

14 The Effects of Soil Moisture and Nutrients on Cropland Productivity in the Highland Area of the Loess Plateau

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Abstract

Soil moisture and nutrient distribution, and their effect on cropland productivity in the tableland area of the Loess Plateau, were studied. For major crops, the following characteristics were investigated: sensitivity to water stress at different stages of growth, methods for improvement of crop water use efficiency and soil nutrient input and output of a cropland ecosystem in the tableland area of the Loess Plateau. This chapter discusses how soil fertility can be improved in a cropland ecosystem, the effects of fertiliser on crop productivity under different patterns of rainfall, how fertiliser use can be linked to productivity, optimum fertilisation and factors affecting the efficiency of fertiliser use. It describes key factors limiting cropland productivity and the main measures by which productivity can be increased in the tablelands of the Loess Plateau.

本文分析了黄土旱塬农田生产力的变化、土壤水分和养分分布特征及其对农田生产力的影响，研究了主要作物水分利用特征、不同生长阶段作物水分敏感性指数、以及提高作物水分利用率的途径；分析了黄土旱塬农田系统土壤养分的输入与输出特征，不同降雨年型肥料对作物生产力的效应；氮磷肥料的利用效率和影响因子，提出了改善农田生态系统土壤肥力的途径。最后，探讨了限制作物生产力的关键因子的变化以及提高农田系统生产力的主要措施配置，分析了黄土旱塬生产力的变化趋势。

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THE HIGHLAND area of the Loess Plateau is situated in the central southern portion of the plateau. The Overview provides background information on the region; Figure 1 of the Overview shows its location. The climate is classified as a semihumid temperate zone with an average annual temperature of 7.0–13.5°C and a frost-free period of 140–230 days. Most areas can support three harvests over two years but some regions in the eastern part can achieve two harvests per year. Average annual precipitation is 500–600 mm, with wide variation between years and seasons, so the soil is frequently deficient in moisture. The area is a typical dryland farming area where agricultural production depends mainly on rainfall. Rainfall is concentrated in the period from July to September, so there is a water shortage in spring and winters are dry and cold. The soil is moderate loamy Heilu soil, formed from deep Malan loessial soil. It is suitable for dryland cultivation due to its porous nature and high capacity to hold water: 500–600 mm of rainfall can be stored in the top 2 m of soil in this region. The soil functions as a reservoir and is important in sustaining production of the staple crops, which are winter wheat and summer corn. These crops account for 70–80% of sowing in the region and 80–90% of food crop production.

Critical problems in agricultural production in the highlands are the small area of land available for growing crops, soil erosion, frequent drought and low crop yield.

The overall aims for ensuring food production in this small highland region, with many slopes and gullies, are:

- to improve the efficiency of water and land resource use, and increase productivity, by increasing fertiliser use through the combined application of manure, nitrogen (N) and phosphorus (P);
- to focus on soil moisture, nutrient cycling and nutrient balance in the cropland ecosystem;
- to investigate the theories and techniques of improving land productivity to promote development of the regional economy; and
- to investigate solutions to the problems of high population density, which places demands on land and water resources and the ecosystem.

The Effect of Soil Moisture on Cropland Productivity

Soil moisture characteristics

In the highland area of the Loess Plateau, most soil is loamy; its moisture capacity reaches 800–900 mm in the 0–200 cm layer because the soil has many interspaces. Precipitation is about 600 mm, so the soil's capacity to hold moisture constantly exceeds precipitation. The deep layer of water held in the soil makes the Loess Plateau a highly suitable environment for plant growth. To promote use of this deep soil moisture by crop roots requires an understanding of crop root growth and stage of development.

Productivity

The highlands of the Loess Plateau are typical dryland farming areas, where soil moisture and nutrients are the main factors limiting crop production. During 1986–90, crop productivity was low and the main limiting factor was soil fertility rather than soil moisture; yields were improved mainly by increasing fertiliser. During this period, lack of nutrients led to a decrease in the yield of winter wheat (by 29.3–54.6%) and of summer corn (by 5.2–35.6%). Fertiliser use gradually improved soil fertility and in 1991–95 low fertility was responsible for only a 1.6–2.8% decrease in yield, with soil moisture the main factor limiting productivity. In 1986–91, moisture shortage led to a fall in the yield of winter wheat (of 3.0–17.9%) and of summer corn (of 4.6–21.7%). However, in 1992–95, the effect of low soil moisture was greater, causing yield to fall by 5.9–75.2% in winter wheat and by 13.3–72.8% in summer corn.

