain level that highly depends on the amount of annual rainfall. The DSL is worst at this point. (5) In the last stage, the plants become old and related physiological activities decline, and thus some extra rainfall can be used to replenish the DSL. The DSL level gradually decreases. Therefore, the growth of the plants and the related eco-hydrological processes substantially affect the level of DSL.

It is expected that long-term climate change, which was indicated by the decreasing rainfall input in the Loess Plateau and increasing air temperature (Y. Q. Wang et al., 2011), highly aggravates the scarcity of soil water and thus affects the five processes of plant growth. While the seasonal drought of climate may also lead to the occurrence of temporal DSL, but this type of DSL generally be restored by rainfall in rainy season (Li, 1983). In regions covered by deep soil and also characterized by great seasonal variation of rainfall, such as in Brazilian Amazon (Markewitz et al., 2010) and Southern Australia (Mendham et al., 2011), temporal DSL may be occurred based on their published data, but this needs further confirmation.

Several studies in the literature have reported that SWC showed an obvious spatio-temporal variation (Duan et al., 2011) and the soil water condition of the soil profile deteriorates gradually with the age of the plant (i.e. alfalfa, Li and Huang, 2008, and Caragana Korshinskii, Wang et al., 2010b). However, we found a different trend in soil water change with the aging of the studied three trees (*C. korshinskii*, *R. pseudoacacia*, apple) in present study: a turning point existed (Fig. 3). This finding is interesting and also reasonable as explained above.

4.2 Effect of dried soil layer on regional hydrological processes and apple yields

The gully regions of the Loess Plateau were found suitable to produce high-quality apples because of their favorable climate, soil, and topographic conditions, so at least 60 % of all arable lands in this area were converted from agricultural land to apple orchards in the past decades (Huang and Gallichand, 2006). The occurrence of substantial DSLs, which was widespread across the study area, is therefore likely to affect regional hydrological processes in soil-plant-atmosphere systems, such as by blocking water interchange between upper soil layers and groundwater and then between the soil and the atmosphere (Huang and Gallichand, 2006; Wang et al., 2010a; Singh, 1998).

Huang et al. (2001) compared the infiltration, runoff, and SWC of the 0 cm to 1000 cm soil profile and found that apple orchards have higher evapotranspiration rates and lower ASW than croplands. More and more rainfall will be consumed by the extensive canopy of apple trees over time. The traditional water cycle model in the crop ecosystem will change and eventually threaten the supply of regional water resources in the Loess Plateau.

For apple trees, the growth age to sustain a certain yield is usually about 30 yr (apple trees older than 30 yr are often cut), whereas the distribution of the formed DSL may last a longer time, which generally exceeds 40 yr (including recovery time). Using a one-dimensional simulation model called simultaneous heat and water transfer, Huang and Gallichand (2006) reported that after orchards were reconverted to winter wheat, the recovery time of the soil water varied from 6.5 to 19.5 yr, with an average of 13.7 yr for the 0 cm to 1000 cm soil profile. Alternatively, if farmers do not change the orchards to cropland and continue to plant young apple trees, the DSL will never be reclaimed, and the yield of the "new orchard" will fluctuate closely with the change in annual rainfall.

Plant roots play a key role in the development of DSL, with their distribution depth and pattern effectively determining the thickness of DSL and the quantity of ASW within the DSL (Table 4). The formed DSL can also affect the water uptake of the roots and thus the growth of the plants, as well as the apple yield. Wang et al. (2010b) reported that the root systems of permanent grasslands (~0 cm to 300 cm) and forests (~0–640 cm or more) are more developed than those of annual crops (~0 cm to 100 cm), and the correlation between SWC and root indices are generally weaker within DSL layers than within the entire soil profile. Chen et al. (2008a) emphasized that the extent of DSL is closely associated with the root distribution of plants and varies with the types and the ages of vegetation. Therefore, considering the depth of roots is very important to understand the relationship between plant growth and DSL dynamics.

