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Sustainable recovery of soil desiccation in semi-humid region on the Loess Plateau

X.C. Wang[a,b], T.N. Muhammad[a,c], M.D. Hao[a,b,*,1], J. Li[a,b]

[a] College of Agronomy, Northwest A & F University, Yangling, Shaanxi, China
[b] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi, China
[c] Department of Agronomy, PMAS-Arid Agriculture University, Murree Road, Rawalpindi, Pakistan

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ABSTRACT

Soil desiccation is one of the key factors to influence the sustainable development of crop production on the Loess Plateau of China. Depletion of soil water during growth period and its recovery in the fallow period is influenced by the amount of rainfall, its distribution, the type of crop and its rotation sequence. This study analyzed depletion and restoration of soil water for different cropping systems, based on a series of long-term experimental data at Changwu Agriculture Station from 1985 to 2001. Results of this study indicated that: (1) temporary soil desiccation took place in 1–3 m soil for MM, PWM and MW cropping system. (2) Permanent soil desiccation took place in 1–5 m and 1–10 m soil for APW and AF cropping system respectively. (3) When a rotation system was built to recover soil desiccation, broomcorn millet and potato can be considered first pea and spring maize also can be considered in rainy years or normal years. During fallow period, mulch or canopy can relief the soil desiccation in winter wheat land.

1. Introduction

Prolonged soil desiccation was first discovered in the semi-arid regions of Shaanxi and Gansu provinces of china in the 1960s (Li, 1983). The problem attracted increased attention in the 1980s when it was found to be widely occurred in forested land (Li, 2001a,b; Wang et al., 2001; Yang and Yu, 1992). It has since become a serious problem across the Loess Plateau of China. The soil desiccation layer is a region within the soil profile excessively depleted of soil water by artificial or non-native vegetation, and irregular or insufficient rainfall recharge (Li, 1983; Huang et al., 2001; He et al., 2003). Artificial grassland and many cropping systems in land with desiccated soil layers are greatly affected by rainfall variation, resulting in low productivity and efficiency even in some average rainfall years (Hou et al., 1999; Li, 2001a,b; Li et al., 2004, 2007; Shan et al., 2008; Wang et al., 2009a,b). Long term soil desiccation has negative impacts on both hydrological conditions and the sustainable development of food production.

On the Loess Plateau, loam soil ranging from 30 to 80 m depth (Zhu et al., 1983) and soil desiccation often takes place in deep soil with a depth ranging from 1 to 10 m (Li, 2001a,b; Wang et al., 2001; Yang and Yu, 1992; Huang and Gallichand, 2006). As we all know, rainfall and groundwater are the only two natural sources to recover soil desiccation. Since ground water cannot be used to recover soil desiccation on the Loess Plateau (Li, 2001a,b), rainfall becomes the only source to recover soil desiccation in deep soil. But there are little water left to recover soil desiccation due to consumption of vegetation in the semi-humid areas with mean annual rainfall from 500 to 600 mm. Therefore, to form and to erase soil desiccation layer both take a long time and both are not discovered in a short period.

Several researchers have addressed soil desiccation and its recovery (Shang guan and Zheng, 2006; Chen et al., 2008; Wang et al., 2008a,b). According to the soil water use by plant, Li (1983) divided soil desiccation into temporary and permanent type. The former mostly takes place in farmer land or in semi-humid region; the latter often appears in grassland and forest land or in semi-arid region. Yang and Yu (1992) expressed that soil desiccation layers on the Loess Plateau of China have three characteristics as following: (1) extension in deep layers, some time reaching 10 m; (2) having water content near or below the permanent wilting point; (3) occurring for significant time durations. Li et al. (2008a,b) has built up a new assessment standard to assess soil desiccation based on soil water content, stable soil water content and soil water content at wilting point.

* Corresponding author at: Institute of soil and water conservation, Northwest A & F University, No. 3 Taicheng Road, Yangling, Shaanxi, China.
E-mail address: xuechunwang@nwsuaf.edu.cn (X.C. Wang).
[1] Tel.: +86 13609259436.

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Simulation and survey methods were the two primary approaches to research soil desiccation and its recovery. Simulation methods include two parts. One is based on computer models whose precision is evaluated by a short-term experimental data (Li et al., 2004, 2007; Huang and Gallichand, 2006). Another is based on series of equations which are built up from a short-term experimental data (Liu et al., 2008). Results got by simulation method depended on the precision of models and the quality of equations. Survey method based on the hypothesis that soil water in the same rainfall areas were the same in different places with same growth-age vegetation covered on the ground (Wan et al., 2007, 2008). This method did not take into account the affect of different rainfall years on the soil desiccation and its recovery. However annual rainfall on the Loess Plateau of China changed with great variance (Chen et al., 2008) and ranged from 300 mm/a to 750 mm/a.

Seasonal variation of rainfall may influence the simulation and the survey results. So, research results for soil desiccation and its recovery were not always consistent (Wan et al., 2007, 2008; Wang et al., 2007, 2009a,b; Liu et al., 2010), especially on the Loess Plateau of China. Wan et al. (2007, 2008) pointed out soil desiccation in 3–10 m soil cannot be recovered in alfalfa land, while Liu et al. (2008, 2010) believed that soil desiccation can recover after the alfalfa plowed 18 years. Li et al. (2004, 2007) researched soil desiccation using EPIC model and showed that soil desiccation mainly take place in 1–3 m soil and cannot recover in winter wheat as well as in spring maize field. Wang et al. (2007) reported that soil desiccation in 0–5 m soil recovers to some degree, when grain crops are cultivated after alfalfa.

Objectives of this paper were (1) to compare soil desiccation and its recovery for different cropping systems based on 17-year-fixed experimental data at Changwu agriculture station from 1985 to 2001. (2) To provide some advices to recover soil desiccation and to prevent the formation of soil desiccation in the semi-humid region of Loess Plateau China.

