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Soil Management Practice Effect on Water Balance of a Dryland Soil during Fallow Period on the Loess Plateau of China

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Abstract

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To understand the mechanisms affecting water balance partitioning during fallow on drylands could improve the fallow management practices in arable land ecosystems. A three-year field experiment was conducted to evaluate the effects of field management regimes on water balance partitioning and fallow efficiency during the fallow periods under a winter wheat (*Triticum aestivum* L.) fallow system on the Loess Plateau, China. The fallow management regimes tested were: (*i*) conventional practice, (*ii*) catch cropping, and (*iii*) no tillage with wheat straw mulching. A process-oriented ecosystem model (CoupModel) was calibrated with field measurements and then used to generate comparative simulations of the water balance partitioning. The simulations indicated that mulching increased the soil water storage change by 38–71 mm during the three fallow periods, thus resulting in higher fallow efficiency by 9–12%, and decreased soil evaporation by 22–72 mm, compared with the conventional practice. Furthermore, water reached deeper horizons, resulting in 7 mm deep percolation in a wet year under mulching but not under conventional practice or catch cropping. The simulation results also showed that the catch cropping decreased the soil water storage change by 13–21 mm, although it lowered soil evaporation by 11–51 mm, and altogether reduced the fallow efficiency by 3–9%, compared to conventional practice. On the Loess Plateau of China mulching proved to be a sound measure for ensuring certain fallow efficiency and possibly benefit to the water cycle, while catch cropping negatively partitioned the water balance. The catch cropping under mulching might be another management regime to be considered.

Keywords: deep percolation; fallow efficiency; modelling; soil evaporation; soil water storage

Water is the most limiting factor for crop production under dryland farming in semiarid areas. In China, dryland farming is practiced on about one third of the arable land, a large part of which (about 40%) is situated on the semiarid Loess Plateau (Li 2004). Winter wheat, as a main cereal crop sown in late September and harvested in early June to early July of the next year, varying with latitudes, occupies 56% of the arable land in the region (Zhu 1989). The prevailing cropping practice is winter wheat – fallow system, one crop per year. However, winter wheat growing season does not coincide with the precipitation season, which is from June to September. Hence, wheat yield is also influenced by the amount of precipitation falling outside the growing season (Li 1983; Huang & Li 2000). The water storage at the sowing time has an important effect on winter wheat yield. Musick *et al.* (1994) found that wheat yields were linearly related to soil water stored at sowing and this positive relationship was more significant than the relationship to seasonal water use. A study by Li and Shu (1991) on the Loess Plateau of China indicated that on average 47% of the wheat yield is dependent upon the stored soil-water at sowing.

doi: 10.17221/255/2014-SWR

Therefore, the successful fallow practice improving the water storage at sowing time is important for wheat production.

The conventional management regime for dryland winter wheat cultivation on the Loess Plateau involves keeping the farmland bare fallow during the rainy summer after the wheat harvest (early June or early July to mid or late September). The aim is to accumulate water from precipitation for use by the subsequent wheat crop (Li & Xiao 1992). However, the fallow efficiency (percentage of rainfall stored in the soil during the fallow period) using this method is low, because the potential evaporation is high when the temperature is high, thus most of the precipitation collected in the soil is lost again through evaporation (Li & Xiao 1992; Latta & O'leary 2003).

The wheat straw mulching is regarded as one of the best ways of retaining more water in the soil and decreasing soil evaporation (Steiner 1989; Li & Xiao 1992). Nevertheless, O'leary and Connor (1997) conclude that in general, zero tillage (primarily with stubble retention) offered large and consistent increases in soil water storage on heavy-textured clay soils in a 420-mm rainfall zone, but on lighter sandy loam soil under the lower rainfall regime (343 mm), the advantage in soil water storage, through both stubble retention and zero tillage, was less frequent. In the southeast of the Loess Plateau, several researchers reported no tillage with mulching improved water conservation at wheat sowing in most years (Jin *et al*. 2007; Su *et al*. 2007), in the west of the Loess Plateau as well (Huang *et al*. 2008). In the same region, however, Zhang *et al*. (2009) found mulching effectiveness differing with land positions and having little effect on the increase of soil water storage at terrace land. Hence, mulching effects rely on various factors, such as soil types and positions, rainfall frequency and patterns, and atmospheric demand.