Historically, fertiliser input in the Loess Plateau region has been low; in large areas of the region fertiliser input is currently insufficient because of economic constraints. Thus, nutrient stress is a limiting factor for improving productivity in the long term. However, water shortage is becoming more important than nutrient stress as a limiting factor for productivity, particularly in regions where initial productivity is high and the rural economy is relatively active.

The Effect of Soil Nutrient Distribution on Cropland Productivity

Soil nutrient distribution in the highlands of the Loess Plateau

Table 1 shows the soil nutrient distribution in the highlands of the Loess Plateau. The coefficient of variation for each nutrient is large, particularly for available P and potassium (K). Overall, the soil is low in organic matter, N and P, but rich in K.

Table 1. Soil nutrient distribution in croplands in the highlands of the Loess Plateau.

	Range	Average
Organic matter	4.78–13.94 g/kg	9.45 g/kg
Nitrogen	0.410–1.055 g/kg	0.75 g/kg
Available nitrogen	34.0–74.9 mg/kg	53.7 mg/kg
Available phosphorus	0–25.3 mg/kg	6.3 mg/kg
Available potassium	88.2–367.3 mg/kg	175.1 mg/kg

Effect of nutrient on cropland productivity

Use of N fertiliser improved the yield of winter wheat. Studies from 1984 to 1995 on Heilu soil showed that adding N increased winter wheat yield by 84.8–186.7% (average 135.5%) (Liang et al. 2000). The increase in wheat yield per kilogram of N was 6.9–27.1 kg (average 17.0 kg). However, as the quantity of added N increased, the impact on yield

decreased. The effect of N fertiliser was also related to the quantity of P added. If enough P was used, N had a greater effect on yield and the decrease in impact with increasing amounts of N was less marked.

The use of P fertiliser improved winter wheat yield in Heilu soil by 0.3–48.4% (average 26.8%). The increase in wheat yield per kilogram of P was 6.3 kg. The effect of P was much greater if it was used together with N, as shown in Table 2. Similarly, the effect of N was greater when combined with P. N combined with P fertiliser produced a wheat yield of 2233–3495 kg/ha (average 3049 kg/ha)—an average increase of 139.6% when compared to using no fertiliser, of 25.4% compared to using only N and of 25.4% compared to using only P.

Table 2. Effect of combining nitrogen and phosphorus fertiliser.

	Increase in yield (%)		
	Nitrogen fertiliser (kg/ha)		
Phosphorus fertiliser (kg/ha)	0	90	180
90	0.3	29.5	39.1
180	2.2	34.9	48.4

Sensitivity of Different Growth Stages of Major Crops to Water Stress

Limited-water irrigation and optimal management of limited water resources is based on variation in the sensitivity of different growth stages of a crop to water stress. Little is known about the water sensitivity of different stages of winter wheat and summer corn on the semiarid Loess Plain. The Jensen multiplication model (Jensen 1986) describing water sensitivity is more sensitive and more practical than the addition model in China (Kang and Dang 1987). Hence, we used the Jensen multiplication model to determine the relation between crop yield and water consumption (Jensen

1986). Taking the relative evaporation at each growth stage (i) as the independent variable, the effect on crop yield can be expressed as follows:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^n \left(\frac{ET_a}{ET_m} \right)^{\lambda_i} \quad (1)$$

where Y_a is actual crop yield, Y_m is maximum crop yield if sufficient water is present, n is the ordinal number of the growth stage, ET_a is actual evapotranspiration, ET_m is maximum evapotranspiration and λ_i is the crop water sensitivity index of each growth stage (that is, the extent to which crop yield is affected by any water deficit). For this model, a high value of λ_i indicates a large reduction in crop output. Hence, λ_i is the crucial parameter in the model.

The aim of this study was to determine changes in water sensitivity for winter wheat and summer corn during the entire growth season, and propose an optimum water supply schedule for these crops in the Loess Plateau region.

Field experiments were conducted in plots sheltered from rain, at the Changwu Agro-Ecological Station of the Chinese Academy of Sciences on the Loess Plateau during 1995–97. Figure 4 of the Overview shows the location of Changwu; the station is approximately 1200 m above sea level. The mean temperature is 9.0–9.5°C and mean annual precipitation is 548 mm.