2. Materials and methods

2.1. Description of study site

The study was carried out at Shilipu village (35°02′N, 107°25′E) from 1985 to 2001, which is located in the Changwu County, a middle region of the Loess Plateau. It is a semi-humid continental monsoon climate zone and is a representative rain-fed area of China. Its climate is typically semi-humid with an annual average temperature of 9.1 °C and average annual rainfall of 560 mm, of which 52.4% falls from June to September. Its main soil is Heilu soil (contained 70% silt and 22% clay). According FAO Taxonomy soil classification standard, this soil belongs to silt clay loam. Water content at field capacity of this soil is 22% (gravimetrically) with wilting point of 8% and stable soil water content of 15%.

2.2. Field experiments

Experimental treatments consisted of six cropping systems as following: alfalfa (*Medicago sativa* L.) (AF); mono winter-wheat (*Triticum aestivum* L.) (MW); mono spring maize (*Zea mays* L.) (MM); Pea (*Pisum sativum* L.)/winter-wheat/winter-wheat+ Broomcorn millet (*Panicum milliaceum* L.) (PWM); 4-year-old alfalfa/potato (*Solanum tuberosum* L.)/winter-wheat/winter-wheat/winter-wheat (APW) and Bare land (BL). Fig. 1 represented the first rotation cycle for different cropping systems and the same rotation cycles followed in the following years. All experiments were established in 18 plots of 10.26 m × 6.5 m (with a buffer zone of 1 m between plots). Plots were arranged in a Randomized Complete Block Design (RCBD) with three replications. According to the requirement of crops, fertilizers were applied and weeds were removed by manually for all experimental fields.

2.3. Sampling and measurement

2.3.1. Soil samples

Soil samples were collected on the 20th day of each month to measure the monthly soil water in 0–2 m soil from 1985 to 1993 for all cropping systems. To research the change of soil water in different years, soil samples were collected before sowing crops and after harvesting crops from 1985 to 2001. For alfalfa soil water in 0–10 m soil water were measured; for winter wheat, spring maize, broomcorn millet, potato and pea soil water in 0–5 m soil were measured. Soil samples were taken by core break method (Bennie et al., 1987) in 10 cm layers to the depth of 2 m and in 20 cm layers between the depth of 2 m and 10 m. Soil water content was measured (gravimetrically) for each soil sample by the oven-drying method (Blake and Hartge, 1986).

2.3.2. Method to calculate depletion and restoration of soil water

This study calculated soil water in 0–2 m soil using Eq. (1) by bulk density (B), soil water content (SW) and the thickness of soil layer (H).

$$\mathrm{ASW} = \sum_{i=1}^{n} B_i \times \mathrm{SW}_i \times H_i \times 10 \tag{1}$$

ASW is the amount of soil water (mm); B is soil bulk density (g/cm^3); H is the thickness of soil layer (cm); SW is soil water content (%).

Crop covering on the ground exhaust water from soil by evapotranspiration and lessen the evaporation by crop canopy at the same time. So we calculate the affect of cropping system on soil water using Eqs. (2) and (3).

$$\mathrm{RDSW} = (\mathrm{SWP}i - \mathrm{SWH}i) - (\mathrm{SWP}b - \mathrm{SWH}b) \tag{2}$$

RDSW is the Relative Depletion of Soil Water in 0–2 m soil. SWH_i, SWP_i is Soil Water in 0–2 m soil of cropping system i, when the crop of cropping system i is harvested and planted respectively. SWH_b, SWP_b is soil water in 0–2 m soil of bare land, when the crop of cropping system i is harvested and planted respectively.

$$\mathrm{RRSW} = (\mathrm{SWI}e - \mathrm{SWI}s) - (\mathrm{SWB}e - \mathrm{SWB}s) \tag{3}$$

RRSW is the Relative Restoration of Soil Water. SWI_e is soil water in 0–2 m soil of cropping system I in month e, when soil water content for cropping system I is the highest in this year. SWI_s is soil water in 0–2 m soil of cropping system I in month s, when soil water is the lowest for cropping system I in this year. SWB_e is soil water in 0–2 m soil for BL cropping system in month e, the same as cropping system I; SWB_s is soil water in 0–2 m soil for BL cropping system in month s, the same as cropping system I.

When the value of RDSW (Relative Depletion of Soil Water) is higher for one cropping system, the depletion amount of soil water by the cropping system is larger. It means the ability of this cropping system to exhaust soil water is higher. When the value of RRSW (Relative Restoration of Soil Water) for one cropping system is higher, the restoration amount of soil water by the cropping system is higher. It means the ability of this cropping system to restore soil water is higher. Therefore, this study can assess the affect of cropping system on depletion and restoration of soil water, based on the value of RDSW and RRSW.