In summary, the plant-soil environment is a mutually interacting system that interfaces at the plant roots. During the life cycle of plants, the soil environment provides them with water, structural physical support, and nutrients, which in turn add metabolites and organic matter back to the soil (Wang et al., 2010b; Lambers et al., 2007; Montaldo et al., 2008). This process is an important part of natural plant cycles and water balance processes (Vörösmarty and Moore, 1991; Portoghese et al., 2008). The formation of DSL is a comprehensive phenomenon caused by the negative water balance between decreasing inputs and increasing outputs (L. Wang et al., 2008; Y. Q. Wang et al., 2011; Yang, 2001; Li, 1983). The nature and the extent of DSL can serve as indicators to evaluate soil desiccation processes and soil water status, and to reflect plant growth dynamics and functional root status in the proximity of the DSL for different ages of plants (Figs. 4 and 5). Meanwhile, the wide distribution of DSL should be monitored because it may affect regional hydrological processes. Although DSLs have yet to be systemically studied at the necessary level (Chen et al., 2008b; Shangguan, 2007), our results proved that co-relationships exist among DSL indices, plant roots, and growth ages of plants. They also provided new information and implications for the restoration and the management of soil water and DSL in the Loess Plateau of China and possibly in other arid and semi-arid regions around the world.

5 Conclusions

The characteristics and evolution trends of soil water and DSLs under three vegetation types (*C. korshinskii*, *R. pseudoacacia*, apple) were investigated in three zones (Ansai, Luochuan, and Changwu) of the Loess Plateau. The changes in SWC, ASW, DSL-SWC, and DSL-QWD with growth age, which were found to be similar, generally showed a decreasing to increasing trend. A turning point in soil water change both in and out of DSL was also found, and this is an interesting finding that may be helpful for the scientific management of orchards.

According to the data that obtained from 18 m soil profiles in Changwu zone, the highest mean velocity of ASW decline was 165 $\mathrm{mm\,yr^{-1}}$ from the 9- to 17-year-old orchards, whereas the maximum mean-forming velocity of DSLT was 168 $\mathrm{cm\,yr^{-1}}$ for the same apple growth age. The period from 9 to 17 yr is vital to maintain the buffering function of deep soil water pool and to avoid the deterioration of soil desiccation.

DSLT was positively correlated with growth age ($P < 0.05$) and root depth ($P < 0.01$), and DSL-QWD was negatively correlated with root depth ($P < 0.05$), while the mean DSL-SWC had no significant correlation with either growth year or root depth.

We only explored the soil water condition and DSL characteristics for a few vegetation types and zones at several growth ages, because of difficulty in collecting deep soil water samples (especially > 1000 cm). Nevertheless, our findings provide pertinent information for water resource management and dryland farming in the Chinese Loess Plateau and possibly in other water-limited regions around the world. Adequate attention should be directed toward the eco-hydrological effects of DSL because they may directly or indirectly affect related physical, chemical, and biological processes in terrestrial ecosystems at both site and regional scales.

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Table 1. Location, climate, and soil information for the three zones in the Loess Plateau of China.

Zone	Ansai	Luochuan	Changwu
Location	109°15′ E, 36°44′ N	109°28′ E, 35°35′ N	107°41′ E, 35°12′ N
Climate			
Annual rainfall (mm)	510 (1951–2001)	568 (1954–2001)	560 (1985–2008)
Annual evaporation (mm)[a]	1293 (1984–2001)	1403 (1994–2001)	1358 (1985–2008)
Climate Wetness Index [b]	0.39	0.40	0.41
Annual temperature (°C)	8.8	9.2	9.1
Soil characteristics			
Texture (~0–10 m)[c]	Silty loam	Silty clay loam	Silty clay loam
BD (0–10 cm, g cm^{-3})	1.27	1.35	1.25
FC (0–10 cm, %)	18.4	20.2	22.4
SFC (0–10 cm, %)	11.4	14.1	15.7
PWP (0–10 cm, %)	4.3	8.6	9.0

Note: BD, bulk density; FC, field capacity; PWP, permanent wilting point; SFC, stable field capacity.

[a] The average annual evaporation for an open pan.

[b] Annual rainfall as a proportion of annual evaporation.

[c] FAO soil classification system.

Table 2. Site conditions of the 22 sampling sites under three zones in the Loess Plateau of China.

