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REPORT

The impact of land use on water loss and soil desiccation in the soil profile

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Abstract Farmlands have gradually been replaced by apple orchards in Shaanxi province, China, and there will be a risk of severe soil-water-storage deficit with the increasing age of the apple trees. To provide a theoretical basis for the sustainable development of agriculture and forestry in the Loess Plateau, soil water content in a 19-year-old apple orchard, a 9-year-old apple orchard, a cornfield and a wheat field in the Changwu Tableland was investigated at different depths from January to October 2014. The results showed that: (1) the soil moisture content is different across the soil profile—for the four plots, the soil moisture of the cornfield is the highest, followed by the 9-year-old apple orchard and the wheat field, and the 19-year-old apple orchard has the lowest soil moisture. (2) There are varying degrees of soil desiccation in the four plots: the most serious degree of desiccation is in the 19-year-old apple orchard, followed by the wheat field and the cornfield, with the least severe desiccation occurring in the 9-year-old apple orchard. Farmland should replace apple orchards for an indefinite period while there is an extremely desiccated soil layer in the apple orchard so as to achieve the purpose of sustainable development. It will be necessary to reduce tree densities, and to carry out other research, if development of the economy and ecology of Changwu is to be sustainable.

Keywords Soil desiccation · Groundwater management · Forestry · Agriculture · China

Introduction

A dried soil layer (DSL) is a hydrological phenomenon occurring in arid, semi-arid, and sub-humid regions, which is caused mainly by the excessive depletion of deep soil water by both native and non-native vegetation, high evapotranspiration, and long-term shortage of rainwater (Chen et al. 2008). Vegetation and topographical factors such as plant species, slope aspect, and gradient, have major effects on DSL formation. A DSL may lead to soil degradation, failure of afforestation, regional vegetation die-off, and aridity in the local climatic environment (Wang et al. 2008). In the Loess Plateau of China, the evapotranspiration from apple orchards and wheat fields exceeds precipitation, and this can deplete soil water and cause the development of a deep dry layer in the soil profile, which is a serious obstacle to sustainable land use (Chen et al. 2008; Wang et al. 2009).

In the south of the Loess Plateau, there is a wide range of climatic patterns, water resources are scanty, and soil desiccation is widespread in the regrown forest and grasslands (Gao et al. 2010; Heathman et al. 2003; Penna et al. 2009; Wang et al. 2008). There is now an increasing number of studies on soil desiccation under different types of land use in the Loess Plateau (Cheng and Liu 2014; Wang et al. 2015a). Natural vegetation (fallow) was found to be the best vegetation type for achieving sustainable soil water content and for preventing soil desiccation in a study area in the Changwu Tableland (Liu and Shao 2016). The rate of soil desiccation is higher in apple orchards aged between 9 and 17 years than other ages in the Changwu study, and the degree of soil desiccation gradually increases with increasing age of the orchards (Wang et al. 2015b). The extent of soil desiccation has a close relationship with root distribution of plants, and desiccation intensity varies with the types and ages of vegetation. Soil desiccation obviously has negative effects on the water cycle component

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associated with soils, greatly reduces the anti-drought capacity of plants, and heavily influences the growth and natural succession of vegetation (Chen et al. 2008). The apple industry has developed rapidly in Shaanxi province, and farmlands have gradually shifted to a business model which is based on apple orchards (Li et al. 2008). Against this background, the present study compared the extent and pattern of soil desiccation among farmlands and apple orchards, and clarified the response of soil moisture to land use.

The aims of the study were to carry out a systematic analysis of soil hydrological characteristics in apple forestlands and farmlands in the southern Loess Plateau, obtain a quantitative analysis of the pattern of soil desiccation, and determine the soil-water depletion depth in the apple forestlands and farmlands by long-term monitoring of soil moisture dynamics and transpiration in these forestlands and farmlands. The results should provide a theoretical basis for the sustainable use and management of soil water in desiccated farmlands and orchards, and an important reference point for adjustments in the direction of the regional agricultural structure and the reconstruction of vegetation.

Materials and methods

Study site

In the work presented here, the Changwu Tableland was adopted as a study area because it is typically representative of the Loess Plateau (Fig. 1). The study area is at the Changwu Agro-ecological Experimental Station on the Loess Plateau, Chinese Academy of Sciences, in the Wangdonggou Watershed, Shaanxi Province, China (107°40′30″–107°42′30″E, 35°12′16″–35°16′00″N). The station is located in the south of the Loess Plateau. This area is flat with deep soil, the elevation is 1,200 m above sea level, and it is typical of the Loess Plateau gully areas where dry farming is carried out. The average annual temperature is 9.1 °C. The climate is sub-humid with high interannual variation in precipitation; the average annual precipitation is 584.1 mm. The precipitation is concentrated in July to September, a period which accounts for 54.9% of the annual rainfall. The average annual evaporation is 1,016.6 mm, which is about 1.7 times higher than the precipitation. The average frost-free period is 191 days year^{-1}, and the average annual solar radiation is 4,837 MJ m^{-2}. The field capacity and wilting coefficient are 23 and 10.6% respectively.

The main farmlands in the study area are planted with wheat and corn; wheat is sown in late September and harvested in late June in the following year, while corn is sown in mid-April and harvested in mid-September. The average (taken over many years) field production of wheat and corn is, respectively, 3,198.2 and 6,037.5 kg hm^{-2}. The area occupied by apple orchards in Changwu has increased year by year, and this has become a pillar industry in the region's economic development.

Sampling sites

The ages of the two Fuji apple orchards are 19 and 9 years, and the study was undertaken in 2014. There is no irrigation and the terrain is flat in each orchard. The managers have applied regular pest control and weeding, branch bending at an appropriate time, and bagging in the orchard. The winter wheat crop was sown on September

