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Effects of Lucerne Removal Time on Soil Water and Productivity in a Lucerne-Wheat Rotation on the Western Loess Plateau

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Abstract: Rainfed spring wheat (*Triticum aestivum* L.) is the most important cereal crop on the Western Loess Plateau. Lucerne (*Medicago sativa* L.) has been very popular. There are problems associated with both continuous cropping and with perennial lucerne systems. The key challenge for rain-fed cropping systems is to adopt strategies that make optimal use of water. Developing lucerne-wheat rotation systems will have significant benefits for agriculture development on the Loess Plateau, nevertheless, it is very important to terminate lucerne at the right time as it affects soil moisture. However, very little research has been done on the timing for termination of old lucerne in the semiarid areas of the Western Loess Plateau. Based on field experiments conducted in a typical semiarid area on the Western Loess Plateau, this paper aimed to investigate the soil water and termination timing of 30 years old lucerne on the productivity of lucerne-wheat rotation. The results showed that the soil profile after long-term lucerne was very dry down to 3 meters, the three year experiment period was not sufficient to allow soil water recharge, even after a high rainfall year. Time of 30 years old lucerne removal (in spring or later in the year) had no significant effect on soil water regimes. As a result, weeds became more competitive, the old lucerne stand showed poor dry matter, yield, had no response to 1 kg ha^{-1} of N application, and was overdue for termination. Following spring wheat made no response to 1 kg ha^{-1} of N fertilizer due to dry soil profile after 30 years lucerne growing.
Keywords: 30 years lucerne; Lucerne-spring wheat rotation; Soil moisture; Productivity; WUE

西部黄土高原苜蓿终止时间对苜蓿-小麦轮作系统生产力及土壤水分的影响

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摘 要: 旱作春小麦 (*Triticum aestivum* L.)是西部黄土高原最重要的禾谷类作物, 该区苜蓿(*Medicago sativa* L.)分布也非常广泛。持续的作物连作和多年苜蓿种植系统都存在很多问题。雨养农业系统发展的关键是最佳水分利用策略的应用。发展合理的苜蓿-小麦轮作系统对该区农业的发展有十分重要的意义。由于苜蓿终止时间严重影响土壤水分, 所以在适宜的时间终止苜蓿就显得十分重要。然而, 关于苜蓿-小麦轮作中老苜蓿在一年中适宜终止时间的研究鲜见报道。本研究利用黄土高原西部典型的半干旱雨养农业区 30 年老苜蓿布设田间试验, 旨在探索老苜蓿地土壤水分状况、苜蓿终止时间和少量氮肥施用对系统生产力及土壤水分的影响。结果表明, 长期种植苜蓿后 0~3 m 土壤水分很少, 即便遇到丰水年(2003 年), 3 年的时间都不足以恢复土壤水分。30 年苜蓿在一年中春季还是秋季终止对土壤水分状况无显著影响。种植苜蓿 30 年后杂草竞争力增强, 苜蓿干物质和产量水平都相当低, 且对 1 kg hm^{-2} 的氮肥使用无明显响应。由于土壤水分含量太低, 后茬春小麦对 1 kg hm^{-2} 的氮肥使用和苜蓿终止时间也无明显响应。因此, 苜蓿

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持续种植时间太长会耗竭土壤水分，使后茬春小麦对苜蓿在一年中的终止时间及少量的氮肥使用无响应，需要 3 年以上时间才有可能恢复土壤含水量。

关键词: 30 年苜蓿; 苜蓿-春小麦轮作; 土壤水分; 生产力; WUE

The Loess Plateau is one of the poorest regions in China. Severe erosion problems across large areas of the plateau have made it difficult to develop agriculture beyond subsistence levels. Despite the Loess Plateau's low and variable rainfall, rain fed spring wheat is the most important crop for people's food security[1-4]. Traditional wheat dominanted agricultural systems contrbute significantly to the erosion problems on the plateau, through extensive tillage and cultivation of sloping areas. As a result grain yield is also low and variable[5-8]. On these degraded soils fertilizer requirements are increasing steadily and farming systems are becoming unsustainable[9-11].

