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Deficit and Recovery of Deep Soil Water Following a Full Cycle of Afforestation and Deforestation of Apple Trees on the Loess Plateau, China

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Abstract: Land-use change could substantially alter the soil water balance and hydrological cycles; however, little is known on the changes in deep soil water following a cycle of afforestation and deforestation. The purpose of this study was to quantify the soil water deficit in an apple orchard and subsequent replenishment of deep soil water after the orchard was felled. Soil water changes were quantified using the "space-for-time" method through a paired plot design. The results showed that the water storage in deep soil (>3 m in depth) began to decrease when the apple tree reached about 10 years of age. The cumulative deficit of deep soil water storage in the 3–18 m soil depth could reach about 1200 mm; however, deep soil water was so depleted that apple trees can no longer adsorb water from the deep soil when apple trees are older (>22 years old). After the apple orchard was converted to cropland, precipitation replenished the desiccated deep soil to a depth of about 7 m in the first two years, but thereafter, both water recovery amount and the advance rate of the wetting front were slowed down. After 15–16 years of recovery, soil water storage increased by 512–646 mm, accounting for 42.7–53.8% of the total cumulative soil water deficit caused by the apple orchard. However, it will take more than 26 years for soil water to be replenished to the level of the original cropland prior to planting apple trees. The considerable water deficit after afforestation and subsequent long water recovery time following deforestation extend our understanding of the effect of deep-rooted trees on water balance at the decade scale.

Keywords: land-use change; deep soil water; apple orchard; Loess Plateau; water storage

1. Introduction

In the past decades, afforestation has considerably increased Earth's vegetation coverage [1–4]; this is particularly the case on the Chinese Loess Plateau [5–7]. However, some of the plantations, for instance apple orchards, need to be felled after a certain stand age due to increased occurrence of diseases and other environmental stresses [8]. Subsequently, shallow-rooted crops (soybean, corn and wheat) are planted. This growing of shallow-rooted crops in rotation with deep-rooted plants could have many benefits, such as disease controls and soil improvement [9,10], but its impact on soil water balance remains poorly understood.

The conversion of agricultural land from shallow-rooted crops to deep-rooted orchards will impact the regional hydrological cycle, especially groundwater recharge [11–16]. Deep-rooted plants preferentially absorb water from shallow soil, but can soak up deep soil water that would otherwise recharge groundwater [17,18]. Li et al. [19] conceptualized deep soil water depletion as a process of one-way mining: Tree roots grow deeper to mine deeper soil water and thus deplete deep soil water, which, in turn, stimulates further root growth [20]. However, when the deep-rooted trees are felled and shallow-rooted crops are planted, soil water content begins to recover, and groundwater recharge could increase by an order of magnitude after several decades of land-use change [21]. There is abundant information on the evolution for soil water content during the development of apple orchards [19,22–29]; however, there is limited information on the evolution of soil water after the trees are felled.

As a fruit tree with high economic return, deep-rooted apple trees (Fuji apple) have been widely cultivated throughout the Chinese Loess Plateau since 1980 [5,30]. In this region, the planting area of apple trees accounts for about 25% of the total agricultural land [31]. The development of an apple orchard strongly influences soil water content [32,33]. The available soil water can fall to less than 16% of field capacity for trees over 30 years old [2,22,23,25]. The roots of apple trees can grow up to 23 m deep [20], and deep-root water uptake has been reported to account for 8% of the total evapotranspiration in an apple orchard [34]. When the depletion of deep soil water reaches the maximum, there are no more deep soil water reserves accessible to the apple trees; as a result, precipitation becomes the only water source for their evapotranspiration. Consequently, an apple tree would likely experience more water stress, decreasing apple yield and being more vulnerable to diseases, eventually leading to disease-induced death or being felled.

Land-use change from deep-rooted to shallow-rooted plantations generally results in reduced evapotranspiration (ET) and heightened groundwater recharge, as many studies have shown [35–38]. However, there is a poor understanding of the rate of the replenishment of soil water storage and how the rate changes with time. Models can provide us with some information about the rates of the processes involved [8], but current models have limited accuracy. Field observations demonstrate that the "space-for-time" substitution method is an effective way to investigate the changes in deep soil water following afforestation and deforestation [34,39]. Therefore, the main purpose of this study was to quantify the deficit of deep soil water following afforestation of apple orchards, and the subsequent recovery of deep soil water after deforestation of the orchards. The results of this study are projected to advance our understanding of the deep-soil water dynamics during the planting cycle of deep-rooted plants rotated with shallow-rooted plants.