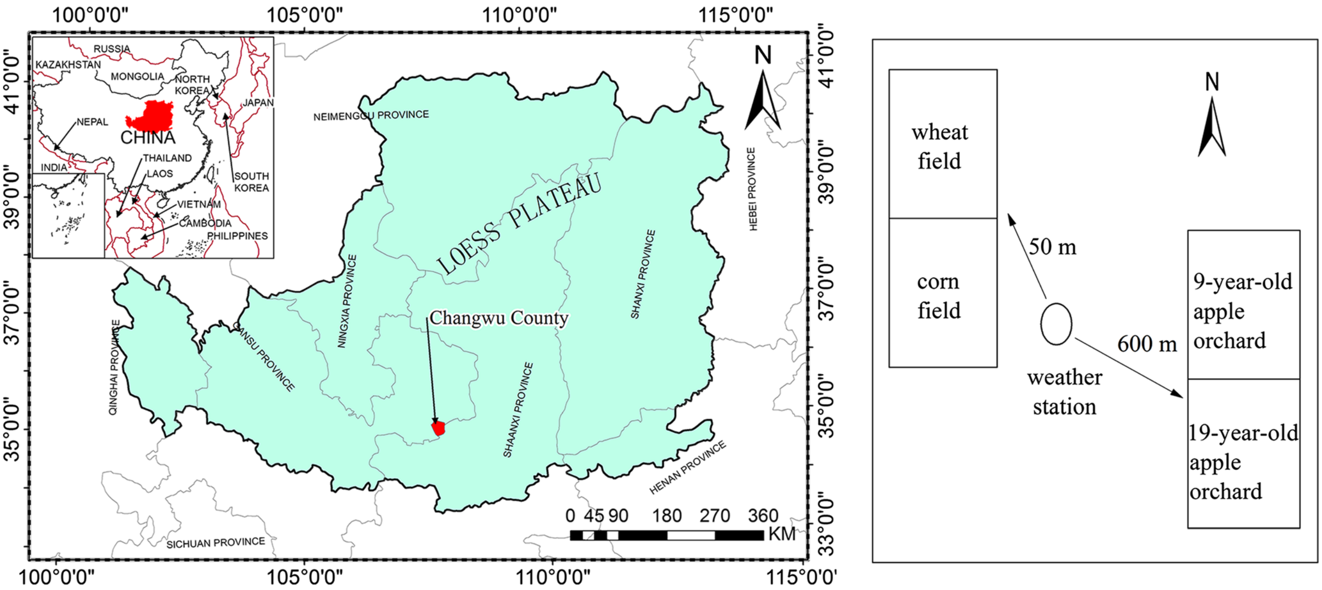


Fig. 1 The location of the study area in Loess Plateau of China

Table 1 Characteristics of the orchards studied

Age (years)	Orchard area (m^2)	DBH (cm)	Spacing (m × m)	Stand density (strain/hm^2)	Height (m)	Sapwood area (cm^2)	No. of trees
9	1,334	9.76	2.5 × 3.5	1,199	3.59	81.69	156
19	1,000.5	14.73	3.0 × 4.0	950	3.92	130.51	96

DBH diameter at breast height of the trees

18, 2013 and harvested on June 25, 2014. The corn was sown on April 15, 2014 and harvested on September 20, 2014. The characteristics of the orchards studied are shown in Table 1. The soil particle composition of the 19-year-old apple orchard, 9-year-old apple orchard and wheat field along the 0–6-m soil profile in this area is shown in the Fig. 2, and it is measured by the laser diffraction method using a Master sizer 2000 (Malvern Instruments Ltd., Melvin, UK). As the cornfield is close to the wheat field, there is no particle composition analysis of the cornfield in Fig. 2. The particle composition analysis indicates that the soil texture of the four plots is quite uniform, and there is no significant difference in the vertical soil physical parameters (such as field capacity and wilting point) between the four study plots. Cao (2012) and Li et al. (2013) reported the similar conclusion, that there is no significant variation of soil texture across the Changwu Tableland.

Measurement methods

Soil water content and soil desiccation index (SDI)

A neutron probe (CNC503B) was used to measure volumetric soil water content (θ_v) twice a month at consecutive 10-cm increments between soil depths of 0 and 100 cm, and at consecutive 20-cm increments at depths of between 100 and 600 cm, in the 19-year-old and 9-year-old apple orchards, the cornfield and the wheat field from April to October 2014. From January to March, measurements were made once a month. Calibration of the neutron probe was carried out using standard methods (Huang and Gallichand 2006).

A DSL (dried soil layer), which appears below the depth to which precipitation recharges the soil moisture, is formed when there is excessive consumption of deep soil moisture. These conditions can form a longstanding DSL in the soil profile (Wang et al. 2015b). This hydrological phenomenon

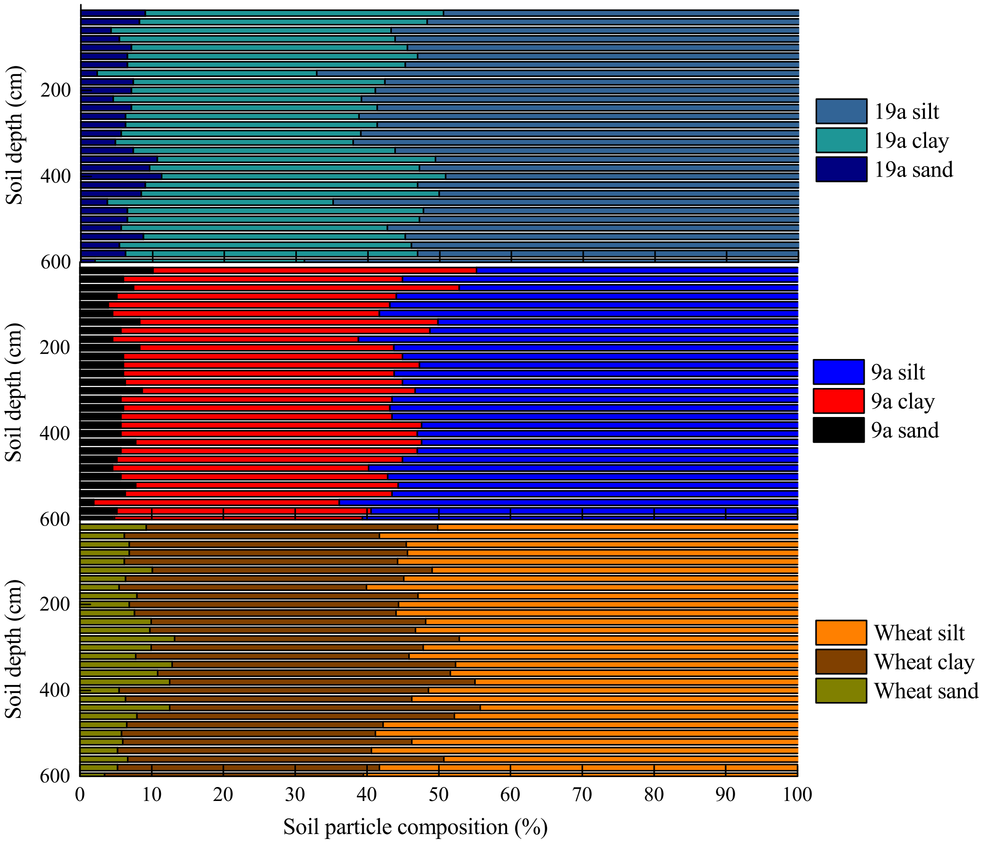


Fig. 2 The particle composition of the 19-year-old (*19a*) apple orchard, the 9-year-old (*9a*) apple orchard and the wheat field along the 0–600-cm soil profile in Changwu

