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Effects of apple orchards converted from farmlands on soil water balance in the deep loess deposits based on HYDRUS-1D model

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ABSTRACT

Land use change (LUC) impacts on the soil water balance is important for effective water resources management and land use planning. The Loess Plateau of China has loess deposits up to 350-m depth and constitutes large reservoirs of soil water storage. In recent decades, areas within these reservoirs have been depleted of their water storage. LUC impacts on soil water storage have been previously investigated in this region; however, LUC impacts on other components of soil water balance such as evapotranspiration and deep drainage have received limited study because of difficulties in direct measurement of these components. Using continuously monitored 10-m soil water profiles under farmland and apple orchards converted from farmlands for 10, 20, and 30 years for the period 2011 − 2013, the HYDRUS-1D model was calibrated and then employed to evaluate long-term LUC impacts on different components of the soil water balance in a typical loess tableland based on climate data for the period 1960 − 2013. Compared with farmlands and young apple orchards (stand age < 10 years), the measured soil water storage under mature apple orchards (stand age > 20 years) was significantly decreased over time. The simulated deep drainage was 12.1 mm year^{-1} under farmland and accounted for 2% of the annual average precipitation, but this value was reduced to near zero under mature apple orchards. The simulated average annual actual evapotranspiration was 565.8 mm and represented 98% of the average annual precipitation under farmlands, but the evapotranspiration was increased under mature apple orchards. The LUC-induced decrease in soil water storage and groundwater recharge threatens the sustainability of water resources and agriculture on the Loess Plateau. The balance between economic development and agriculture ecosystems and environmental sustainability are, therefore, important considerations in future land use planning.

1. Introduction

Land use change (LUC) has altered more than a third of the global land area (Vitousek et al., 1997). Moreover, LUC will continue in the context of the growing global population (Wagener et al., 2010; Mirus et al., 2017). LUC not only changes the global vegetation patterns, but directly affects the water balance of the soil-plant-atmosphere continuum (Baker and Miller, 2013; Feng et al., 2016). The conversion of farmland into economic forest is popular and it can rapidly change the agroecosystem (Nosetto et al., 2005; Hu et al., 2009; Ziadat and Taimeh, 2013; Chi et al., 2019); in turn, it changes the environment such as the soil water balance of the ecosystem (Hu et al., 2010; Suo et al., 2018; Yu et al., 2018; Li et al., 2019b). Although a lot of studies have investigated the effects of LUC on soil water contents (Ren et al., 2018; Su and Shangguan, 2018; Jia et al., 2019; Ye et al., 2019), the LUC impacts on other components of soil water balance such as evapotranspiration (ET) and deep drainage have not been fully studied because of difficulties in direct measurement of these components (White et al., 2000; Turkeltaub et al., 2018). Therefore, based on experiments in small plots for runoff, erosion, and other hydrological processes (Fu et al., 2012; Sarkar et al., 2015; Mayerhofer et al., 2017; Petroselli and Tauro, 2017), more detailed and complicated processes can be investigated by modeling techniques. Investigation of the LUC effects on soil water balance by a combination of experimental research and modeling technique is thus of utmost importance for the management of agriculture, ecosystems, and environment.

In specific, three methods, i.e. water balance method, tracer method, and numerical modeling, have been previously used to

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investigate LUC impacts on the soil water balance (Scanlon et al., 1997; Jha et al., 2017; Li et al., 2017b; Huang et al., 2018). The water balance method is applicable to a wide range of space and time scales and may be used to evaluate results from lysimeters to entire continents (Scanlon et al., 1997, 2002); however, the accuracy of the estimated recharge rate may be very uncertain in arid regions where the recharge rates are smaller than the errors of the water balance method (Hendrickx, 1992; Gee and Hillel, 2010; Jian et al., 2015; Duan et al., 2016). The tracer method has several advantages over the water balance method. For example, the precision of recharge estimations is typically satisfactory even in regions with limited recharge rates (Allison et al., 1994; Koeniger et al., 2016), and the method may be useful for the estimation of a range of different hydrologic fluxes (Scanlon et al., 2002; Vries and Simmers, 2002; Scanlon, 2004; Cartwright et al., 2017). However, a single specific tracer usually performs the best for a specific hydrologic component, and choosing an appropriate tracer is thus important for accurate estimation of hydrologic fluxes (Scanlon et al., 2002; Li and Si, 2018; Li et al., 2019d). Numerical modeling may be theoretically applied to the simulation of numerous aspects of the water budget and scenario analysis (White et al., 2000; Scanlon, 2004), but the reliability of these estimates need verification with field information such as lysimeter data and tracers (Scanlon et al., 2002). When choosing an appropriate method, various factors should be considered to obtain the most accurate estimations (Allison et al., 1994; Scanlon et al., 1997, 2002; Durner and Iden, 2011).

China's Loess Plateau (Fig. 1) typically has issues associated with severe water scarcity because of the arid to subhumid climate (Li et al., 2009). With loess soils up to 350-m depth, the thick loess constitutes a large soil water reservoir (Xiong et al., 2014; Zhu et al., 2018). The large subsurface water storage, therefore, dominates the hydrological processes in this region (Li et al., 2017c). However, the continued reduction of soil water reserves has been widely reported because of previous land use practices (Gates et al., 2011; Wang et al., 2015b; Huang et al., 2018; Turkeltaub et al., 2018). In attempts to reduce severe soil erosion losses, the vegetation has been largely changed during the last few decades by converting steep farmlands to forestlands and/or grasslands to control soil erosion (Li et al., 2016, 2017a).

One important LUC practice has been the transformation of farmlands to apple orchards for vegetation restoration and economic development. As an example, Shaanxi Province now ranks as having the largest areas of apple orchards in China (about 7252 km^2), and produces apples for one-seventh of the world (Jia et al., 2014; Qu and Zhou, 2016). Previous investigations have documented the spatio-temporal patterns in soil water reserves and the corresponding controlling factors, and found that soil water depletion increased with the increased age of apple orchards (Wang et al., 2015a, b; Suo et al., 2018; Turkeltaub et al., 2018; Yu et al., 2018; Li et al., 2019b). Since apple production represents a significant source of income increased attention is being paid to the balance between economic development and the sustainability of water resources. However, our scientific knowledge remains limited regarding the relationships between LUC and components of the soil water balance such as evapotranspiration and groundwater recharge as the arid climates and thick loess hinder the direct measurement of these components of the water balance. As such, we feel that numerical modeling offers the most promising approach to more fully understand the soil water balance within this region.

The objectives of this study were to (i) model the soil water balance under different land use types using the HYDRUS-1D model, and (ii) to quantify the effects of LUC (i.e. farmlands converted to apple orchards) on the soil water balance. The HYDRUS-1D model was calibrated and validated using measured parameter data for 2011 − 2012 and 2012 − 2013, respectively. Long term simulations of the soil water balance were then estimated using weather data from 1960 − 2013. Our results will benefit water resources management in regions with large soil water storage reservoirs within thick vadose zones.

2. Materials and methods

2.1. Description of study area

We chose the Changwu Loess Tableland as the study area (Fig. 1). The loess tableland is flat with an elevation of 1200 m with surrounding gullies that isolate the tableland from adjacent regions. The flat surface results in negligible quantities of runoff. The region utilizes rainfed agriculture without irrigation such as the region does not obtain additional water from adjacent regions. The hydrological fluxes are primarily vertical, and the subsurface water recharge only originates from precipitation (Huang et al., 2013; Li et al., 2017b; Tan et al., 2017).