2. Materials and Methods

2.1. Site Description

The study area is located in the Changwu county (35°12.7′ N to 35°16.717′ N), in the highland region of the Loess Plateau, Shaanxi Province, China (Figure 1a). The topography is relatively flat (slope < 0.05) with elevation ranging from 1170 m to 1310 m above the sea level. The area experiences a semi-humid climate with an average annual precipitation of 580 mm (Figure 1b), 70% of which falls from June to September [25]. Rainfed agriculture has been the dominant production system. Annual winter wheat or maize used to be the main crops; however, 60% of the arable land has been replaced with apple orchards since 2000 because this area produces high quality apples [8,40]. Further, because each farmer owns only a fraction of a hectare, and farmers can grow any crop, the landscape is characterized by a mosaic distribution of wheat/maize fields and apple orchards of different stand ages. Within the sampling area, there is a long-term weather station in Changwu where we obtained the weather data (http://rs.cern.ac.cn/index.jsp).

Due to the aeolian nature of the Loess Plateau, the soil horizons are highly similar across the region [41,42]. The soil texture is silt loam [20]. Groundwater in the region is more than 50 m deep and, therefore, has little effect on the root zone soil water [43].

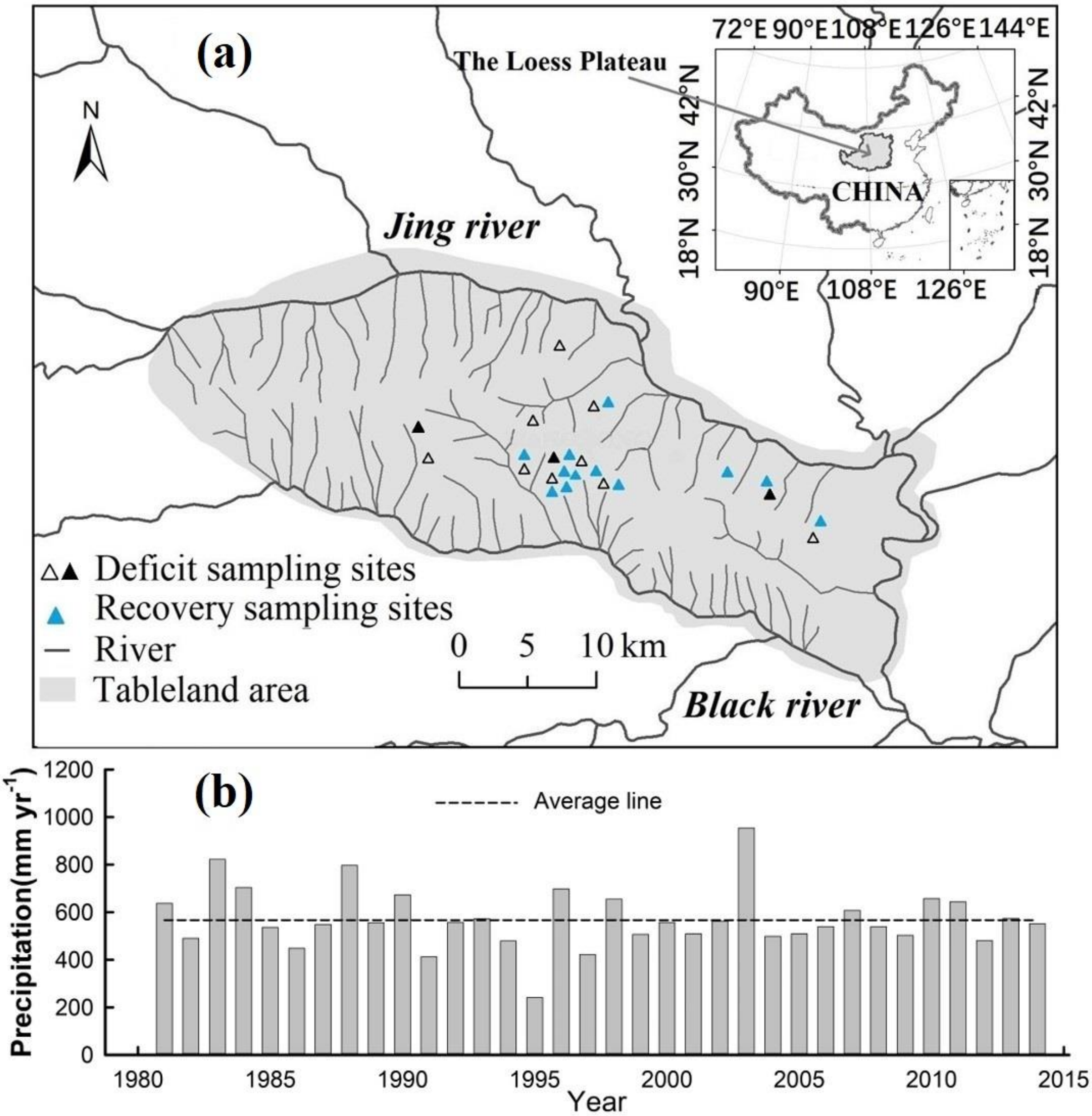

Figure 1. The locations of sampling sites (**a**) and the annual precipitation at Changwu Station from 1981 to 2014 (**b**). Empty triangles represent new sampling sites during depletion (black triangle) and blue filled triangles represent new recovery sites from this study. Filled black triangles indicate the sampling sites presented in Zhang et al. (2017) [44] and Li et al. (2019) [19]. The data of following is available online at http://rs.cern.ac.cn/index.jsp, Figure 1b.

2.2. Soil Sampling and Analysis

Our group has already performed many observations to clarify how apple trees use water in deep soil, and therefore how this affects groundwater recharge. These studies found a continuous decrease in soil water content in deep soil following afforestation [19,44], and the decreased soil water content in deep soil prevent groundwater recharge [34,45]. In this study, we first synthesize our previous published and newly collected soil water profiles to enrich our understanding of apple trees' water use in deep soil, and then investigate the water recovery process by measuring soil water profiles in deforested apple orchards with different ages.

A paired plot design was adopted for this study to minimize the effects of spatial variability in soil properties and weather parameters [34]. Twelve paired-plot sites were sampled in May 2014, with each site thus containing a standing apple orchard and an adjacent cropland. The apple orchard ages were 5, 8, 11, 12, 17, 18, 19, 19, 20, 22, 24 and 26 years at the 12 different sites. Here, the annual cropland serves as the control site to study how soil water is depleted due to growing apple trees relative to the annual cropland. The annual crop field in the pair has been cultivated since the 1950s, though different crops may have been grown. The standing apple orchard in the pair was directly established on the long-term crop field