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Status and circulation characteristics of soil water in dryland field of southeast Shanxi Province

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Abstract—Based on the observed soil water data from experimental site located in southeast of Shanxi Province, the physical characteristics of soil water, crop effect on soil moisture, and the field water circulation pattern were studied by using the water balance method. The results suggested that soil water deficit often exists in fields of these areas. From May to June, the amount of water deficit in bare-land rises to the maximum (232.8 mm) and falls to the minimum (66.6 mm) from August to September. By comparison, because of crop transpiration, both soil water deficit and dry soil layer in cultivated land are 15.1—40.4 mm more and 20—70 mm deeper respectively than those of bare-land. Crops mainly planted in these areas have a relatively weak utilization ability to soil water. Winter wheat has the highest utilization ability to soil water among the crops planted in these areas. The soil water utilization ability of winter wheat is 26.2%—30.6% and winter wheat can use soil water that lies in soil layer below a depth of over 200 cm. Spring corn and millet can only consume soil water with the maximum ability of 13.4% and the deepest layer of 0—50 cm or 0—100cm, which shows that the soil water utilization ability of winter wheat is higher than that of spring crops. After crop is ripe, more than 41% of available soil water remains unused in field. So, increasing soil water storage and improving crop utilization ability to soil water by adopting efficient agrotechnique measures are the main ways for improving agricultural productivity in dry farming areas of Northern China.

Keywords: soil water; field water deficit; crop utilization ability to soil water; dry land; southeast of Shanxi Province.

1 Introduction

The southeast areas of Shanxi Province stand in the southeast of the Loess Plateau and have a varied topography. The soil of these areas is cinnamon derived from loess with a loamy texture, and a deep soil layer. The ground water table is generally more than 10 m. These areas are the typical dry-farming areas where farming water consumption mainly comes from precipitation. The main crops are winter wheat, spring maize, spring millet and potato, the main cultivation system is one cropping a year.

According to climatic regionalization, the climate in these areas belongs to warm-temperate continental monsoon climate with dry and cold winter, hot and rainy summer and a high variability of annual precipitation. Drought occurs frequently in winter and spring, and even appears occasionally in summer. Drought and water shortage are the main natural factors that limit agricultural productivity. Since soil is a kind of main natural agricultural resources, the physical characteristics of soil water, the control and adjustment effect and the utilization ability of soil to moisture, have a significance in determining and adopting the agrotechnical measures for drought fighting and prevention. There are some studies on physical characteristics and circulation pattern of loess and blank soil water (Li, 1983; Qiao, 1979). Since 1986, the seventh national five-year key research project named "Field water balance and its regulation techniques in dry land of northern China" has been carried out in southeast of Shanxi Province. Based on observed soil water data between 1987 and 1990 from the experimental site locating in Tunliu County of Shanxi Province, this paper studies the physical characteristics of soil water, crop effect on soil water and the field water circulation pattern by water balance method.

2 Methodology

Located at Tunliu County, Shanxi Province, the experimental site has a latitude of 36°11′—36°31′N, a longitude of 112°17′—113°03′E, and an average altitude of 950 m. The terrain in this experimental site is flat and the fields have deep soil layers. The soil has a low fertility with organic material 0.04%—0.08%, total nitrogen 0.03%—0.05%. The experimental years happen to include three kinds of hydrological year, i.e., low precipitation year (1987), high precipitation year (1988) and normal precipitation year (1989, 1990). Experimental crops are winter wheat, spring maize and spring millet. The former cropping, fertilization and field management for each crop are the same. Each experimental plot has an area of 66.7 m^2. All these experiments are repeated three times simultaneously and are randomly arranged.

Soil moisture is measured by oven drying method. The soil is sampled with a soil auger from the soil surface to a depth of 200 cm. Soil layer of 0—10 cm is sampled a sample every 5 cm, 10—100 cm every 10 cm and 100—200 cm every 20 cm. Soil moisture is determined once every 10 days at 1, 11 and 21 of each month, and is repeated three time simultaneously from the sowing date to the harvest time. In addition, soil moisture is also measured at main growing periods or after rainy periods.