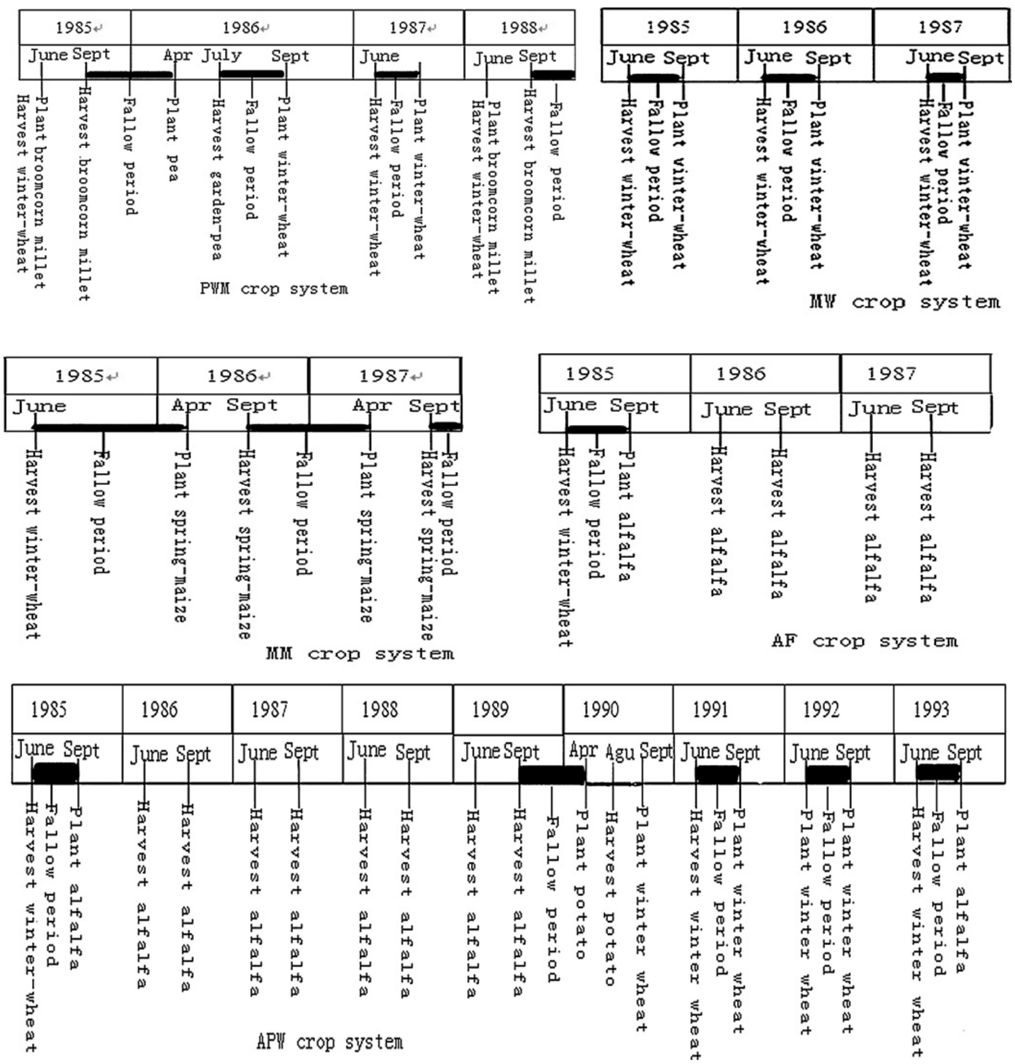

Fig. 1. Rotation sequences for different cropping systems, all sequence start from 1986.

2.3.3. Method to assess soil desiccation

In this research, we divided soil desiccation into 5 grades (Table 1), based on Soil Desiccation Index (SDI, Eq. (4)) (Li et al., 2008a,b).

$$SDI = \frac{SW - SWW}{SSW - SWW} \tag{4}$$

where SDI is Soil Desiccation Index; SWW is Soil Water content at Wilting point; SSW is stable soil water content; SW is soil water content.

Based on Eq. (4), we got Eq. (5). Then we use Eq. (5) to calculate the range of soil water content for each soil desiccation grade. At last we built up a decision table (Table 1) for soil desiccation grade, based on Eq. (5), wilting point and stable soil water content of Heilu soil.

$$SWC = SDI \times (SSW - SWW) + SWW \tag{5}$$

where SDI is Soil Desiccation Index; SWW is SOIL Water content at Wilting point; SSW is Stable Soil Water content; SWC is Soil Water content calculated by SDI, SSW and SWW.

Table 1
Decision table for soil desiccation grade of Heilu soil based on soil water content.

Soil desiccation grade	SWC (%)	SDI
No desiccation	SWM ≥ 15.5	SDI ≥ 1.00
Slightly	15.5 > SWM ≥ 13.9	1.00 > SDI ≥ 0.75
Serious	13.9 > SWM ≥ 12.3	0.75 > SDI ≥ 0.50
Strong	12.3 > SWM ≥ 10.3	0.50 > SDI ≥ 0.25
Extreme	SWM < 10.3	SDI < 0.25

SDI is Soil Desiccation Index, SWC is soil water content measured by SDI, stable soil water content and soil water content at wilting point.

Table 2
Different rain fall years of Changwu meteorological station from 1985 to 1996.

Category of rain fall years	Annual precipitation	Year
Rainy years	>600mm	1988, 1990, 1996 and 1998
Normal years	500–600mm	1985, 1987, 1989, 1992, 1993,1999,2000 and 2001
Drought years	<500mm	1986, 1991, 1994, 1995 and 1997

2.3.4. Category of the rainfall years

Based on the mean annual rainfall of 560 mm, this study classified the years from 1985 to 2001 into three categories as in Table 2.

According to the mean monthly rainfall, the period from January of 1985 to July of 1992 was classified into three categories as following. (1) Normal period, from January of 1985 to December of 1987 with the mean monthly rainfall of 46.4 mm. (2) Rainy period, from January of 1988 to May of 1991with the mean monthly rainfall of 53.2 mm. (3) Drought period, from June of 1991 to July of 1992 with the mean monthly rainfall of 40.5 mm.

2.3.5. Statistical methods

Statistical analysis was performed using ANOVA (SAS Institute, 1989). Multiple comparisons were conducted with least significant difference (LSD) at the 0.05 probability level.

3. Results

3.1. Monthly soil water

Among all cropping systems, BL had the highest value of mean monthly soil water in 0–2 m soil (493 mm). The following cropping systems were PWM, MM, APW, AF and MW with the value of 442 mm, 433 mm, 428 mm, 423 mm and 419 mm respectively. Soil water in 0–2 m soil decreased significantly for PWM, MM, APW, AF and MW cropping system, compared with that for BL cropping system (Fig. 2).

Mean monthly soil water in 0–2 m soil varied significantly in different rainfall periods. In rainy period, its value for BL, PWM, MM, APW, AF and MW were 506 mm, 469 mm, 465 mm, 475 mm, 466 mm and 435 mm respectively. In normal period, 486 mm, 443 mm, 409 mm, 410 mm, 394 mm and 425 mm. In drought period, 463 mm, 372 mm, 364 mm, 369 mm, 349 mm and 355 mm.

3.2. Relative depletion of soil water

AF cropping system had the highest mean RDSW value of 70 mm/a (Table 3). The following cropping system was MW, PWM, APW and MM with the mean RDSW value of 69 mm/a, 61 mm/a, 53 mm/a, and 51 mm/a respectively.