The presence of mulch on the soil surface can influence the partitioning of water balance. Understanding the mechanisms affecting water balance partitioning during fallow on drylands could improve the fallow management practices in arable land ecosystems, to maximize the stored soil water at crop sowing time. Previously, Zhang *et al*. (2007a) evaluated different soil management regimes effects on annual water balance and wheat water use efficiency by model simulation. The study presented here is focused on assessing effects of the wheat straw mulching and the catch cropping on the partitioning of water balance components during the fallow period and on the fallow efficiency by using the simulated results.

MATERIAL AND METHODS

Site description and experimental design. The experiment was conducted in Heyang county (35°19'37"N, 110°4'57"E, altitude 910 m a.s.l.), Shaanxi Province. The site is located on a large flat area in the southeastern part of the Loess Plateau. The soil (Heilu soil, see Zhu *et al*. 1983) represents the main soil type widespread in the region. According to the USDA classification system, the soil is defined as silt loam and, according to the FAO-UNESCO soil map (FAO-UNESCO 1974), the soil type is a Chromic Cambisol.

The study included three treatments. The first was conventional practice (C), wheat harvest leaving stubble (5–10 cm) and roots; the soil was then tilled to ca. 20 cm depth by spade and left bare during fallow time. The second treatment was catch cropping (CC), wheat harvest leaving stubble (5–10 cm) and roots; a catch crop (bean) was directly sown without applying any fertilizer and harvested about one month before wheat sowing. The harvested bean biomass was immediately incorporated into the soil by manual ploughing. The catch crops used were green bean (*Phaseolus vulgaris* L.) in the first year and black bean (*Glycine max* (L.) Merr.) in the next two years. The harvest times for the catch crops were Aug 30, 2002, Aug 12, 2003, and Aug 23, 2004, respectively. The third treatment was mulching (M), wheat harvest leaving stubble (5–10 cm) and roots; it remained unploughed and air-dried, unchopped wheat straw (about 0.8 kg/m^2) was evenly distributed over the soil surface and kept at relatively constant levels for the duration of the fallow. The duration of three fallow periods was 104 days (June 11–Sept 23, 2002), 103 days (June 13–Sept 24, 2003) and 102 days (June 11–Sept 21, 2004), respectively. Three replicates of each treatment were randomly distributed in the field. The size of each plot was 5 × 5 m, with 0.3 m wide and 0.1 m high separating ridges.

Field measurements. Before the experiment started, soil moisture sensors (Theta probe ML2, Delta-T Devices Ltd, Cambridge, UK) were installed with one replicate per treatment at the depths of 10, 40, 100, and 200 cm, to monitor soil moisture in the respective horizons. In addition, soil temperature sensors (Thermistor, Campbell Scientific, Inc., Logan, USA) were also installed in the same plot at the depths of

doi: 10.17221/255/2014-SWR

5 and 10 cm, to monitor soil temperatures. Hourly readings were recorded throughout the experimental period. The soil moisture sensors were calibrated in the field by comparing its readings with soil moisture measured gravimetrically during the experimental period. To compare variations within each treatment, water content was occasionally measured gravimetrically in all replicate plots. The dry weights of catch crop were measured prior to its manual "ploughing-in".

Meteorological data. A climate station equipped with a data logger (CR10x; Campbell Scientific, Inc.) near the field plots measured air temperature, air humidity, and wind speed every minute, and stored hourly mean values of these variables, and accumulated global radiation and precipitation values, throughout the experimental period. The measuring heights were 2 m for air temperature and air humidity, and 4 m for wind speed. The sensors were factory calibrated before installation.

Model description. The CoupModel is a one-dimensional model simulating fluxes of water, heat, carbon, and nitrogen in the soil–plant–atmosphere system (Jansson & Karlberg 2004), coupling the former SOIL (Johnsson & Jansson 1991) and SOIL-N (Eckersten *et al.* 2001) models. A detailed technical description of the model was given by Jansson and Karlberg (2004).