Lucerne (*Medicago sativa* L.), sometimes referred to as "the King of fodders" is the most nutritious perennial plant with the highest nutrient value as a forage. Lucerne has been adapted to a wide range of environments in the Western Loess Plateau and is grown in many areas, particularly following the implementation of a central government policy aimed at reverting crop land to grass and forestry[12].

There are problems associated with both continuous cropping and perenial pasture systems[13]. Continuous wheat cropping reduces soil nitrogen content thereby leading to a decline in soil fertility[14-16]. Much research has shown that perenial pastures reduce soil moisture content to very low levels, reducing their own productivity and that of any subsequent crop[17]. Cereal-legume rotations can overcome these problems by increasing soil nitrogen availablity under the legume pasture phase, whilst allowing soil moisture to recharge under cereal crops[18]. Among the many different possible rotation systems, a lucerne-wheat rotation has been found to be best for soil and water conservation[19]. Research by Pan, et al. on the Loess Plateau has shown that wheat yield after lucerne can be increased by 34.0%–115.3%. Organic matter and water stable aggregate at a depth of 0–20 cm were increased by 0.3%–0.5% and 20%–30% compared with continuious wheat cropping[20]. Therefore, developing lucerne-wheat rotation systems will have significant benefits for agriculture on the Loess Plateau—increasing crop production, helping develop animal husbandry, reducing erosion and improving the sustainability of agricultural systems.

The key challenge for rain-fed cropping systems is to adopt strategies that make optimal use of water and soil nutrients[21]. A lucerne-wheat rotation is good for improving water use efficiency and NO_3-N use efficiency. However, it is important to terminate lucerne at the right time as late termination can reduce soil moisture content to a level where recharge by rainfall may be insufficient. This can have negative effects to wheat yield after lucerne[18, 22]. The process and extent of soil water recharge is affected by environment and soil type[23-24], and has a significant effect on the performance of the next crop. Very little research has been done on this issue for old lucerne in the semiarid areas of the Western Loess Plateau.

This paper is a study of field experiments conducted in Dingxi City, Gansu Province, a typical semiarid area on the Western Loess Plateau for 30 years lucerne, aimed to investigate soil water and its recharging, lucerne productivity after 30 years growing, and effect of timing of lucerne termination and N application on soil water and following crop under a lucerne-wheat rotation. Measurements of soil water content, biomass and water use efficiency (WUE) of lucerne, and biomass, grain yield and WUE of wheat were taken and discussed.

1 Materials and methods

1.1 Experiment site

The field experiments were conducted in Dingxi, Gansu province, northwest China. The site is located at longitude 104º44′E , latitude 35º28′N, at an altitude of 1 971 m above sea level. In this region average radiation is 591.89 J cm^{-2} and sunshine hours are 2 476.6 h (REF). Average annual rainfall over 35 years is 391 mm, about 54% of it occurring between July and September. The summer is warm and wet, with temperatures of up to 38℃, but winter is cold and dry with temperatures dropping to –22℃. Accumulated temperatures above 5℃ and 10℃ are 2 782.5℃ and 2 239.1℃ respectively (Fig. 1 and Fig. 2).

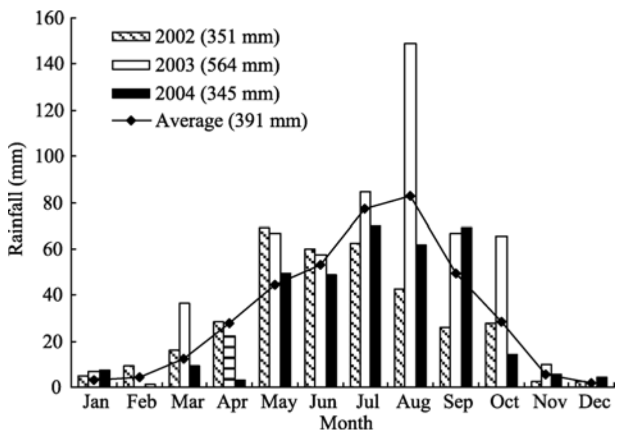

Fig. 1 Monthly rainfall in 2002–2004 compared with averaged long-term (1970–2004) in Dingxi