In drought years, the mean value of RDSW was the highest over normal years, rainy years for AF, APW and MM cropping systems. This sequence was not always consistent for different cropping systems as in PWM and MW. For PWM cropping system, due to the cover of canopy after winter wheat, the mean value of RDSW in normal years was the highest, in drought years was the second and in rainy years was the lowest. For MW cropping system, due to the difference between the distribution of rainfall and the growth period of winter wheat, its sequence changed into normal years, rainy years and drought years.

Depletion of soil water decreases, provided with suitable crop canopy covered on the ground, especially in rainy years. For PWM cropping system, broomcorn millet covered on the ground after winter wheat; for WM cropping system did not covered any crop on the ground after winter whet. Relative depletion of soil water in 0–2 m soil for PWM cropping system were less than WM cropping system in rainy years (1988). In 1990, potato covered on the ground from April to August, soil water in 0–2 m soil for APW cropping system increased 6.76 mm compared with that for BL cropping system (Table 3). From June to August were rainy period in 1988 and 1992. Canopy of spring maize decreased evaporation of soil water in this period, therefore, depletion of soil water decreased in MM cropping system compared with that in BL cropping system (Table 3).

3.3. Relative restoration of soil water

MW cropping system attained the highest RRSW value of 91 mm/a (Table 4). The following cropping system was PWM, APW, AF and MM cropping system with the mean value of 86 mm/a, 47 mm/a, 47 mm/a, and 38 mm/a sequentially.

The mean value of RRSW showed higher in drought years followed by normal years and rainy years (Table 4). This sequence was not always the same for different cropping systems, PWM and APW for example. For PWM cropping system, the mean value of RRSW in rainy years was the highest with the value of 107.12 mm/a. In drought years was the second with the value of 83.35 mm/a. In normal years was the lowest with the value of 77.91 mm/a. For APW cropping system, the mean value of RRSW in drought years was the highest over rainy years and normal years. The distribution of crop and rainfall as well as the difference of soil water content in different years were the main reason to this result.

Restoration of soil water decreased in drought years, AF, APW and MM cropping system for example. Restoration of soil water for AF cropping system decreased in drought years, compared with that for BL cropping system (Table 4). In drought year (1986), the specie of crop cultivated in AF and APW were the same, both were alfalfa. Restoration of soil water in 0–2 m soil for AF and APW both decreased 7.15 mm compared with that for BL (Table 4). Mean monthly rainfall from September to next March in 1986, 1989 and 1993 was 77, 86 and 87 mm respectively, lower than that of mean values. Therefore, restoration of soil water in 0–2 m soil for MM cropping system decreased in these 3 years, compared with that for BL cropping system (Table 4).

3.4. Process of soil desiccation and its recovery

For AF cropping system, soil desiccation mainly took place in 1–10 m soil (Fig. 3), and its grade reached from slightly in 1985 to strong in 2001. In 1985, the thickness of soil desiccation layer was 1 m (1–2 m soil) with slightly desiccation grade. In 1987, its thickness was more than 4 m (1–5 m soil) with the desiccation grade of higher than slightly (serious in 1–4 m soil and slightly in 4–5 m soil). Due to the annual rainfall of 790 mm in 1988, soil desiccation for all soil layers in 1–5 m soil recovered to no soil desiccation. From 1989 to 1991, soil desiccation grade in 2–5 m soil existed between slightly and serious desiccation. In 1992 and 1993, soil desiccation grade in 0–3 m soil recovered to some degree. From 1994 to 2001 soil desiccation in 0–10 m soil reached to higher grade. Though soil desiccation grade in 1–2 m soil recovered to no soil desiccation in some rainy years (1996 and 1999), its grade in 0–6 m soil reached to strong grade at the end of this experiment (2001).

In alfalfa land, the thickness of soil desiccation reached to 10 m, and its recovery depended on the amount of rainfall in 1 year. Soil desiccation grade in 0–8 m soil recovered to no soil desiccation in 1988 with the annual rainfall of 790 mm. In 0–2 m soil recovered to no soil desiccation both in 1990 and 1996 with the rainfall of 673 mm and 698 mm respectively. Soil desiccation grade recovered to no soil desiccation only in 0–2 m soil in normal years except in 1992. Fig. 2 represents that in 1991 soil water content in 0–6 m soil were more than 12.3%, and metrological data showed that more than 200 mm rainfall in August of 1992. Therefore, 0–6 m soil recovered to no soil desiccation in 1992. In drought years, more soil water was exhausted than restored. Therefore, soil desiccation deteriorated in the growth period and was difficult to recover in the fallow period.

In mono winter wheat field (MW cropping system), soil desiccation mainly occurred in 1–3 m soil (Fig. 4). Its thickness increased and its grade reached to higher with prolongation of cultivation years. Soil desiccation grade in 1–2.5 m soil was higher than slightly grade (1985 and 1987) and developed into serious grade (1988 and 1989). In 1993, it developed into strong desiccation grade, and in the following years of 1994, 1995 and 1996, reached to strong or serious desiccation grade. In 1997, soil desiccation grade in 1–2.5 m soil was higher than strong grade. In 1998, a rainy year with the

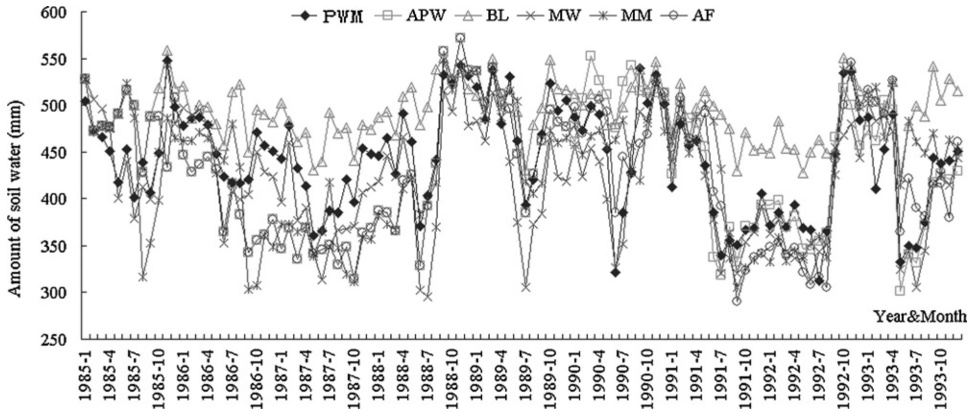

Fig. 2. Monthly soil water in 0–2 m soil for different cropping systems from 1985 to 1993.
The crop rotations studied were: (AF) Alfalfa monoculture; (MW) winter wheat monoculture; (MM) spring maize monoculture; (APW) 4-year-old alfalfa/potato/winter-wheat/winter-wheat/winter-wheat; (PWM) pea/winter-wheat/winter-wheat+broomcorn millet; (BL) bare land.