and, therefore, was the first woody species grown on the land since the 1950s. The soil water profiles in the 5-, 8-, 12-, 17- and 24-year-old orchards were newly added data in this study, and the remaining water profiles were from our previous publications [19,34]. We combined these newly collected profiles with the published water profiles to improve our understanding of an apple tree's water-use processes in deep soil. Moreover, to study how soil water is replenished in the field with crops growing on a felled apple orchard, another 12 sites were sampled in May 2015 with each paired-plot site thus containing a standing apple orchard and cropland formed after an apple orchard was felled. The ages of the apple orchard were 2, 2, 3, 4, 5, 5, 6, 7, 7, 8, 15 and 16 years, respectively. Different from the first 12 sites, the standing apple orchard here serves as the control site, which were established by planting apple saplings in the field that was previously long-term cropland, whereas the cropland in the pair was established on felled apple orchards. All the above 24 sites were close to the Changwu Experimental Station (Figure 1a), and the sampling depth for both the cropland and the orchard at each site was based on the soil water depletion/recovery depth of the orchards. The recovery depth was defined as the depth below which the soil water contents in the croplands were converged with that in the standing orchard.

Soil cores were extracted from the center of each of the orchard and cropland that were paired, by hand auger (6 cm in diameter), and before the rainy season. The samples were collected at 20 cm intervals to a depth of 0–10 m, 0–13 m and 0–18 m according to the max deficit depth or recovery depth. The gravimetric soil water content of each 20 cm segment was measured using the oven dry method, and subsequently converted to volumetric soil water content soil bulk density [46].

2.3. Calculation of Variation in Deep Soil Water Storage

Due to the long lifespan of apple trees, "space-for-time" substitution was used to determine the deficit and replenishment of deep soil water storage according to the differences in soil water content between recovering cropland and old apple orchards [34]. The cumulative deficit (CD) and replenishment (CR) of soil water storage was calculated by

$$\mathrm{R} = \int_0^L (\theta_{t2} - \theta_{t1}) dz \tag{1}$$

where R is the CD for afforestation and CR for deforestation (mm); θ_{t2} is the soil water content of the cropland (mm^3 mm^{-3}); θ_{t1} is the soil water content of the orchard (mm^3 mm^{-3}); and L is the soil profile depth (mm).

To explore soil water storage dynamics, we focused on soil water content and soil water storage at depths below 3 m, because the top 3 m soil layers are susceptible to variability from a single precipitation event. To take the effects of climate into account, we calculated the cumulative difference between annual potential evapotranspiration and annual precipitation:

$$\Delta W = \sum_{j=1}^{n} \left(ET_{0j} - P_j \right) \tag{2}$$

where ΔW is the potential water deficit; n is the stand age of the apple tree; ET_{0j} is the potential evapotranspiration at year j, calculated using the modified Penman–Monteith equation [47]; and P_j is the annual precipitation at year j.