is a feature of semi-arid and sub-humid environmental conditions in the Loess Plateau, where it is a manifestation of a dry environment and dry soil. In this study, soil stable moisture content (SSM; Cao et al. 2012) is the key index for judging soil desiccation in an orchard, and the arithmetic mean value of field capacity and wilting humidity is used to represent the SSM. It is a stable field capacity at which soil water remains stable or soil capillaries break (Wang et al. 2008). To gain a more accurate and quantitative description of the intensity of soil desiccation, the SDI is used, and the formula for this index is:

$$\mathrm{SDI}=\left(1-\frac{\theta-\mathrm{SW}}{\mathrm{SSM}-\mathrm{SW}}\right)\times 100\%=\frac{\mathrm{SSM}-\theta}{\mathrm{SSM}-\mathrm{SW}}\times 100\% \quad (1)$$

where SDI is soil desiccation index (%); θ is soil moisture content (%); SW is wilting humidity (%); and SSM is stable soil moisture content (%). Depending on the value of SDI, the intensity of soil desiccation can be divided into six grades: (1) extremely desiccated soil, which has a SDI of more than 100%; (2) strongly desiccated soil, which has a SDI between 75 and 100%; (3) severe desiccation, which is indicated by a SDI between 50 and 75%; (4) moderately desiccated soil, which has a SDI between 25 and 50%; (5) mild desiccation, which corresponds to a SDI between 0 and 25%; (6) If SDI < 0, the soil is not desiccated.

The coefficient of variation (CV)

The coefficient of variation is defined by:

$$\mathrm{CV}=\frac{\mathrm{SD}}{\mathrm{MN}}\times 100\% \quad (2)$$

for which the SD and MN are the standard deviation and mean value of soil water content during the experiment, respectively.

The depletion and recharge depths of soil water in different plots are determined by analyzing the soil water profile dynamics. The depletion depth is the deepest soil layer of intense variation of soil moisture in the non-precipitation period, and the recharge depth is the deepest soil layer that has some variation after the precipitation period.

Evapotranspiration

Potential evapotranspiration ($\mathrm{ET_r}$) is calculated by the Penman-Monteith equation (Allen et al. 1998):

$$\mathrm{ET_r}=\frac{0.408\varDelta(R_\mathrm{n}-G)+\gamma\dfrac{900}{(T+273)}U_2(e_\mathrm{s}-e_\mathrm{a})}{\varDelta+\gamma(1+0.34U_2)} \quad (3)$$

where $\mathrm{ET_r}$ is the latent heat flux (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux (MJ m^{-2} day^{-1}), γ is the hygrometer constant (kPa °C^{-1}), T is air temperature (°C), U_2 is wind speed at 2 m (m s^{-1}) above ground level, e_s and e_a are the saturation vapor pressure (kPa) and actual vapor pressure (kPa) during the calculated period, respectively, and $\varDelta$ is the slope of the curve for saturated vapor pressure vs. temperature (kPa °C^{-1}). These parameters and the precipitation (P, mm) are all measured at regular intervals by an automatic weather station which is 50 m away from the experimental plots.

In deriving the evapotranspiration in the orchard, the transpiration of individual trees was measured by the sap flow technique using the thermal dissipation probe (TDP) method of Granier (1987). Two cylindrical sensor probes about 1.2 mm in diameter were inserted into the sapwood of the tree trunk. The liquid flux (F_s, in L h^{-1}) of an individual tree was calculated as:

$$F_\mathrm{s}=A_s\times 0.0119\left(\frac{\Delta T_\mathrm{max}-\Delta T}{\Delta T}\right)^{1.231}\times 3.6 \quad (4)$$

where ΔT_max is the maximum temperature difference (°C) between the probe which has no heat flow and the reference probe. The transpiration rate for the orchard was calculated as:

$$T=nF_\mathrm{sd}\Big/S=n\times 24\overline{F_s}\Big/S \quad (5)$$

where T is the daily transpiration of the orchard (mm day^{-1}), n is the number of apple trees in the orchard, F_sd is the daily liquid flux of an individual tree (L day^{-1}), S is the area of the orchard (m^2), 24 is the number of hours in the whole day, $\overline{F_s}$ is the mean hourly liquid flux (L h^{-1}). The daily evaporation of soil at a depth of 0–15 cm in the orchard was measured with a micro-lysimeter (Li et al. 2007) manufactured with PVC. In the test area, 10 points were selected in which to place the micro-lysimeters, and these were weighed at 08:00 every morning. The evaporation during a rainy day was taken as the minimum value from the nearest cloudy day, and the soil in the micro-lysimeter was replaced every 3–5 days. Evaporation from the orchard was calculated as:

$$E=\frac{\varDelta m}{\rho S'} \quad (6)$$

where E is evaporation (mm day^{-1}), Δm is the difference in weight between two adjacent days (g), ρ is the density of water (g cm^{-3}), and S' is the cross-sectional area of the micro-lysimeter (m^2). The canopy-intercepted precipitation (I_P) is calculated by measuring the throughfall and stemflow (Wang et al. 2013). Evapotranspiration from the orchard was calculated as:

$$\mathrm{ET}=E+T+I_\mathrm{p} \quad (7)$$

where ET is evapotranspiration (mm day^{-1}), E is the evaporation of the orchard (mm day^{-1}), T is the transpiration of the orchard (mm day^{-1}), and I_P is the canopy-intercepted precipitation (mm day^{-1}).

Soil water storage (SWS)

The formula used to calculate SWS is:

$$\mathrm{SWS} = \sum \theta_v \cdot h \tag{8}$$

where SWS is soil water storage (cm), θ_v is volumetric soil water content (%), and h is soil depth (cm).

Data analysis

Microsoft Office Excel 2013, JMP, ARCGis10.2, and Origin 9.0 were used to analyze the data and to draw figures.

Results and analysis

Soil water profile dynamics

Precipitation causes rapid changes in the 0–200 cm soil moisture, whereas soil moisture below 200 cm reflects the long-term effects of different land-use patterns. The dynamics of volumetric soil water with depth and time in the four land-use types are presented in Fig. 3. It can clearly be seen that, of the four plots, the soil moisture of the cornfield is the highest, followed by the 9-year-old apple orchard and the wheat field, and the 19-year-old apple orchard has the lowest soil moisture. Changes in soil moisture under different land-use patterns show obvious seasonal characteristics, and the soil moisture content is different across the soil profile. This results from the patterns of growth of the different plants and the local phenology. There is a decrease in soil moisture from 0 cm down to 300 cm and an increase from 300 to 600 cm in the 9-year-old apple orchard. The soil moisture in the 300–600 cm layer is, at approximately 25%, higher than that in the surface layer, and it remains relatively constant over time (Fig. 3b). In the 19-year-old apple orchard, much of the soil moisture at a depth of 0–250 cm is absorbed by fruiting trees. During a period of insufficient precipitation (July), the soil moisture decreases from the top to the bottom of the soil profile. During the rainy season, when the soil moisture is recharged, it increases from top to bottom; the soil moisture content of the upper layer undergoes large fluctuations. In the layer at a depth of 250–600 cm, the greater age of the orchard means that the variation in soil moisture is not extensive; it is consistently about 15% (Fig. 3a). Wheat fields and cornfields are the main types of farmland in this region. Soil-water profile dynamics in these two agricultural systems show a similar trend, in that moisture content initially reduces and then increases. The vertical trend in soil moisture in the cornfield shows a reduction from 0 to 300 cm, and an increase from 300 to 600 cm (Fig. 3c). The moisture content of the 0–300 cm soil layer in the wheat field varies widely each month (Fig. 3d); this shows that 0–300 cm is the main layer affected by rainfall infiltration and water absorption. In this layer, soil moisture changes drastically with time, alternating between dry and wet. In contrast, from 300–600 cm, the soil moisture content changes little each month, and it increases with soil depth.