Table 3
Relative depletion of soil water in 0–2 m soil for different cropping systems in different rainfall years.

Rain fall years	Year	AF	MW	PWM	APW	MM	Average(mm/a)
Rainy years	1988(mm)	10.27	69.81	−36.79	10.27	−97.63	19.01 a
	1990(mm)	89.31	40.3	30.26	−6.76	81.12	
	Average(mm/a)	49.79	55.05	−3.26	1.75	−8.25	
Normal years	1985(mm)	108.68	87.75	92.43	–	134.55	67.25 b
	1987(mm)	38.61	80.08	44.26	38.61	56.03	
	1989(mm)	60.71	83.33	13.78	60.71	75.27	
	1992(mm)	38.87	27.04	91.39	4.29	−85.41	
	1993(mm)	107.9	140.27	154.96	105.17	69.81	
	Average(mm/a)	70.95	83.69	79.36	52.19	50.05	
Drought years	1986(mm)	86.58	15.86	78	86.58	113.49	86.39 c
	1991(mm)	87.88	75.92	79.17	125.84	114.27	
	Average(mm/a)	87.23	45.89	78.58	106.21	113.88	

The crop rotations studied were: (AF) Alfalfa monoculture; (MW) winter wheat monoculture; (MM) spring maize monoculture; (APW) 4-year-old alfalfa/potato/winter-wheat/winter-wheat/winter-wheat; (PWM) pea/winter-wheat/winter-wheat+broomcorn millet; (BL) bare land.

rainfall of 658 mm, soil water not only in 1.5–2.5 m recovered to more than 15.5%, but also in 2.5–3 m soil recovered to some degree. From 1999 to 2001 soil desiccation layer reached to 3 m depth with strong desiccation grade in 1–2.5 m soil and serious desiccation grade in 2.5–3 m soil.

For MW cropping system, soil desiccation mainly occurred in 1–3 m soil and its recovery in different rainfall years was different. In rainy years, soil desiccation grade in 0–3 m soil recovered to no soil desiccation during the fallow period. In normal years, though soil desiccation in 0–3 m soil reached to extreme grade when the winter wheat was harvested, soil desiccation in 0–2 m soil recovered to no soil desiccation grade during the fallow period. In drought years, due to more depletion and less rainfall, soil water in 0–3 m soil was difficult to restore.

In mono spring maize field (MM cropping system), soil desiccation mainly took place in 1–2 m soil before 1996, and it developed to 1–3 m soil after 1999 (Fig. 5). In 1986 and 1987, soil desiccation in 1–2 m soil was serious grade and in 2–3 m was no soil desiccation. In 1988, a rainy year with the annual rainfall of more than 700 mm, soil desiccation in 1–2 m soil recovered to no soil desiccation and soil water content in 2–3 m soil also restored. In 1997, the soil desiccation in 1–2 m soil was serious grade and in 2–3 m was slightly

Table 4
Relative restoration of soil water in 0–2 m soil for different cropping systems in different rainfall years.

Rain fall years	Year	MW	PWM	APW	AF	MM	Average(mm/a)
Rainy years	1988(mm)	163.67	109.46	126.36	126.36	30.29	92.79 a
	1990(mm)	135.98	104.78	−23.92	56.81	98.15	
	Average(mm/a)	149.82	107.12	51.22	91.58	64.22	
Normal years	1985(mm)	83.07	78.78	–	35.49	129.74	57.94 b
	1987(mm)	80.86	78.39	35.36	35.36	27.04	
	1989(mm)	27.69	26.39	5.98	5.98	−25.61	
	1992(mm)	48.1	119.6	49.53	129.74	108.55	
	1993(mm)	120.9	86.41	81.25	53.04	−15.99	
	Average(mm/a)	72.12	77.91	43.03	51.92	44.74	
Drought years	1986(mm)	47.58	65.44	−7.15	−7.15	−53.56	39.29 c
	1991(mm)	107.25	101.27	110.89	−13.91	42.25	
	Average(mm/a)	77.41	83.35	51.87	−10.53	−5.65	

The crop rotations studied were: (AF) Alfalfa monoculture; (MW) winter wheat monoculture; (MM) spring maize monoculture; (APW) 4-year-old alfalfa/potato/winter-wheat/winter-wheat/winter-wheat; (PWM) pea/winter-wheat/winter-wheat+broomcorn millet; (BL) bare land.

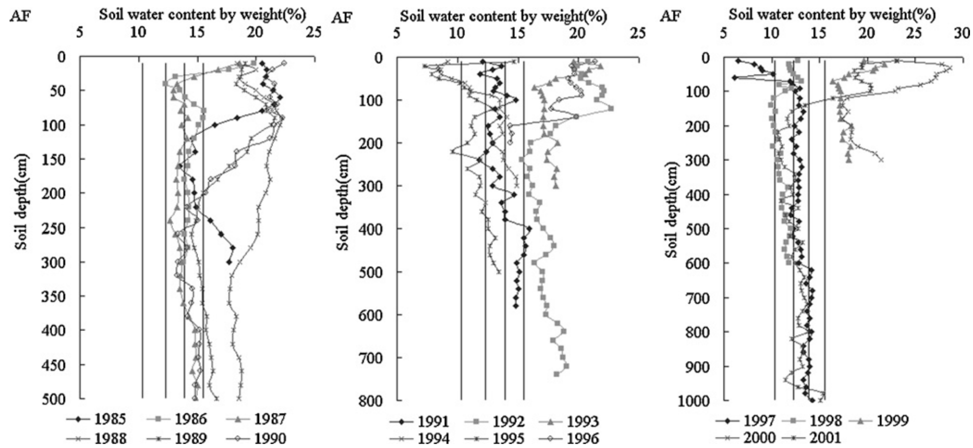

Fig. 3. Dynamic change of soil water (annual average) in alfalfa land at the semi-humid areas of the Loess Plateau of China.