Significance tests (ANOVA) were processed using the SPSS package (Version 22.0, Chicago, IL, USA) after verifying the assumptions of normality.

2.4. Study Limitations

Mass planting of apple trees on the Loess Plateau began in the late 1980s and early 1990s. Felling old orchards has only started in recent years. Therefore, we were not able to obtain data with a recovery time of 9 to 14 years and longer than 16 years. In addition, not all farmers have kept detailed records regarding the cropping history after orchards were felled. Therefore, we were not able to account for the evapotranspiration difference between different crops. However, the difference in ET between different crops is perhaps much smaller than the difference between deep-rooted and shallow-rooted plants, thus the error introduced by assuming similar ET demand of different crops may not affect the conclusion of this study.

3. Results

3.1. Soil Water Content and Soil Water Deficit in Apple Orchards

For croplands, soil water contents fluctuated below 3 m, and these variations were caused by soil texture variations to some extent [34]. Soil water contents have no significant relationship with silt contents (0.002–0.02 mm) in the cropland near the 26-year-old apple orchard nor with sand (0.02–2 mm), but the significantly correlatd with clay contents (<0.002 mm) (R^2 = 0.43; p < 0.05).

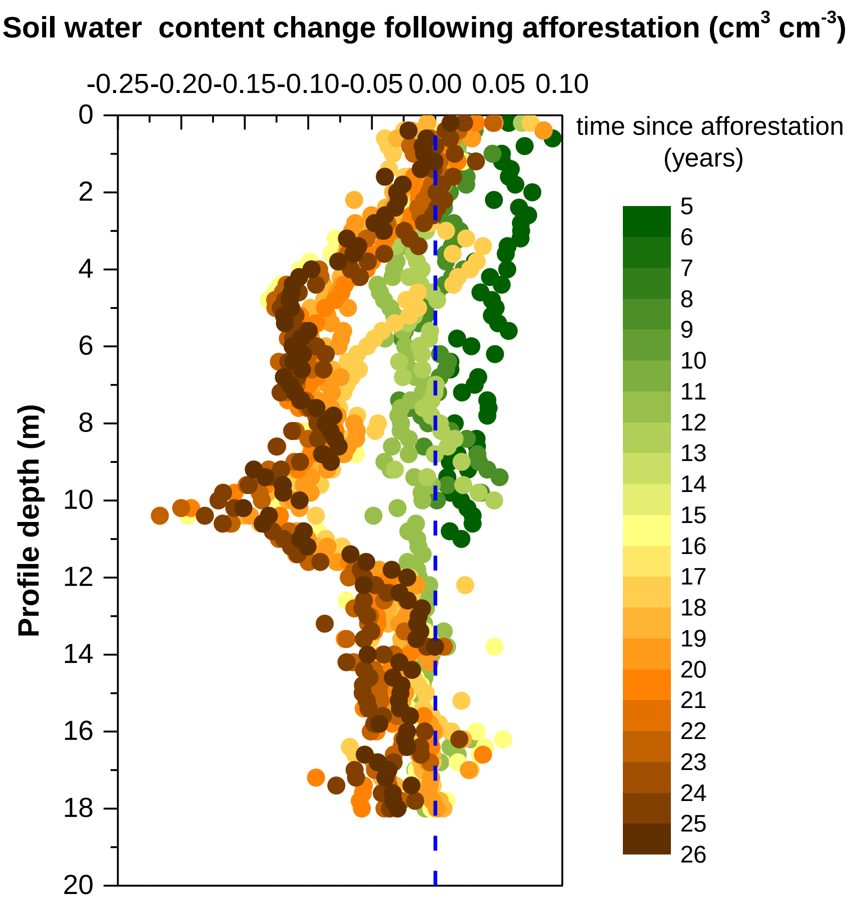

Figure 2. Soil water content change following afforestation. In each site, soil water content change was calculated using the soil water content in the apple orchard minus that in the corresponding farmland. Therefore, negative values represent a soil water decrease following afforestation, and positive values represent an increase in soil water content.

Soil water content slightly increased after planting apple trees for 5 years, and the difference in the average soil water content between the two types of land use was 0.033 cm^3 cm^{-3}, which equated to an increase in soil water storage of 270.6 mm in the orchard compared to the cropland (Figure 2, Table 1). As the orchard stand age further increased, the soil water content started to decrease. The average soil water content beneath an 8-year-old orchard was 0.006 cm^3 cm^{-3} higher than that of the cropland, which is equivalent to an increase in soil water storage of 43.3 mm. When the stand age reached 11 years, the average water content under the orchard was 0.001 cm^3 cm^{-3} greater than that of the cropland, which equated to an increase of 6.1 mm in soil water storage. The difference in average soil water content between the 11-year-old orchard and the cropland was not significant ($p > 0.05$).