Model application. The meteorological variables used as driving variables in the simulations presented here were daily air temperature, relative air humidity, wind speed, precipitation, and global radiation. In addition, soil properties such as hydraulic conductivity and soil water retention curves were used as model input (Zhang *et al.* 2007b), while the Brooks-Corey equation (Brooks & Corey 1964) was used to describe soil water retention and, in combination with Mualem's equation (Mualem 1976), to estimate unsaturated hydraulic conductivity (Zhang *et al.* 2007b). The same soil hydraulic properties were applied for all treatments. The measured soil water content profile and soil temperature profile (apart from measured values, other layers assumed to be 15°C) were used as initial conditions for each treatment. The simulated soil profile (0–240 cm) was composed of 11 soil compartments (0–5, 5–15, 15–25, 25–35, 35–45, 45–55, 55–65, 65–80, 80–120, 120–160, and 160–240 cm deep). The simulations were conducted under the assumption that the soil hydraulic properties remained unchanged during the experimental period. The calibration procedure of the model was the same as that reported by Zhang *et al.* (2007a). Several parameters were tuned to provide a reasonable agreement between the simulated results and measured soil moisture and soil temperatures for all of the three years. In the catch cropping treatment, all parameters were set to the same values as in the conventional management. To simulate a catch crop (bean), the wheat parameterization (Zhang *et al.* 2007a) was adjusted to fit the measurements of total above-ground biomass, soil temperature, and soil moisture contents. The same sowing and harvest times of the catch crop were used in the simulation as well as in the field operations.

Analytical method. The equation of field water balance is as follows:

$$P = E + T + D + R + \Delta S \qquad (1)$$

where:
P – precipitation
E – soil evaporation
T – crop transpiration
R – surface runoff
D – deep percolation below the root zone, in the present paper considered as 2.4 m below the soil surface
ΔS – change in soil water storage (240 cm soil profile)

In this study surface runoff was zero because the topography was flat. All terms in Eq. (1) are cumulative totals since the beginning of the fallow season.

The fallow efficiency (*FE*) is calculated as:

$$FE = \Delta S/P \qquad (2)$$

RESULTS

Weather condition. Precipitation during three experimental fallow periods and the 30-year average (1976–2005) were 244, 515, 384, and 356 mm, respectively (Table 1). Correspondingly, the potential evaporation totals, estimated from the Penman equation (Penman 1948) over the three fallow periods, were 500, 402, and 446 mm, respectively. Furthermore, both fallow rainfalls and potential evaporation accounted for large proportions of annual values, because the fallow period is a combination of high rainfall and high temperature. In comparison with the 30-year average, the three experimental fallow periods reflected the dry, wet, and normal rainfall conditions, respectively, and the rainfalls and their distribution showed great within-fallow-period variability. In 2002, the rainfalls increased from June to September and the highest value was in September.

doi: 10.17221/255/2014-SWR

Table 1. Fallow precipitation and the potential evaporation[a] during 2002, 2003, and 2004 fallow seasons[b] compared with long-term monthly totals (1976–2005) at the experimental site (in mm)

Period	Precipitation				Potential evaporation		
	2002	2003	2004	1976–2005	2002	2003	2004
June	17.6	61.3	51.3	56.7	124.4	111.1	128.1
July	48.4	160.6	95.3	109.4	179.2	134.1	138.3
August	85.3	205.0	181.9	113.4	124.1	91.2	114.6
September	92.8	87.8	55.2	76.9	72.3	65.5	64.5
Fallow	244	515	384	356	500	402	446
Annual	468	825	641	535	1152	976	–
Fallow/Annual	0.52	0.62	0.60	0.67	0.43	0.41	–

[a]Potential evaporation was calculated according to Penman (1948); [b]the first fallow was from June 10–Sept 23, 2002, the second one from June 12–Sept 24, 2003, and the third one from June 10–Sept 21, 2004; the fallow rainfall for the long-term (1976–2005) is taken as a sum of full four months (June to September) and, strictly speaking, is not fully comparable with the sums over particular fallow periods

In 2003, the rainfalls mainly occurred in July and August, and the least precipitation appeared in June. In 2004, about 50% of fallow rainfall fell in August. The potential evaporation showed the highest values in July for all the three fallows, then followed by June and August; it was the least in September. This implies that rainfall in September might be more retained in soil, while rainfall in July was prone to evaporation.

Model prediction. The model predicted the soil moisture dynamics for all treatments reasonably well during the course of the experiment (Figure 1). The determination coefficients R^2 between the simulated and

