Variations in water content of soil in apricot orchards in the western hilly regions of the Chinese Loess Plateau

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Abstract
Large changes in land use and land cover types have been occurring in the hill and gully regions of the Loess Plateau since the end of the 1990s. This study revealed dynamic variations of soil water in different layers of representative land use and land cover types under different annual precipitation regimes and assessed the effects on soil water circulation in large areas of apricot [Armeniaca sibirica (L.) Lam.] trees, which have extensive and deep root systems. The results show distinct soil water deficit with a water content of generally <17% (60% of field capacity) in the deep layers of the soil profile of the apricot orchards. Several years after afforestation, perennial soil water deficit layers have subsequently developed around the root zone or even extended to deeper soil layers in the apricot orchards. In the soil profiles, increasing Cl contents are not related to increasing δ²H and δ¹⁸O values. This finding suggests that the extreme deficit of soil water and dry layer developments is mainly caused by intense transpiration, rather than by evaporation alone. The occurrence and development of soil water deficit layers in the deep soil profiles were the dominant factors that caused tree growth degradation and gradual death, due to lack of adequate stored soil water in the deep layers for use during a long arid time. Thus, the large-scale establishment of arbor trees will likely lead to long-term soil desiccation in the arid or semiarid regions on the Loess Plateau.

1 | INTRODUCTION

Current rates, extents, and intensities of land use and land cover changes (LUCC) are far greater than ever in the history, driving unprecedented changes in ecosystems and environmental processes at local, regional, and global scales. Monitoring and mediating the negative consequences of LUCC while sustaining production of essential resources has there-
water demand of forest–grass vegetation (Zhang et al., 2014). However, >20 yr into the program, some ecosystem problems have arisen as the area of afforestation has increased and the area of arable lands has decreased (Wang, Shao, & Shao, 2010; Yang, Wei, Chen, Chen, & Wang, 2014). The subsurface, even deep soil, shows a trend of desiccation caused by large amounts of evapotranspiration in these orchards (Cheng & Liu, 2014). In many places, most trees with broadleaves, like apricot [Armeniaca sibirica (L.) Lam.] trees that were planted early in the GFGP, had initially grown rapidly but subsequently deteriorated gradually or even died for unclear reasons. Most apricot trees and apple [Malus prunifolia (Willd.) Borkh.] trees that were planted later developed rapidly into stunted plants like old trees, with withered, yellowed leaves and no fruit. Generally, orchards like apricot trees can endure arid climate and resist various diseases or pests. In addition, the local farmers always take great care of these economic woods and have many methods to prevent them from suffering diseases or pests. In the field, it can be observed that an apricot tree can live longer than 50 yr or even 100 yr and can produce fruits only if it grows alone or with very sparse density. All these findings prove that dramatic change of climate, diseases and pests, or other occasional events are not the main factors that cause deterioration and even death of these apricot trees.

Ecological restoration has so far brought about both positive and negative effects on the overall ecosystem services. Major changes are emerging in regional hydrology, biogeochemical cycles, and biological diversity, leading to deep soil desiccation, decline in ecosystem productivity, and climate change (Foley et al., 2005). Therefore, many scientists have urgently called for long-term monitoring of the effects of the GFGP (Chen, Shao, & Li, 2008; Cheng & Liu, 2014; Fu, Chen, Ma, Zhou, & Wang, 2000; Shangguan & Zheng, 2006; Wang, Wang, Wei, Shao, & Li, 2008). Regional desiccation of soil resulting from changes in LUCC may generate disastrous changes in the fragile ecosystems with increasing human disturbance of natural ecosystems (Chen et al., 2015; Dardanelli, Bachmeier, Sereno, & Gil, 1997; Jiang, Cheng, Yang, & Yang, 2013), affecting human communities that are dependent on limited local water resources (Li et al., 2016). The positive aspects of soil conservation as a result of the LUC projects are generally seen by the local governments and communities. Still, the negative effects on the ecology, the environment, and water resources because of high density of reforestation over large areas have been noted. In particular, scientists have called attention to the transient and perennial soil desiccation for the reason that stored soil water is essential and supports agricultural production and ecological demands in the arid hill and gully regions of the Loess Plateau (Ampofo, 2006; Zhang & Shangguan, 2018).

Historically, the ecosystems were preserved in a natural state, and the soil water circulation was in balance with precipitation in areas with smaller populations and little

**Core Ideas**

- Great changes in land use and cover types have been occurring.
- Isotopic monitoring data proved no water available to recharge deep soil water.
- Soil water deficit is very distinct and is caused by strong evapotranspiration.

LUCC. Large-scale human activities such as the GFGP have greatly changed the natural land cover types and inevitably disrupted the regional soil water balance. The local farmers have been provided with economic incentives to plant all kinds of orchards with exotic and fast-growing species. Apricot trees are a favored and lucrative species in the hill and gully regions because of the demand for fresh fruits. Besides, dried apricot skin and kernel can be processed into food and Chinese medicine. Apricot trees have vigorous and deep root systems that can extract soil water from deep layers, enabling the trees to survive in seasonal arid climates (Paltineanu et al., 2016). Historically, apricot trees were planted in scattered orchards far from arable lands. In the last 20 yr, the practice has changed, and extensive apricot orchards have been established on former sloped or terraced field.