The study area has a subhumid climate with annual average precipitation of 580.0 mm for 1960 − 2013. The dominant soil type is a medium loamy loess soil with a parent material of Malan loess. The water table is 30 m–100 m below the surface, but has been significantly

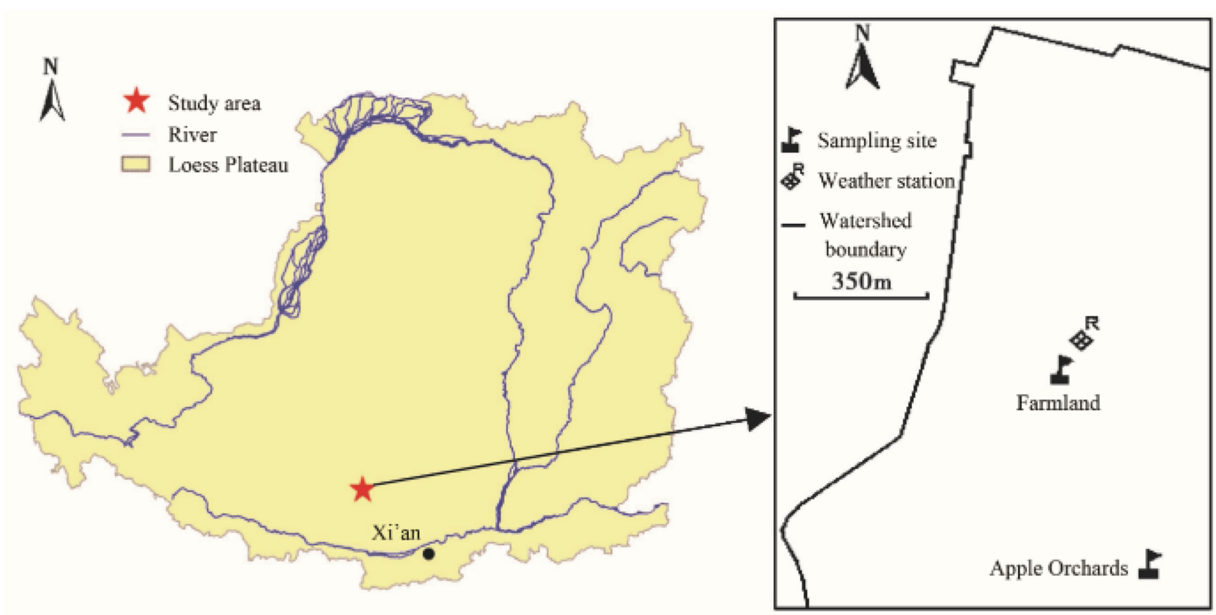

Fig. 1. Location of the study area on the Loess Plateau of China and distribution of the sampling sites within the Wangdonggou Watershed.

declining during the past 30 years (Huang et al., 2013). This area has experienced substantial land use changes with much of the farmland in the region being converted to apple orchards within the past 30 years (Li et al., 2016; Peng and Li, 2018). As apple trees are deep-rooted plants and the roots can reach up to 22 m, the orchards have consumed more soil water in comparison to water use under farmlands (Huang et al., 2018; Li et al., 2018; Zhang et al., 2018; Li et al., 2019a). Therefore, this area was as an ideal location to investigate the relationships between LUC and soil water balance.

2.2. Data collection

The HYDRUS-1D (Simunek et al., 2013) model was employed to simulate the soil water balance. The observed climate, root distribution, leaf area index, and soil properties were the basic inputs. The climate data was obtained from the weather station of Changwu Agroecosystem Experimental Station (Fig. 1). The root distribution and leaf area index were obtained from our own sampling and measurements.

The procedure for soil and root sampling/characterization was as follows. Soil samples were collected for 10 m deep under four land use types, which included long-term farmlands with rotation of winter wheat and spring maize (abbreviated as F), and apple orchards with trees approximately 10 years old (planted in 2002, abbreviated as A10), trees approximately 20 years old (planted in 1994, abbreviated as A20), and trees approximately 30 years old (planted in 1985, abbreviated as A30). The area of each land under investigation was greater than 50 m × 50 m. The distance between any two fields was less than 500 m to ensure that the sampling areas had similar climate, soil, and topography. The areas were all managed by local farmers using traditional agricultural practices without irrigation. Thus, our modeling efforts simulated primarily the LUC impacts on the soil water balance within deep loess deposits.

At each site, soil samples were collected with a 5-cm diam soil auger to a 10-m depth. Samples were taken from the 0 − 6 m and 6 − 10 m depths at intervals of 0.2 and 0.5 m, respectively. Then, an aluminum neutron-probe access tube of 18-m long was installed at each site. A slow neutron counter was used to measure soil water contents at 20-cm intervals after calibration and validation. More detailed information about soil sampling and other measurements can be found in our previous study (Wang et al., 2015b). Although root and soil hydraulic parameters may slowly change over extended time periods, for our use in modeling, these parameters were considered a snapshot in time and were only determined once. The soil water contents and meteorological data were determined from measured values.

2.3. Model configuration

To simulate the soil water balance under different land use types using the HYDRUS-1D model, a vertical 10-m soil profile was considered as the flow domain (Fig. 2). Initial conditions were defined in terms of soil water contents in the flow domain on the starting day of simulation. The upper boundary was defined as the atmospheric boundary conditions that included surface runoff. The lower boundary was set as the free drainage boundary since the water table typically occurred at a 30-m depth which was a much lower depth than the simulated domain. The lower boundary water flux was assumed to constitute the groundwater recharge. Rainfall and evapotranspiration were specified at the upper boundary on a daily basis. The Hargreaves equation (Hargreaves, 1994) was employed to calculate the potential evapotranspiration. The daily potential evapotranspiration value was partitioned into potential soil evaporation and potential plant transpiration. The potential plant transpiration was based on the leaf area index values from the previous day using Beer's law (Ritchie, 1972).

The governing equation used in this study was the Richards's equation for one-dimensional root water uptake without compensation (Richards, 1931) The unsaturated hydraulic properties were described using the van Genuchten equations (Van Genuchten, 1980). The hydraulic parameters for the van Genuchten-Mualem model were initially estimated from our own measurements (α, n, Ks), and then optimized by the HYDRUS-1D's inverse solution for these parameters (Table 1). The root water uptake stress response function was defined according to Feddes et al. (1974) based on four soil water pressure heads. Without measured data, we used the HYDRUS-1D's built-in database of wheat and deciduous fruit crop growth properties to represent the behavior for farmlands and apple orchards.

2.4. Simulating soil water balance

Since irrigation was not used, precipitation (P) was the sole source of water inputs within the study region. The water table is over 30 m below surface, which precludes any upward capillary flow. The soil water balance can thus be described as $\triangle S = P–ET–Q–D$. Specifically, the change in soil water ($\triangle S$) is controlled by precipitation (P), actual evapotranspiration (ET), runoff (Q) and drainage (D). The model directly calculates the actual evaporation and transpiration given the soil moisture conditions and the root water uptake functions (Feddes et al., 1974; Vrugt et al., 2001). The actual soil surface evaporation fluxes are simulated using the surface energy balance equation for bare soil (Saito et al., 2006; Moghadas et al., 2013). The runoff is simulated using the kinematic wave equation (Köhne et al., 2011). The deep drainage rate is simulated by discretization of Darcy's law (Turkeltaub et al., 2014; Fan et al., 2015). Detailed information concerning the specific methods may be found in the manual for the HYDRUS-1D model (Simunek et al., 2013).

Based on the above water balance equation, the applicability of the HYDRUS-1D model was addressed. To perform the model runs, soil water contents under F and A30 treatments were simulated. The study period 2011 − 2013 was divided into two sub-periods, i.e. 2011.09.23 − 2012.09.30 and 2012.10.01 − 2013.10.31. The two sub-periods were, respectively, used for model calibration and validation. The performance of HYDRUS-1D on soil water simulation was evaluated using three indicators including coefficients of determination (R^2), Nash-Sutcliffe model efficiency (NSE), and root mean square errors (RMSE).

Temporal changes in soil water during model calibration and validation are presented in Fig. 3 for various soil depths under F and A30. Generally, the soil water within the 0 − 2 m soil profile responded to rainfall events; however, the values below 2 m were stable. The observed soil water contents were satisfactorily simulated at different depths (Fig. 3). The NSE and R^2 were, respectively, larger than 0.55 and 0.65, while the RMSE was less than 0.02 during the calibration and validation periods (Table 2). The good model performance in simulating the temporal changes and vertical distributions of soil water during the validation period implies that HYDRUS-1D is effective for soil water balance simulation for the deep soil profiles in the study region.

2.5. Analyzing LUC impacts on soil water balance

When analyzing the measured soil water data, the statistical parameters including mean, sum and standard deviation were calculated. With the above analysis, the LUC impacts on soil water may be analyzed. To further examine the LUC impacts on the other components of the water balance, HYDRUS-1D was extended using the measured climate data to simulate the soil water balance over the period 1960 − 2013. Finding of a previous research indicated that the climate data can fully present the long-term characteristics of the hydrological conditions (Hu et al., 2009; Huang et al., 2011). As the soil water profiles and soil water storages under the A10 and F were similar, we have presented the results under the F, A20, and A30 land uses to discuss the impacts of LUC on the water balance.