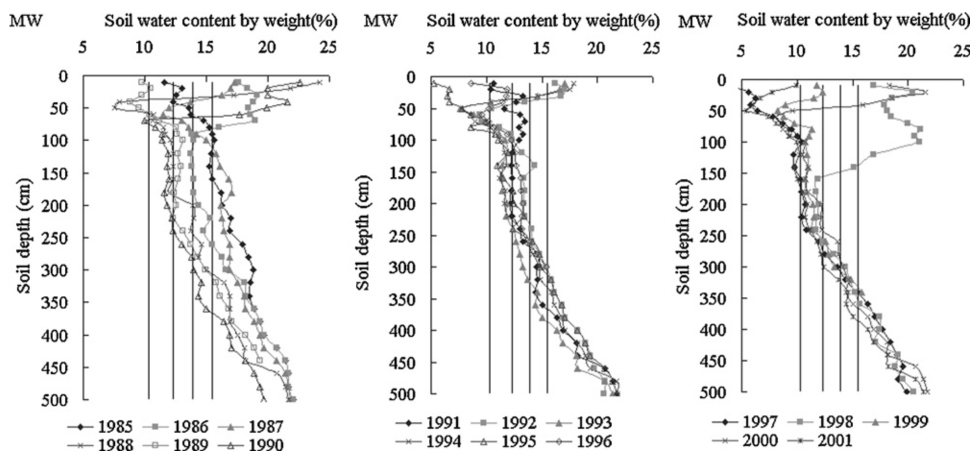

Fig. 4. Dynamic change of soil water (annual average) in winter wheat field at the semi-humid areas of the Loess Plateau China.

grade. In 1998, soil desiccation in 1–3 m soil recovered to no soil desiccation. Then in 1999, soil desiccation in 1–3 m soil reached to strong grade but it was slightly recovered in 2000 and reached to serious grade in 2001.

For MM cropping system, recovery of soil desiccation varied greatly in different rainfall years. In rainy years, except 1996, soil desiccation grade in 0–3 m soil recovered to no soil desiccation when spring maize was harvested in September of each year. In 1996, soil desiccation layer with lightly grade existed in 0–1.5 m soil, when spring maize was harvested, but it recovered to no soil desiccation grade during the fallow period. In normal years, soil desiccation recovered to no soil desiccation grade in 0–3 m soil during the fallow period in winter. During growth period, soil desiccation of slightly and serious grade took place in 1.5–3 m and

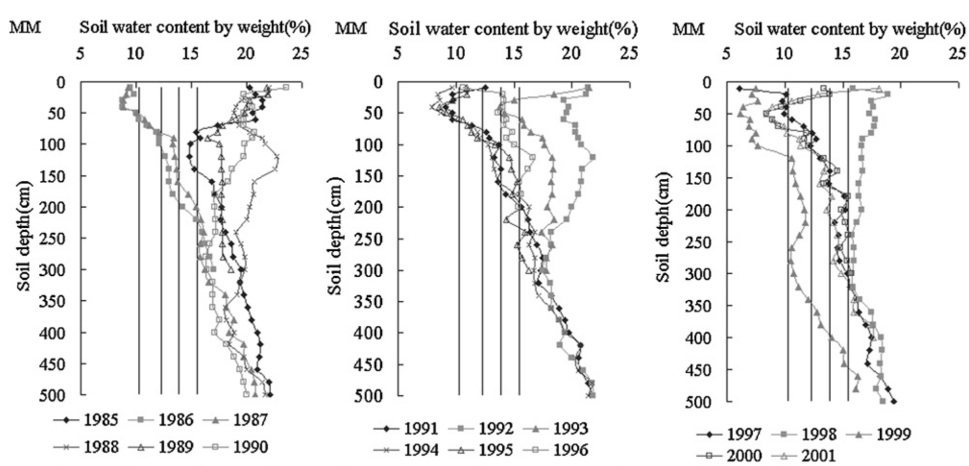

Fig. 5. Dynamic change of soil water (annual average) in spring maize field at the semi-humid areas of the Loess Plateau of China.

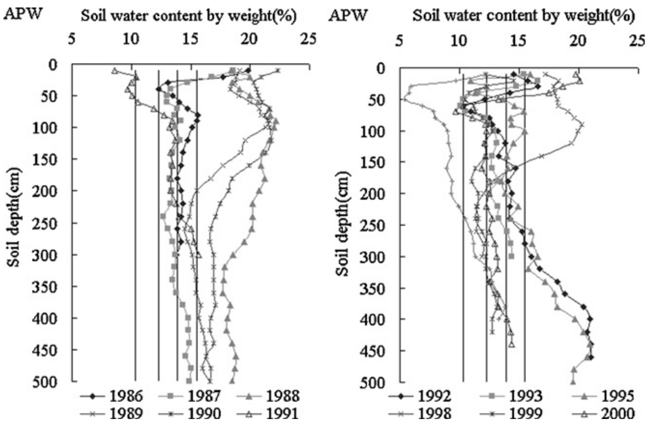

Fig. 6. Dynamic change of soil water (annual average) in APW rotation land (its sequence was 4-year alfalfa, potato, winter-wheat, winter-wheat and winter-wheat) at the semi-humid areas of the Loess Plateau of China.