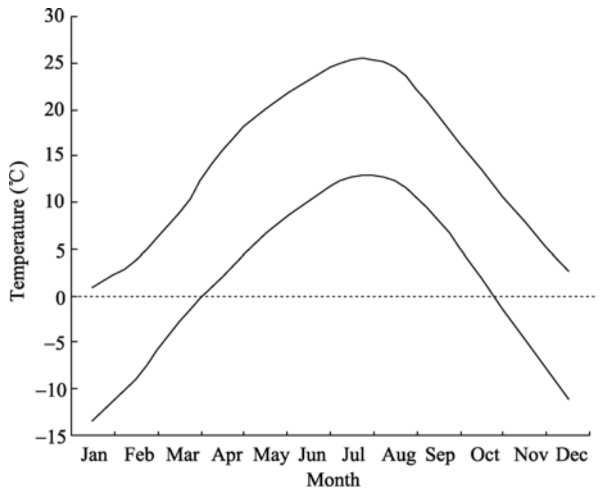

Fig. 2 Averaged long-term daily max and min temperatures (1970–2004) in Dingxi

Experiment period rainfall data, Fig. 1, were collected at the research site and compared to long term average monthly rainfall data (source: Gansu Provincial Meteorological Bureau). Fig. 2, long term temperature data, were also obtained from Gansu Provincial Meteorological Bureau.

The soil of the study area is loess soil, locally known as Huangmian soil. Table 1 shows the physical and chemical properties of Huangmian soil. It is a uniform soil with high soil pH down to 3 m. OC and TN are high at the top of the soil profile, but decline slightly deeper in the profile. TP is high but available P is low. AK is also high, sufficient for crop production. Bulk density is consistent (around 1.2) down the profile.

1.2 Experimental design

Eight treatments were designed for this experiment (Table 2), all the plots were arranged in a split-plot design with lucerne-spring wheat rotation as the main plot, N supplies (0 and 15 kg ha^{-1}) as sub-plots. Each plot measured 4 m×10 m.

Table 1 General soil chemical and physical properties of Huangmian soil at Dingxi site (Aug, 2001)

Soil depth	pH	OC (%)	T-N (%)	T-P (%)	A-N (mg kg^{-1})	A-P (P_2O_5, mg kg^{-1})	A-K (K_2O, mg kg^{-1})	B.D (g cm^{-3})
0–10 cm	8.29	0.836	0.105	0.157	22.88	6.98	195.44	1.25
10–30 cm	8.35	0.691	0.79	0.156	28.06	5.94	124.31	1.20
30–60 cm	8.42	0.572	0.63	0.153	16.86	2.74	115.88	1.21
60–90 cm	8.44	0.693	0.72	0.161	19.28	2.99	135.44	1.25
90–120 cm	8.44	0.749	0.82	0.154	16.06	3.65	132.94	1.11
120–150 cm	8.48	0.702	0.75	0.149	14.89	2.81	106.38	1.13
150–200 cm	8.43	0.776	0.86	0.158	15.19	2.85	91.81	1.18
200–250 cm	8.36	0.881	0.98	0.166	13.89	3.73	103.56	1.09
250–300 cm	8.27	0.675	0.71	0.155	15.49	2.82	101.75	1.13

Table 2 Treatment description and experiment management details at Dingxi

Treatment and code	Lucerne termination time	Fallow period	Cropping details	N application rate (kg ha^{-1})
Continuous lucerne (LC)	—	—	—	
Continuous lucerne with nitrogen (LCN)	—	—	—	15
Fallow (LF)	May, 2001	Keep fallow since May, 2001	—	
Fallow with nitrogen (LFN)	May, 2001	Keep fallow since May, 2001	—	15
Lucerne-short fallow-wheat (LFsW)	Oct, 2001	5 month	Following Lucerne termination, spring wheat was sown in March each year from 2002 to 2004.	
Lucerne-short fallow-wheat with nitrogen (LFsWN)	Oct, 2001	5 month		15
Lucerne-long fallow-wheat (LFlW)	May, 2001	10 month		
Lucerne-long fallow-wheat with nitrogen (LFlWN)	May, 2001	10 month		15

Lucerne was established about 30 years before experiment. N was applied at wheat sowing.