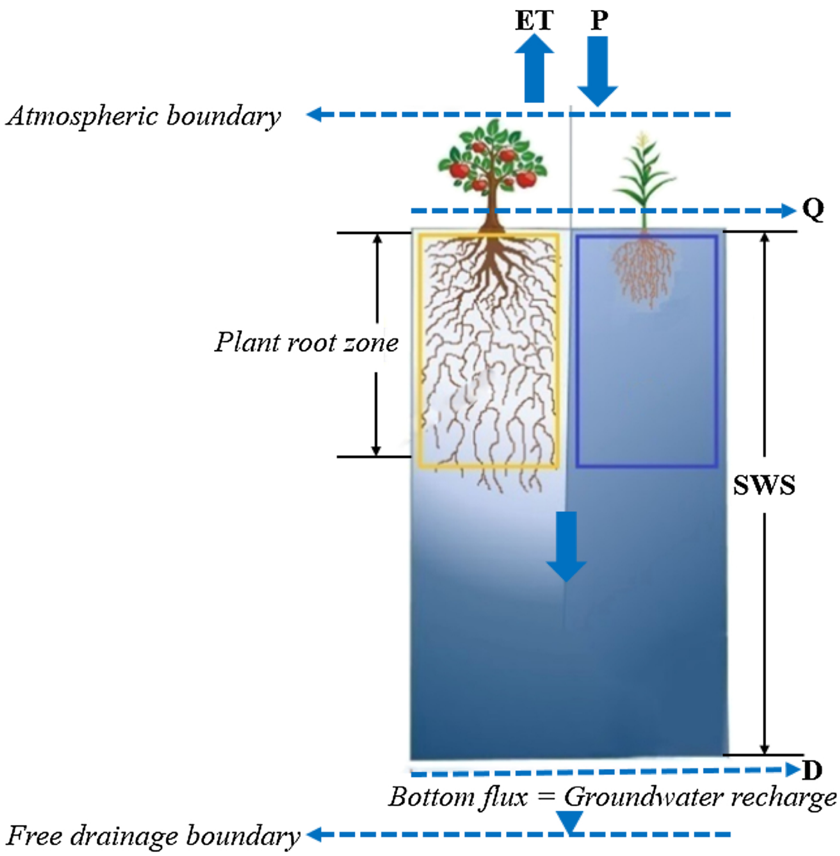

Fig. 2. Schematic diagram showing the boundary conditions and fluxes for farmland and apple orchards. Please note evapotranspiration (ET), precipitation (P), runoff (Q), soil water storage (SWS), and lateral drainage (D) are the acronyms describing inputs, outputs, and fluxes.

Table 1
Basic soil physical properties and optimized soil hydraulic parameters.

Profile depth (cm)	Particle size distribution (%)			Bulk density (g cm^{-3})	Soil hydraulic parameters					
	Sand	Silt	Clay		Θr (cm^3 cm^{-3})	Θs (cm^3 cm^{-3})	α (cm^{-1})	n (-)	Ks (cm day^{-1})	L (-)
0˜10; 40˜240	3.2	74.2	22.6	1.4	0.058	0.4	0.021	1.262	143.5	0.5
10˜40; 240˜500	2.8	82.2	15	1.28	0.04	0.416	0.01	1.256	50	0.5
500˜1000	1.4	81.6	17	1.32	0.04	0.428	0.004	1.423	38.5	0.5

Note: θr: residual water content; θs: saturated water content; α: the inverse of the air-entry value; n: a pore-size distribution index; Ks: saturated hydraulic conductivity; L: a pore-connectivity parameters and in the hydraulic conductivity function was set (Mualem, 1976) to be about 0.5 as an average for many soils.

3. Results

3.1. Measured soil water profiles

The measured soil water contents indicated large amounts of variation within the 0 − 5 m soil profile, but the water content stabilized below 5 m, which was the overall pattern of observed soil water vertical distributions presented for the different land use types (Fig. 4). Within the 0 − 5 m soil depth, the soil water profiles did not present consistent patterns of values across the different land use types (Fig. 4e). Below the 5-m soil depth, the soil water contents under the F land use exhibited similar patterns and magnitudes of values as observed under the A10 land use. Although the soil water contents under the A20 and A30 land use were also similar, the former two soil profiles (under the F and A10 land uses) had much larger soil water content values than observed under the latter two profiles (under the A20 and A30 land uses). The results of paired *t*-test comparisons further showed that the soil water contents under the F and A10 land uses were not significantly different, but the soil water contents were significantly different from the values under the A20 and A30 land uses ($p < 0.001$) (Fig. 5).

The measured soil water contents temporally averaged across the entire soil profile for the different land use were the largest for the A10 land use (19.5 ± 1.0%), followed by the F land use (18.5 ± 1.4%) and the lowest for the A20 and A30 land uses (14.7 ± 2.4% and 16.1 ± 3.1%, respectively) (Fig. 4e). Compared with the F land use, the measured soil water storage under the A10 land use had almost no water deficit, but the water deficit decreased by 22% and 14% under the A20 and A30 land uses, respectively (Fig. 5a). The measured soil water storage under the F and A10 land uses were very similar (1307 and 1305 mm, respectively), but the soil water storage values decreased by 383 mm–394 mm under the A20 and A30 land uses, respectively (Fig. 5b).

3.2. Simulated soil water balance

The simulated annual average values of hydrological fluxes for the time period of 1960 − 2013 are presented in Table 3. As the runoff or changes in soil water storage are negligible, we have focused on the

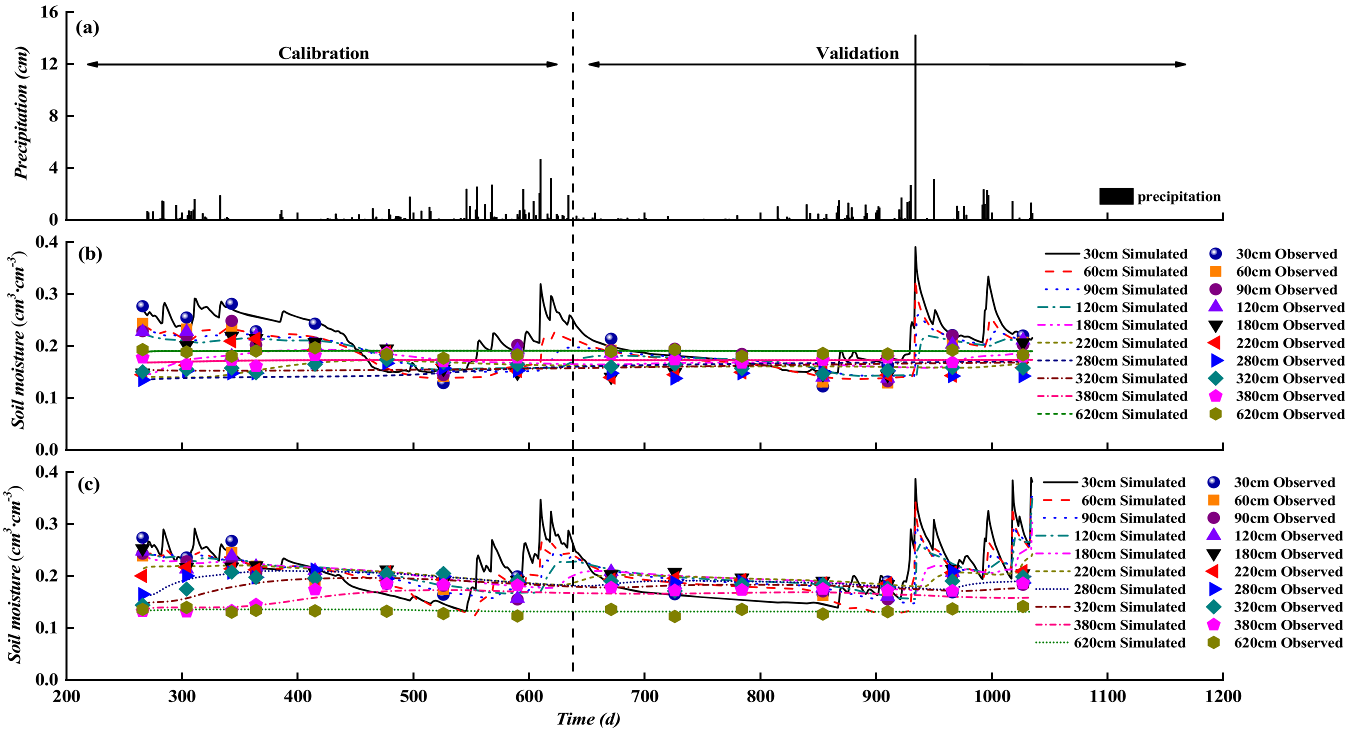

Fig. 3. Temporal variations in the (a) precipitation and the soil water contents within the 30- to 620-cm soil depth profile in 2011 − 2013 during the HYDRUS-1D calibration and validation (b) under farmlands and (c) apple orchards established for 30 years. Soil water content observed measured values are indicated by symbols and simulated values are indicated by lines.