After the apple trees reached 12 years of age, soil water content in orchards appeared lower than that in cropland, and the average difference in soil water content between the apple orchard and the cropland was 0.005 cm^3 cm^{-3}, which equated to a deficit of 37.6 mm in soil water storage (Table 1). After the apple tree stands reached the ages of 17 and 19 years, the average soil water contents decreased by 0.038 and 0.063 cm^3 cm^{-3} compared to the croplands, which equated to deficits of 576.1 and 956.5 mm in soil water storage, respectively. In apple orchards older than 20 years, the deficit of soil water storage changed slowly, reaching a maximum of 1242 mm at 22 years of age (Table 1). By 26 years old, the apple orchards were no longer viable producers of apples and, therefore, there was a slight decrease in soil water deficit that reflects poor growth.

Table 1. Soil water content change ($\Delta\overline{\theta}$) and cumulative deficit of soil water (CD) between the apple orchard and nearby cropland.

Age (year)	**5**	**8**	**11**	**12**	**17**	**18**	**19**	**19**	**20**	**22**	**24**	**26**
$\Delta\overline{\theta}$ (cm^3 cm^{-3})	0.033 *	0.006	0.001	−0.005	−0.038 *	−0.060 *	−0.063 *	−0.046 *	−0.074 *	−0.083 *	−0.080 *	−0.070 *
CD (mm)	−271	−43	−6	38	576	902	957	695	1118	1243	1202	1066

Note: Soil water content change was calculated using soil water content in the apple orchard minus that in the corresponding farmland. * Significant difference in soil water content (θ) ($p < 0.05$)

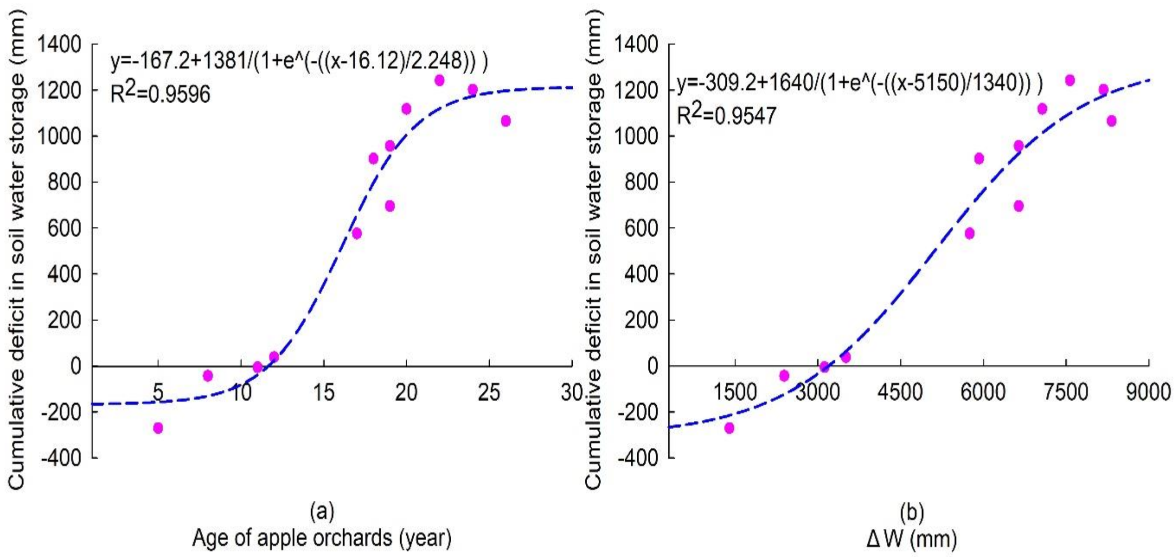

Figure 3. Cumulative deficit in soil water storage as a function of stand age (**a**) and as a function of cumulative annual potential water deficit (ΔW, the cumulative difference between annual potential evapotranspiration and annual precipitation; (**b**)) at Changwu, Shaanxi province, China.

Figure 3 shows the relationship between the cumulative deficit (CD) in soil water storage and the age of the apple orchard. There is a statistically significant correlation between the CD and the age of the apple orchard ($R^2 = 0.96$, $p < 0.05$) and between the CD and cumulative annual potential water deficit (the cumulative difference between annual potential evapotranspiration and annual precipitation, ΔW) ($R^2 = 0.95$, $p < 0.05$). These results suggest that with increasing tree age, local precipitation cannot satisfy the water demand of the apple tree, and, therefore, deep soil water was extracted for transpiration, which further resulted in continuous soil water loss in deep soil.