1.3 Initial soil measurements

Before the very beginning of the experiment, measurements of soil chemical and physical properties, and soil water down to 3 meters were taken across the whole lucerne paddock. Measurements were taken at nine soil depths: 0–10 cm, 10–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, 120–150 cm, 150–200 cm, 200–250 cm, and 250–300 cm.

1.4 Regular soil water measurements

Soil water was measured every two weeks using oven method for 0–10 cm samples and a neutron moisture meter for 10–300 cm samples. Basal sampling layer distribution was used for both soil water and nutrients measurements.

1.5 Crop measurements

1.5.1 Dry matter accumulation To measure dry matter, wheat samples from each plot were collected in three 1 m rows at three-leaf stage, flowering stage and maturity. Lucerne and weeds dry matter were measured using three quadrates with an area of 0.5 m×0.5 m in each lucerne plot. These measurements were made at when lucerne was cut each year. Due to the age of the lucerne and the Dingxi conditions, lucerne was only cut once per year.

No lucerne data could be collected in 2003 due to the SARS epidemic in the area during the harvest season. Restrictions on the area were lifted in time to collect wheat data.

1.5.2　Wheat yield and biomass　At wheat maturity, 0.5 m from the margins of every plot were discarded and total biomass and grain yield were measured and calculated from harvested area.

1.6　Water use efficiency (WUE) calculation

Accumulated water use or evapotranspiration (ET) was calculated using the water balance equation: ET (mm) = P–ΔS, where P is the in-crop precipitation, ΔS is the change in soil water storage of the whole soil profile. Water use efficiency for wheat grain yield (kg ha^{-1}) and lucerne biomass (kg ha^{-1}) were calculated by the following equation: WUE (kg mm^{-1} ha^{-1}) = grain yield (or lucerne biomass)/ET

1.7　Data analysis

All data collected from the experiments was analysed using Data Process System.

2　Results

2.1　Soil water regimes and profiles at sowing and harvest of wheat

The total soil water content of each treatment to a depth of 3 m are shown in Fig. 3. The lucerne ley had been standing 30 years before the experiment began, resulting in very low initial total water storage of only 295 mm down to 3 m. This is lower than the threshold value for wheat of 319 mm.

Despite the removal of lucerne in May and October 2001, no significant difference between treatments emerged until spring wheat sowing in 2002. Subsequently, with rainfall occurring during the April to August crop growing season, soil water of the LF treatment began to recharge, but water depleting continued in the other treatments due to crop growth. By the August 2002 wheat harvest, the LF treatment had stored 30 mm more water than the other treatments. Aside from this, seasonal factors were greater than any difference between treatments.

Very dry conditions prevailed in the second half of 2002, through to sowing in March 2003. As such, all treatments had similar water storage. Following sowing,