Table 2
Performance of HYDRUS-1D model on soil moisture simulation.

Periods	Time	Land use types	Sample size	R^2	RMSE	NSE
Calibration	2011.09.23˜2012.09.30	F	70	0.65	0.02	0.55
		A30	70	0.85	0.01	0.83
Validation	2012.10.01˜2013.10.31	F	70	0.85	0.01	0.76
		A30	60	0.74	0.01	0.65

R^2, coefficients of determination; NSE, Nash-Sutcliffe model efficiency; RMSE, root mean square errors.

simulated deep drainage and actual ET in this section. The simulated deep drainage under the F land use was estimated as 12.1 mm year^{-1}, representing 2% of the annual average precipitation. However, the simulated deep drainage values under the A20 and A30 land uses were both 0.3 mm year^{-1}. The simulated average annual actual ET was 565.8 mm under the F land use and could be attributed to 98% of the average annual precipitation. However, the simulated average annual ET values were, respectively, 576.7 and 577.7 mm under the A20 and A30 land uses and could be attributed to approximately 100% of the average annual precipitation.

4. Discussion

4.1. Is the modeled soil water balance reliable?

Although the temporal dynamics and/or vertical distribution of the soil water has been satisfactorily simulated by HYDRUS-1D, the confirmation of model reliability is insufficient without validation of the other variables. We, therefore, collected the results of actual ET and groundwater recharge from other studies to further evaluate the model performance. The actual ET was also estimated by lysimeter, the thermal dissipation probe, or the water mass balance method. The groundwater recharge was estimated by either the tracer method or by modelling (Tables 4 and 5).

The simulated actual ET under the apple orchards by HYDRUS-1D represented 100% of the average annual precipitation, which is similar to results from previous studies since the corresponding values are 82 − 110% for the Loess Plateau (Table 4). In the same study area, Mu and Wang (2017) used lysimeters to measure the actual ET under apple orchards that had been growing for 9 and 19 years and found that the ET accounted for 87 − 108% of the mean precipitation, which strongly supports our simulated results.

Our simulation of recharge under farmland was 12.1 mm year^{-1} and represented 2% of the average annual precipitation. Previous studies presented recharge rates of 0 − 67 mm year^{-1} that accounted for 0 − 10.8% of the average annual precipitation (Table 5). Therefore, our simulation results are similar to the results from other studies using tracer techniques or other modeling work. Huang and Gallichand (2006) estimated the deep drainage under farmlands and apple orchards as 9.3 − 18.3 mm. Zhang et al. (2018) presented values of 12 mm under farmlands using the chloride mass balance method and accounted for 2 − 3% of the average annual precipitation. Additional verification is provided by other studies (Li et al., 2018; Zhang et al., 2018) that provided estimated recharge rates under mature apple orchards to have values essentially equal to zero which are similar recharge values as estimated by our results.

We also compared the observed and simulated water deficits between apple orchards and farmland for the period 2011 − 2013 to validate the model performance. For the observed soil water storage in the 10-m profiles, the A10 land use had almost no water deficit, but the A20 and A30 land uses decreased water storage by 22% and 14%, respectively (Fig. 5a). The simulated soil water storage decreased by 20% and 14% under the A20 and A30 land uses, respectively, in comparison to the F land use (Fig. 5c). All indications are that the water deficits attributed to land use change from farmland to apple orchards were well simulated by HYDRUS-1D. The relative error of the water mass balance within the 10-m profiles ranged from 0 to 0.2% (Table 3) and

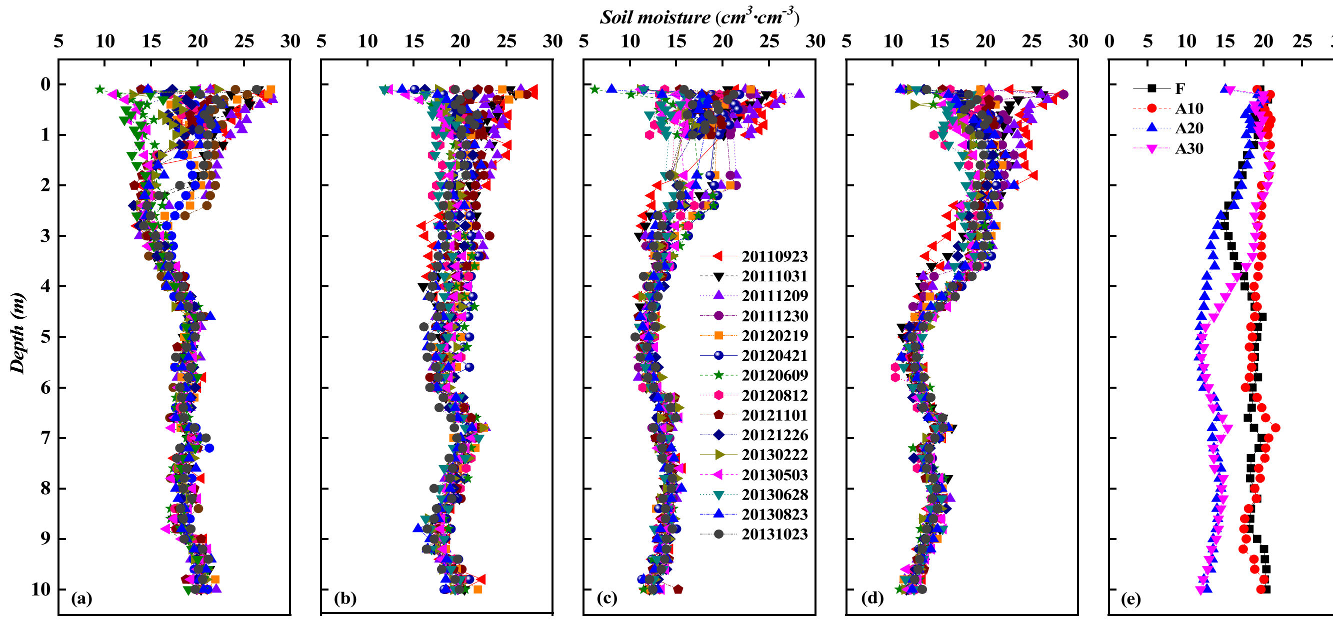

Fig. 4. The vertical distributions of observed soil moisture under (a) farmland, (b) apple tree planted in 2002, (c) apple tree planted in 1994 and (d) apple tree planted in 1985 during the period 2011.09 − 2013.10, and (e) the soil moisture temporally averaged the period 2011 − 2013.