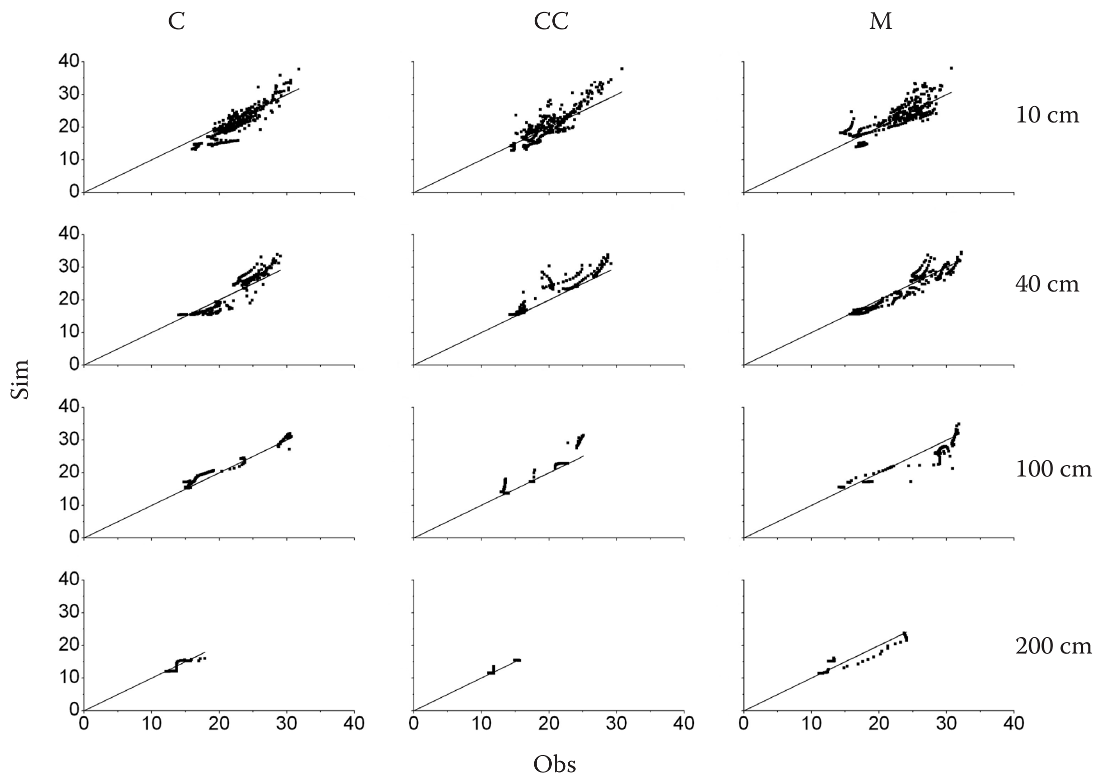

Figure 1. Correlation between the measured (Obs) and simulated (Sim) depth-averaged volumetric soil water contents (% by volume) for the 0–200 cm soil profile during the three fallow periods under particular treatments; C – conventional treatment; CC – cover crop treatment; M – mulch treatment

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observed values ranged from 0.681 to 0.962; in general, the R^2 values were lower for the 10-cm depth (Table 2). The root mean square error (RMSE) values were less than 3.0% (by volume). In most cases the model predicted higher water contents than the measured values, with differences between the simulated and measured mean values ranging from 0.05 to 1.29% (Table 2). The model described the differences between the treatments consistently, and similarly to the measurements. The simulated water contents in the deeper layers showed a good agreement with the measured values. At 10 cm the simulated water content was overestimated during wet conditions (high peaks), but was similar to the values measured during dry periods.

The model also predicted well the soil temperature dynamics during three fallow periods (Figure 2). The determination coefficients R^2 between simulated and observed values ranged from 0.808 to 0.945, and the RMSE values were less than 2.5°C. In most cases the model underestimated high soil temperatures, with differences between the simulated and measured mean values ranging from 0.6 to 2.1°C (Table 2). Moreover, the modelled biomass values of catch crop were within the range of the measured values ± 2 SD (standard deviation) (Figure 3).

Overall, we demonstrated that the ecosystem model CoupModel provided good simulations of the dynamics of water content changes and soil temperatures and the crop biomass for different soil management regimes and climate variations during fallow periods on a loess soil in China. The model described the soil wetting, drying, and heat cycles well, although there were some discrepancies between the simulated and measured values.