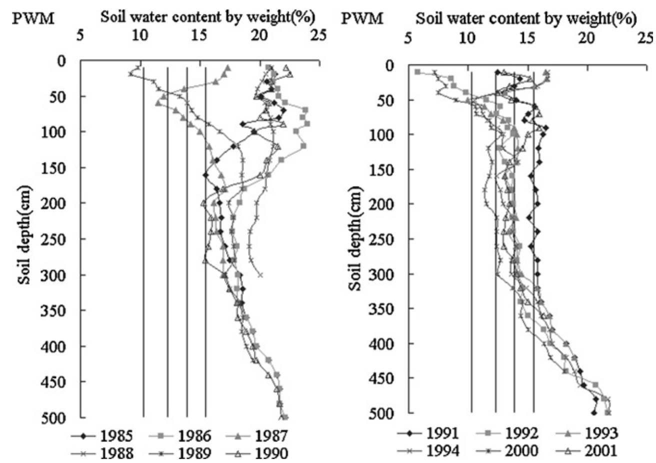

Fig. 7. Dynamic change of soil water (annual average) in PWM rotation land (its sequence was winter-wheat, winter-wheat+broomcorn millet, and garden-pea) at the semi-humid areas of the Loess Plateau of China.

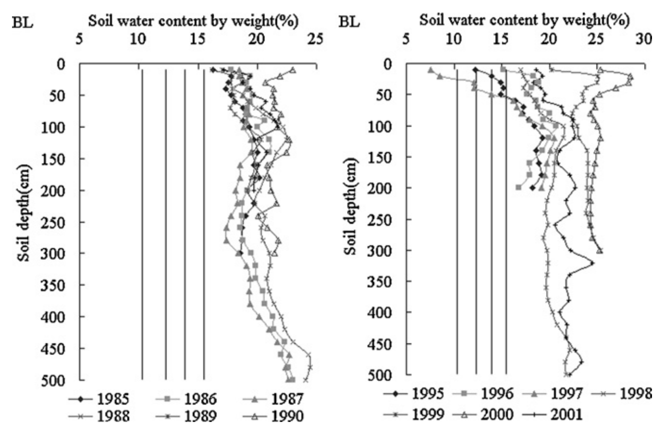

Fig. 8. Dynamic change of soil water (annual average) in bare land in the semi-humid areas of the Loess Plateau of China.

0–1.5 m soil, in the drought period, respectively. However, soil water content in 0–1.5 m soil restored to more than 15% during fallow period in the winter.

For APW cropping system, soil desiccation mainly developed in 1–5 m soil layer (Fig. 6). In 1986, soil desiccation layer formed in 1–3 m soil with slightly desiccation grade. During 1987, it developed into 1–4 m soil with serious grade and in 4–5 m soil with slightly grade. In 1988, due to the annual rainfall of 790 mm, soil desiccation in 1–5 m soil became into no soil desiccation grade. In 1989, it reached to slight grade in 2–3 m soil. In 1990, a drought year, soil desiccation in 0–5 m soil recovered to no soil desiccation grade, due to planting of potato. From 1991 to 1993, soil water in 0–3 m soil reduced continuously and soil desiccation grade in 1–2.5 m soil had reached to serious grade when the first rotation cycle finished in 1993.

In the second rotation cycle, soil desiccation in 1995 was slightly grade in 1–3 m soil and no soil desiccation in 3–5 m soil. In 1998 soil water in 0–2 m soil restored and soil desiccation grade reached to almost no desiccation grade (no soil desiccation in 0–1.5 m soil), due to planting of potato crop. From 1999 to 2001 soil water content in 0–3 m soil decreased continuously, and soil desiccation reached to the higher grade, due to depletion of soil water by winter wheat. When the experiment finished in 2001, soil desiccation reached to extreme grade in 1–3 m soil.

For the APW cropping system, occurrence of soil desiccation layer in different rotation cycles was different, and the abilities of different crops to recover soil desiccation were also different. When alfalfa was 2 years old, soil desiccation took place in 0–5 m soil due to depletion of soil water by alfalfa in 1987 (the first rotation cycle). However, only in 0–3 m soil in 1995 (the second rotation cycle). When potato was planted, soil desiccation in 0–5 m soil recovered to no soil desiccation grade in 1990 (the first rotation cycle), but only in 0–2 m soil recovered to no soil desiccation grade in 1998 (the second rotation cycle). When winter wheat was cultivated 3 years after potato, soil desiccation in 1–3 m soil was serious grade in 1993 (the first rotation cycle), while it reached to extreme grade in 2001 (the second rotation cycle).

For PWM cropping system, soil desiccation layer mainly existed in 1–3 m soil (Fig. 7). Before 1990, no soil desiccation grade was found in 1–3 m soil. During 1991, soil water content in 1–3 m soil was near to 15.5%. Then soil water content decreased continuously from 1991 to 2000, and soil desiccation grade reached to higher than strong grade in 1–3 m soil (strong in 1–2 m soil and serious in 2–3 m). When the experiment finished in 2001, soil desiccation in 1–3 m soil reached to serious grade.

For PWM cropping system, no soil desiccation took place in 0–5 m soil layers until 1991. During the growing season (from 1992 to 2001), soil desiccation took place in 1–3 m soil with slightly or serious grade and in the fallow period, it recovered to no soil desiccation or slightly grade. Comparing with other cropping systems, PWM cropping system has the highest soil water content, due to the following reasons. (1) Broomcorn millet and pea both exhausted little soil water from the soil; (2) covering of broomcorn on the ground after winter wheat, reduced evaporation of soil water. Therefore broomcorn millet was the best cover crop for the fallow period after winter wheat to lessen the evaporation from soil surface in the semi-humid region of Loess Plateau.

No soil desiccation took place in bare land from 1985 to 2001 and soil water content in 0–1 m soil varied with variation of rainfall year by year (Fig. 8). Soil water in 0–5 m soil varied in extreme rainy years and extreme drought years, though no crop was on the ground during that period. In 1988, soil water in 1–5 m soil increased (366 m) compared with in 1987, and in 2001 soil water reduced (212 mm) compared with in 1998.