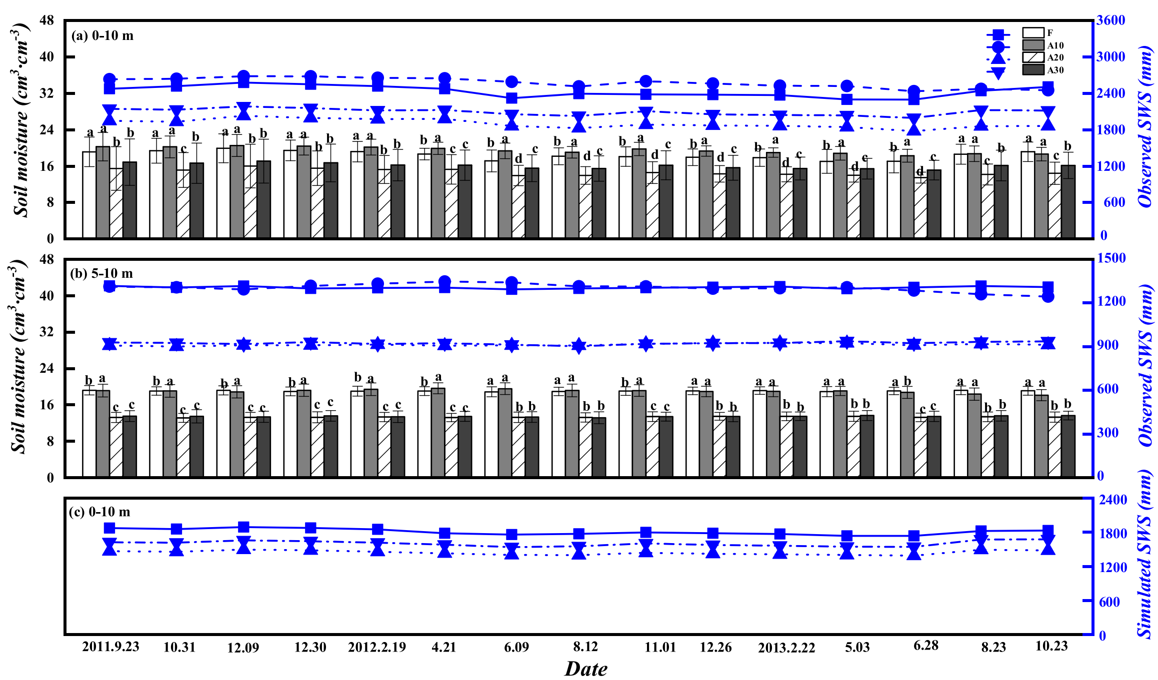

Fig. 5. Soil water contents and soil water storage (SWS) under farmland (F) and apple orchards converted from farmland for 10 (A10), 20 (A20), and 30 (A30) years. The bars represent soil moisture and blue lines represent soil water storage. (a) and (b) respectively presented the measured values in the depth profiles of 0 − 10 m and 5 − 10 m. (c) is the simulated water storage for the profile of 0 − 10 m. The letters above the bars represent statistically significant groupings of soil moisture at the significance level of p = 0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Simulated the average annual of different components of the soil water balance for 1960 − 2013 under farmland (F), apple orchards converted from farmland for 20 (A20) and 30 (A30) years.

Land use types	P (mm year^{-1})	Q (mm year^{-1})	ET (mm year^{-1})	D (mm year^{-1})	△S (mm year^{-1})	Absolute errors (mm)	Relative errors (%)
F	580.0	0.1	565.8	12.1	1.6	0.4	0.1
A20	580.0	0	576.7	0.3	3.0	0	0
A30	580.0	0	577.7	0.3	3.0	1.0	0.2

Notes: P: precipitation; Q: runoff; ET: actual evapotranspiration; D: deep drainage; △S: change in soil water storage between the first and last day of the period 1960 − 2013.

Table 4
Estimated actual evapotranspiration by different methods.

No	Methods	Location	Land use	P (mm)	ET (mm)	ET/P (%)	Publication
1	Lysimeter & TDP	Changwu, Shaanxi	A9 and A19	242.6 − 348.4	211 − 311.4	87 − 108	Mu and Wang (2017)
2	Lysimeter & TDP	Mizhi, Shaanxi	A6	322.7 − 323.1	352.3 − 355	109 − 110	Li et al. (2017a)
3	Lysimeter	Luochuan, Shaanxi	F, A8, A15, and A28	530.9 − 588.5	546 − 616.6	94 − 105	Huang et al. (2001)
4	Sap flow & micro-lysimeter	Changwu, Shaanxi	A7 and A17	383.3 − 407	312.4 − 367.2	82 − 94	Di and Li (2017)
5	Water balance method	Brazilian Cerrado	F and woods	1388	654 − 1201	47.1 − 86.5	Anache et al. (2019)
6	Water balance method	Arizona, USA	G and arbors	349	335	95.8	Scott and Biederman (2019)
7	Water balance method	Changwu, Shaanxi	A7-A9	430.2 − 499.4	442.3 − 517.6	100 − 104	Wang et al. (2016)
8	Water balance method	Loess Plateau	Bushes and arbors	172 − 563	292 − 332.1	59 − 193	Zhang and Huang (2013)
9	Remote sensing & ^{13}C	Central Argentina	G and Eucalyptus	1352	649.7 − 1175.3	48 − 87	Nosetto et al. (2005)
10	Modeling	Pampas of Argentina	soybeans and G	924 − 928	832 − 695	74.9 − 90	Kroes et al. (2019)
11	Modeling	Changwu, Shaanxi	F, A20, and A30	580	565.8 − 577.7	98 − 100	This study

Notes: P: precipitation; ET: actual evapotranspiration; TDP: thermal dissipation probe; F: farmland; G: grassland; A: apple orchard (the number represent the ages of apple tree).

Table 5
Estimated groundwater recharge by different methods.

No	Methods	Location	Land use	Mean P	D (mm yr^{-1})	D/P (%)	Publication
1	CMB	Australia	F and Eucalyptus	250 − 450	0.01 − 51	0 − 20%	Allison et al. (1990)
2	CMB	Changwu, Shaanxi	F and A	577	33.0; 19.1	7.3; 4.2	Huang et al. (2018)
3	CMB & Isotope	Heihe watershed, Gansu & Shaanxi	F, G and A	584	14	2	Li et al. (2017b)
4	CMB & Nitrate	Luochuan, Shaanxi	F and A	623	36 − 67	5.8 − 0.8	Huang et al. (2016)
5	Chloride-water balance	Changwu and Jingchuan, Shaanxi & Gansu	F and A	571	12	2	Zhang et al. (2018)
6	CMB & Water balance	Central Argentina	F and forests	447 − 542	0.33 − 128.4	0 − 29%	Santoni et al. (2010)
7	Tritium-water balance	Changwu, Shaanxi	F and A	578	0 − 38	0 − 6.6	Li et al. (2018)
8	Modeling & Isotope	Southwest Niger	F and G	557	2 − 25	0 − 5	Favreau et al. (2009)
9	Water balance method	Arizona, USA	G and arbor	349	−9	−2.7	Scott and Biederman (2019)
10	Modeling	Changwu, Shaanxi	F and A	545	9.3 − 18.3	2.0 − 3.0	Huang and Gallichand (2006)
11	Modeling	Luochuan, Shaanxi	F	568	17	3	Zhang et al. (2007)
12	Modeling	Changwu, Shaanxi	F and A	580	12.1	2	This study

Notes: P: precipitation; D: groundwater recharge in terms of deep drainage; CMB: chloride mass balance; F: farmland; G: grassland; A: apple orchard.

indicated that the simulated soil water balance was within an acceptable error range.

4.2. How does land use change influence soil water balance?

The conversion from farmlands to forest generally decreases soil water storage (Bari and Schofield, 1992; Favreau et al., 2009; Gates et al., 2011; Feng et al., 2016). Our study showed that the measured soil water storage under the F land use was similar to measured values under the A10 land use, but was reduced under the A20 and A30 land uses (Table 3). These results suggested that the apple orchards did not have significant impacts on soil water storage until the orchards were older than 10 years. However, the measured soil water and water storage, either for the entire profiles or for the profiles of 5 − 10 m, were negatively correlated with the ages of the apple orchards ($p < 0.05$, Fig. 6), which highlights the higher water demand of the older apple orchards. Further, the relationship between soil water and apple orchards ages for the 5 − 10 m depth profiles ($R^2 = 0.78$) have higher correlation coefficients relative to the entire profiles and implied that the soil water within the deep soil layers is more subject to the water uptake of the apple orchards.