Soil evaporation. The simulated dynamics of soil evaporation is illustrated in Figure 4. The conventional treatment developed the highest amount of soil evaporation during the course of three tested fallows. The catch cropping yielded the lowest amount of soil evaporation during its growing. The differences

Table 2. Numbers of observations (n) of soil moisture (q, % by volume) and soil temperature (T, °C) during three fallow seasons, determination coefficient (R^2) between simulated and measured values, root mean square errors (RMSE) of simulated vs observed values, mean values from simulation (M-sim) and from measurement (M-obs) under particular management practices at the Heyang site

Treatment	Item	n	R^2	RMSE	M-sim	M-obs
C	$q_{10\ cm}$	315	0.852	2.52	21.54	22.77
	$q_{40\ cm}$	315	0.885	2.24	20.67	20.72
	$q_{100\ cm}$	315	0.962	1.21	18.40	17.78
	$q_{200\ cm}$	315	0.807	1.17	13.26	13.75
	$T_{5\ cm}$	133	0.945	2.36	22.34	24.42
	$T_{10\ cm}$	280	0.908	1.87	22.19	23.67
CC	$q_{10\ cm}$	315	0.775	2.70	20.59	20.13
	$q_{40\ cm}$	315	0.897	2.22	19.94	18.65
	$q_{100\ cm}$	315	0.803	2.39	17.21	16.18
	$q_{200\ cm}$	315	0.961	0.87	12.85	12.90
	$T_{5\ cm}$	186	0.870	1.52	23.58	24.52
	$T_{10\ cm}$	237	0.838	1.33	23.36	24.08
M	$q_{10\ cm}$	315	0.681	2.72	23.30	22.74
	$q_{40\ cm}$	315	0.918	1.65	22.37	22.76
	$q_{100\ cm}$	315	0.939	1.95	19.90	20.29
	$q_{200\ cm}$	315	0.780	1.59	13.43	12.98
	$T_{5\ cm}$	315	0.853	1.23	21.86	22.48
	$T_{10\ cm}$	315	0.808	1.36	21.65	22.41

C – conventional treatment; CC – cover crop treatment; M – mulch treatment;

RMSE = $\sqrt{1/n\sum_{i=1}^{n}(y_{i\mathrm{sim}} - y_{i\mathrm{obs}})^2}$ where: y_{isim} and y_{iobs} are the simulated and observed soil moisture contents

doi: 10.17221/255/2014-SWR

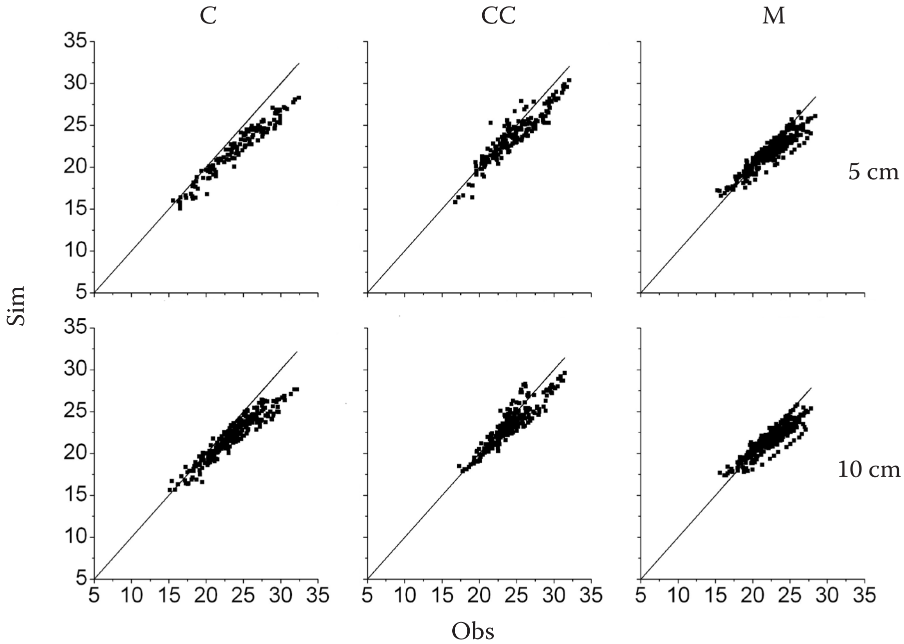

Figure 2. Correlation between the measured (Obs) and simulated (Sim) soil temperatures (°C) for the 5 cm and 10 cm soil depths during the three fallow periods under particular treatments; C – conventional treatment; CC – cover crop treatment; M – mulch treatment

between treatments of surface cover (mulching and catch cropping) and non-cover (conventional) were less significant under dry condition (e.g. 2002) than under wet condition (e.g. 2003). In the beginning of each fallow the rainfalls did not meet the amounts of soil evaporation, and this process lasted for about two months in 2002, but much shorter in 2003 and 2004.