Location	No	Growth age (yr)	Sampling depth (m)	Vegetation type	Land use	Sampling time
Ansai	AS1	1	6	Soybean	Farmland	30 May 2009
	AS2	10	6	*Caragana korshinskii*	Shrubland	31 May 2009
	AS3	16	6	*Caragana korshinskii*	Shrubland	30 May 2009
	AS4	26	6	*Caragana korshinskii*	Shrubland	31 May 2009
	AS5	31	6	*Caragana korshinskii*	Shrubland	31 May 2009
	AS6	40	6	*Caragana korshinskii*	Shrubland	31 May 2009
Ansai	as1	1	6	Soybean	Farmland	30 May 2009
	as2	9	6	*Robinia pseudoacacia*	Forestland	30 May 2009
	as3	15	6	*Robinia pseudoacacia*	Forestland	1 Jun 2009
	as4	29	6	*Robinia pseudoacacia*	Forestland	1 Jun 2009
	as5	34	6	*Robinia pseudoacacia*	Forestland	1 Jun 2009
Luochuan	LC1	1	10	Maize	Farmland	19 May 2009
	LC2	5	10	Apple	Orchard	19 May 2009
	LC3	12	10	Apple	Orchard	20 May 2009
	LC4	18	10	Apple	Orchard	20 May 2009
	LC5	30	10	Apple	Orchard	21 May 2009
Changwu	CW1	1	18	Wheat	Farmland	9 Aug 2011
	CW2	5	18	Apple	Orchard	10 Aug 2011
	CW3	9	18	Apple	Orchard	11 Aug 2011
	CW4	17	18	Apple	Orchard	17 Aug 2011
	CW5	22	18	Apple	Orchard	15 Aug 2011
	CW6	26	18	Apple	Orchard	13 Aug 2011

Table 3. Basic statistics of soil water content under the three zones in the Loess Plateau of China.

Location	No	*n*	Minimum (%)	Maximum (%)	Mean (%)	CV (%)	Skewness	Kurtosis
Ansai	AS1	60	8.8	18.8	13.5	20	0.184	−1.027
	AS2	60	6.0	10.9	8.1	15	−0.059	−0.710
	AS3	60	5.6	11.1	8.1	14	−0.047	−0.265
	AS4	60	3.6	10.0	5.3	26	1.274	1.148
	AS5	60	4.2	10.2	6.1	23	0.673	−0.030
	AS6	60	5.1	10.7	6.3	12	3.566	19.357
Average			5.6	11.9	7.9	18		
Ansai	as1	60	8.8	18.8	13.5	20	0.184	−1.027
	as2	60	5.9	12.7	8.1	17	0.320	0.678
	as3	60	3.7	7.3	5.2	19	0.628	−0.494
	as4	60	4.3	8.7	6.1	22	0.517	−1.035
	as5	60	5.5	8.7	7.2	11	−0.116	−0.893
Average			5.6	11.2	8.0	18		
Luochuan	LC1	60	12.7	21.7	17.7	14	−0.603	−0.810
	LC2	60	13.2	22.5	17.0	12	0.112	−0.269
	LC3	60	8.9	19.4	13.1	19	0.496	−0.151
	LC4	60	7.1	15.4	11.2	15	0.445	0.174
	LC5	60	7.9	18.3	14.4	16	−0.448	0.224
Average			10.0	19.4	14.7	15		
Changwu	CW1	79	9.1	22.1	16.3	17	−0.479	−0.224
	CW2	79	11.8	23.1	18.6	12	−0.410	0.000
	CW3	79	14.2	23.3	17.3	11	0.884	1.004
	CW4	79	8.8	16.0	12.2	14	0.470	−0.311
	CW5	79	11.1	19.3	14.0	14	0.704	−0.193
	CW6	79	10.7	17.2	13.2	12	0.573	−0.174
Average			10.9	20.2	15.3	13		

Note: *n*, number of samples; CV, coefficient of variation.

Table 4. Pearson correlation coefficients between dried soil layer (DSL) evaluation indices and the growth ages and the root depths of the apple trees in Changwu zone in the Loess Plateau of China.

Items	Growth age	Root Depth	DSLT	DSL-QWD	DSL-SWC
Growth age	1.000				
Root depth	0.978^b	1.000			
DSLT	0.947^a	0.985^b	1.000		
DSL-QWD	−0.820	-0.914^a	-0.959^a	1.000	
DSL-SWC	−0.477	−0.668	−0.772	0.918	1.000

Note: DSLT, thickness of DSL; DSL-QWD, quantity of water deficit for DSL; DSL-SWC, soil water content within the DSL.

[a] Correlation is significant at the 0.05 level (2-tailed).

[b] Correlation is significant at the 0.01 level (2-tailed).