The results show that there are varying degrees of soil desiccation in the 19-year-old and 9-year-old apple orchards, the cornfield and the wheat field, and that the most serious degree of desiccation is in the 19-year-old apple orchard, followed by the wheat field and the cornfield, with the least severe desiccation occurring in the 9-year-old apple orchard (Fig. 4). Figure 4a shows that soil desiccation conditions in the 0–200 cm soil layer in the 19-year-old apple orchard underwent seasonal variations. The degree of soil desiccation in January–May is, from top to bottom, not desiccated, slightly desiccated and moderately desiccated; that is, the degree of desiccation increased with depth. The degree of soil desiccation gradually increased from the top to the bottom of the soil profile. Soil desiccation in the 19-year-old apple orchard is mitigated by the abundance of rain, so that the degree of 0–200 cm soil desiccation is decreased. The other soil layers in this orchard exhibited severe desiccation at 200–250 cm and strong desiccation at 250–320 cm. The water supplement derived from precipitation does not reach the 250–320-cm soil layer; hence, there is a water deficit in this layer, which is a developing DSL. The 320–600 cm soil layer shows extreme desiccation, with a soil moisture content less than the wilting humidity. There is a seasonal dry layer at 0–30 cm in the 9-year-old orchard, but this would be eliminated when rain fell. A mildly desiccated soil layer at 90–320 cm appeared in the 9-year-old apple orchard between July 30th and September 20th, which is due to the early absorption of soil water and the reduction in precipitation compensation at this time (Fig. 4b). In summary, the soil moisture conditions are good in the 9-year-old apple orchard. The degree of soil desiccation in the cornfield is slightly more severe than that in the 9-year-old apple orchard, but the SWS was similar to that in the 9-year-old apple orchard. Figure 4c shows that there is severe and intense soil desiccation in the 0–20 cm soil layer of the cornfields, and that a temporary DSL extends to a depth of 140 cm, while there is little precipitation in July; however, recovery takes place following a precipitation supplement. No DSL appears below 240 cm. The DSL phenomenon is more serious in the wheat field (Fig. 4d). In this field, the soil layer at 0–70 cm is extremely desiccated from mid-April to July, when it forms a temporary dried layer. A strongly desiccated layer occurs at a depth of 70–100 cm, there is severe desiccation at 100–220 cm, and the degree of desiccation is sequentially