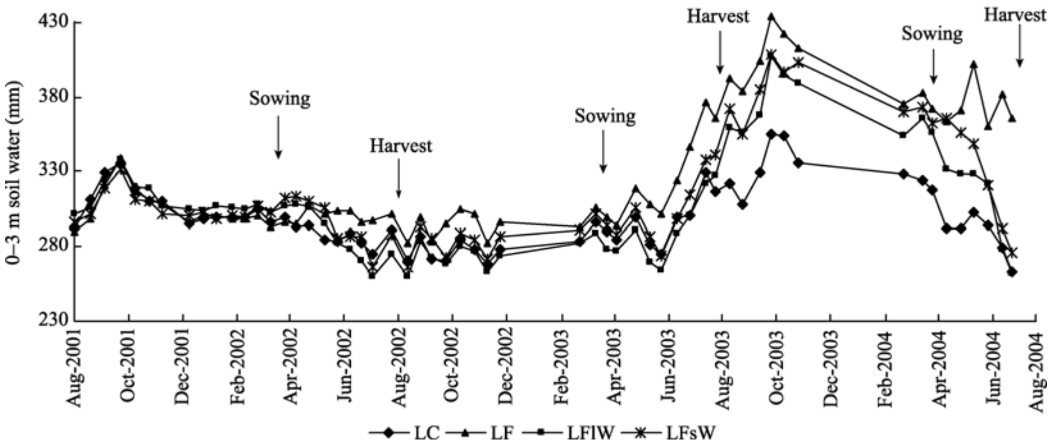

Fig. 3　Total soil water content down to 3 m for each treatment in Dingxi

Sowing and harvest labels in Figure 3 refer to sowing and harvest of wheat, wheat was sown in middle March and harvested in August each year.

however, 2003 was a relatively wet year, particularly in August (Fig. 1). The soil water profiles of all treatments peaked in the middle of October, 2003. LF accumulated 80 mm more water than continuous lucerne (LC) and 25 mm more than the lucerne-wheat rotation treatments (LF_lW and LF_sW). Interestingly, there was no difference in soil water content between LF_lW and LF_sW treatments. It is also interesting to note that even after a very wet season in 2003 the water storage of the LF treatment was only 52.7% of DUL (823 mm).

2004 was the driest year of the experiment period, especially during crop growing season, with only 127 mm rain falling before harvest (Fig. 1). All the treatments' soil water was depleted very quickly during this period, especially LC, LF_lW and LF_sW, all declining to below 280 mm. LF also lost soil water through evaporation through its bare surface, but lost less than the other treatments where crops were using soil water. The 2004 harvest period showed the strongest difference between treatments. LF stored 104 mm more water than LC. However, again there was still no obvious difference between LF_lW and LF_sW.

Fig. 4 and Fig. 5 show soil water content down the soil profile of each treatment at sowing and harvest of spring wheat. Throughout the 2001–2004 experimental period, soil profiles of all treatments were very dry. Notably, Fig. 4 and Fig. 5 show that there was no change in soil water content at depths below 1.8 m. This suggests that the 30-year-old lucerne stand has dried out the soil down to at least 3m and at depths below 1.8 m, soil water may not be recharged following lucerne, even after a high rainfall year like 2003 (564 mm). Below 1.8 m the soil water content of these treatments was considerably below that of the CLL of spring wheat. Approximately 60 mm more water would be needed below 1.8 m to bring soil water content to a level where wheat could extract it for production. After three years, water storage of fallow treatments (LF and LFN) were still very low, at only 44.3% of DUL and only 46 mm more than CLL. Therefore, when designing a lucerne-crop rotation system, local scientists should be concerned about the soil water depletion by lucerne at depth and total amount.

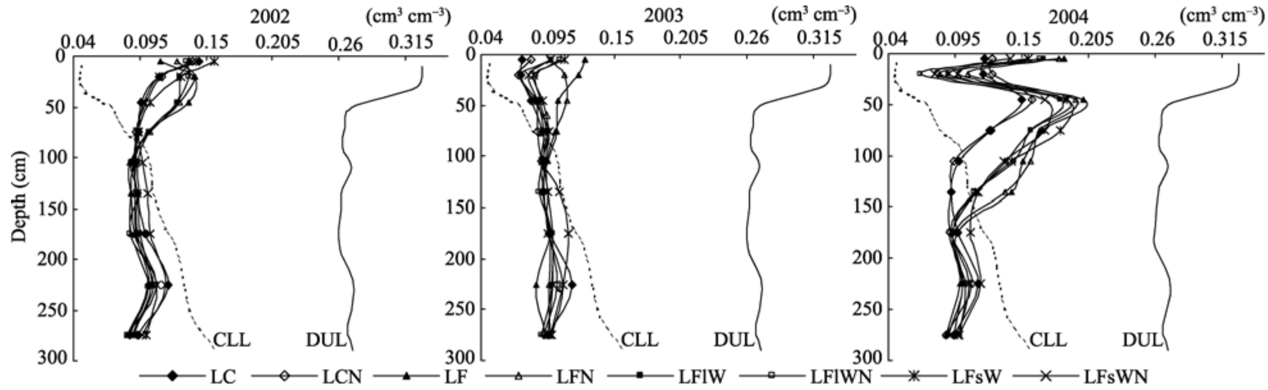

Fig. 4 Soil water content down the soil profile of each treatment at sowing of spring wheat (wheat was sown in middle march each year)