The mature apple orchards demonstrated the need for more water to meet the greater ET demand relative to farmlands (Table 3). However, the soil water storage in shallow soil layers cannot meet the requirement of the mature apple orchards. With roots that extended over 10 m deep, the mature apple orchards thus transpire water stored for several decades within the deeper soil layers (Zhang et al., 2017), and further promotes the forming of dried soil layers (Wang et al., 2015b). However, the depleted soil water cannot be easily replenished over time because of the high ET and low infiltration rates (Wang et al., 2013; Zhang et al., 2016). This set of conditions has resulted in a reduction in groundwater recharge because of the greater water usage within the

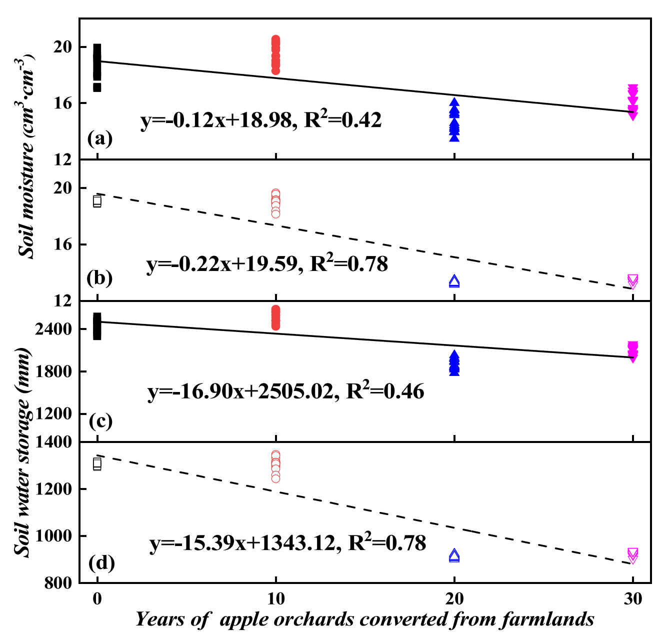

Fig. 6. Comparison of observed (a), (b) soil moisture and (c), (d) soil water storage under different land use types. The solid legends (solid lines) and hollow legends (dish lines) represent data for the profiles of 0 − 10 m and 5 − 10 m, respectively. The x-axis is the number of years since farmlands were converted to apple orchards.

mature orchards. Therefore, the ages of the apple orchards have had a significant negative correlation with groundwater recharge ($R^2 = 0.99$), but a positive correlation with the actual ET ($R^2 = 0.87$) that has occurred (Fig. 7).

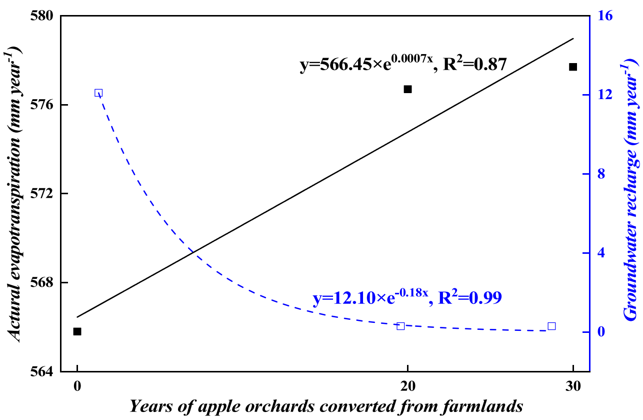

Fig. 7. Comparison of simulated groundwater recharge and actual evapotranspiration under different land use types. The hollow legends, blue dash lines, and solid legends, black solid lines represent data for the simulated groundwater recharge and actual evapotranspiration under different land use types, respectively. The x-axis is the number of years since farmlands were converted to apple orchards. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The deep rooting system of the more mature apple orchards is probably the key factor that has resulted in lower subsurface water storage under the apple orchards (Huang et al., 2018; Li et al., 2018; Zhang et al., 2018; Li et al., 2019a). Li et al. (2019b) reported that the apple trees accessed deep soil water reserves by growing deep roots, with the resulting desiccated soil possibly stimulating apple trees to extend their roots into deeper, moister soil. However, quantifying the root system is labor intensive and time-consuming; as such, it would be better to find an alternative index to characterize the extent of the apple orchard rooting system. Based on the model simulations, the developed quantitative relationships (Figs. 6 & 7) between the ages of the apple orchards and the components of the soil water balance (e.g. soil water contents, water storage and groundwater recharge) appear to be satisfactory, and provides an effective means to interpret the impacts of apple orchards on the soil water balance. These relationships may be further extended to incorporate additional physical conditions such as soil properties and climate.

The LUC-induced changes in soil water balance have been found in other regions of the world (Anache et al., 2019; Kroes et al., 2019; Li et al., 2019b, c; Scott and Biederman, 2019). We collected the actual evapotranspiration and groundwater recharge under different land use types across the world with mean annual rainfall of 172 to 1388 mm (Table 4 and 5), and found that the conversion from shallow-rooted to deep-rooted plants increase actual evapotranspiration by 13% to 85% and decrease groundwater recharge by 73 to 97% ignoring those with small absolute values. The deep-rooted plants have higher water demands to meet the ET requirements, which leads to the decrease of groundwater recharge (Allison et al., 1990; Bari and Schofield, 1992; Nosetto et al., 2005; Favreau et al., 2009; Santoni et al., 2010).

4.3. What is the implication to water resources management?

Although the land use has been substantially changed within the Loess Plateau, the spatial pattern is not actually consistent with the potential natural vegetation (Peng and Li, 2018), and, thus, threatens the sustainability of water resources within some regions (Feng et al., 2016). To increase economic income, a large acreage of farmlands had been converted to apple orchards within some regions, and has potentially decreased subsurface water storage (Huang et al., 2018; Li et al., 2018; Zhang et al., 2018; Li et al., 2019a). However, subsurface water including soil water storage and groundwater is a very important water resource within some regions since these two water sources have been shown to contribute to over 70% of the streamflow (Li et al., 2017c). Therefore, it is urgent to discuss the strategies involved with the trade-offs between continued economic development and the sustainability of water resources.

The depleted soil water, caused by the high water demands of the more mature apple orchards, cannot be replenished before the next growing season and thus results in a progressively increasing soil water deficit as the orchards age increases. Considering the results of our simulations that demonstrated the impacts of maturing apple orchards on gradually reducing the groundwater recharge, indications are that the apple orchards should be removed at an appropriate age of the orchards to maintain sustainable groundwater resources within some regions. The age of apple orchards may be determined through an examination of the developed relationships between apple orchards ages and the hydrological components presented in Figs. 6 and 7.

Although we did not simulate alternative approaches as there is not currently any measured data to calibrate and validate our model, possible alternative approaches might be to reduce the planting density of apple trees at the time of orchard establishment, to cut and remove the orchard at an appropriate age, or to reduce the density of trees within the orchards at an economically acceptable age somewhere between 10 and 20 years of orchard maturity. In either approach, the overall purpose would be to thin the orchards so that more land surface is available for increased rainfall infiltration into the soil. Although there are many factors that must be considered, these alternative approaches might result in increased groundwater recharge and would be a potential topic for consideration in a future study.

5. Conclusions

To investigate the effects of apple orchards converted from farmlands on the soil water balance in a region with a thick loess cover, we simulated the soil water conditions under farmland and apple orchards of different ages. The simulated soil water contents were all very close to the measured observations used during the calibration and validation phases in the preliminary evaluations of the HYDRUS-1D model and all indications were that the HYDRUS-1D model produced acceptable simulation results. The calibrated and validated model was further used to separate the input components of the soil water balance in simulations using weather data from 1960 – 2013. These results demonstrated that the apple orchards converted from farmlands significantly reduced soil water storage within the upper 10-m soil profile depth, reduced groundwater recharge, and increased actual ET. Although there were no significant differences in soil water balance when the farmlands and the 10 year's apple orchard land uses were compared, the LUC effects on reducing the soil water balance were closely linked with the stand age of the mature apple orchards.

It is urgent to regulate the management of apple orchards to sustain the water resources within some regions of the Loess Plateau. Possible management approaches might be to cut the apple trees within the mature orchard at an appropriate age, thin the apple tree density within the orchards at an economically feasible time, or reduce the planting density at the time of orchard establishment.