Crop water consumption is determined by field water balance method. In natural condition, the equation of farmland water balance can be expressed as (Zhao, 1995):

$$\Delta W = P + U - R - F - ETa, \tag{1}$$

where, ΔW is the variation of soil water storage; P is the precipitation; U is the ground water recharge; R is the runoff; F is the seepage discharge; ETa is the actual evapotranspiration from farmland, i.e., crop water consumption. The unit of each item in Equation(1) is mm.

ΔW is equal to the difference of soil water storage between the beginning and the end of one certain period. When $\Delta W > 0$, it means that the soil water storage increases; when $\Delta W < 0$, it means that the soil water storage decreases, i.e., crops are supplied with soil water storage by soil. Since the ground water table is generally below a depth of 15m in this region and soil moisture is measured within soil layer as deep as 200 cm, the ground water recharge and the seepage discharge can be neglected. So Equation(1) can be simplified as:

$$ETa = P - R - \Delta W. \tag{2}$$

Equation(2) means that under dry-farming condition, crop water consumption is the algebraic sum of the available precipitation and the variation of soil water storage during crop growing period.

The runoff can be computed by empirical formula (Zhong, 1997), i.e.,

If $P - \Delta W > ETc$, then $ETa = ETc$, $R = P - \Delta W - ETc$;

If $P - \Delta W \leqslant ETc$, then $ETa = P - \Delta W$, $R = 0$.

where, ETc is the crop water requirement, which can be calculated by the method of FAO (Doorenbos, 1979; 1977).

3 Results and analysis

3.1 Physical characteristics of soil water

The physical characteristics of soil water have a direct influence on soil water state and its availability to crops. In the practice of farmland water management, it is generally acknowledged that the upper limit of soil moisture suitable to crops is the field water capacity, and the lower limit is 65%—75% of field water capacity that is analogous to stable field moisture (Li, 1962; Qiao, 1979). Soil water can not be used by crops when actual soil moisture is below withering moisture. So according to these three soil water constants, i.e. field water capacity, stable field moisture and withering moisture, soil water can be simply classified into three grades, i.e. unavailable soil water (when soil water content is below withering moisture), hardly available soil water (when soil water content is between withering moisture and stable field moisture) and readily available soil water (when soil water content is between stable field water and field water capacity). It can be seen from Table 1 that the soil has a strong ability for soil water storage and preservation. From observed results, between 0 and 200 cm soil layers, soil bulk density is 1.28%—1.48 g/cm^3, mean withering moisture is 7.3%, mean field moisture capacity is 23.1% and available soil water is 13%—21%. When actual soil moisture is equal to field moisture capacity, the total water retaining capacity of 0—200 cm soil layer is 637.2 mm (437.2 mm is the available soil water and 192.9 mm is the readily available soil water, occupying 79.3% and 35.0% of mean annual precipitation respectively). Besides, the soil has a prosperous porosity. Total porosity in soil layer of 0—200 cm is 43%—51%. Aeration porosity is 10%—21% when the actual soil moisture is equal to field moisture capacity, which indicates a good aeration status and water permeability of soil. This kind of soil is very beneficial to the growth of crop root system, thus enabling crops to use water storage in deep soil layers. So, adopting rational cropping system and proper cultivation measures so as to take in and store natural precipitation and preserve moisture in soil layers as much as possible, is very important for the prevention of seasonal drought.

Table 1 Physical features of agricultural soil water in the southeast areas of Shanxi Province