Many studies have focused on variations in soil water in different land cover types in hillslope areas in comparable arid and semiarid regions in the world (Lawrence & Hornberger, 2007; Voortman, Fujita, Bartholomeus, Aggenbach, & Witte, 2017). On the Loess Plateau, soil water circulation and variation have long been an issue of focus (Yang et al., 2014; Zhang & Shangguan, 2018). However, fewer studies have evaluated the effects of extensive monocultures, such as the apricot orchards on the Loess Plateau, on soil water content (SWC), storage, and circulation. Moreover, previous studies have mainly focused on the lower altitude, wetter lands on the central Loess Plateau. In contrast, the higher, more arid hill and gully regions of the western plateau have rarely been researched. Monitoring of soil water dynamics in such fragile ecological zones is becoming increasingly necessary as the region affected by the GFGP expands.

In this study, three typical land use and land cover types of the hill and gully area of the western Loess Plateau were examined: (a) apricot orchards established between 1999 and 2008, (b) arable land that has not been changed over the last 100 yr, and (c) arable land that was abandoned before 2008 (i.e., wasteland). The aims of this study include observation of soil water dynamics over a period of 2 yr under different annual precipitation regimes and assessment of the effects of large apricot orchards on soil water storage. The more general objective is determination of the distribution and formation mechanism of dry soil layers in the hilly regions of the Loess
Plateau. The findings of the research can support the use of strategies for (a) enhancing effectiveness of the afforestation, (b) soil water conservation for ecosystem sustainability, and (c) ecological restoration.

2 | MATERIALS AND METHODS

2.1 | Site description

The study area lies between the western Liupan Mountains and eastern Huajia Mountains, an area of steeply incised valleys and rolling hills (Figure 1). It is characterized by thick loess deposits (generally >100 m, ranging from 30 to 200 m). The upper layer (~50 cm) is generally dark loessal soil with high organic matter content. The soil overlies Malan loess with low organic content (Derbyshire, Meng, Wang, Zhou, & Li, 1995). The basic properties of the soil are a loose structure and a high silt content. In the field, except for the upper 50 cm with distinct dark loessal soil, it is difficult to distinguish between horizontal layers in the soil profile with the naked eye. The general soil physical and chemical properties can be found in Table 1, with data from adjacent areas for three similar land cover types (i.e., wasteland, orchard, and arable land; Gong et al., 2006; Zhang, 1991). The bulk densities and filed capacities of the loess soil for different land cover types in the upper 40 cm are 1.17–1.207 g cm$^{-3}$ and 20.91% (mass) in wasteland, 1.14–1.27 g cm$^{-3}$ and 24.00% in cropland, and 1.19–1.32 g cm$^{-3}$ and 19.78% in orchard. At the monitoring sites, the field capacity at a depth of ~1.0 m in the cropland changes from 25.0 to 28.4% (mass) (Tan, Liu, Rao, W.B., & Zhang, 2017). The values seem to be higher than that of the surface layer (<40 cm). Here, the definition of field capacity is the amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. According to field observations and experiments in the summer at monitoring sites, wheat (Triticum aestivum L.) crops will wither if the soil moisture content is <15% (mass). The groundwater table is generally >10 m below the surface around the monitoring area. Present land cover types include active land, wasteland, and orchard. Current crops are mainly wheat, corn (Zea mays L.), and potato (Solanum tuberosum L.). Planted apricot trees are the dominant species and occupy >80% of the orchard around study area.

The research area is in the semi-arid zone receiving summer rain from the East Asian monsoon. Over 80% of the total annual precipitation occurs in summer. The average precipitation and temperature from 1990 to 2018 at Pingliang Meteorology Station near the study area (Figure 2) was 513 mm yr$^{-1}$ and 9.65 °C. Detailed meteorological information during the study period, from 2012 to 2014, and supplemental information for 2018 is summarized in Table 2. It can be seen from Table 2 that 2012 was an average year, 2013 and 2018 were the wettest years recorded, and 2014 was a typical wet year.

2.2 | Soil sample collection and analysis

A site at Longchuan County in Tongwei, Gansu Province, located in the high hills of the Loess Plateau, was selected for the seasonal monitoring stations in this study during the two years from early 2013 to the end of 2014 (Figure 1). We selected this area as a monitoring site is mainly because (a) the area shows a typical semi-arid climate without any irrigation methods to resist temporal extreme drought; (b) observable LUCC are expected in this area, where most of the arable lands have been converted to apricot, apple, and pear (Prunus ussuriensis Maxim) orchards with extensive area and high density since 1980 under the GFGP; and (c) most of the apricot trees initially grew and yielded well but gradually deteriorated several years later for unknown causes. Around this site, the following were selected for monitoring: (a) an apricot orchard with an area of ~2 km$^{2}$ and an age >15 yr, (b) a 0.8-km$^{2}$ area of arable land formerly used for cultivation of crops (wheat, corn, or potato) and abandoned >15 yr ago, and (c) a 1.0-km$^{2}$ area of arable land that has been cultivated for crops (only for wheat in recent decades) for several hundreds of years. These land parcels are located halfway up a hill and face south, with similar altitudes and topographic features (Table 1). The distance between the different sites is <1 km, and the slope gradients are relatively gentle, <15°.