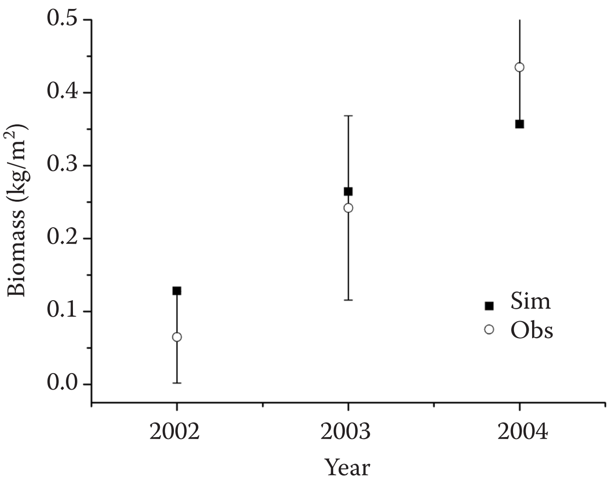

Figure 3. Measured and simulated biomass yields of catch crops during the 2002, 2003, and 2004 fallow periods; vertical bars express two times standard deviations

Soil water storage and fallow efficiency. The simulated water storage in the upper 55 cm soil layer showed the mulching treatment was associated with the highest water storage in two of three fallow periods (2002 and 2004) (Table 3). The differences of stored water between mulching and conventional treatments varied from 0 to 18 mm for particular

Table 3. Simulated changes (increase) in soil water storage (in mm) from the previous harvest to the following sowing at different soil layers under particular treatments

Soil layer (cm)	Year	Treatments		
		C	CC	M
0–55	2002	39	42	57
	2003	45	44	45
	2004	51	45	63
55–120	2002	2	0	23
	2003	79	84	81
	2004	50	40	64
120–240	2002	1	0	0
	2003	79	61	148
	2004	7	3	22

See footnote to Table 1 for the exact lengths of fallow seasons; C – conventional treatment; CC – cover crop treatment; M – mulch treatment

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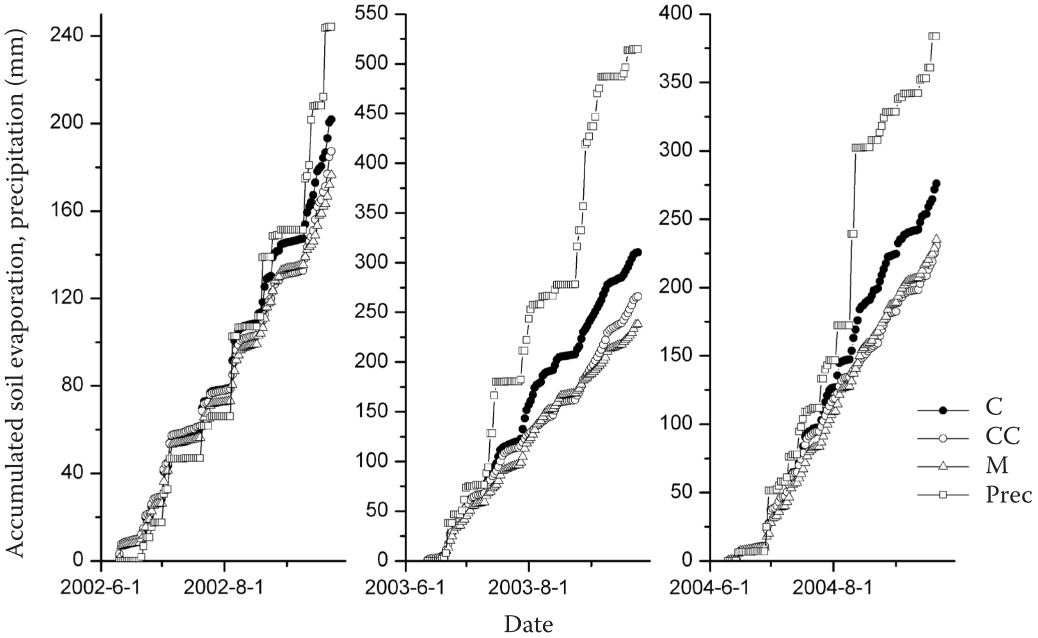

Figure 4. Simulated cumulative soil evaporation under particular treatments and precipitation during the 2002, 2003, and 2004 fallow periods; C – conventional treatment; CC – cover crop treatment; M – mulch treatment; Prec – precipitation

fallow periods. The amounts of stored water associated with the conventional practice and catch cropping treatments were similar except in 2004. In the 55–120 cm layer, the amount of water stored varied greatly between treatments from year to year (Table 3). The mulching manifested the highest water storage, while the catch cropping displayed the lowest level in 2002 and 2004. All treatments had similar water storage levels in 2003. The amount of water stored in the 120–240 cm layer was similar in