3.2. Soil Water Content and Soil Water Recovery after Apple Trees Were Felled

Two years after the apple trees were felled, the soil water contents from the 3 to 8 m depth were significantly higher in all the croplands than in the paired standing apple orchard ($p < 0.05$) (Figure 4). In the first two years, the soil water content recovered rapidly in the vertical direction, with the recharge depth exceeding 7 m and average annual recharge exceeding 100 mm. After two years, the increase in recharge depth slowed, and the annual recharge also showed a decreasing trend with an increase in replenishment time (Figure 4, Table 2). After 15–16 years of replenishment, soil water storage increased by 512–646 mm (CR), accounting for 42.7–53.8% of the total cumulative deficit.

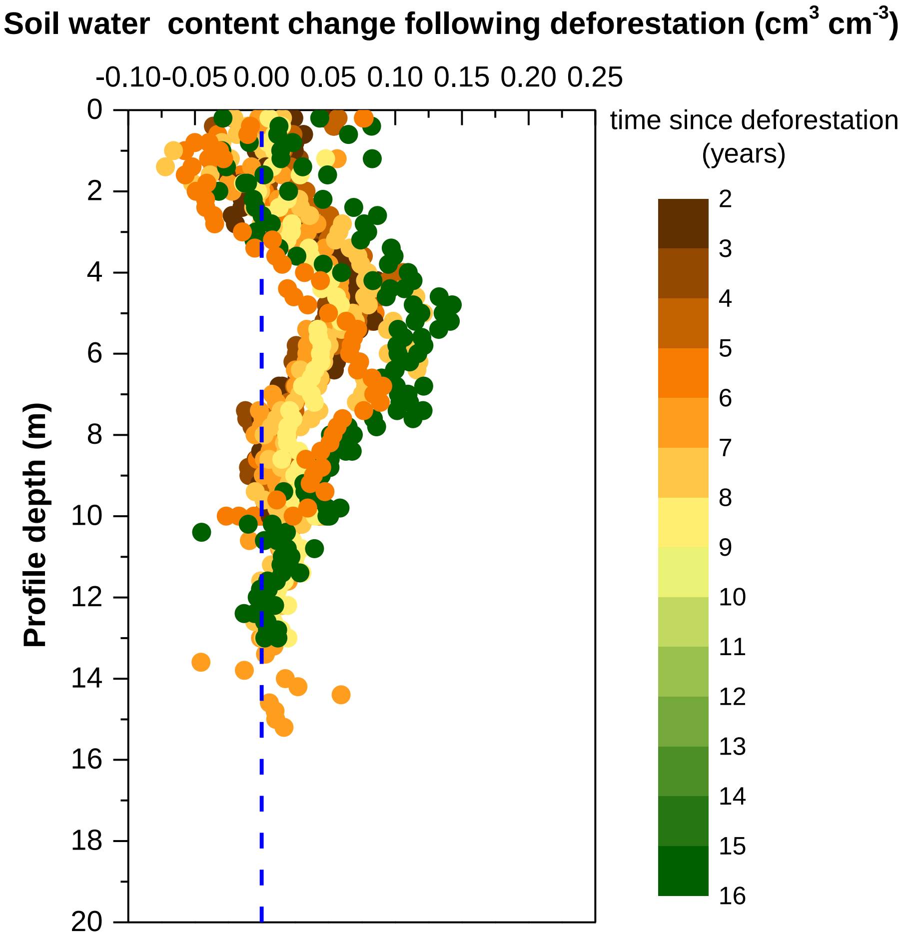

Figure 4. Soil water content change following deforestation. In each site, soil water content change was calculated using the soil water content in the deforested apple orchard minus that in the corresponding standing orchard. Thus, negative values represent a soil water decrease after deforestation, and positive values represent an increase in soil water content.

Table 2. Recovery depth (RD), difference of average soil water content ($\Delta\overline{\theta}$), cumulative recharge (CR) of soil water storage compared with the nearby orchard, average annual recharge (Ave-R) and average annual precipitation (Ave-P)

Recovery Time (Year)	2	2	3	4	5	5	6	7	7	8	15	16
RD (m)	6.6	7.4	7.2	7.6	8.4	8.6	7.2	8.2	8.0	10.0	10.0	10.0
$\Delta\overline{\theta}$ ($cm^3\ cm^{-3}$)	0.059	0.046	0.040	0.058	0.043	0.051	0.039	0.077	0.050	0.036	0.092	0.073
CR (mm)	213	203	167	266	232	288	166	400	252	252	646	512
Ave-R (mm)	106	101	56	66	46	58	28	57	39	31	43	32
Ave-P (mm)	536	536	549	532	554	554	571	562	562	559	577	575