The apricot orchard was selected for the following reasons: (a) apricot trees are commonly planted on the hills of the western Loess Plateau, (b) the trees in the study area have deteriorated several years after planting, and (c) the trees have vigorous and deep root systems. Detailed site information is shown in Table 1.
TABLE 1  Records of the basic characteristics of the monitoring sites at Longchuan in the hill and gully regions of China’s Loess Plateau

| Land cover type | Location | Elevation | Soil bulk density<sup>a</sup> | Field capacity<sup>b</sup> |
|-----------------|----------|-----------|-----------------------------|--------------------------|
| Arable land     | 35°20'33.00" N, 105°27'42.00" E | 1,730 | 1.14–1.27 | 24 |
| Apricot orchard | 35°20'15.60" N, 105°27'25.51" E | 1,737 | 1.19–1.32 | 19.78 |
| Wasteland       | 35°20'21.60" N, 105°27'17.20" E | 1,740 | 1.17–1.207 | 20.91 |

<sup>a</sup>Based on Gong et al. (2006).
<sup>b</sup>Based on Zhang (1991). Both studies were carried out in Anjiapo catchment (35°33'-35°35' N, 104°38'-104°40' E) near our study area, as shown in Figure 1.

FIGURE 2  Variation of annual total precipitation and mean temperature from 1990 to 2018. The dash line refers to annual mean total precipitation in the past 25 yr

During the 2-yr monitoring period, soil profile samples were collected in May 2013 (after long dry seasons in 2012 and early 2013, before the summer rainy season), and 2 mo after the end of the rainy seasons in November 2013 and 2014. Soil water samples were also collected during the rainy and intense evaporation season in July 2014 to evaluate the effects of heavy rains and high evaporation on soil water replenishment and desiccation. November can be regarded as a stable period for soil water, falling within a season in which summer recharge has been redistributed within the loess profile, and prior to winter snowfall. Supplemental soil water samples were also collected three years later in January 2018, in order to examine the long-term trends in soil moisture content. Soil samples were collected by using a hollow-stem hand auger. The cores were taken from depths reaching 5 or 6 m from surface, representing approximately the top 5 or 6 m of loess. Bulk soil samples of ~200 g were collected at intervals of 50 cm for stable isotope analyses of soil water. The samples were immediately sealed in airtight polyethylene bottles to minimize evaporation or atmospheric moisture contamination in the field. One hundred and thirty five samples in total during monitoring periods were collected for three types of soil profile.

Approximately 80-g soil samples were collected at intervals of 0.5 m for gravimetric analysis of moisture content and were sealed in aluminum boxes. The initial weights (soil plus box) were determined using a high-precision balance. The samples were dried at 105 °C for 24 h and reweighed. The weight change gives the gravimetric water content. Double-deionized water (50 ml) was added to each oven-dried (50 g) sample. The samples were shaken for 8 h. The resulting solution was separated by centrifugation and passed through a 0.45-μm filter. The solutes were then analyzed for Cl by ion chromatography with errors <5%. The water for the stable isotope analyses was extracted by azeotropic distillation, as described in Tan et al. (2017). The water extracted from soils was directly introduced into a sample injection system of a Flash EA attached via a micro-pump to a Mat 253 mass spectrometer for stable isotope measurements. This procedure was performed at the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, at Hohai University, China. The results were reported relative to Vienna Standard Mean Ocean Water (VSMOW), with SDs of ±1‰ (δ<sup>2</sup>H) and ±0.20‰ (δ<sup>18</sup>O). In this study, the traditional field method (Twarakavi, Sakai, & Simunek, 2009) was applied for estimating field capacity. This method involves...
Table 2 Variation of monthly total precipitation and mean temperature during the study period at Pingliang Meteorology Station (from 2012 to 2014, and supplemental information for 2018)

| Month | Year | 2012 | 2013 | 2014 | 2018 |
|-------|------|------|------|------|------|
|       |      | Precipitation, mm |      |      |      |
| Jan.  | 8.0  | 0.9  | 0.0  | 16.0 |      |
| Feb.  | 2.4  | 7.0  | 18.0 | 8.0  |      |
| Mar.  | 20.0 | 4.0  | 16.0 | 21.0 |      |
| Apr.  | 39.0 | 36.0 | 72.0 | 56.0 |      |
| May   | 50.0 | 89.0 | 11.0 | 60.0 |      |
| June  | 84.0 | 102.0| 56.0 | 149.0|      |
| July  | 43.0 | 236.0| 27.0 | 239.0|      |
| Aug.  | 130.0| 97.0 | 99.0 | 120.0|      |
| Sept. | 86.0 | 154.0| 205.0| 55.0 |      |
| Oct.  | 12.0 | 25.0 | 70.0 | 22.0 |      |
| Nov.  | 3.1  | 9.0  | 11.0 | 27.0 |      |
| Dec.  | 1.0  | 0.1  | 0.1  | 1.0  |      |
| Total | 478.5| 760.0| 585.1| 774.0|

wetting a covered soil profile and waiting for drainage to cease. Due to the difficulty to collect deep soil samples, an average field capacity from the nearby arable land at a depth of ~1.0 m was selected to represent the monitoring sites.

3 | RESULTS

3.1 | Temporal variations for typical land use types

3.1.1 | Apricot orchard

Large temporal fluctuations were observed in the SWC at depths shallower than 3.5 m in the profiles (Figure 3). Higher peaks appeared at 1.0 m in November 2013 and 2014, but not in May 2013 and July 2014 (Figure 3a). Below 2.0 m, the SWC was <17% at all monitoring times.