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References

Allison, G.B., Cook, P.G., Barnett, S.R., Walker, G.R., Jolly, I.D., Hughes, M.W., 1990. Land clearance and river salinisation in the western Murray Basin. Australia. Journal

of Hydrology 119, 1–20.
Allison, G.B., Gee, G.W., Tyler, S.W., 1994. Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. Soil Sci. Soc. Am. J. 58, 6–14.
Anache, J.A.A., Wendland, E., Rosalem, L.M.P., Youlton, C., Oliveira, P.T.S., 2019. Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado. Hydrol. Earth Syst. Sci. 23, 1263–1279.
Baker, T.J., Miller, S.N., 2013. Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed. J. Hydrol. (Amst) 486, 100–111.
Bari, M.A., Schofield, N.J., 1992. Lowering of a shallow, saline water table extensive eucalypt reforestation. J. Hydrol. (Amst) 133, 273–291.
Cartwright, I., Cendón, D., Currell, M., Meredith, K., 2017. A review of radioactive isotopes and other residence time tracers in understanding groundwater recharge: possibilities, challenges, and limitations. J. Hydrol. (Amst) 555, 797–811.
Chi, W., Zhao, Y., Kuang, W., He, H., 2019. Impacts of anthropogenic land use/cover changes on soil wind erosion in China. Sci. Total Environ. 668, 204–215.
Di, W., Li, W., 2017. Dynamics of evapotranspiration partitioning for apple trees of different ages in a semiarid region of northwest China. Agr. Water Manage. 191, 1–15.
Duan, L., Huang, M., Zhang, L., 2016. Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China. J. Hydrol. (Amst) 537, 356–366.
Durner, W., Iden, S.C., 2011. Extended multistep outflow method for the accurate determination of soil hydraulic properties near water saturation. Water Resour. Res. 47, 427–438.
Fan, J.L., Baumgartl, T., Scheuermann, A., Lockington, D.A., 2015. Modeling effects of canopy and roots on soil moisture and deep drainage. Vadose Zone J. 14.
Favreau, G., Cappelaere, B., Massuel, S., Leblanc, M., Boucher, M., Boulain, N., Leduc, C., 2009. Land clearing, climate variability, and water resources increase in semiarid southwest Niger: a review. Water Resour. Res. 45 W00A16.
Feddes, R.A., Bresler, E., Neuman, S.P., 1974. Field-test of a modified numerical-model for water uptake by root systems. Water Resour. Res. 10, 1199–1206.
Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., Wu, B., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Chang. 6, 1019–1022.
Fu, C.S., Chen, J.Y., Dong, L.Y., Jiang, H.B., 2012. Field investigation and modeling of runoff generation in a granitic catchment in Zhuhai, China. J. Hydrol. (Amst) 458, 87–102.
Gates, J.B., Scanlon, B.R., Mu, X., Zhang, L., 2011. Impacts of soil conservation on groundwater recharge in the semi-arid Loess Plateau, China. Hydrogeol. J. 19, 865–875.
Gee, G.W., Hillel, D., 2010. Groundwater recharge in arid regions: review and critique of estimation methods. Hydrol. Process. 2, 255–266.
Hargreaves, G.H., 1994. Defining and using reference evapotranspiration. J. Irrig. Drain. Eng. 120, 1132–1139.
Hendrickx, J.M.H., 1992. Groundwater recharge. A guide to understanding and estimating natural recharge. J. Environ. Qual. 21 512.
Hu, W., Shao, M.A., Han, F.P., Reichardt, K., Tan, J., 2010. Watershed scale temporal stability of soil water content. Geoderma 158, 181–198.
Hu, W., Shao, M.G., Wang, Q.J., Fan, J., Horton, R., 2009. Temporal changes of soil hydraulic properties under different land uses. Geoderma 149, 355–366.
Huang, M., He, F., Yang, X., Li, Y., 2001. Effect of apple production base on regional water cycle in Weibei upland of the Loess Plateau. J. Geogr. Sci. 11 (2), 239–243.
Huang, T., Yang, S., Liu, J., Li, Z., 2016. How much information can soil solute profiles reveal about groundwater recharge? Geosci. J. 20, 495–502.
Huang, M., Barbour, S.L., Elshorbagy, A., Zettl, J.D., Si, B.C., 2011. Water availability and forest growth in coarse-textured soils. Can. J. Soil Sci. 91, 199–210.
Huang, M., Gallichand, J., 2006. Use of the SHAW model to assess soil water recovery after apple trees in the gully region of the Loess Plateau, China. Agric. Water Manag. 85, 67–76.
Huang, T., Pang, Z., Edmunds, W.M., 2013. Soil profile evolution following land-use change: implications for groundwater quantity and quality. Hydrol. Process. 27, 1238–1252.
Huang, Y., Chang, Q., Li, Z., 2018. Land use change impacts on the amount and quality of recharge water in the loess tablelands of China. Sci. Total Environ. 628–629, 443–452.
Jha, R.K., Sahoo, B., Panda, R.K., 2017. Modeling the water and nitrogen transports in a soil–paddy–atmosphere system using HYDRUS-1D and lysimeter experiment. Paddy Water Environ. 15, 831–846.
Jia, X., Fu, B., Feng, X., Hou, G., Liu, Y., Wang, X., 2014. The tradeoff and synergy between ecosystem services in the Grain-for-Green areas in Northern Shaanxi, China. Ecol. Indic. 43, 103–113.
Jia, X., Shao, M., Yu, D., Zhang, Y., Binley, A., 2019. Spatial variations in soil-water carrying capacity of three typical revegetation species on the Loess Plateau, China. Agric. Ecosyst. Environ. 273, 25–35.
Jian, S., Zhao, C., Fang, S., Yu, K., 2015. Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau. Agric. For. Meteorol. 206, 85–96.
Koeniger, P., Gaj, M., Beyer, M., Himmelsbach, T., 2016. Review on soil water isotope-based groundwater recharge estimations. Hydrol. Process. 30, 2817–2834.
Köhne, J.M., Wöhling, T., Pot, V., Benoit, P., Leguédois, S., Bissonnais, Y.L., Šimůnek, J., 2011. Coupled simulation of surface runoff and soil water flow using multi-objective parameter estimation. J. Hydrol. (Amst) 403, 141–156.
Kroes, J., van Dam, J., Supit, I., de Abelleyra, D., Veron, S., de Wit, A., Boogaard, H., Angelini, M., Damiano, F., Groenendijk, P., Wesseling, J., Veldhuizen, A., 2019. Agrohydrological analysis of groundwater recharge and land use changes in the Pampas of Argentina. Agric. Water Manag. 213, 843–857.
Li, H., Si, B.C., Li, M., 2018. Rooting depth controls potential groundwater recharge on hillslopes. J. Hydrol. (Amst) 564, 164–174.
Li, H., Si, B.C., Wu, P.T., McDonnell, J.J., 2019a. Water mining from the deep critical zone by apple trees growing on loess. Hydrol. Process. 33, 320–327.
Li, H.J., Si, B.C., Ma, X.J., Wu, P.T., 2019b. Deep soil water extraction by apple sequesters organic carbon via root biomass rather than altering soil organic carbon content. Sci. Total Environ. 670, 662–671.
Li, H.J., Si, B.C., Wu, P.T., McDonnell, J.J., 2019c. Water mining from the deep critical zone by apple trees growing on loess. Hydrol. Process. 33, 320–327.
Li, J., Li, Z., Lü, Z., 2016. Analysis of spatiotemporal variations in land use on the Loess Plateau of China during 1986–2010. Environ. Earth Sci. 75, 997.
Li, J., Peng, S., Li, Z., 2017a. Detecting and attributing vegetation changes on China's Loess Plateau. Agric. For. Meteorol. 247, 260–270.
Li, Z., Chen, X., Liu, W., Si, B., 2017b. Determination of groundwater recharge mechanism in the deep loessial unsaturated zone by environmental tracers. Sci. Total Environ. 586, 827–835.
Li, Z., Jasechko, S., Si, B., 2019d. Uncertainties in tritium mass balance models for groundwater recharge estimation. J. Hydrol. (Amst) 571, 150–158.
Li, Z., Lin, X., Xiang, W., Chen, X., Huang, T., 2017c. Stable isotope tracing of headwater sources in a river on China's Loess Plateau. Hydrol. Sci. J. Des Sci. Hydrol. 62, 2150–2159.
Li, Z., Liu, W., Zhang, X., Zheng, F., 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. J. Hydrol. (Amst) 377, 35–42.