Depth, cm	Density,	Total porosity,	Soil water constant, %				Soil water constant, mm				Under FWC	
	g/cm^3	%	A	B	C	D	A	B	C	D	E	F
0—5	1.28	51	26.4	18.5	5.6	3.7	16.9	11.8	3.6	2.4	13.3	17.2
5—10	1.28	51	23.5	16.5	6.4	4.3	15.0	10.5	4.1	2.7	10.9	20.9
10—20	1.36	48	21.7	15.2	6.2	4.1	29.5	20.7	8.4	5.6	21.1	18.5
20—30	1.41	46	22.0	15.4	7.5	5.0	31.0	21.7	10.6	7.1	20.4	15.0
30—40	1.44	45	21.5	15.1	6.4	4.3	31.0	21.7	9.2	6.1	21.8	14.0
40—50	1.48	45	22.0	16.1	6.5	4.3	32.6	23.8	9.6	6.4	23.0	12.4
50—60	1.45	44	22.7	15.9	7.8	5.2	32.9	23.0	11.3	7.5	21.6	11.1
60—70	1.46	44	23.2	16.2	7.4	4.9	33.9	23.7	10.8	7.2	23.1	10.1
70—80	1.46	45	23.4	17.4	7.4	4.9	34.2	25.5	10.8	7.2	23.4	10.8
80—90	1.40	46	23.2	16.2	7.5	5.0	32.5	22.8	10.5	7.0	22.0	13.5
90—100	1.43	45	20.8	14.6	6.6	4.4	29.7	20.8	9.4	6.3	20.3	15.3
100—120	1.38	47	21.7	15.2	6.8	4.5	59.9	41.9	10.8	12.5	41.1	17.1
120—140	1.34	48	24.0	16.8	8.1	5.4	64.3	45.0	21.7	14.5	42.6	15.8
140—160	1.34	48	24.3	17.0	7.5	5.0	65.1	45.6	20.1	13.4	45.0	15.4
160—180	1.32	49	24.2	16.9	7.4	4.9	63.9	44.7	19.5	13.0	44.4	17.1
180—200	1.35	48	24.0	16.8	8.0	5.3	64.8	45.4	21.6	14.4	43.2	15.6
Average	1.38	48	23.1	16.2	7.3	4.8	—	—	—	—	—	15.1
Sum	—	—	—	—	—	—	637	449	200	133	437	—

Note: A: field water capacity; B: Stable field moisture; C: withering moisture; D: maximum hygroscopic moisture; E: available soil water content, mm; F: aeration porosity, %; FWC: field water capacity

3.2 Crop utilization to soil water

Crop utilization to soil water depends upon crop species, growing state and the seasonal distribution of precipitation during growing period (Qiao, 1979), which can be mainly expressed with the utilization ability to soil water and the utilization depth to soil water.

3.2.1 Crop utilization depth to soil water

Crop utilization depth to soil water is determined by comparison of vertical distribution curves of soil moisture between harvest and pre-sowing time. The depth where the two curves cross is the crop utilization depth to soil water. The crop utilization depth to soil water varies with the distribution density of crop rhizotaxis and its extension depth. Fig.1 shows that the soil water content of 0—200 cm soil layers at harvest time is lower than that at pre-sowing time both for winter wheat and spring corn, which suggests that utilization depth of winter wheat and spring corn to soil water is very deep and can reach below a depth of 200 cm, and even 350 cm in some areas (Li, 1983). The utilization depth of spring millet to soil water is 120 cm. Soil water content below 120 cm soil layers could have an increase to some extent, which suggests a shallow utilization depth of spring millet to soil water.

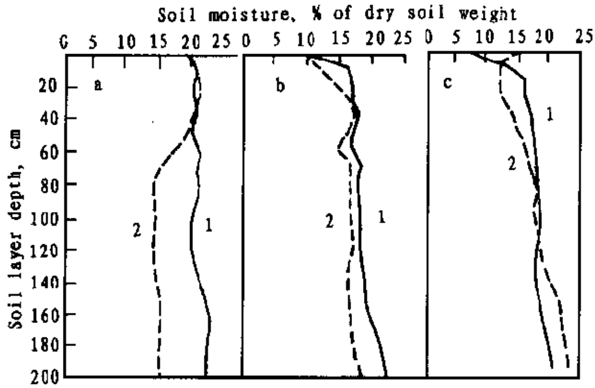

Fig.1 The utilization of crops to soil water
1. sowing; 2. harvest
a. winter wheat (1987—1989); b. spring corn (1989);
c. spring millet (1989)

3.2.2 Crop utilization ability to soil water

Crop utilization ability to soil water can be expressed with ratio of amount of used water to field moisture capacity (in percentage). The amount of used water is the difference of soil water storage between sowing and harvest time. When the difference is positive, it means that the precipitation during crop growing period is less than crop water consumption, and their difference is the amount of the used water; when the difference is negative, it means that the precipitation during crop growing period is more than crop water consumption, and the surplus precipitation is stored in soil which results in an increase of soil water storage.