The Cl content of the soil water exhibited large temporal variations throughout the profiles except for the upper layer (Figure 4a). Two distinct wide peaks in May 2013 and November 2014 could be observed at approximately 1.5 and 3.0 m. These values were much lower in November 2013 and July 2014. Compared with the deeper layers, the Cl content exhibited lower values near the surface.

The stable H and O isotopic compositions of the soil water indicate larger temporal variations throughout the profiles can be observed (Figure 5a). Both the H and O isotopic curves in November 2013 were obviously different from those at other times. Among the average values, the upper layers exhibited larger temporal variations in $\delta^{2}H$ and $\delta^{18}O$, with CVs of 5.91 and 9.86‰, respectively. In contrast, the lower soil profiles exhibited smaller temporal variations in $\delta^{2}H$ and $\delta^{18}O$, with smaller CVs of 3.51 and 2.52‰, respectively (Table 3).

3.1.2 | Arable land

The SWC exhibited large temporal variations at depths shallower than 3.5 m in the profile, and the SWC distinctly increased in November 2013 but was relatively deficient in November 2014. The upper layers exhibited lower SWC in May 2013 and July 2014 with respect to other times (Figure 3b). A sharp variation in the SWC occurred at depths deeper than 3.5 m, and the SWC increased downwards to a depth of 6.0 m or more in all the profiles. The temporal variation in the SWC also remained relatively small at depths deeper than 3.5 m. As a result of recent recharge from snow melt, the SWC increased above a depth of 1.0 m in the profile in January 2018. However, the variation in the SWC at depths deeper than 3.5 m in the profile in January 2018 showed a similar trend to that of other times. The Cl concentration of the soil water exhibited a large temporal variation above a depth of 3.5 m but was more stable in the lower soil profile (Figure 4b). It was distinctly enriched at a depth of 1.5 m in May 2013 after experiencing a long arid season during which intense evapoconcentration occurred. In addition, the use of chemical fertilizers (potash as KCl) in late spring may also increase Cl content in the upper soil layer in the arable land. The Cl concentration greatly decreased at depths below 3.5 m during all the monitoring times except for November 2014.

The stable H and O isotope compositions of the soil water exhibited large temporal variations throughout the profiles because of differences in the SWC and Cl contents. No obvious inflection point at a depth of 3.5 m was observed (Figure 5b). However, we still identified differences in the average $\delta^{2}H$ and $\delta^{18}O$ values above and below a depth of 3.5 m. In contrast, in the layers above and below 3.5 m,
**FIGURE 3** Soil moisture variations in different soil layers among three land cover types at the Longchuan monitoring site during different months from May 2013 to January 2018; the dashed gray lines denote stable field capacity (17%), which can be considered the lower limit of the dry layer: (a) apricot orchard, (b) arable land, and (c) wasteland.

**FIGURE 4** Chloride concentration of the soil moisture in different soil layers among three land cover types at the Longchuan monitoring site during different months from May 2013 to November 2014: (a) apricot orchard, (b) arable land, and (c) wasteland.
**FIGURE 5** Depth profiles of $\delta^{18}$O and $\delta^2$H in the soil moisture from different land cover types at the Longchuan monitoring sites during different months from May 2013 to November 2014: (a) apricot orchard, (b) arable land, and (c) wasteland

**Table 3** The average values and temporal CVs above and beneath 3.5 m in different land covering soil profiles at different months at the Longchuan monitoring site

| Land type    | Month    | SW  | $\delta^2$H | $\delta^{18}$O | SW  | $\delta^2$H | $\delta^{18}$O |
|--------------|----------|-----|-------------|---------------|-----|-------------|---------------|
|              |          | %   | %           | %             | %   | %           | %             |
| Apricot orchard | May 2013 | 14.19 | 84.6 | -58.5 | -7.06 | 14.52 | 72.25 | -71.7 | -9.19 |
|              | Nov. 2013 | 18.99 | 37.20 | -61.1 | -8.14 | 17.51 | 18.72 | -75.5 | -9.68 |
|              | July 2014 | 14.99 | 36.55 | -62.5 | -7.31 | 14.91 | 27.03 | -78.3 | -9.71 |
|              | Nov. 2014 | 17.62 | 49.52 | -68.6 | -9.04 | 16.22 | 54.81 | -72.5 | -9.25 |
|              | CV       | 11.80 | 37.6 | 5.9 | 9.86 | 7.45 | 49.64 | 3.5 | 2.52 |
| Arable land  | May 2013 | 16.91 | 223.5 | -66.3 | -8.73 | 22.15 | 43.20 | -80.3 | -10.43 |
|              | Nov. 2013 | 21.67 | 70.71 | -65.7 | -8.84 | 22.30 | 32.13 | -75.5 | -9.81 |
|              | July 2014 | 14.57 | 77.05 | -66.7 | -8.66 | 20.78 | 26.83 | -82.3 | -10.93 |
|              | Nov. 2014 | 17.83 | 32.96 | -68.9 | -8.93 | 21.29 | 25.29 | -78.5 | -10.32 |
|              | CV       | 14.43 | 71.92 | 1.8 | 1.19 | 2.88 | 22.03 | 3.2 | 3.85 |
| Wasteland    | May 2013 | 16.44 | 34.97 | -59.9 | -7.44 | 16.82 | 34.37 | -68.2 | -8.34 |
|              | Nov. 2013 | 19.16 | 27.39 | -66.1 | -8.97 | 18.16 | 30.07 | -74.3 | -9.12 |
|              | July 2014 | 19.68 | 34.72 | -72.9 | -9.57 | 18.16 | 59.11 | -73.3 | -8.92 |
|              | CV       | 7.71 | 10.87 | 8.0 | 10.33 | 3.57 | 31.07 | 3.7 | 3.76 |
the average δ2H and δ18O values showed minor temporal differences, with smaller CV, Cl content, and SWC.