Li, Z., Si, B.C., 2018. Reconstructed precipitation tritium leads to overestimated groundwater recharge. J. Geophys. Res. Atmos. 123, 9858–9867.
Mayerhofer, C., Meissl, G., Klebinder, K., Kohl, B., Markart, G., 2017. Comparison of the results of a small-plot and a large-plot rainfall simulator - Effects of land use and land cover on surface runoff in Alpine catchments. Catena 156, 184–196.
Mirus, B.B., Ebel, B.A., Mohr, C.H., Zegre, N., 2017. Disturbance hydrology: preparing for an increasingly disturbed future. Water Resour. Res. 53, 10007–10016.
Moghadas, D., Jadoon, K.Z., Vanderborght, J., Lambot, S., Vereecken, H., 2013. Effects of near surface soil moisture profiles during evaporation on far-field ground-penetrating radar data: a numerical study. Vadose Zone J 12.
Mu, Y., Wang, Y., 2017. Study on soil water balance of apple orchards in the loess tableland of China. Research of Agricultural Modernization 38, 161–167.
Nosetto, M.D., Jobbagy, E.G., Paruelo, J.M., 2005. Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. Glob. Chang. Biol. 11, 1101–1117.
Peng, S., Li, Z., 2018. Incorporation of potential natural vegetation into revegetation programmes for sustainable land management. Land Degrad. Dev. 29, 3503–3511.
Petroselli, A., Tauro, F., 2017. Cape Fear: monitoring basic hydrological processes in an outdoor hillslope plot. Environ. Monit. Assess 189.
Qu, Z., Zhou, G., 2016. Dynamics of decadal changes in the distribution of cultivation regions with climate suitbale for the Fuji apple in China. Acta Ecol. Sin. 36, 7551–7561.
Ren, Z., Li, Z., Liu, X., Li, P., Cheng, S., Xu, G., 2018. Comparing watershed afforestation and natural revegetation impacts on soil moisture in the semiarid Loess Plateau of China. Sci. Rep. 8, 2972.
Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics 1, 318–333.
Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204–1213.
Saito, H., Simunek, J., Mohanty, B.P., 2006. Numerical analysis of coupled water, vapor, and heat transport in the vadose zone. Vadose Zone J. 5, 784–800.
Santoni, C.S., Jobbágy, E.G., Contreras, S., 2010. Vadose zone transport in dry forests of central Argentina: role of land use. Water Resour. Res. 46, 480–490.
Sarkar, R., Dutta, S., Dubey, A.K., 2015. An insight into the runoff generation processes in wet sub-tropics: field evidences from a vegetated hillslope plot. Catena 128, 31–43.
Scanlon, B.R., 2004. Evaluation of methods of estimating recharge in semiarid and arid regions in the southwestern U.S. Water Science and Application 9, 235–254.
Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10 347-347.
Scanlon, B.R., Tyler, S.W., Wierenga, P.J., 1997. Hydrologic issues in arid, unsaturated systems and implications for contaminant transport. Rev. Geophys. 35, 461–490.
Scott, R.L., Biederman, J.A., 2019. Critical zone water balance over 13 years in a Semiarid Savanna. Water Resour. Res. 55, 574–588.
Simunek, J.J., Šejna, M., Saito, H., Sakai, M., Van Genuchten, M., 2013. The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.17. HYDRUS Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California.
Su, B., Shangguan, Z., 2018. Decline in soil moisture due to vegetation restoration on the Loess Plateau of China. Land Degrad. Dev.
Suo, L., Huang, M., Zhang, Y., Duan, L., Shan, Y., 2018. Soil moisture dynamics and dominant controls at different spatial scales over semiarid and semi-humid areas. J. Hydrol. (Amst) 562, 635–647.
Tan, H., Liu, Z., Rao, W., Wei, H., Zhang, Y., Jin, B., 2017. Stable isotopes of soil water: Implications for soil water and shallow groundwater recharge in hill and gully regions of the Loess Plateau, China. Agric. Ecosyst. Environ. 243, 1–9.
Turkeltaub, T., Dahan, O., Kurtzman, D., 2014. Investigation of groundwater recharge under agricultural fields using transient deep vadose zone data. Vadose Zone J. 13 0.
Turkeltaub, T., Jia, X., Zhu, Y., Shao, M.-A., Binley, A., 2018. Recharge and nitrate transport through the deep vadose zone of the Loess Plateau: a regional scale model investigation. Water Resour. Res. 54, 4332–4346.
Van Genuchten, M.T., 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils Soil Science Society of America Journal 44, 892.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277, 494–499.
Vries, J.J.D., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeol. J. 10, 5–17.
Vrugt, J.A., van Wijk, M.T., Hopmans, J.W., Šimunek, J., 2001. One-, two-, and three-dimensional root water uptake functions for transient modeling. Water Resour. Res. 37, 2457–2470.
Wagener, T., Sivapalan, M., Troch, P.A., McGlynn, B.L., Harman, C.J., Gupta, H.V., Kumar, P., Rao, P.S.C., Basu, N.B., Wilson, J.S., 2010. The future of hydrology: an evolving science for a changing world. Water Resour. Res 46.
Wang, S., Wang, L., Han, X., Zhang, L., 2016. Evapotranspiration characteristics of apple orchard at peak period of fruiting in Loess Tableland. Scientia Silvae Sinicae 52, 128–135.
Wang, Y., Hu, W., Zhu, Y., Shao, M.A., Xiao, S., Zhang, C., 2015a. Vertical distribution and temporal stability of soil water in 21-m profiles under different land uses on the Loess Plateau in China. J. Hydrol. (Amst) 527, 543–554.
Wang, Y., Shao, M., Liu, Z., Zhang, C., 2015b. Characteristics of dried soil layers under apple orchards of different ages and their applications in soil water managements on the Loess Plateau of China. Pedosphere 25, 546–554.
Wang, Y., Shao, Ma., Liu, Z., 2013. Vertical distribution and influencing factors of soil water content within 21-m profile on the Chinese Loess Plateau. Geoderma 193-194, 300–310.
White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and sensitivity analysis of the BIOME–BGC terrestrial ecosystem model: net primary production controls. Earth Interact. 4, 1–84.
Xiong, L., Tang, G., Li, F., Yuan, B., Lu, Z., 2014. Modeling the evolution of loess-covered landforms in the Loess Plateau of China using a DEM of underground bedrock surface. Geomorphology 209, 18–26.
Ye, L., Fang, L., Shi, Z., Deng, L., Tan, W., 2019. Spatio-temporal dynamics of soil moisture driven by 'Grain for Green' program on the Loess Plateau, China. Agric. Ecosyst. Environ. 269, 204–214.
Yu, B., Liu, G., Liu, Q., Wang, X., Feng, J., Huang, C., 2018. Soil moisture variations at different topographic domains and land use types in the semi-arid Loess Plateau, China. Catena 165, 125–132.
Zhang, Y., Xiao, Q., Huang, M., 2016. Temporal stability analysis identifies soil water relations under different land use types in an oasis agroforestry ecosystem. Geoderma 271, 150–160.
Zhang, S., Simelton, E., Lövdahl, L., Grip, H., Chen, D., 2007. Simulated long-term effects of different soil management regimes on the water balance in the Loess Plateau, China. Field Crop. Res. 100, 311–319.
Zhang, Y., Huang, M., 2013. Evapotranspiration characteristics and their influencing factors for arbors and shrubs with different precipitation patterns in Loess Plateau. Bulletin of Soil and Water Conservation 33, 207–212.
Zhang, Z., Evaristo, J., Li, Z., Si, B., McDonnell, J.J., 2017. Tritium analysis shows apple trees may be transpiring water several decades old. Hydrol. Process. 31, 1196–1201.
Zhang, Z., Li, M., Si, B., Feng, H., 2018. Deep rooted apple trees decrease groundwater recharge in the highland region of the Loess Plateau, China. Sci. Total Environ. 622–623, 584–593.
Zhu, Y., Jia, X., Shao, M., 2018. Loess thickness variations across the Loess Plateau of China. Surv. Geophys. 39, 715–727.
Ziadat, F.M., Taimeh, A.Y., 2013. Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment. Land Degrad. Dev. 24, 582–590.