During growing period, winter wheat consumes not only natural precipitation, but also a lot of soil water stored before sowing time in order to make up the deficiency of precipitation, which results in a high utilization ability to soil water. Winter wheat absorbs 116.5—133.6 mm soil water from 0—200 cm soil layers with a utilization ability of 26.6%—30.5%, especially absorbs soil water from soil layers below a depth of 100 cm with a utilization ability of 19.0%—43.7%. The precipitation during growing period can almost meet the water consumption of spring crops (Zhao, 1990b), so the soil water stored before sowing time is less consumed. The maximum amount of water used by spring crops in 0—200 cm soil layers is 58.7 mm with the largest utilization ability 13.4%. Spring crops mainly use the water in 0—50 cm or 0—100 cm soil layers. Soil moisture below 100 cm layers is hardly used (Table 2).

Since the same crop in different year has different growing status, its utilization ability to soil water is different. In 1987, summer and autumn were dry and rainless, spring maize and spring millet had bad growing state, their utilization depth to soil water was only 0—50 cm. Owing to drought and water shortage, winter wheat was sowed and sprouted later, seedlings were very weak before overwintering stage. Soil water in deep soil layers was hardly used and winter wheat utilization ability to moisture in 100—200 cm soil layers was only 19.0%. In 1988, summer and autumn were rainy, water storage in 0—200 cm soil layers of spring maize field had an increase. Winter wheat was sowed in time, seedlings were prosperous and strong, which was beneficial to the utilization of soil water storage in deep soil layers. Winter wheat utilization ability to soil water storage in 100—200 cm layers rose as high as 43.7%. Rainy season came earlier in 1989, spring crops were sowed in time and their seedlings were strong. The utilization depth to soil water was relatively deeper: more than 200 cm deep for spring corn and 100 cm for spring millet (Table 2).

Table 2 Crop utilization ability to soil water

Crops	Years	Items	Depth, cm						
			0—50	50—100	100—160	160—200	0—100	100—200	0—200
Winter wheat	1987—1988	Use amount, mm	38.6	36.8	36.9	4.2	74.4	41.1	116.5
		Use ability, %	34.9	33.3	28.7	4.8	34.1	19.0	26.5
	1988—1989	Use amount, mm	-0.6	39.6	55.1	39.5	39.0	94.6	133.6
		Use ability, %	-0.5	35.9	42.8	45.1	17.7	43.7	30.6
Spring corn	1987	Use amount, mm	34.9	-21.3	-6.3	—	13.6	-6.3*	7.3**
		Use ability, %	31.6	-19.3	-4.9	—	6.2	-2.9	1.7
	1988	Use amount, mm	-63.6	-35.4	-22.9	-15.4	-99.0	-38.3	-137.3
		Use ability, %	-57.6	-32.1	-17.8	-17.6	-44.8	-17.7	-31.4
	1989	Use amount, mm	11.1	9.2	17.4	21.0	20.3	38.4	58.7
		Use ability, %	10.0	8.3	13.5	24.0	9.2	17.8	13.4
Spring millet	1987	Use amount, mm	34.9	-20.7	-6.9	—	14.2	-6.9*	7.3**
		Use ability, %	31.6	-18.8	-5.4	—	6.4	-3.2	1.7
	1989	Use amount, mm	15.0	3.4	-15.3	-11.1	18.4	-26.4	-8.0
		Use ability, %	13.6	3.1	-11.9	-12.7	8.3	-12.2	-1.8
Available soil water, mm			—	110.4	127.8	87.6	220.9	216.3	437.2

Note: — shows an increase of soil water; *, ** indicate the use amount and ability of crops to soil water at a depth of 100—160 cm and 0—160 cm respectively.

Summarily, the utilization capacity of main crops to soil water is low, including winter wheat whose utilization capacity to soil water is relatively higher. During the experimental years, the mean utilization capacity of winter wheat to soil water in 0—200 cm layers was 125.1 mm which occupied only 29.0% of available soil water. So the potential productivity of soil water could be further improved in these areas.

3.3 Circulation features of soil water

3.3.1 Water consumption of main crops in dryland

Crop field water consumption is the sum of crop transpiration and soil evaporation in rows. Crop water consumption in dryland mainly comes from natural precipitation and soil water supply (Zhao, 1990a). Because water requirement dynamic of spring crops is almost coherent with the seasonal distribution of precipitation, water consumption is relatively higher and mainly comes from precipitation during growing period. Over 85% of water consumption of spring corn (about 400 mm) and over 90% of water consumption of spring millet (about 380 mm) come from precipitation during growing period. In some years, soil water storage in spring crop field has an increase, which suggests that precipitation during growing period is used not only for field evaporation and crop transpiration, but also for soil water storage. Precipitation during the growing period of winter wheat is very limited. Water consumption of winter wheat is about 350 mm, 60% of which comes from precipitation and the other 40% from soil water stored before sowing time (Table 3). Thus, if efficient measures are taken so that precipitation is collected and stored as much as possible in field during the fallow period of rainy summer, the potential productivity of winter wheat could be further improved.