3.1.3 | Wasteland

The SWC in the profiles was high and exhibited large temporal variations above a depth of 3.5 m, gradually decreasing towards deeper layers (Figure 3c). The SWC was the lowest in the upper soil profile in May 2013, after experiencing a longer drought in 2012 and early 2013. In contrast, the SWC in November 2013 and 2014 and particularly in January 2018 exhibited a distinct increasing trend in the upper layer, but a decrease in the lower profile below a depth of 3.5 m. The Cl content of the soil water exhibited similar temporal variation. Consistent distinct peaks at a depth of ~3.5 m were identified at different times (Figure 4c). Except for November 2014, the average Cl content in the upper and lower soil layers exhibited smaller variations at different times (Table 3).

A larger temporal variation in the stable H and O isotopic compositions of the soil water was observed above a depth of 2.5 m, which decreased in the lower layers (Figure 5c). The δ2H and δ18O values in the profile exhibited a smaller variation range below a depth of 1.5 m in different layers in May 2013 after the arid season. However, distinct peaks and valleys could be observed in the profile in November 2013 after heavy summer rainfall. The average δ2H and δ18O values in the upper (<3.5 m) and lower (>3.5 m) profiles exhibited obvious differences and a wider range of temporal variations (Table 3).

3.2 | Comparison of different land use profiles

3.2.1 | The upper layers in the profiles

When comparing the arable land, apricot orchard, and wasteland, the SWC in all the profiles for layers above a depth of 3.5 m exhibited larger temporal variations and gradual decreases in the lower layers. The Cl content was also high at approximately <3.0-m depths. In the field, we observed no distinct change in the soil properties such as color and texture at depths shallower than ~3.0 m. Generally, intense evaporation cannot exceed a depth of 2.5 m (1.0–2.5 m) in the loess deposit region (Tan et al., 2017). The research area was in the hill and gully regions of the Loess Plateau and the monitoring sites were selected on the shady side, facing away from the sun. The evaporation limit should be much deeper (Ruiz-Sánchez, Plana, OrtunO, Tapia, & Abrisqueta, 2005). The depth of the background moisture is 0–100 cm underground for growing wheat (Fang, Liu, Zhu, & Deng, 2008). In the soil profiles below a depth of 3.5 m, the SWC on the arable land was the highest and increased in the deeper layers (Figure 3). In contrast, the SWC of the wasteland was lower than that of the arable land but higher than that of the apricot orchard, decreasing in the deeper layers. The SWC of the apricot orchard was much lower than that of the arable land and remained stable from a depth below 2.0 m to the bottom of the monitoring depth. The Cl content curves in the profiles were also very different for different land use and cover types (Figure 4). The Cl content at depths shallower than 3.5 m was much higher on the arable land, with values 10–100 times higher in May and July than those of the other land use types. These abnormal scenarios could have been caused by fertilizer use during the growing season in spring and early summer. Winter wheat is commonly planted on the bare high hills of the Loess Plateau. Chemical fertilizers such as potash (KCl) and NH4Cl are the main methods to increase productivity. Thus, the sharp increase in the Cl content in the upper soil layers in May and July on the arable land was related to input of chemical fertilizers. According to the stable H and O isotopic curves of the soil water, no obvious difference existed among the different land use and cover types at a specific time, except for a larger difference at depths <2.0 m (Figure 5). It is expected that different land cover types should show significant temporal variations in the δ2H and δ18O values in the upper layer near the surface, due to different evaporation intensities and infiltration rates of the general precipitation events.

4 | DISCUSSION

4.1 | Soil water recharge

The SWC, Cl content, and stable H and O isotopic compositions of the soil water at different depths show temporal variations. The decrease in SWC is neither related to Cl
accumulation nor to δ^2H or δ^{18}O enrichment. These characteristics suggest that the SWCs in the profiles were related to temporal replenishment in addition to evaporation. In the case that the soil water originates from deep, upward-moving, confined groundwater (so-called ancient water), the δ^2H and δ^{18}O values of the soil water in the deeper layers, where the evaporation is smaller, should be stable and show gradual enrichment in heavier isotopes toward the upper layers where higher evaporation near the surface lakes place (Kendall & McDonnell, 1998). However, these types of variation trends did not appear in the stable isotopic curves or Cl content trends from bottom to top within the soil profiles.