4. Discussion

4.1. Soil Water Deficit in Deep Soil as a Result of Replacing Shallow-Rooted Plants by Deep-Rooted Plants

When the annual croplands were converted into apple orchards, the young trees' transpiration was less than the annual crops' transpiration, such as wheat, corn and soybeans [48–56]. This left more precipitation to infiltrate into the soil and resulted in a slight soil water increase at the initial stage of afforestation (Figure 3). But as the stand age increased as in the case of an 8-year-old orchard, the apple trees took up more water than the paired annual crop field. By 11 years old, the extra water accumulated (relative to the annual cropland) in the first 5 years could have balanced the higher amount of water depleted from the 6th to 11th year, causing the lack of a significant difference in the soil water contents between the paired annual cropland and the 11-year-old apple orchard ($p > 0.05$).

When the apple trees were 8 years old, their roots penetrated to a depth of 9.6 m, and the roots of the 22-year-old apple trees extended to 23.2 m below the soil surface [20]. Therefore, the deepening rate of the apple tree roots was almost eight times faster than the water infiltration velocity in the flat area on the Loess plateau, supporting deep roots taking up water before it could infiltrate further into the soil [34,57]. As shown convincingly by Li et al (2019) [20], these roots can effectively absorb water at the root growth front, depleting the soil water at the front. Therefore, soil water storage gradually decreased with increasing stand age as older apple trees have a deeper rooting depth and thus deplete soil water at a greater depth (Figure 2). The 17-year-old apple trees reached their peak apple production, causing a rapid decrease in soil water storage in the orchards (Figure 2) [25,58,59]. When the stand age of the tree reached 26 years, the water content of the apple orchard had stabilized at about 0.17 $cm^3\ cm^{-3}$ at the depths from 5 m to 10 m, indicating that there was little absorption of deep soil water by apple trees, which may be attributed to the higher soil water availability below 10 m [19] and the compensated root water uptake mechanism: Plant roots tend to extract more water from the moister zone to compensate for the water deficit in the drier root zone [60].

There were significant correlations between the CD and the age of an apple orchard (Figure 3a). This could be explained by the deepening roots as stand age increased. There was also a significant correlation between the CD and ΔW (the cumulative difference between annual potential evapotranspiration and annual precipitation), indicating that drought may have caused apple trees to absorb the deep soil water (Figure 3b). Isotopic analysis of stem water had revealed that grass, subshrubs and deep-rooted shrubs took up deeper soil water under drought conditions, but adsorbed shallow soil water after a large rainfall event in summer [17]. Drought also causes trees to increase their water foraging capacity in deep soils by increasing biomass allocation underground and having deeper roots [61].

4.2. Deep Soil Water Replenishment When Deep-Rooted Plants Have Been Replaced by Shallow-Rooted Plants

The deep soil water content started to be replenished after the apple trees were felled, and the amount of cumulative recharge increased as the elapsed time increased (Figures 4 and 5, and Table 2). Two years after the apple trees were cut down, the soil water content quickly started to recover to a depth of about 7 m. However, the replenishment to the deeper soil was slow, reaching a depth of 10 m after eight to sixteen years following deforestation. The lack of soil water replenishment at depths below 10 m may be attributed to the existence of high clay contents from 7.6 to 12.6 m and calcareous concretion between 10.6 and 13.6 m [34]. There was some scatter in Figure 5, which is probably attributed to the difference in cultivated annual crops (such as soybean, corn and wheat) [48,51,53,55,56] and the variation of precipitation during the replenishment period (Figure 1b). The differences in their rooting depths and canopy structure could result in the differing amount of water that penetrates through the root zone to recharge deeper soil [34,45,62].