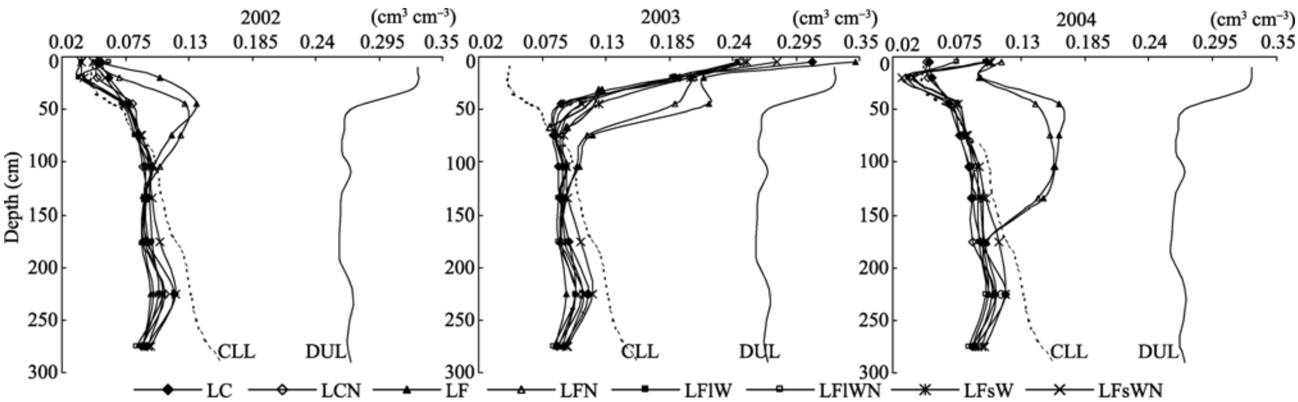

Fig. 5 Soil water content down the soil profile of each treatment at harvest of spring wheat (wheat was harvested in August each year)

2.2 Biomass and water use efficiency of lucerne and weeds

According to Table 3, lucerne dry matter production was low in this very old lucerne ley, as low as 334.9 kg ha^{-1} under the LCN treatment in 2004. The main reasons for this might be the continuous invasion of weeds (mainly annuals), age and poor plant density of the stands. This also led to water use efficiency of lucerne being quite low, between 4.03 and 6.42 kg ha^{-1} mm^{-1}. Although it was very dry in 2004, total biomass of lucerne and weeds and WUE of lucerne were increased because of high rainfall in 2003. Therefore, soil water storage is very important for crop growth in a dry year.

After 30 years there were many weeds in the lucerne ley. Weeds became more competitive than lucerne in 2004, their total biomass surpassing that of the lucerne itself. This suggests that while rainfall can increase growth of weeds, it does not bring about a simultaneous improvement in lucerne growth. As a result of this both dry matter of lucerne and the weeds in lucerne paddock were measured (Table 3).

2.3 Biomass, grain yield, and water use efficiency of spring wheat

Crop yield, harvest index and water use efficiency are presented in Table 4. Generally there was no difference between treatments. Wheat yields were low, especially in 2003 when, although the in crop rainfall (210 mm) was the same as 2002, and the annual rainfall was the highest of the experiment period, most of the in crop rain occurred exactly before harvest. It had been particularly dry in the 15 days around flowering. The late rain had almost no effect on grain formation and filling, therefore, the harvest index and water use efficiency calculated from grain yield were abnormally low. Grain yield was highest in 2004, perhaps due to the late rainfall in 2003, suggesting that soil water storage is important for wheat grain yield, much as the higher biomass of lucerne and weeds in 2004, seemed to be due to water stored from 2003.