The soil water samples collected at all the times plot close to the local meteoric water line (LMWL, Figure 6). The weighted average isotopic composition of larger precipitation events (>5 mm) during the monitoring time plots close to the intermediate area of the soil samples, affirming that local precipitation was the recharge source for the soil water. Redistribution and mixing of immobile water in the soil and mobile recharge water during precipitation events should have occurred when precipitation infiltrated into the soil profile. With increasing proportion of immobile soil water, the soil water samples plot along the upper-right LMWL or evaporation line. Thus, most of the soil samples plot in the right or upper-right area of the weighted average value of the local meteoric water. Some soil samples collected at different times or different depths within the soil profile plot in the left or lower-left areas of the weighted average value of the meteoric water, indicating depletion of heavier isotopes. Rapid infiltration of precipitation (with depleted heavier isotopes compared with soil water) and condensation of water vapor near soil surface under larger temperature differences between day and night may cause the samples to plot in the lower-left area of the LMWL. It is generally believed that condensed water vapor is one of the recharge sources for shallow soil water in the hill and gully regions of the Loess Plateau because of the larger temperature differences between day and night (Guo & Han, 2002).

Regarding the infiltration processes of precipitation, soil water evaporation, and vegetation transpiration in the upper soil profiles, a large difference at different times and under different land uses and land cover types are found. The large temporal SWC variations at depths of <3.5 m was mainly caused by the amount of precipitation, infiltration, and intensity of evaporation and/or evapotranspiration. However, the distinctly different shapes of the SWC curves during a season may be caused by different recharge rate. For example, the deficient soil water at depths of <3.5 m, which was caused by higher evaporation during the drought season, was restored after the heavy summer rainfall recharge in May 2013 or July 2014. However, even in the extremely wet year of 2013, the abnormally deficient SWC between the 3.5-m depth and the bottom of the monitoring profiles (6.0 m) in the apricot orchard did not recover and remained very low by November 2013. Compared with the arable land, water deficit in the lower soil profile of the apricot orchard was much more distinct. Thus, soil water deficiency in the deeper profile of the soil of the apricot orchard should be more serious in the dry season or relatively dry years.

Larger variations in the temporal infiltration depth and mode of precipitation occurred in the stable H and O isotopic compositions across the monitored soil profiles of the arable land. Chloride accumulated at a depth of ~3.0 m in May 2013 and July 2014 because of fertilizer (KCl and NH₄Cl) use near the surface. However, the Cl contents below 3.5-m depth greatly decreased, and the curves became smooth. In particular, the prominent Cl peaks decreased significantly in the soil profiles in November after the rainy season recharge and crop growing season. Apparently, some accumulated Cl near the surface was absorbed by the crops (winter wheat) with fertilizers during spring and early summer growing seasons. Because the arable land is located on sloping land, it is also possible that some Cl was leached by surface runoff during heavy storms. However, this should be limited to the surface layer. The obviously low Cl content in the soil profile in November 2013 with respect to May 2013 may also be caused by spatial variations in fertilization.

Compared with the arable land, SWC, Cl contents, and stable isotopic compositions of the soil water in the apricot orchard and wasteland showed different characteristics. Larger temporal variations in the SWC, Cl contents, and stable H and O isotopic compositions are observed, mainly at depths shallower than 2.0 m, indicating that temporal replenishment of soil water mainly occurred to a depth of 2.0 m. This seems to be more obvious in January 2018, after infiltration of snow melt water. The SWC increased greatly to a depth of 1.0 m. The Cl concentration in the soil water was high at depths >2.0 m for all the monitoring times. Except for the profile in November 2013, which followed abnormal summer precipitation, the stable H and O isotopes of the soil water showed very small variations and almost no identifiable differences in the average δ^{18}O values within the uncertainties for the apricot orchard. Thus, the amount of soil water replenishment below a depth of 2.0 m for the apricot orchard should be negligible. This caused distinct accumulation of Cl above a depth of 5.0 m because of the lack of mobile soil water to leach Cl into deeper layers. In May 2013, the SWC dropped to the lowest value (~10%) between depths of 2.0 and 3.0 m, after experiencing a longer drought season. Although the SWC increased at depths above 3.0 m in the November profiles after the summer rainfall recharge, and after the unusually heavy rainfall that occurred in the summer of 2013, the SWC in the deeper layer at depths below 3.0 m
was still very low, with no obvious increase. Several heavy rainfall events with a monthly total precipitation of ∼148 mm occurred in September 2014. In the soil profile of the apricot orchard collected in the last 2 mo of November 2014, a very wide Cl peak can be seen at depths between 2.0 and 5.5 m, indicating that some water had moved downward to these layers. However, the SWC was still low, with no distinct variations below a 3.5-m depth, indicating that the amount of replenishment of soil water after the heavy rainfall in September 2014 was very limited, and the deficit in soil water had not significantly changed. Similar to the apricot orchard, 2 mo after the unusually heavy summer precipitation in 2013 and heavy rainfall in September 2014, the replenishment of the soil water in the lower profile of the wasteland was very limited and the depleted water was not restored. This is also reflected in the small variations in the stable H and O isotopic compositions of the soil water in the lower part of the profiles.