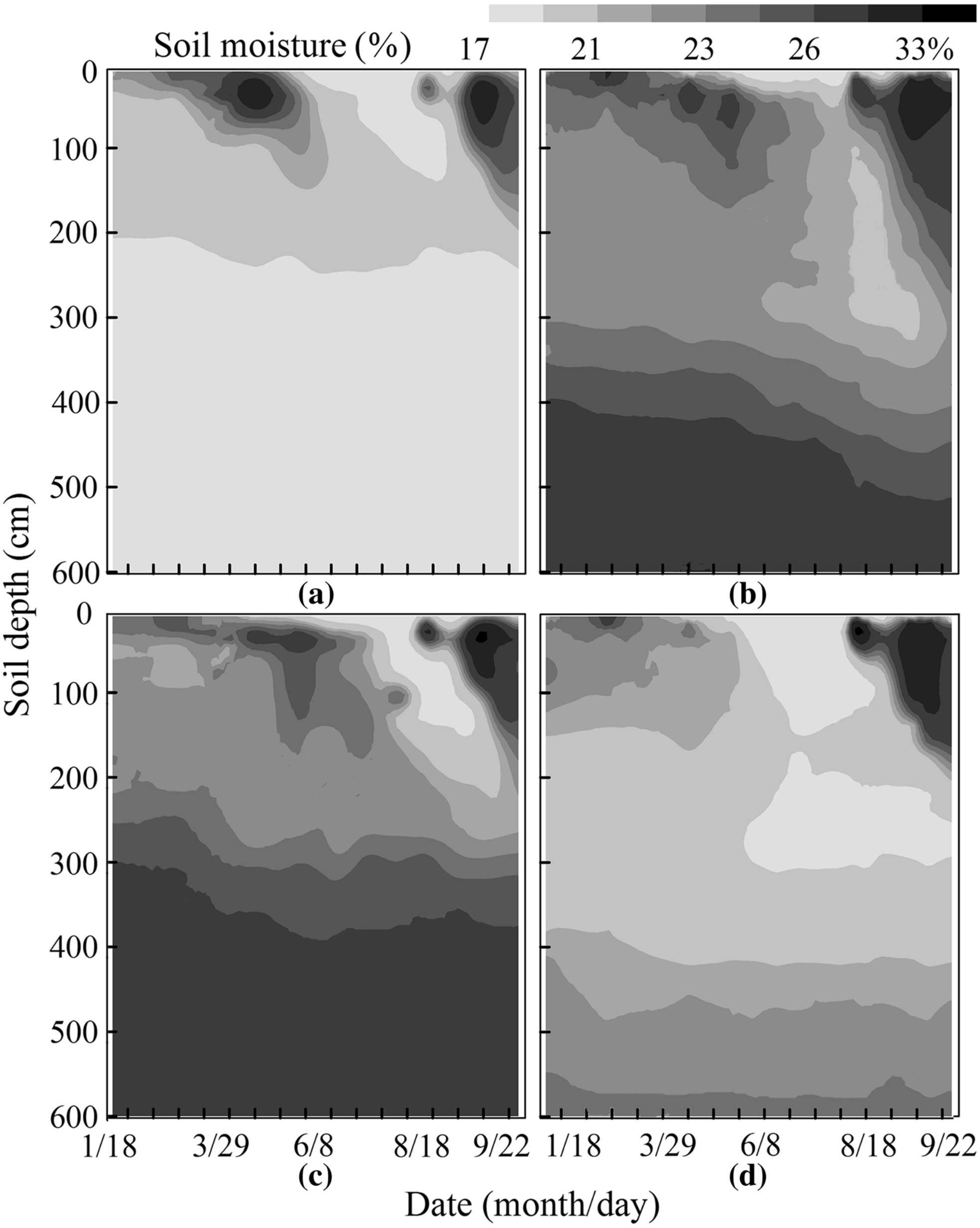


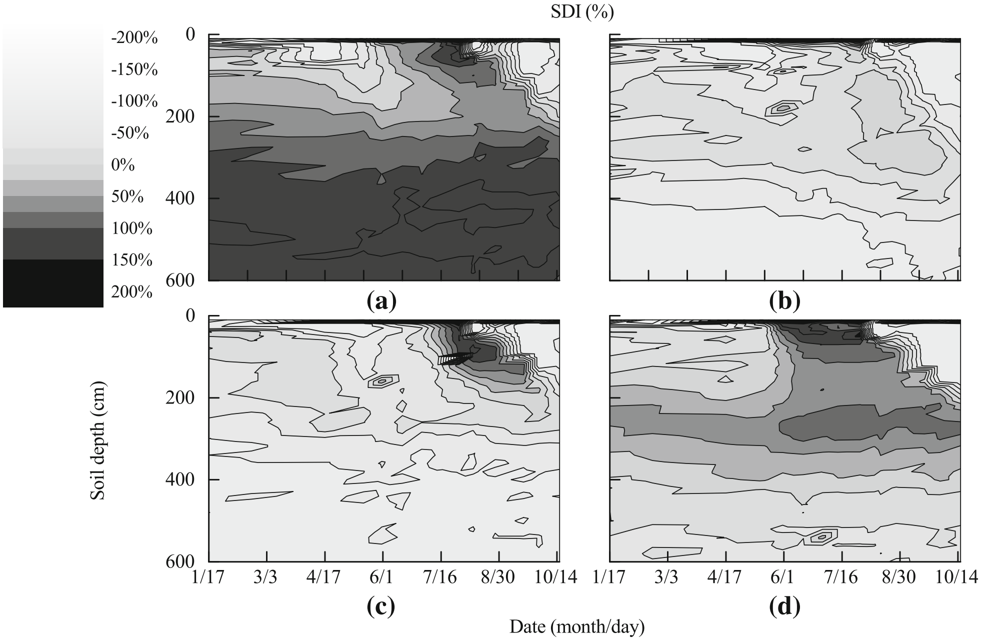
Fig. 3 The soil water profile dynamics of **a** 19-year-old apple orchard, **b** 9-year-old apple orchard, **c** cornfield and **d** wheat field in 2014

strong, severe, moderate, mild and non-dried in soil layers from 220 cm downwards. The results show that transpiration ceased following the harvest on June 25th. Subsequently the 10–40 cm soil layer, which was previously extremely desiccated, became a strongly desiccated layer, and the soil moisture conditions improved; however, a temporary DSL formed in early August when there was little precipitation.

Soil water depletion and recharge depth

Soil moisture shows great spatial heterogeneity, and it is affected by precipitation, evapotranspiration, topography and type of land use. Shallow soil moisture (at depths of 0–200 cm) shows greater fluctuation than that of the deep layer, and there is no strong fluctuation across seasons (Fig. 5). The coefficient of variation (CV) is used to reflect the vertical distribution of soil moisture stability. Generally, variation is considered to be weak where CV < 10%, moderate where CV is 10–100%, and an intense variation where CV > 100% (Wang et al. 2012a). Figure 5 indicates that the extent of variation in soil moisture in the 19-year-old apple orchard, the 9-year-old apple orchard, the cornfield and the wheat field decreases from top to bottom. The intersection of CV curves and the auxiliary line occurs at the shallowest depth in the case of the 9-year-old apple orchard, and soil moisture at a depth of 50 cm showed weak variation for this orchard. The soil moisture in the 19-year-old apple orchard and the cornfield shows moderate variation in the upper soil layers, but by depths of,

Fig. 4 Intensity of soil desiccation (soil desiccation index, *SDI*) in **a** 19-year-old apple orchard, **b** 9-year-old apple orchard, **c** cornfield and **d** wheat field



respectively, 150 and 160 cm the variation is only weak. The intersection of the CV curve and the auxiliary line corresponding to a coefficient of variation of 10% occurs at the lowest depth in the wheat field; here there is weak variation below 180 cm. These findings indicate that the stability of 0–200 cm soil moisture is relatively better in orchards than in farmlands.

The depletion and recharge depths of soil water refer, respectively, to the maximum depth of consumption by plants and the infiltration depth that precipitation can reach, in a given year under a specific type of land use. By analyzing the depletion and recharge depths of soil water in the 0–600 cm profile in 19-year-old and 9-year-old apple orchards, corn and wheat fields (Fig. 3), it was shown that a significant effect on the depletion and recharge depths of soil water was exerted by the type of land use (Table 2). The soil water depletion and recharge depths of the 19-year-old apple orchard are about 600 and 250 cm respectively. For the 9-year-old apple orchard, the supplementary moisture provided by precipitation is greater than the depletion caused by the trees, so that the depletion and recharge depths are about 320 cm, and greater than 600 cm, respectively. Corn and wheat consumed soil water down to 300 and 400 cm respectively, and the recharge depths of soil water in the two fields are more than 600 cm.

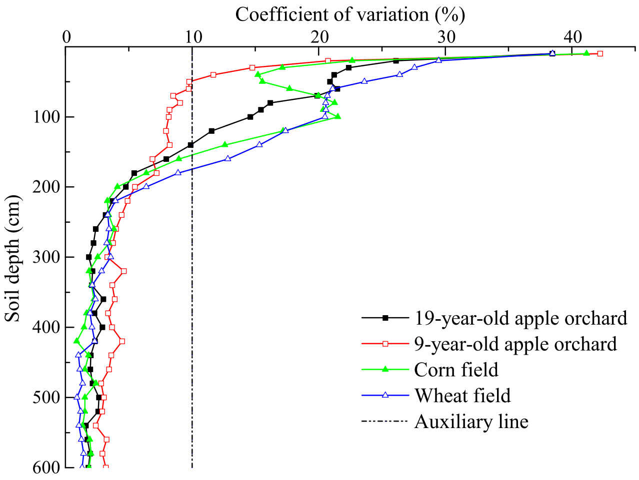


Fig. 5 Coefficient of variation plotted against soil depth for the four land-use types in 2014

The ratio between evaporation and evapotranspiration for orchards

ET is one of the important factors affecting soil-water storage. The ratio of evaporation to evapotranspiration reflects the ability and efficiency of plant utilization of soil moisture. It has a great significance to understand the law of water use and make suitable measures of high efficient water use for the regional soil-water resources by analyzing the dynamic variation of the proportion during the growing season. Figure 6 shows the evapotranspiration and the ratio between evaporation and

Table 2 Depletion and recharge depths of soil water in different land-use types in 2014

Type	Depletion depth (cm)	Recharge depth (cm)
19-year-old orchard	600	250
9-year-old orchard	320	>600
Cornfield	300	>600
Wheat field	400	>600