The crops studied were winter wheat (variety Changwu 134) and summer corn (variety Danyu 13). For each crop, we investigated the soil moisture level and the stage at which the crop was irrigated. Three levels of soil moisture were tested:

low (D) with a relative water content of 45–55%, medium (Z) with a relative water content of 55–70%, and high (G) with a relative water content of 75–85%. Water treatment stages differed for the two crops. Development of winter wheat was divided into five stages: seedling (early October to early March), vegetative (early March to early April), jointing (early April to early May), heading (early May to early June) and the milk phase. Development of summer corn was divided into four stages: jointing (mid-June to mid-July), preheading (mid-July to early August), flowering (early to late August) and the milk phase (late August to late September). A total of 15 different irrigation treatments were tested in winter wheat and summer corn, using a random design with two replications for each treatment. Plots were watered regularly according to soil moisture content. Before ploughing, N and P were sprinkled on the soil surface at rates of 138 kg/ha and 112.5 kg/ha, respectively.

Time-domain reflectometry (TDR) was used to measure the soil water content at 15-day intervals. Crop water use was calculated from the soil water content measured at each growth stage. Crop yield was determined at maturity. The least squares difference method was used to test significant difference and the Jensen model was used to calculate crop water sensitivity at different growth stages.

Determination of crop water sensitivity

Data from the field experiments were used to calculate relative evapotranspiration from different growth stages and relative yield from different irrigation treatments using the Jensen model and the following equations (Equation 2 is for winter wheat in 1995–96; Equation 3 is for summer corn in 1996–97):

$$\frac{Y_a}{Y_m} = \left(\frac{ET_{a1}}{ET_{m1}} \right)^{0.253} \times \left(\frac{ET_{a2}}{ET_{m2}} \right)^{0.024} \times \left(\frac{ET_{a3}}{ET_{m3}} \right)^{0.17} \times \left(\frac{ET_{a4}}{ET_{m4}} \right)^{0.07} \times \left(\frac{ET_{a5}}{ET_{m5}} \right)^{0.014} \quad (2)$$

$$\frac{Y_a}{Y_m} = \left(\frac{ET_{a1}}{ET_{m1}} \right)^{0.0936} \times \left(\frac{ET_{a2}}{ET_{m2}} \right)^{0.2097} \times \left(\frac{ET_{a3}}{ET_{m3}} \right)^{0.1989} \times \left(\frac{ET_{a4}}{ET_{m4}} \right)^{0.026} \quad (3)$$

Water sensitivity at different stages

Equation 2 shows that the water stress index λ_i varied greatly among the different growth stages of winter wheat. The stage from seedling to vegetative had a high λ_i value and was crucial for the crop. The λ_i value was lowest during the vegetative to jointing stage because the plants were relatively small at this stage and the temperature was low, so the plants grew slowly. Winter wheat grows rapidly from the jointing to the heading stage when leaves and stems and reproductive growth occur simultaneously. Leaf area increased rapidly at this stage and the weather became warmer, giving a high level of transpiration from the leaves. Thus, water deficit in this period greatly affected yield and the value of λ_i was high. The water stress index was also high from the heading to milk stage. This period is crucial for seed formation, so water deficit affects reproductive growth. During the milk to mature stage, plant leaves begin to turn yellow, transpiration decreases and the effect of water deficit on yield is reduced. The λ_i value at this stage was low; this was expected because oversupply of water in this period delays maturity. Overall, the seeding to vegetative stage was the most sensitive to water deficit, followed by the jointing to heading stage, the heading to milk stage, the milk to mature stage and the vegetative to jointing stage.

Equation 3 shows that the water stress index varied greatly among the different growth stages of summer corn. For the reasons given above for winter wheat, the λ_i value was low during the early period of nutritive growth before jointing but was high after jointing, due to nutritive and reproductive growth and increasing temperatures. The λ_i value was also high in the heading to milk stage, which is crucial to yield. During the milk to mature stage, the effect of water deficit on yield decreased, again for the reasons given above for winter wheat.

Irrigation efficiency and water use efficiency of crops under limited water supply

At different stages of growth, water deficit affects yield differently. Table 3 shows that a yield of

4500 kg/ha can be achieved with some water deficit. Controlled water deficit can benefit the output of winter wheat. For a target yield of 4500–5000 kg/ha, soil moisture should be sufficient before winter and at particular stages during the growth period. Of greatest benefit to output were alternate medium and high water treatments during the early period and water stress treatment during the late milk stage. For a target yield of 3750–4500 kg/ha, at least one stage of sufficient soil water during the whole growth period is needed. Alternate medium and high water treatments during earlier stages and water stress at a later stage were beneficial to yield. For a target output of less than 3750 kg/ha, there could be two stages of water stress treatment during the whole growth period.