4.2 Temporal variations in soil water storage

Generally, the SWC near the surface varies greatly and is randomly affected by precipitation events and evaporation. For this reason, in order to study the relatively stable temporal variations in the soil water storage, the soil layer below 2.5-m depth was selected. Previous analyses showed that the SWC exhibits sharp variations at a depth of ∼3.5 m, representing the limiting depth of evaporation. Thus, the strata with identical thickness at depths from 2.5 to 3.5 m and from 4.0 to 5.0 m in the soil profiles were selected to compare the temporal soil water storage under different land use and land cover types. Here, the soil depths between 2.5 and 3.5 m represent the strata above the evaporation front, and those between 4.0 and 5.0 m represent the strata with weak evaporation effects. The following equation is used to calculate the soil water storage to a specific depth of 1.0 m:

\[ W = \sum_{i=1}^{n} \theta_{mi} \rho h_i \]

where \( W \) is the soil water storage at a specific depth (mm), \( n \) is the number of soil strata, \( \theta_{mi} \) is the soil moisture content of strata \( i \) (g g\(^{-1}\)), \( \rho \) is the average soil bulk density (g cm\(^{-3}\)), and \( h_i \) is the depth at interval \( i \) (mm). It is difficult to measure the soil bulk density in the deep soil layers. The average
value (1.46 g cm\(^{-3}\)) of the surface layers (approximately 0.5 to 2.0 m) was used in this equation because variations in soil properties are relatively small for a typical profile. Although this value may not be very accurate for assessing deep soils, it can be used to track the temporal variation trend.

The temporal soil water storage in both the upper and lower soil layers was the highest in the arable land, followed by the wasteland and apricot orchard, during the 2-yr monitoring timeframe and the supplemental time of January 2018 (Figure 7). Correspondingly, the total soil water storage in the lower part of the profile of the apricot orchard remained stagnant, showing almost no variations. Even after strong recharge during the unusually heavy rainy season in 2013, normal rainfall in July 2014, and intense rainfall in September 2014, the soil water storage in the upper soil layer of the apricot orchard exhibited small variations while the water storage in the lower layer was low and retained unchanged. Although the upper layer of the wasteland exhibited larger temporal soil water storage, no increasing trend was observed in the lower layer, even after heavy rainy season recharge in 2013. Notably, the soil water storage in the upper layer (from 2.5 to 3.5 m) and lower layer (from 4.0 to 5.0 m) of the arable land was 36 and 30\% higher, respectively, than that in the apricot orchard in May 2013 after a longer period of aridity. Thus, the soil water deficit in the profile of the apricot orchard was very distinct compared with that of the arable land, which in this scenario showed no variation even 3 yr later in January 2018. Despite smaller temporal soil water storage in the deeper layer of the arable land, the total amount of storage was the highest compared with that in the wasteland and in the apricot orchard. The soil water storage in the lower profile was almost unaffected despite the larger temporal variations in the upper layer of the apricot orchard. Similar to the apricot orchard, the larger temporal variations in the soil water storage of the wasteland mainly occurred at depths above 3.5 m; however, the total storage in the deeper layer was higher than that in the apricot orchard. Hence, the soil water storage capacity indicates that arable land is a better land use type for storing deep soil water and is more favorable for precipitation infiltration to replenish deep soil layers. Wasteland is unfavorable for precipitation infiltration to recharge deep soil layers. In contrast, apricot orchard is unfavorable for soil water storage and deep soil water replenishment. Arable land is the best and apricot orchard is the worst land use and land cover type for maintaining hydrological circulation of soil water in the loess profile of the hill and gully regions of the western Loess Plateau.

### 4.3 Soil desiccation and formation mechanisms

Historically, apricot trees had been sporadically planted because larger trees can severely affect nearby crop growth and productivity. Over the last 20 yr, larger areas with high densities of apricot orchard have been planted with the development of afforestation programs. Two negative effects have gradually occurred over the 10-yr period of tree crown expansion on these apricot orchards. One effect is that the crops that are grown on primary fertilized arable lands around the woods exhibit unhealthy growth, greatly reduced productivity, or even lose facility for continued cultivation. The other effect is that most trees gradually deteriorate several years later and appear as small, old trees with withered and yellow leaves, losing their economic value because of a lack of fruit, or even dying.

It remains unclear why most trees grow well during younger stages but gradually deteriorate or even die several years later. Most studies have concluded that this phenomenon is caused by soil desiccation and water deficits as a result of unreasonable land use (Jiang et al., 2013; Zhang et al., 2014). Apricot orchards are good examples of large quantity of soil water consumption. A water content of 75\% of field capacity should be close to the upper limit of the SWC in the soil layer (Cheng & Liu, 2014). Scientists generally agree that an SWC <60\% of field capacity is a normal value for dry layers, which represents the spatiotemporal stability of a lower SWC (Wang et al., 2008). Dry soil layers with SWCs <60\% of field capacity can be considered impossible to replenish under baseline climate conditions. Thus, a 60\% of the local field capacity (average = 28.44\%) can be used as the upper limit of the dry soil layers in the hill and gully regions of the Loess Plateau (~17\%). This value can be classified as the soil with distinct deficit water or dry layer if the SWC is constantly <17\% at a specific depth (deeper than 1 m) in a normal year.

The dashed line in Figure 3 denotes the borderline of the upper limit of the dry soil layer. The SWC was occasionally lower than the critical values of the stable field capacity but was replenished after the heavy summer rainfalls in 2013 in the upper 2.5 m of the arable land. No stable dry layers existed below a depth of 2.5 m. The SWC was temporarily lower or close to the critical values below a depth of 4.0 m in the wasteland. However, this land cannot be classified as having typical perennial dry layers for temporal variations of SWC. In contrast, characteristic soil desiccation and its developments occurred in the apricot orchard. The previous soil water deficit above a depth of 2.5 m was somewhat replenished after an unusually heavy precipitation in summer 2013 and several heavy rainfall events in September 2014. However, the SWC below a depth of 2.5 m in the apricot orchard exhibited lower values than the critical value over 2 yr of monitoring time. The layer with unusual deficit soil water below the depth of 2.5 m was also maintained in winter (January) 2018. Even after the extremely large precipitation events in summer 2013, the depleted water in the dry layers below a depth of 2.5 m was not restored. During a normal precipitation year, the dry soil could not be restored at all.
These observations unequivocally confirm the existence of perennial dry soil layers that had developed below depths of 2.5–6.0 m, even deeper for apricot trees that are >10 yr old.