Crop yield showed no response to the nitrogen treatments, where 15 kg ha^{-1} of N had been added. The most likely reason for this is the very dry soil profile following the long term Lucerne.

Table 3　Biomass and water use efficiency of lucerne and weeds in 30 year old lucerne stands

Year	Biomass (kg ha^{-1})						WUE (kg mm^{-1} ha^{-1})	
	LC			LCN			LC	LCN
	Lucerne	Weeds	Total	Lucerne	Weeds	Total		
2002	964.4	9.7	974.1	983.3	12.0	995.3	4.03	4.23
2003	NA	NA	NA	NA	NA	NA		
2004	526.9	700.1	1227	334.9	856.1	1191	6.42	6.17

NA: not available.

Table 4　Biomass, grain yield and water use efficiency of spring wheat sown following the termination of 30 year old lucerne stands in Dingxi

Treatment code	Biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	HI	Soil water change (harvest-sow) (mm)	WUE (biomass) (kg mm^{-1} ha^{-1})	WUE (grain yield) (kg mm^{-1} ha^{-1})
2002 (in crop rain: 211 mm)						
LF_lW	5000±489	1777±82	0.36±0.05	−47.7	19.32	6.86
LF_lWN	4694±417	1797±123	0.38±0.04	−43.8	18.42	7.05
LF_sW	4083±436	1618±96	0.40±0.05	−40.4	16.24	6.43
LF_sWN	4889±359	1489±77	0.30±0.04	−28.4	20.41	6.22
2003 (in crop rain: 210 mm)						
LF_lW	4068±192	358±11	0.09±0.00	39.7	23.89	1.92
LF_lWN	4382±44	381±56	0.09±0.01	34.7	25.00	2.06
LF_sW	3294±655	603±34	0.18±0.03	47.4	20.26	3.18
LF_sWN	4453±503	512±43	0.12±0.02	49.4	27.73	2.81
2004 (in crop rain: 127 mm)						
LF_lW	4933±9	1888±77	0.38±0.01	−91.9	22.57	8.64
LF_lWN	5178±92	1921±113	0.37±0.04	−98.9	22.95	8.51
LF_sW	4244±169	1903±74	0.45±0.05	−94.7	19.17	8.60
LF_sWN	4756±166	1938±2	0.41±0.04	−81.6	22.83	9.31

3　Discussion

Soil moisture content after lucerne is one of the key factors affecting later crop growth. A great deal of research has been done on this issue[25-26]. Results from this experiment show that the 30 years lucerne stand has depleted soil water, thus soil profile is very dry down to 3 m. The three year experiment period was not sufficient for soil water recharge, especially for layers below 1.8 m.

Although significant effects of temination time of lucerne on soil water had been detected in many research[7, 27], in the results of this experiment time of lucerne termination (in spring or later) had no effect on soil water regimes, probably because the soil was rather dry after 30 years depleting.

Lucerne is a very important forage plant on the Loess Plateau due to its high nutrient content and high productivity. Lots of research has shown that lucerne obtains its peak productivity between its fifth and eighth years, then it begin to decrease[11, 28]. Terminating lucerne at the right time is very important. The 30-year-old lucerne stand showed poor dry matter yields due to its age, invasion of weeds and poor plant density, it should be terminated earlier. In rainfed areas, wheat yield depends on both rainfall and soil water stored in the soil during fallow[3, 29]. In this research, as soil moisture following long term lucerne is very low, subsequent spring wheat yielded poorly.

Lots of researches have been done on wheat yield response to N. Both wheat yield and protein content are sensitive to nitrogen application rate [30-32]. However, following removal of a long-term lucerne stand, soil moisture was very low and spring wheat made no response to small amounts of N fertilizer. Clearly, response to N in cereal crops relies on adequate soil water availability.

4 Conclusions

If lucerne stands for too long, it will deplete soil water, resulting in that lucerne yields rather poorly, time of old lucerne removal within a year has no significant effect on soil water regimes, following spring wheat has no significant response to time of previous lucerne removal and to small amounts of N application. It will take more than three years for soil water to be recharged.

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