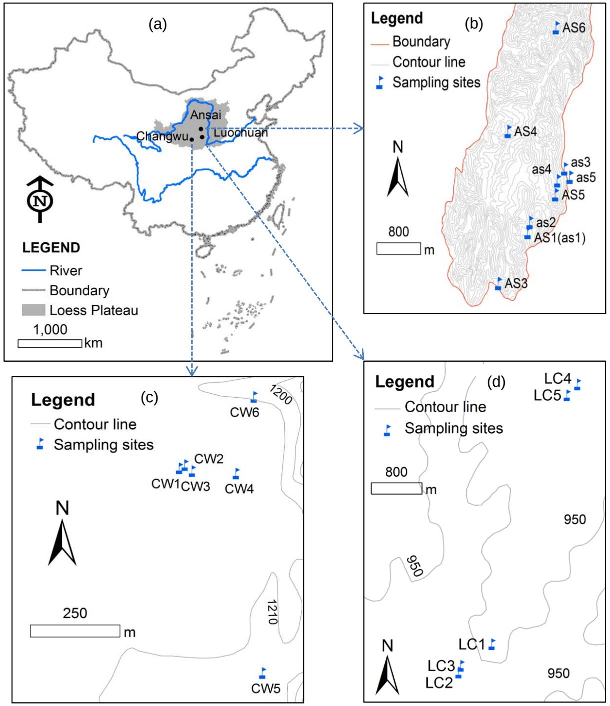

Fig. 1. Location of Ansai, Luochuan, and Changwu zones in the Loess Plateau of China and distribution of sampling sites in each zone.

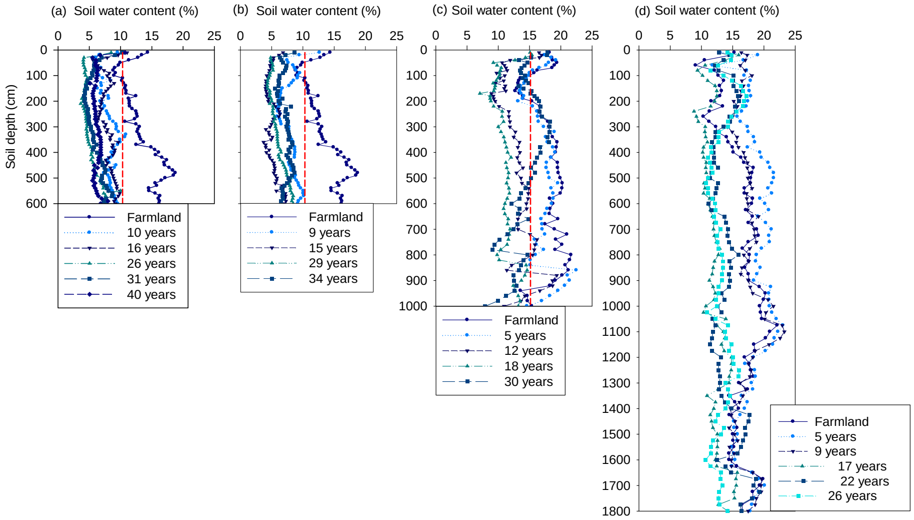

Fig. 2. Vertical distribution of soil water content in Ansai (**a** *Caragana korshinskii* land and **b** *Robinia pseudoacacia* land), Luochuan (**c** apple orchard), and Changwu (**d** apple orchard) zone in the Loess Plateau of China. Red dotted line represents the criteria of dried soil layer (stable field capacity).

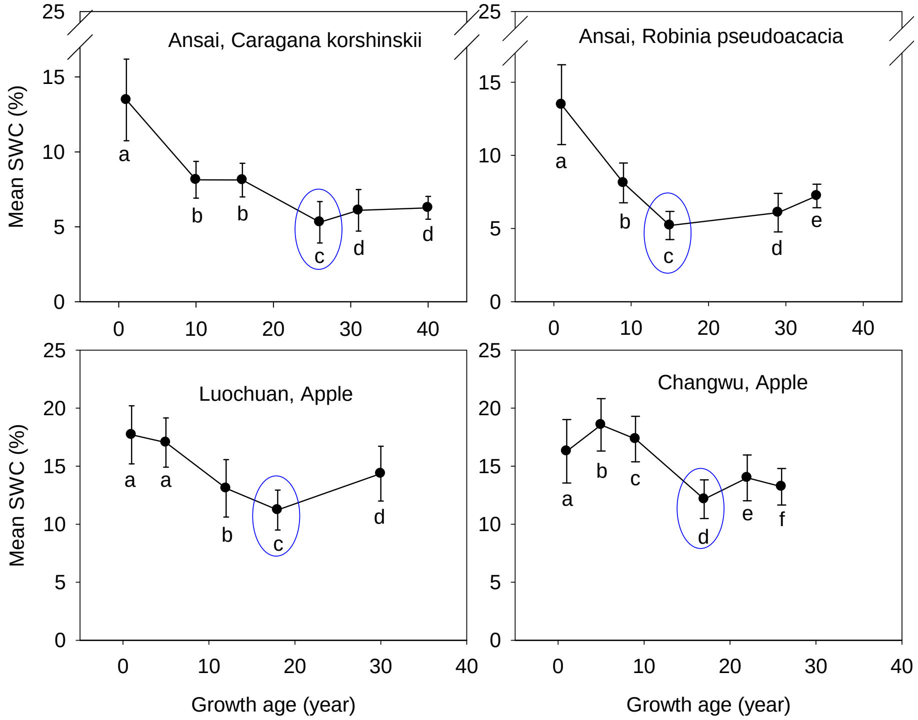

Fig. 3. Changes of mean soil water content (SWC) with the increasing of plant growth ages in Ansai, Luochuan, and Changwu zones in the Loess Plateau of China. Blue circle represents the tuning point of SWC change. The data corresponding to 1-yr was collected in permanent farmland.