Table 3 Water consumption and its composition of main crops

Crops	Years	Water consumption and its composition				
		Available precipitation		Soil water supply		Water consumption
		mm	%	mm	%	mm
Winter wheat	1987—1988	159.0	59.3	109.2	40.7	268.2
	1988—1989	196.8	59.3	135.3	40.7	332.1
	1989—1990	327.6	87.5	46.6	12.5	374.2
Spring corn	1987	382.4	94.1	22.9	5.7	405.3
	1988	488.6	125.1	-97.9	-25.1	390.8
	1989	347.8	86.6	54.0	13.4	401.2
Spring millet	1987	361.3	93.5	24.8	6.5	386.1
	1989	397.8	105.3	-20.0	-5.3	377.8

The duration of seeding-jointing stage for winter wheat occupies 2/3 of the total growing period, but crop water consumption during this stage only takes up 40%—50% of the total crop water consumption and mainly comes from precipitation. Crop water consumption during jointing-mature stage takes up 50%—60% of the total crop water consumption. At about heading period, crop water consumption rises to the maximum, and soil water supply occupies 60% of crop water consumption during this stage. From seeding date to late jointing stage of spring crops, because stems are small, dry material accumulates slowly, crop water consumption decreases and generally occupies 1/4 of total crop water consumption. After jointing stage, stems grow rapidly. From jointing to late filling stage, both the speed of dry material accumulation and the crop water consumption for field evapotranspiration rise to the maximum. Afterwards, water consumption tends to decrease gradually (Table 4). At certain growing stages of spring crops, some soil water storage is also needed to meet crop water requirement. Thus under dry farming condition, to store soil water as much as passible is one of the important ways for the prevention of seasonal drought.

Table 4 Water consumption pattern of main crops, mm

Crops	Items	Sowing-jointing	Jointing-heading	Heading-heavest	Whole growing period	Notes
Spring	Precipitation	158.6	140.0	116.2	414.8	Average of
corn	Soil water supply	-8.8	-20.9	14.0	-15.7	1987—1989
	Water consumption	149.8	119.1	130.2	399.1	
Spring	Precipitation	148.3	82.7	120.0	351.0	Average of
millet	Soil water supply	-52.0	37.0	46.0	31.0	1987 and 1989
	Water consumption	96.3	119.7	166.0	382.0	
Winter	Precipitation	105.2	50.1	71.3	226.6	Average of
wheat	Soil water supply	48.4	29.4	20.6	98.4	1987—1990
	Water consumption	153.6	79.5	91.9	325.0	

3.3.2 Soil water deficit

The soil water deficit is the difference between the actual soil water content and the field water capacity. Because precipitation is less than potential evapotranspiration in these areas, soil is always in state of water deficiency. Soil water deficiency can even occur in rainy seasons (Fig. 2).

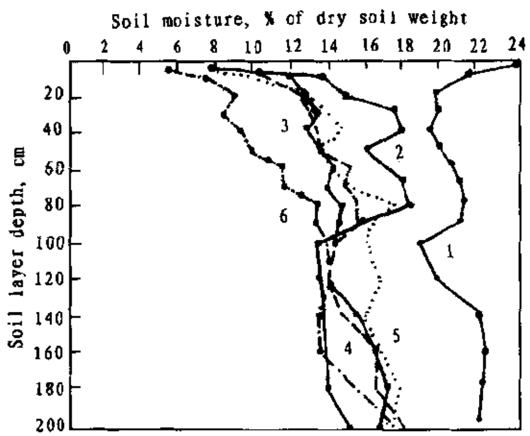

Fig. 2 Soil moisture distribution profile of main crops field in rainy season (14th August, 1989)
1. field moisture capacity; 2. winter wheat; 3. spring corn; 4. spring millet; 5. potato; 6. spring soybean

According to the seasonal distribution of soil water, the maximum of soil water deficit in bare-land is 232.8 mm which occurs mostly from May to June, and the minimum is 66.6 mm which mainly takes place in August and September. Influenced by soil evaporation and crop transpiration, soil water deficit of 0—200 cm soil layers in field with crops is 15.1—40.4 mm more than that in bare-land and the depth of dry soil layers in field with crops is 20—70 cm deeper than that in bare-land, which shows that the water consumption ability of field with crops is higher than that of bare-land (Table 5).