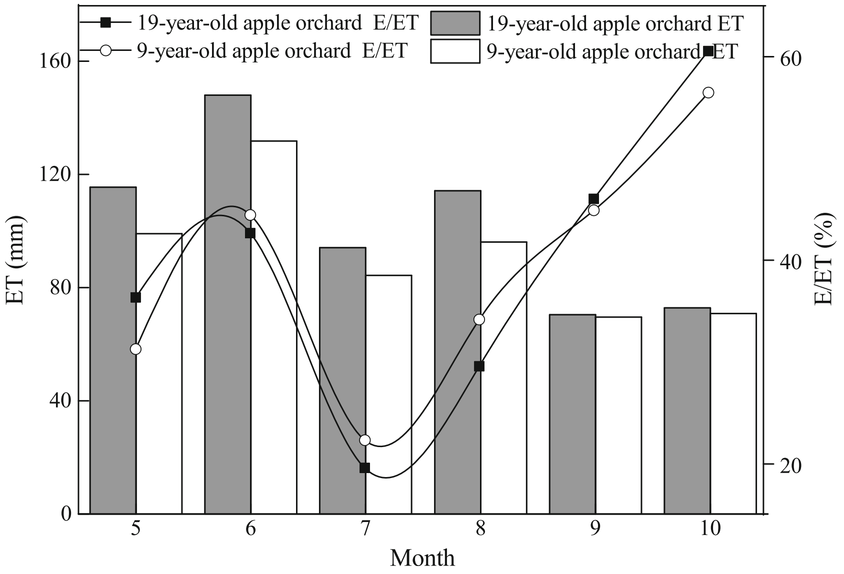


Fig. 6 E/ET and transpiration of apple orchards of different ages in 2014

evapotranspiration for orchards of different ages with different growth patterns. The results show that evapotranspiration from the 19-year-old apple orchard is greater than that from the 9-year-old apple orchard throughout the entire study (May–Oct.). The maximum values, which occur in June, are 148.0 and 131.8 mm respectively, and the minimum are in September, with values of 70.4 and 69.6 mm. E/ET is 19.61–60.57% in the 19-year-old apple orchard and 22.34–56.45% in the 9-year-old orchard, and both orchards show a similar trend consisting of an initial increase followed by a decrease. The apple fruit are mature by the end of August, and at this stage, the physiological activity of the fruit would decline, which would have some effect on the rate of transpiration. The E/ET ratio for the 19-year-old apple orchard rises sharply from August onwards, whereas the value for the 9-year-old orchard rises more slowly. The E/ET ratio is greater for the 9-year-old orchard than for the 19-year-old orchard in June, July and August, whereas the opposite is true for the other months during the period of the study.

DSL response to precipitation

The precipitation in 2014 was 578.8 mm, representing 99.1% of the average precipitation measured over several years. This year was thus a normal year. The precipitation in August and September accounted for 57.2% of the total in 2014 (Fig. 7). The results of soil moisture monitoring show that the mean SWS in the 19-year-old apple orchard, the 9-year-old apple orchard, the cornfield and the wheat field are, respectively, 132.8, 183.6, 186.5 and 158.6 cm; they vary from 120–140, 170–190, 170–190 and 150–170 cm, and the coefficients of variation are 5.5, 4.2, 4.6, and 2.6% respectively. Among the four land-use types, the curve representing SWS in the 9-year-

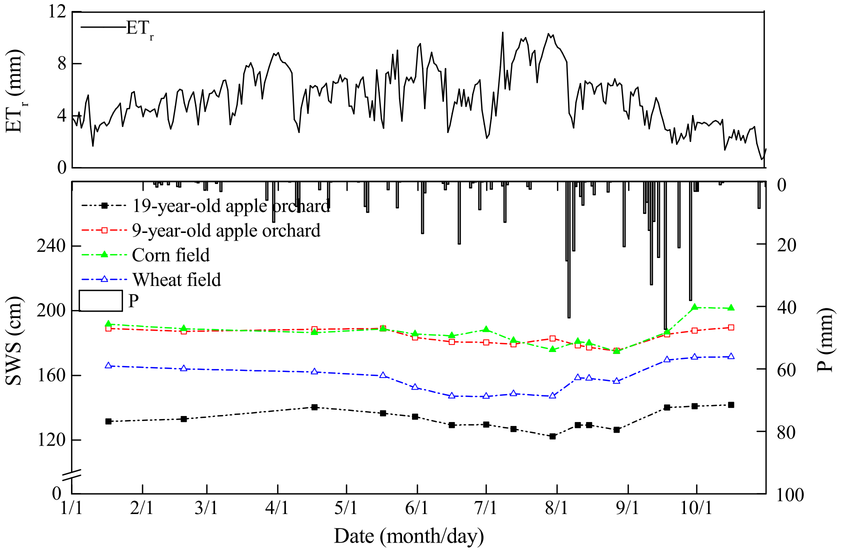


Fig. 7 Temporal variation in potential evapotranspiration (ET_r), precipitation (P) and 0–600-cm soil-water storage (SWS) in 2014

old apple orchard substantially coincides with that of the cornfield; the values here are higher than those for the other two land uses (Fig. 7). SWS did not change significantly from January 15th to May 15th. During this period, the loss of soil water is almost balanced by the input, due to precipitation and also because evapotranspiration is lower. From May 15th to July 30th, precipitation is scarce and soil-water consumption as a result of evapotranspiration is relatively high, so the trend in SWS is one of decrease. Rainfall is concentrated between August 1st and October 15th, and evapotranspiration is low. In particular, between August 5th and September 15th, the amount of soil water stored is significantly increased by the large amount of precipitation. In a word, the mean SWS of the 9-year-old apple orchard, cornfield and wheat field is significantly 38, 40 and 19% higher than the 19-year-old orchard ($p<0.05$), respectively (Fig. 8).