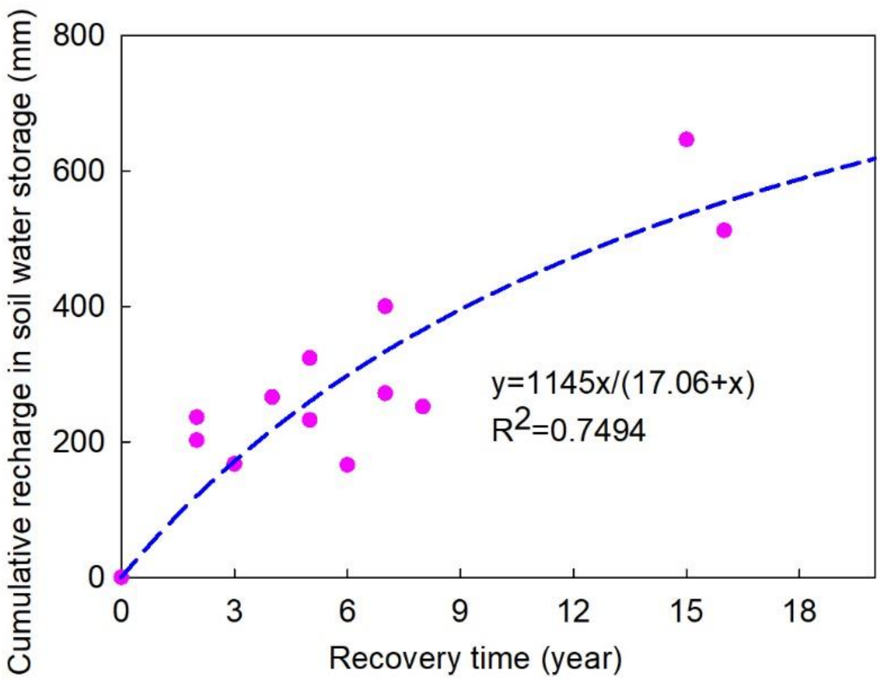

Figure 5. Total recharge in soil water storage as a function of elapsed time after the orchard was felled at Changwu, Shaanxi province, China.

There was a significant correlation between the CR and elapsed time after the orchard was felled ($R^2 = 0.749$, $p < 0.05$). Extrapolating the fitted trend line to its pre-apple orchard soil water storage levels, leads to a stand age of more than 26 years (Figure 5). This means to restore the water storage to its pre-orchard level, it may take more than 26 years of annual crop cultivation after felling an orchard, while for apple trees, it takes only 11 years (from 11 to 22 years) to exhaust the available water in deep soil (Figures 3 and 5). This indicated that during the afforestation and deforestation cycle of apple trees, deep soil experiences a rapid water depletion process, but a slow water recovery. The rapid water depletion may be attributed to the higher atmospheric water demand in the study site (as indicated by potential water deficit in Figure 3) and the deep rooting characteristic of apple trees, which directly supports water extraction in deep soil [19]. In the first two years, soil water storage recovered rapidly and reached nearly 17% of the CD, but the replenishment rates in subsequent years were much slower. The decreasing water replenishment rate may be caused by the gradually decreased water potential gradient. The water depletion and recovery process found in this study are far different from the forest growing in humid climates. In tropical forests and forests with high precipitation, trees were found to extract water to a depth of more than ten meters in the dry season, while the extracted water in the dry season can be fully replenished in the subsequent wet season [61,63]. Therefore, for tree plantations, the water depletion and recovery cycle is only one year in humid climates, but can be extended to decades in dry climates.

4.3. Sustainable Management of Apple Plantations

On the Loess Plateau, deep soil water reservoirs cannot continuously provide water for trees because the extracted water from the deep soil cannot be replenished in a wet season as it does in humid regions [63]. For this reason, the Chinese Loess Plateau in the sub-humid region could not sustain a productive apple orchard for more than 25 to 30 years. To continue to grow apple trees, the depleted soil water reserve must be replenished. The time required to restore the deep soil water reserve to the level of long-term cultivated annual cropland was more than 26 years (Figure 5). Because soil water storage in the first 11 years for an apple orchard was very similar to the adjacent cropland (Table 1), growing young apple trees (<11 years old) is similar to growing annual crops in terms of soil water replenishment. Therefore, we can reduce the replenishment time from 26 years to 15 years. Consequently, the apple orchard–cropland rotation should be about 40–45 years. This means that the area of newly planted fruit trees should be no more than 2.2–2.5% of the planned apple acreage in each year.

5. Conclusions

In this study, we systematically investigated the evolution of deep soil water contents for the whole rotation of deep-rooted apple. The main conclusions are as follows:

1. After cropland was converted into an apple orchard, soil water content increased before the apple trees reached 5 years of age. When the trees were older, they would use water from the deep soil, which led to deficits in soil water storage. The deficit can reach a maximum cumulative deficit of more than 1200 mm when the stand age of the apple trees reached 22 years. The annual precipitation cannot meet the water demand of the apple trees after several years of afforestation, thus stimulating trees to progressively mine deep soil water, causing intensive deep soil water deficits in old orchards.
2. Two years after the apple trees were cut down, soil water storage quickly recovered by about 200 mm. After 15–16 years of recovery, soil water storage increased by 512–646 mm, accounting for 43–54% of the total cumulative deficit. According to the trend line of soil water recovery derived in this study, it would take more than 26 years for the soil water storage to return to the level of the original cropland.
3. To develop economic orchards in arid and semi-arid areas and to maintain sustainability, a holistic understanding of soil water consumption and replenishment should be considered when making a planting plan. This study suggests that new apple orchards should only account for 1.8–2.0% of the total planted area each year.

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