Soil water deficit can occur all around the year. Influenced by field transpiration, from May to June, soil water deficit in winter wheat field of 0—200 cm soil layers is 40—50 mm more than that of bare-land (Fig. 3). Recharged by precipitation during summer fallow period, the water storage of 0—200 cm soil layers can recover nearly to that of bare-land. This kind of soil water circulation belongs to yearly recovering utilization type (Mei, 1990), which is beneficial to the insurance of field water supply in dryland.

Table 5 Soil water deficit of main crops field (0—200 cm soil layers)

Field types	Maximum soil water deficit, mm		Minimum soil water deficit, mm		Mean annual	Maximum annual	Depth of
	Soil water storage	Soil water deficit	Soil water storage	Soil water deficit	range of water deficit, mm	range of water deficit, mm	dry soil layer, cm
Bare land	404.4	232.8	570.6	66.6	166.2	177.5	100
Winter wheat	364.0	273.2	567.4	69.8	203.4	228.7	170
Spring corn	364.4	272.8	555.5	81.7	191.1	201.3	150
Spring millet	383.8	253.4	552.8	84.4	169.0	182.5	120

3.3.3 Soil water remainder

The amount of available soil water that remains in soil layers at harvest time varies with the water consumption of different crops. In order to study main crop utilization degree to soil water, the percentage of available soil water storage at harvest time to available soil water storage under field moisture capacity is adopted in this paper. After consumed by one cropping, over 41% of available soil water remains unused (Table 6). Under the same condition, more water remains in spring crop field than that in winter wheat field, and more in spring millet field than that in spring maize filed. All of these shows that adopting efficient agrotechnique measures to increase crop utilization ratio to soil water storage is one of the main ways for water-saving and yield-raising.

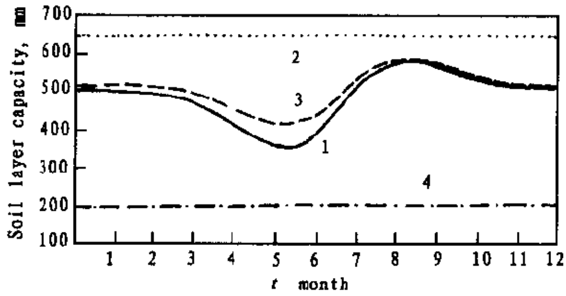

Fig.3 Seasonal variation of soil water deficit in field of winter wheat and bare land
1. winter wheat field; 2. field moisture capacity; 3. bare land; 4. withering moisture

Table 6 Percentage of remained available soil water at harvest time

Crops	Years	Available soil water storage at harvest time, mm	Available soil water storage under field moisture capacity, mm	Percentage of remained available soil water, %
Winter	1987—1988	182.7	437.2	41.8
wheat	1988—1989	244.9	437.2	56.0
	1989—1990	198.2	437.2	45.3
Spring	1987*	156.7	349.6	44.8
corn	1988	367.3	437.2	84.0
	1989	236.3	437.2	49.9
Spring	1987*	161.4	349.6	46.2
millet	1989	283.9	437.2	64.9

Note: Year with " * " means soil water storage of 0—160 cm soil layers, others show that of 0—200 cm soil layers

4 Conclusions

The analysis and results show that the soil water storage is one of main resources of water consumption of main crops in these dry farming areas, especially for winter wheat. But crop utilization ability to soil water is very low, the maximum utilization ability of spring corn and spring millet is only 13.4%, and that of winter wheat is 26.6%—30.6% which is relatively higher. At mature period and harvest time, over 41% of available soil water remains unused in soil layers. Thus adopting efficient agrotechnique measures to increase soil water storage and to raise soil moisture utilization efficiency of crops is one of the main ways for water-saving and yield-raising, and for drought-fighting and prevention in these dry farming areas.

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