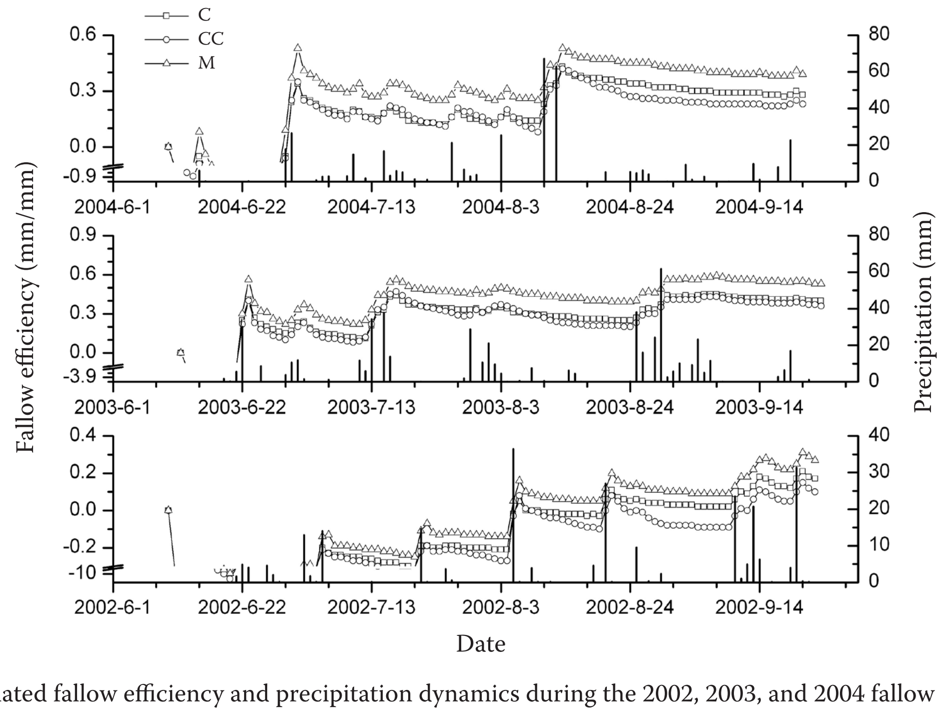

Figure 5. Simulated fallow efficiency and precipitation dynamics during the 2002, 2003, and 2004 fallow periods under particular treatments; C – conventional treatment; CC – cover crop treatment; M – mulch treatment; the break was applied for values between –11 and –0.4 on *Y*-axis

doi: 10.17221/255/2014-SWR

Table 4. Simulated water balance components (in mm) and fallow efficiency (*FE*, %) for fallow periods and 240 cm soil profile under different treatments at Heyang site

Year	Treatment	Precipitation	Deep percolation	Soil evaporation	Transpiration + interception	Water storage change (increase)	*FE*
	C	244	0	198 (81)	–	46 (19)	18.9
2002	CC	244	0	187 (77)	32 (13)	25 (10)	10.2
	M	244	0	176 (72)	–	68 (28)	27.9
	C	515	0	310 (60)	–	205 (40)	39.8
2003	CC	515	0	266 (52)	59 (11)	190 (37)	36.9
	M	515	7 (1)	238 (46)	–	270 (52)	52.4
	C	384	0	276 (72)	–	108 (28)	28.1
2004	CC	384	0	225 (59)	64 (17)	95 (25)	24.7
	M	384	0	235 (61)	–	149 (39)	38.8

C – conventional treatment; CC – cover crop treatment; M – mulch treatment; numbers in parentheses are the corresponding percentage of precipitation

all treatments in 2002, while the mulched plots had higher levels of water storage than the other treatments in 2003 and 2004 (Table 3).

The dynamics of *FE* during the three fallows under the three treatments is shown in Figure 5. The *FE* showed negative in the beginning of each fallow period. The time at which *FE* started to be positive differed from treatment to treatment and from year to year. In 2002, the negative *FE* was observed before August 5th for all treatments. The positive *FE* had been observed since then on the mulching treatment, while it fluctuated around zero until August 20th and only thereafter became positive for the treatment of conventional practice. In sharp contrast to mulching, *FE* fluctuated around zero till September 10th when it showed positive for the treatment of catch cropping. In 2003 and 2004, the *FE* showed negative before the end of June, thereafter became positive for all the treatments. The catch cropping showed similar or lower fallow efficiency compared with the conventional practice, while mulching had the highest fallow efficiency.