Among the treatments in which the yield was higher than 3750 kg/ha, two alternating serious water-deficit stages gave a noticeably higher yield than did two continuous serious water-deficit stages. There were remarkable positive relationships between biomass and irrigation volume ($r = 0.82$, $n = 15$) and with grain yield and irrigation volume ($r = 0.82$, $n = 15$). During the seeding stage, there were also positive relationships between biomass and irrigation volume and between grain yield and irrigation volume ($r = 0.75$, $r = 0.74$, $n = 15$): irrigation during the seeding stage was important to promote early vigour, for the plant to live through winter safely and to gain high yield.

This was contrary to previous results, which showed two critical water sensitive stages for winter wheat: the first from the mother cell quartet of pollen to pollen forming stage, the second from the beginning of milk stage to the milk mature stage (Shan 1996). There are two possible reasons for this. First, the experimental treatments were different. Our study began water treatments before winter, when the seedling was incomplete; we used different drought degree treatments; and we divided the soil water treatment into five stages during the whole growth period. The previous study began most water treatments when the seedling was complete

Table 3. Effect of irrigation volume on irrigation efficiency (IE) and water use efficiency (WUE) of winter wheat, 1996–97^a

Treatment ^b	Yield (kg/ha)	Irrigation (mm)	WU ^c (mm)	IE (kg/ha/mm)	WUE (kg/ha/mm)
D-D-D-D-D	2025	97	213	20.88	9.5
D-D-D-G-Z	3180	187	300	17.00	10.6
D-G-Z-D-D	3375	167	278	20.21	12.1
G-D-Z-G-Z	3405	269	385	12.66	8.8
Z-Z-Z-Z-Z	3570	241	359	14.8	9.9
D-Z-D-D-Z	3705	183	291	20.2	12.7
Z-D-D-Z-G	3870	241	338	16.1	11.5
Z-G-D-D-G	4020	281	387	14.3	10.4
Z-G-Z-D-D	4080	216	323	18.9	12.6
G-G-D-Z-D	4230	268	389	15.8	10.9
D-Z-G-Z-G	4245	302	403	14.1	10.5
G-G-G-G-G	4500	408	519	11.0	8.7
Z-Z-G-G-D	4500	302	420	14.9	10.7
G-Z-G-D-Z	4575	257	383	17.8	11.9
G-Z-G-G-D	4920	306	390	16.1	12.6

^a Each value is the mean of four measurements from separate plots

^b D = low soil moisture with soil relative water content at 45–55%; Z = middle soil moisture with soil relative water content at 55–70%; G = high soil moisture with soil relative water content at 75–85% for the five winter wheat growth stages introduced previously.

^c WU = water quantity used (mm)

(after winter and the start of vegetative growth) and strong, and used different periods and degrees of water treatment. Second, our study was conducted in highland and gully regions in the semiarid environment of the Loess Plateau; this area is typical dry farmland, and drought was the main obstacle to crop production. We considered it important for winter wheat to have early vigour, grow strongly, live through winter safely and give a high yield (Liang and Richards 1999). The previous study focused on high yield rather than on water saving and high water use efficiency. If a grain yield of more than 3750 kg/ha is desired, the total water use should be 320–420 mm, with an irrigation volume between 260 mm and 300 mm at the seedling stage and before flowering; this will produce a high yield and a high irrigation efficiency.

Table 4 shows that there were great differences in the grain yield of summer corn under different water treatments. The yield was lowest under sustained water stress and highest when there was sufficient irrigation during the total growth period of summer corn; the yield under light water stress was between these two extremes. Alternating water supply to the soil had different effects on grain yield in corn. Yield was lowest when plants suffered from serious water stress at all four growth stages; when three growth stages suffered from serious water stress, the yield was lower than when only two stages suffered such stress; similarly, when two stages suffered from serious water stress, the yield was lower than when one stage suffered from such stress during the growth period. Moreover, the yield depended on which stage was affected: water stress

Table 4. Effect of irrigation volume on irrigation efficiency (IE) and water use efficiency (WUE) of corn, 1995–96.^a

Treatment ^b	Yield (kg/ha)	Irrigation (mm)	WU ^c (mm)	IE (kg/ha/mm)	WUE (kg/ha/mm)
D-D-D-D	4370	136	218	32.1	20.1
Z-D-D-D	5216	186	286	28.0	18.2
Z-D-D-Z	5643	174	256	32.43	22.4
D-Z-Z-Z	6219	254	342	24.5	18.2
Z-D-Z-Z	6228	270	360	23.1	17.3
Z-Z-D-Z	6572	335	416	19.6	15.8
Z-Z-Z-D	6905	220	322	31.4	21.4
Z-Z-Z-G	7497	259	357	28.9	21.0
Z-G-Z-Z	7497	277	370	27.1	20.3
G-Z-Z-Z	7641	383	473	20.0	16.2
Z-Z-Z-Z	7991	277	370	28.8	21.6
Z-Z-G-Z	8244	391	515	21.1	16.1
Z-G-G-G	8945	492	564	18.2	15.9
G-G-G-G	9371	554	661	16.9	14.2
Z-G-G-Z	10,062	447	526	22.5	19.1