To explore the mechanism of dry layer formation in the deep layer of apricot orchard, Cl contents and δ²H data (δ¹⁸O, as well) are analyzed. No consistent temporal variations in the Cl content and stable H and O isotopic compositions of the soil water were found. Some wide and high Cl content peaks were present in the soil profiles, indicating a longer Cl accumulation time. However, variation in the Cl content is not related to the stable isotopic composition. The layers with increased Cl do not show increased δ²H and δ¹⁸O values. Thus, the extreme deficit in soil water and perennial developments of dry layers in the lower soil profile of the apricot orchard should have formed from intense transpiration rather than evaporation. Otherwise, evaporation alone would result in increase in both Cl and heavier isotopes at a specific depth in the soil profile. Unlike evaporation, intense transpiration could exhaust deep soil water and create soil water deficit and increase Cl concentration, but it should have no effect on stable isotopic fractionation. Even if recharge occurred, the real amount of water that could be recharged to the deep soil was very limited and could not have effectively restored the water deficit. This observation also explains the mechanism governing smaller temporal variations in the average δ²H and δ¹⁸O of the soil water in the deeper layers of soil in the apricot orchard.

The current apricot orchards were transformed from arable land >10 yr ago. The geomorphology or topography and the soil properties and textures do not exhibit significant differences in the arable land, apricot orchard or wasteland that were monitored in this study. However, over 10 yr, tree planting had completely changed the soil water hydrology. Water storage in the deep soil layers has been greatly reduced due to higher evapotranspiration, and perennial dry layers have formed, it has not been able to restore the dry layers even in an unusually wet year such as 2013. Thus, the artificial changes in the land use and land cover types from large-scale afforestation, particularly with tree species such as apricot trees with large and deep root systems and large areas of planting, have caused dry layers in the deep soil profile. The real formation mechanism is that the trees continually extract soil water from the deep layers to maintain intense evapotranspiration during arid seasons. Even water from larger precipitation events cannot infiltrate through the evaporation front. The downward infiltration and percolation of soil water is gradually redistributed as lateral recharge and prevents from replenishing the deep soil layers because the soil water could not overcome the high soil matrix potential in the dry layers. The greater the soil water deficit is in the deep layers, the more difficulty the limited soil water in the upper or surface layer will experience when percolating through the dry layers to recharge the deep soil water. That is, the drier upper soil layer inhibits soil water recharge in the lower layer. The occurrence and development of dry soil layers in the deep soil profile is a dominant factor that has caused tree growth deterioration and gradual death because of an inadequate amount of stored soil water in the deep layers during arid seasons. That said, it is just the large scale and high density of apricot tree planting that cause perennial dry soil layer development. Correspondingly, the development of deficit water in the deep soil gradually makes apricot tree deteriorate and even die.

### 4.4 Soil water conservation in the hill and gully regions of the Loess Plateau

Most areas in the hill and gully regions of the Loess Plateau are arid to semiarid with potential annual evaporation
5 | CONCLUSIONS

1. Apricot and other fruit trees have been widely planted as profitable orchards on the arid to semiarid hills of the western Loess Plateau over the last 20 yr since the implementation of GFGP by the Chinese government. These trees have relatively high survival rates due to their vigorous and deep root systems. However, perennial dry layers have subsequently developed around the root zone or even extended to deeper layers in apricot orchards several years later. Even in an unusually wet year such as 2013, water deficit in the dry layers could not be efficiently restored. The occurrence and development of dry soil layers in the deep soil profile is the dominant factor that has caused tree growth degradation and gradual death, because the amount of stored soil water in deep layers that needs to be extracted during arid seasons was inadequate.

2. The extremely depleted soil water and development of perennial dry layers in the lower soil profile of the apricot orchards should have been caused by intense transpiration in addition to evaporation. Evaporation slightly affected the SWC at depths deeper than 3.5 m in the soil deposit profile. The formation mechanism of the dry layer is that the trees continually overextracted soil water from deep layers to maintain intense evapotranspiration, while the infiltration and downward percolation of soil water was gradually redistributed to lateral recharge and was prevented from replenishing the deep soil layers because the soil water could not overcome the high soil matrix potential in the dry layers.

3. In the loess profile in the hill and gully regions of the semiarid western Loess Plateau, arable land is more conducive to storage of soil water and precipitation infiltration to replenish deep soil layers. This may be the best land use type to maintain hydrological circulation of soil water. Wasteland tends to hinder precipitation infiltrating and recharging the deep soil layers.

4. Apricot trees tend to have higher rates of evapotranspiration. In order to conserve soil water resources in the arid and semiarid hill and gully regions of the Loess Plateau, large-area afforestation with such species is not recommended for implementation of the GFGP. Otherwise, the problem of soil desiccation and the development of dry layers will become increasingly severe on the Loess Plateau.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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