4. Discussions

Alfalfa needed more water than other crops (Blad and Rosenberg, 1976; Saeed and Ei-Nadi, 1997). Results of this paper displayed that value of RRSW was less than that of RDSW for AF cropping system with the mean value of −10.53 mm/a, and

87.23 mm/a respectively, especially in drought years. Therefore, the relative depletion of soil water for AF cropping system was the highest (Table 3). Alfalfa can take up water from deep soil layers (Wan et al., 2008). This study showed that soil water in 0–10 m soil reduced in drought years, and soil desiccation layer for AF cropping system had reached to 10 m soil, when the experiment finished in 2001(16-year-old). Soil water in deep soil has a great significance for sustainable crop production in the semi-humid region of Loess Plateau. Soil desiccation layer formed in alfalfa land would negatively impact the growth and yield of following crops (Li, 2002). Research conducted on the ideal alfalfa stand age in the semi-arid region of the Loess Plateau was 6–9 years (Cheng et al., 2005). However no such work was reported for the semi humid region of the Loess Plateau. Therefore, the ideal stand age of alfalfa has great importance for the future research in the semi-humid region.

MW cropping system, characterized by nearly 4-month summer fallow period from early June to late September after winter wheat, was common in wheat-growing areas of the Loess Plateau. The large amount of evaporation from the bare soil surface reduced restoration of soil water during the fallow period (Li et al., 2002). Soil water depletion during the growth period can be restored during the fallow period if appropriate fertilizer was applied for mono winter wheat cropping system (Huang et al., 2003). Results of this study suggested that the value of RDSW was higher than RRSW (Tables 3 and 4) for MW cropping system. Therefore, its soil desiccation layer reached to 3 m soil with extreme grade in 1–2.5 m soil in 2001(Fig. 4).

Depletion of soil water decreased, if proper canopy covered on the ground, especially in rainy years and in rainy months. With the ground cover of broomcorn millet after winter wheat, relative depletion of soil water for PWM cropping system decreased in rainy years (Table 4), same results reported by Wang et al. (2008a,b). To reduce evaporation of soil water, some mulching techniques including plastic film mulching and straw mulching has been researched and applied during the fallow period for MW cropping system (Li et al., 1999; Gao and Zhao, 1995). After winter wheat was harvest, to plant some broomcorn millet or to left some stems of winter wheat on the ground will relief the soil desiccation in mono winter wheat field.

For APW cropping system, no soil desiccation layer was found in 0–5 m soil at the beginning of the first rotation cycle in 1985. However, it was found in 1–3 m soil with serious grade at the beginning of the second rotation cycle in 1993. Xu and Shan (2003) found the existing of soil desiccation layer affected the growth of alfalfa root into deeper soil. When the stand age of alfalfa was 2 years, soil desiccation layer reached to 3 m soil in 1995 shallower than that in 1987 (reached to 4 m soil). In the second rotation cycle soil water in deep soil was not used effectively due to the existing of soil desiccation layer with serious grade in 1–3 m soil before alfalfa was planted. However, extreme soil desiccation grade, higher than that at the beginning of the second rotation cycle (1993), was found in 1–3 m soil at the beginning of the third rotation cycle (2001). Therefore, APW cropping system did not support the sustainable development of agriculture in semi-humid region of the Loess Plateau.

Huang et al. (2008) found that soil water depletion in potato land was less than that in bare land due to the canopy covering on the ground during the growth period. Here our study found that soil desiccation recovered when potato was planted after alfalfa in 1990 and 1998. The research results showed potato recovered soil water after alfalfa and the existing of soil desiccation layer before alfalfa disadvantaged using efficiency of deep soil water. Prolonging the cultivation years of potato after alfalfa and shortening the cultivation years of winter wheat may be benefit to the sustainable development of APW cropping system.

The growth stage of spring maize occurred from April to August, which was an accord with the rainfall period from June to September. With the great canopy covering on the ground (leaf area index was 4.5, Chen et al., 2007), depletion of soil water for MM cropping system was less than in bare land (Table 3). Our research represents that temporary soil desiccation took place in 1–3 m soil in spring maize field. In normal and rainy years no soil desiccation took place for MM cropping system when spring maize was harvest in September (Fig. 5). To plant spring maize may be better than to plant winter wheat after potato in APW cropping system.

This research showed that potato can be used to recover soil water, after soil desiccation layer was formed in alfalfa land. When broomcorn millet covered on the ground, the value of RDSW decreased in drought year (1991) and rainy year (1988). Therefore, both potato and broomcorn millet can be used to recover soil water when soil desiccation layer was formed. Pea was short period crop with little depletion of soil water (Wang et al., 2008a,b). Value of both RDSW and RRSW were lower for pea than other crops (Table 3 1986, 1989 and 1990; Table 4 1986 1989 and 1990). Depletion of soil water for MM cropping system was less than in bare land (Table 3). This research indicated that both pea and spring maize led to a temporary soil desiccation layer which can be recovered to no soil desiccation in rainy years or fallow period. So, pea and spring maize also can be used to recover soil desiccation layers in rainy years.

Comparing with other cropping systems, PWM cropping system was the better to restore soil water. First, before 1991 no soil desiccation took place in 1–3 m soil. Second, from 1992 to 2001, soil desiccation took place in 1–3 m soil during the growth period (Fig. 7) but it recovered to no soil desiccation during the fallow period.

5. Conclusions

Depletion of soil water in growth period and its recovery in the fallow period both were affected by the amount of annual rainfall and its distribution, the species of crop and their rotation sequences. The results of this study led to the following conclusions. (1) Temporary soil desiccation took place for MM, PWM and MW cropping system in 1–3 m soil, and permanent soil desiccation took place for APW and AF cropping system in 1–5 m and 1–10 m soil respectively. (2) Broomcorn millet and potato was the proper crops to recover soil desiccation followed by spring maize and pea. (3) When a rotation system was built to recover soil desiccation, Broomcorn millet and potato can be considered first, pea and spring maize also can be considered in rainy years or normal years. During fallow period, mulch or canopy can relief the soil desiccation in winter wheat land.

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