^a Each value is the mean of four measurements from separate plots

^b D = low soil moisture with soil relative water content at 45–55%;

Z = middle soil moisture with soil relative water content at 55–70%;

G = high soil moisture with soil relative water content at 75–85% for the four summer corn growth stages introduced previously

^c WU = water quantity used (mm)

had a greater effect on yield after jointing and from the heading to milk stage than from the milk to mature stage. Grain yields of more than 7000 kg/ha could be obtained for corn when there was only light water stress if no serious water stress occurred at any time during the growth period.

Discussion

In the areas where water was limited, the central task was to save water while obtaining a high yield efficiently. The main objective of optimising or managing limited water resources is to increase the economic yield per unit water volume (Aston and van Bavel 1972; Blank 1975; Liang and Richards 1999; Shan 1996; Steinberg and Henningger 1997).

The results showed an obvious relationship between yield and irrigation volume. Moreover, for wheat

yield, irrigation volume produced different effects at different stages of plant growth. Yield was most affected when seedlings were irrigated before March; irrigation at the jointing to heading stage produced the next greatest effect. The effect of irrigation at the vegetative to jointing stage and after the milk stage was relatively unimportant.

Crop sensitivity to water stress was relatively high. The water stress sensitivity index, λ_i , was relatively large at the seedling stage but relatively low during the vegetative to jointing stage. The λ_i value increased after the jointing stage and was also high during the heading to milk stage, but began to decrease during the milk to mature stage (Equation 2). The reason may be that the seedling stage is the crucial stage for root elongation and root system development. Liang and Kang (2000) studied the relationship between photosynthetic and soil water

deficit at different growth stages; the highest ratio of photosynthetic sensitivity to soil water deficit occurred at the booting to heading stage. At this time, the temperature was relatively high, water consumption was relatively large, water requirements were urgent and there was an increased sensitivity to water deficit. This suggests that water deficit affects not only photosynthesis, but also grain yield. The yield would be little affected if water stress occurred after the vegetative or milk stages, but would be affected greatly if the water stress occurred after the jointing or heading stage. Thus supplementary irrigation should be arranged, if possible, for the seedling and jointing to heading stages. If soil water content during the seedling stage is sufficient for the formation of a strong seedling, irrigation should be applied if possible at the booting to heading stage rather than at other stages.

The water sensitivity index λ_i of summer corn also differed at different growth stages. It was relatively low before jointing, and it was high after the jointing stage and during the heading to milk stage; however, it began to decrease during the milk to mature stage. Water stress before jointing or after the milk stage had little effect on yield, but water stress after the jointing or heading stage affected the yield greatly. Hence, the heading stages should be given the highest priority for irrigation, followed by the after-jointing stage.

Soil nutrient input and output of cropland ecosystems

The soils of most cropland areas in the Loess Plateau region contain insufficient N for wheat and corn. In addition, there is not enough P available in the soil to satisfy crop needs. Consequently, both N and P are added in fertiliser. The soils of the Loess Plateau are rich in K, so K fertiliser is not usually applied.

Studies at Changwu Agro-Ecological Station from 1984 to 1995 have shown that the efficiency of fertiliser use depends on precipitation. The fertiliser use efficiency for N was 6.4–58.6% (average 35.3%,

coefficient of variation 48.7%); for P, the figure was 3.7–19.8% (average 14.2%, coefficient of variation 39.5%).

The fertiliser use efficiency for N and P depended on the quantity of fertiliser used. For P fertiliser (phosphorus oxide, P_2O_5) applied at 90 kg/ha and N fertiliser applied at 45–180 kg/ha, the fertiliser use efficiency was 25.4–42.9% (average 36.3%) in wheat.

Main Conclusions

Long-term research on the Loess Plateau has shown that cropland productivity depends on many production factors. If fertility or water were limiting factors for the crop, the yield depended on time, space and productivity level. This was not the case for dryland farming areas, in which increased fertiliser application was the key to increasing yield and water use efficiency under certain water conditions. As productivity improves, water becomes more important in determining yield.

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