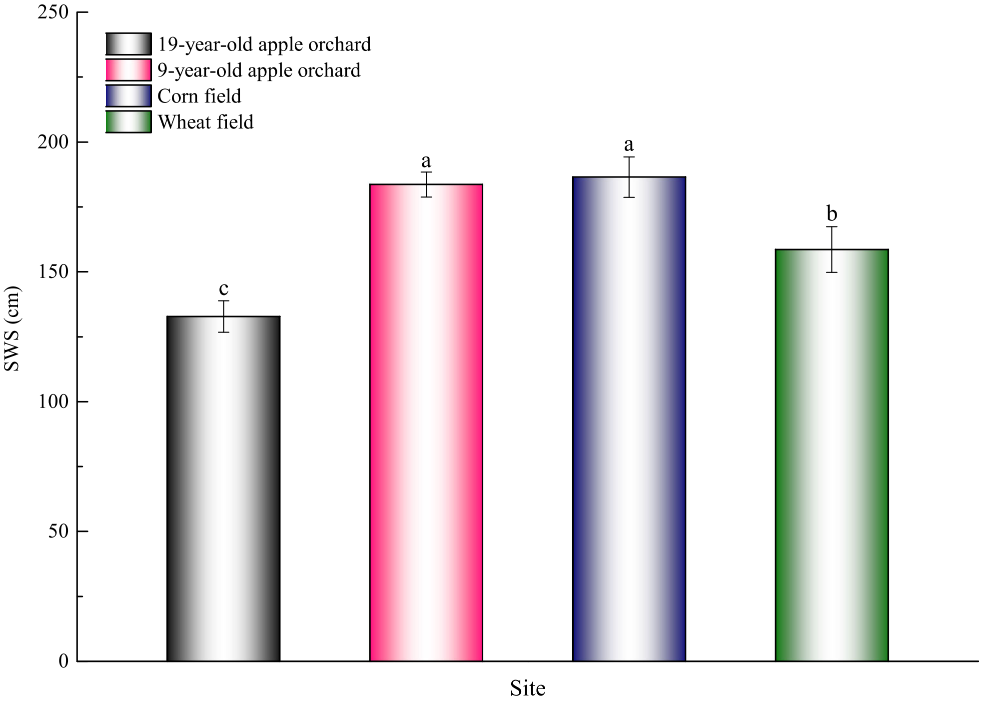
Figure 9 shows the change in SWS among the duration of the study (ΔW) in different layers of the four plots in 2014. It is obvious that the soil water in the surface layer (0–100 cm) can be replenished, and the ΔW is not significantly different among the 19-year-old apple orchard, 9-year-old apple orchard and the wheat field, while there is a significant difference from the cornfield to the others ($p<0.05$). The ΔW of the orchard is greater than that of the cornfield, and the ΔW of the wheat field is more than that of the cornfield ($p<0.05$). When the farmland is fallow, its surface is exposed, and the rate of transpiration in the orchard is lower at this time. Soil evaporation from farmland is greater than that from the orchard, so the ΔW of the orchard is greater than that of the cornfield. The ΔW of the wheat field is more than that of the cornfield, due to the period of harvest, since wheat is harvested in June while corn is harvested in September; thus, the soil moisture of the cornfield cannot be replenished sufficiently during this period. The ΔW in the 100–200 cm soil layer is greater than that in the 0–100 cm soil layer for all plots except the cornfield, which is because soil evaporation from the 100–200 cm soil layer is less than that from the 0–100 cm, but the period of supplementation in the cornfield is shorter than that in the other plots. In this layer, the ΔW of the cornfield is significantly different to the other plots, and it is significantly different between the 9-year-old apple orchard and the wheat field ($p<0.05$). In the soil layers at depths of 200–300 and 300–600 cm, there is a lack of precipitation recharge in the 19-year-old apple orchard, where the water consumption is also the highest, so ΔW is negative, whereas the other plots show positive ΔW values; additionally, the ΔW is significantly different among the 19-year-old apple orchard and other plots ($p<0.05$). The increment for the 9-year-old apple orchard is greater than that for the cornfield and less than that for the wheat field. This indicates that the water consumption of the 19-year-old apple orchard is greater than that of farmland, and that water consumption in the 9-year-old apple orchard is greater than that in the cornfield and less than that in the wheat field.

Discussion and implications

Soil-water conditions among the vertical profile

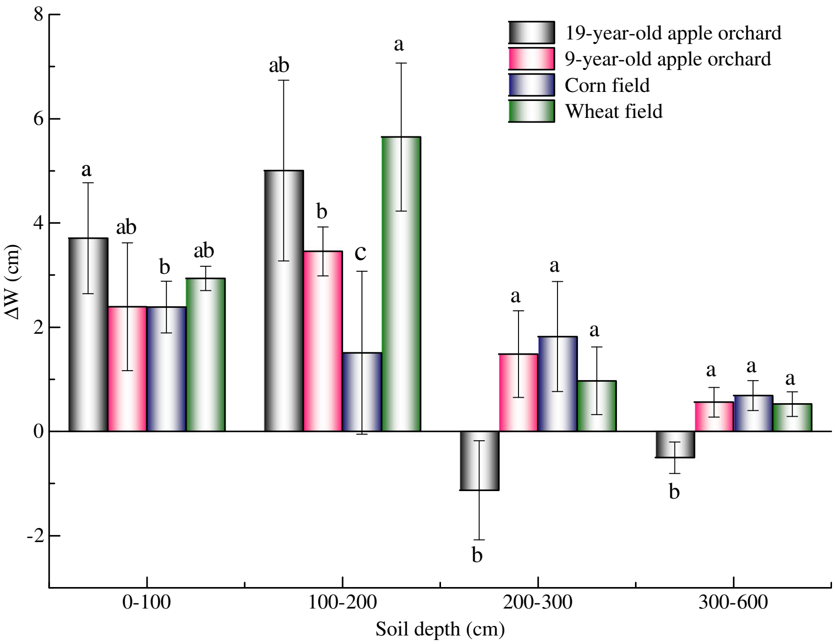
There is significant variation in soil moisture conditions. This study shows that soil moisture conditions at 0–600 cm are better

Fig. 8 The mean soil-water storage (SWS) during 2014 for the four sites for the 0–600-cm soil. The letters *a*, *b*, *c* indicate significant differences between different land-use types, $p<0.05$



]

Fig. 9 Change in SWS among the duration of the study (Δ*W*) in different layers of the four plots in 2014. The letters *a*, *b*, *c* and *ab* indicate significant differences between different land-use types, $p<0.05$



in the 9-year-old apple orchard than in the 19-year-old orchard; this is in accordance with the finding of Wang et al. (2012b), that the soil moisture in the 0–1,800-cm soil layer of an apple orchard decreases with an increase in the age of the orchard. And Yan et al. (2015) also showed that the DSL thickness (DSLT) increased with increasing apple orchard age on the order of 5 years (120 cm) < 12 years (620 cm) < 18 years (>900 cm). The winter wheat is sown in autumn and reaped in the summer of the following year; the entire growth period of this crop is in the dry season that falls between the rainy seasons of the two successive years, so the soil moisture in the wheat field is less than the cornfield. The wheat field undergoes its fallow period from July to mid-October. This period is during the rainfall season in the Loess Plateau, and precipitation is abundant. The process of plowing after the wheat harvest is conducive to soil recovery, making it possible for the soil moisture level to partially or fully recover to the level needed to support transpiration and soil evaporation during the growing season.