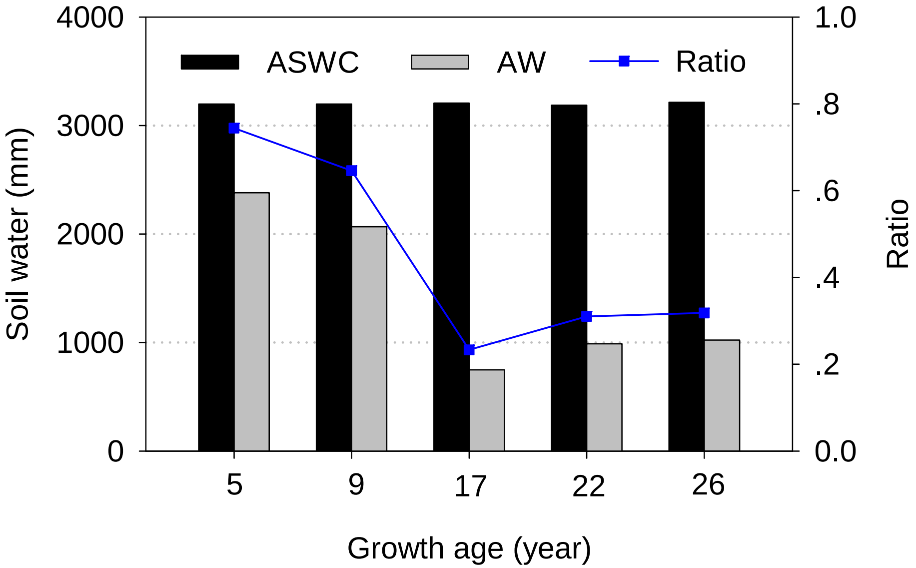

Fig. 4. The capacities of available soil water (CASW) and available soil water (ASW) from 0 cm to 1800 cm soil depths of different growth ages of apple orchards in Changwu zone in the Loess Plateau of China. Ratio = ASW/CASW.

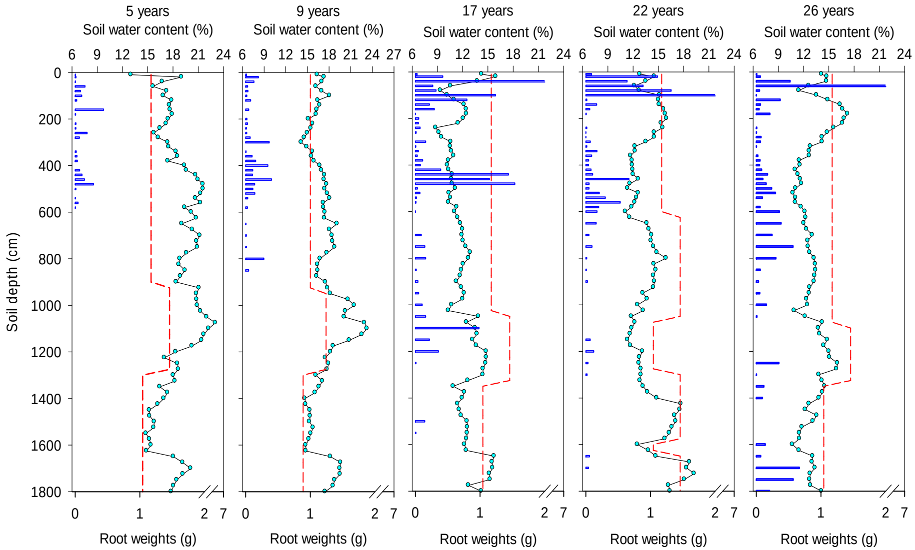

Fig. 5. Profile distribution of soil water content (cyan circle), stable field capacity (red line), and plant root weights (blue color) of the 0 cm to 1800 cm soil profile at different growth ages of apple orchards in Changwu County in the gully regions of the Southern Loess Plateau.