Water balance. The simulated water balance for the three treatments is presented in Table 4. During the fallow periods, soil evaporation was the highest under conventional practice, accounting for 60–81% of the precipitation, the lowest under mulching (46–72%), and the medium under catch cropping (52–77%). On average, soil evaporation was reduced by 45 mm per season due to mulching and by 35 mm per season due to catch cropping, compared with the conventional practice. Deep percolation only occurred on the mulching treatment in 2003 and occupied only 1% of precipitation. The transpiration under catch cropping accounted for 11–17% of the precipitation. On average, the mulching increased soil water storage over the fallow season by 42 mm, relative to the conventional treatment, while the catch cropping decreased soil water storage by 17 mm.

DISCUSSION AND CONCLUSIONS

On the Loess Plateau of China, the issue of fallow management practice is of a considerable practical interest because water supply is the major factor limiting crop yield. According to the simulations in the present study, the mulching increased soil water storage relative to conventional practice by 38–71 mm. The improvement of water storage under mulching during the fallow time was more efficient during the wet year (2003) than during a dry year (e.g. 2002). The amount of water gained under the mulching, if used with the water-use efficiency 15 kg grain/ha/mm (Zhang *et al*. 2007a), is sufficient to increase yield by 0.57–1.07 t/ha. The effect of mulching with zero tillage on increasing soil water storage in this study was generally consistent with that reported elsewhere (e.g. Unger 1978; Jin *et al*. 2007) under different weather patterns.

The soil water storage or fallow efficiency depends on soil evaporation which is related to the rainfall patterns and the atmospheric demand. Soil evaporation, a two-stage process (Ritchie 1972), is mainly controlled by the atmospheric demand in the first stage (when the soil is wet) and by water availability and hydraulic conductivity of soil in the second stage, when it is drier. However, the role of mulching in lessening soil

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evaporation is mainly in the first stage (Zhang *et al.* 2007a). In the present study, the rainfall in the 2002 fallow period was lower than the long-term average (Table 1) and only its 27% fell in the first half of the fallow duration. The soil evaporation often underwent its second stage, when the effect of mulch was low, and, therefore, the evaporated soil water depth was greater than the rainfall (Figure 4), which led to the negative fallow efficiency before August 5th for all treatments (Figure 5). Consequently, the role of management practices was minor under the rather dry condition. With the increase of rainfall frequency and quantity, mulching played positive role in augmenting fallow efficiency by 7% at the end of August and by 9% at the end of that fallow, relative to conventional practice (Table 4). Nevertheless, the role of mulching was less efficient under high potential evaporation (August) than under the low one (September) (Figure 5, Table 1). In 2003, because of high frequency of rainfalls and low potential evaporation, the fallow efficiency was the highest among the three investigated fallows, and the mulching effectiveness was also more apparent than that in the other two fallows, due to noticeably reduced soil evaporation (Figure 4). In 2004, the most rainfalls fell in August, especially in the first half of August, when fallow efficiency reached above 0.4 under both conventional tillage and catch cropping and more than 0.5 under mulching, while later on the rainfalls were less frequent, soil evaporation went over to the second stage, and the fallow efficiency dropped. Overall, on the Loess Plateau of China, where summer fallow coincides with the rainy season, soil evaporation could be effectively damped by mulching (Figure 4). Thus, the mulching could ensure fallow efficiency.

In comparison with conventional practice, catch cropping had negative effects on the repartitioning of water balance. The catch cropping decreased water storage at the time of wheat sowing for all three fallows, more during a dry year than during a wet year, due to the catch crop transpiration and in spite of reducing soil evaporation during its growing, compared with the conventional practice (Tables 3 and 4). After three successive years of catch crops incorporated into the soil, the organic matter content remained unchanged (data not shown). The expected positive effect of the catch cropping on soil organic matter content was obviously too minor to be detected after such a short time. From the economic point of view, the catch crop used as green manure is not a profitable management practice in the short term (Zhang *et al.* 2009). Therefore, planting short-lived cash crop, for example peanut as shown by Jin *et al.* (2007), or the cash crop for animal feeding grown under mulching, can be alternative approaches to the fallow management practice in the region, provided that the subsequent wheat yield is not adversely impacted.

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