Soil desiccation is another manifestation of soil-water deficit. This study found that a temporary DSL occurs in the 9-year-old apple orchard and the corn and wheat fields during seasonal water shortages, but there is no soil desiccation in the deeper layers. Soil desiccation is most severe in the 19-year-old apple orchard, where a permanent DSL is present below 320 cm. This is consistent with the conclusion of Zhao et al. (2007) that soil desiccation would not appear in young orchards, that weak soil desiccation would occur in a 10-year-old orchard, and that the layer would develop rapidly from the age of 15 onwards. The amount of precipitation is low in June–July (Fig. 7), and there is intense radiation, light and other meteorological factors. Moreover, the fruit is at the stage of rapid growth and the tree is leafy; thus, rates of evaporation from the shallow soil and transpiration were both high and soil desiccation is more serious than in the January–May period though water resources are limited during both periods. The research of Li (2001) also indicated that as a result of precipitation infiltration, the 0–300 cm soil layer in an orchard consists of alternate layers of wet and dry soil, and that DSL is distributed at 300–940 cm. Cao et al. (2012) considered that the degree of soil desiccation in rainfed cropland is weaker than that in apple orchards. However in the present study, it is found that soil desiccation in the wheat field is more severe than that in the 9-year-apple orchard, where water conditions are better than those in the 19-year-old apple orchard. These finding indicate that soil-water conditions are related to the age of the orchard. The input of soil water in a young orchard is high relative to the level of evapotranspiration, and the water conditions are better than those in farmland, but with increasing age of the orchard, soil desiccation will be aggravated, so that the soil desiccation in farmland is less than that in older orchards. Fan et al. (2006) and Wang et al. (2003) thought that the depth and extent of recovery of soil moisture increase with increasing number of years of plowing. Since the recharge depth is less than the depth to which the fruiting trees cause depletion of soil water, there is a DSL in the 300–600-cm region in the 19-year-old apple orchard. Accordingly, appropriate human intervention is needed in orchards which have reached their full fruiting potential and are suffering from soil desiccation. If this is done, the trees may have a good rate of survival and develop normally, and trees suffering from the early symptoms of water deficit may be able to recover. Otherwise, as soil desiccation becomes more severe, the orchard will degenerate due to the soil moisture deficit, and some trees may even die.

The consumption and supplementation of soil moisture under different land-use types

The consumption of soil moisture and the depth of supplementation in the 19-year-old apple orchard, the 9-year-old apple orchard, the cornfield and the wheat field under the same conditions of weather and terrain shows a significant variation. This is consistent with the view of Fan et al. (2016b), who studied moisture consumption and supplementation under different land-use types. In the present study, the estimated soil-water depletion depths of corn and wheat fields are 240 and 300 cm, respectively. It is different with Fan et al. (2016a) in that the average maximum rooting depth of corn and wheat are 118 and 150 cm, which is due to the fact that the cropland was an apple orchard 6 years ago. After this change, the soil moisture condition improved to some degree, but the deep soil moisture had not been fully supplemented; thus, there are still some dried soil layers below 118 and 150 cm on the corn and wheat field, which could be caused by water consumption of the apple tree's deep roots at least 6 years ago.

The influence of evapotranspiration on soil water for the two orchards

The present study found that the level of evapotranspiration is relatively higher in the 19-year-old apple orchard than in the 9-year-old orchard (Fig. 3), while the depth to which supplementary moisture penetrates is less in the 19-year-old orchard (Fig. 3). It appears that the soil moisture in the deep soil layer of the 19-year-old apple orchard is significantly less than the soil moisture in the stabilizing layer in the 9-year-old orchard, and this is consistent with research carried out on shrubs by Bao et al. (2015).

The ΔW response to precipitation

This study also showed that SWS fluctuates with changes in precipitation and the trend is basically the same in all cases. The level of supplement is inadequate when the amount of precipitation is small, so that the water available does not meet the evapotranspiration requirements of the crops and the orchards. Thus, the amount of stored water was low between May and July, when there was little precipitation, whereas it increased in response to more abundant precipitation. This view is similar to that of Wang et al. (2001), who found that the average soil moisture in a profile is lowest in September, and Yu et al. (2011), who concluded that the soil moisture deficit in a spring cornfield would reach a peak value in May–August. Water dynamics are complex in the shallow soil (0–200 cm); this soil layer is susceptible to rainfall and plant uptake directly and, in addition, the solar radiation and wind are the indirect factors. Also, the roots of the vegetation are concentrated in this layer; hence, it is the main site for the exchange of water and heat. Beneath 200 cm, the influence of the external climate and vegetation is reduced, and land-use patterns become the dominant factor governing soil moisture. Hu et al. (2010) found that the relative level of soil-water storage in a 0–400 cm soil layer followed the trend 0–100 cm > 100–200 cm > 200–300 cm > 300–400 cm, and noted that the result is affected by the distribution of precipitation, soil evaporation and plant transpiration. The soil-moisture profile of the four land-use type across the 0–200 cm layer followed the pattern low–high–low, consistent with the findings of Jia and Shao (2014).

Conclusion

1. Variability in soil moisture content decreased with increasing soil depth, and there are seasonal changes in soil moisture content across the profile. The processes of depletion and recharge of soil moisture are significantly influenced by the types of land use. The soil-water depletion depths of the 19-year-old apple orchard, the 9-year-old apple orchard, the cornfield and the wheat field were, respectively, 600, 320, 300 and 400 cm, and the recharge depth of the 19-year-old apple orchard was 250 cm, while those of the others were greater than 600 cm. The amount of SWS in the 0–600 cm soil layer in land with the four types of land use followed the trend cornfield > 9-year-old apple orchard > wheat field > 19-year-old apple orchard, and soil-water storage fluctuated with changes in precipitation, but lagged behind these changes.
2. There are different degrees of soil desiccation in the 19-year-old apple orchard, the 9-year-old apple orchard, the cornfield and the wheat field. Due to seasonal water shortages, soil desiccation of the 19-year-old apple orchard, 9-year-old apple orchard, cornfield and wheat field in shallow soil (0–200 cm) sustained about 270, 0, 60 and 90 days respectively, but this phenomenon was eased by precipitation recharge. In addition, the 320–600 cm soil layer of the 19-year-old apple orchard exhibited extreme desiccation, and the dried layer is permanent. In the 250–300 cm soil layer of the wheat field, there is a severe dried soil layer; however, there were no DSLs in the deeper layers of the cornfield and 9-year-old apple orchard. Farmland should replace apple orchards for an indefinite period while there is an extremely desiccated soil layer in the apple orchard so as to achieve the purpose of sustainable development.
3. Under the background of "Green to Grain" in China, the conversion of farmlands to apple forest in Changwu Tableland is viable; however, there will be a risk of severe soil-water storage deficit and soil desiccation with the increasing age of apple tree. This would lead to a physical

land degradation such as desertification, salinization and soil compaction (Yang, 1996); thus, to limit the economic and ecological role of the apple orchard, it will be necessary to reduce tree densities, take effective measures for water conservation and carry out other research if development of the economy and ecology of Changwu is to be sustainable.

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