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Long-term fertilization effects on grain yield, water-use efficiency and soil fertility in the dryland of Loess Plateau in China

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Abstract

Wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) rotation system is important for food security in the Loess Plateau of China. Grain yield and water-use efficiency (WUE: grain yield per unit of water consumed) trends, and changes in soil properties during a 24-year fertilization experiment in Pingliang, Gansu, China, were recorded. Mean yields of wheat for the 16 years started in 1981 ranged from 1.29 t ha^{-1} for the unfertilized plots (CK) to 4.71 t ha^{-1} for the plots that received manure (M) annually with inorganic nitrogen (N) and phosphorus (P) fertilizers (MNP). Corn yields for the 6 years started in 1979 averaged 2.29 and 5.61 t ha^{-1} in the same treatments. Yields and WUEs declined significantly with lapse of time except CK and MNP for wheat. Wheat yields with the N and M declined at rate of 77 and 81 kg ha^{-1} $year^{-1}$, but the decline of 57 kg ha^{-1} $year^{-1}$ for NP was similar to that of 61 ha^{-1} $year^{-1}$ for straw with N annually and P every second year (SNP). Likewise, the corn yields and WUEs declined from 160 to 250 kg ha^{-1} $year^{-1}$ and from 0.01 to 0.03 kg m^{-3} $year^{-1}$ among treatments, respectively. These declines were likely to loss of soil fertility and gradual dry weather. Yields were significantly correlated with seasonal evapotranspiration with slopes ranging from 0.5 to 1.27 kg m^{-3} for wheat and from 1.15 to 2.03 kg m^{-3} for corn. Soil organic carbon (SOC), total N (TN), and total P (TP) gradually built up with time except the CK, in which TN and TP remained unchanged but SOC and available P (AP) decreased. Soil AP decreased in the N. Soil available K declined rapidly without straw or manure. Balanced fertilization should be encouraged to ensure sustainable productivity in this intensive cropping system. The greatest SOC increases of about 160 mg ha^{-1} $year^{-1}$ occurred in the SNP and MNP, suggesting that long-term additions of organic materials to soil could increase soil water-holding capacity which, in return, improves water availability to plants and arrests yield declines, and decrease CO_2 emission from agricultural soils and sustain land productivity.

Keywords: Corn; Crop water stress index; Grain yield; Long-term fertilization; Soil fertility; Water-use efficiency; Wheat

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1. Introduction

Northwest China is a vast semi-arid area with average annual precipitation ranging from 300 to 600 mm and more than 90% of the cropland in this

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area receives no irrigation. The main crops are wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) which are periodically rotated. This rotation is a necessary for food security in this dryland region (Xing et al., 2001). In this system, three or more years of continuous wheat are commonly grown and then rotated to two or more years of continuous corn. Winter wheat is seeded about 20 September and harvested in late June. Corn is seeded about 20 April and harvested near the end of September. In a typical system where winter wheat follows corn, there is no fallow and wheat is seeded immediately following corn harvest. In all other combinations, land is fallowed between crops, which is helpful for water storage to store water in the soil for the subsequent crop. Shangguan et al. (2002) reported that fallow efficiencies, expressed as soil water accumulation divided by precipitation received during fallow periods, for the area were about 35–40%. The importance of storing soil water during fallow periods for increasing grain yields of subsequent crops has been supported by many dryland studies including those in the Southern Great Plains in USA by Johnson (1964), Unger (1972), Musick et al. (1994) and in the China Loess Plateau by Shangguan et al. (2002).

There are about 1.3 million ha of wheat and corn rotations in the Loess Plateau region of Northwest China. These lands are mostly in the highland plateaus of East Gansu and North Shaanxi and West Shanxi and account for about 40% of the local food needs (Fan and Song, 2000). The highland plateau is a relatively continuous integrated grain production belt among the hills and gullies of the Loess Plateau, and has an annual precipitation of 500–600 mm. The productivity of grain crops is affected significantly by water availability and fertilization. The importance of fertilization for increasing yield and improving soil quality in this area has been affirmed. Lu et al. (1998) reported that inorganic nitrogen (N) and phosphorus (P) fertilization increased grain yields in China by 50–60%. They stated that grain production in the region was not keeping pace with demand even though the area population growth rate was less than 1%. This is because highly erodible land is being retired to grassland and acreage for higher income crops is expanding. Improving the sustainable productivity of the cropland and increasing water-use efficiency by optimizing the relationships between nutrients and water will be required to meet the food demand of the region's growing population. Maintenance of soil fertility will be essential to improve and sustain yields, and soil organic matter (SOM) management is necessary as it directly and indirectly affects various chemical, physical, and biological soil properties that affect crop performance. SOM is recognized as a cornerstone for successful farming in most areas (Vanlauwe et al., 2001; Merckx et al., 2001; Zhang and He, 2004). Challenges for dryland farming in Northwest China are low water-use efficiency (WUE), expressed as grain yield per unit of water consumed, resulting from low SOM and low soil fertility (Zhu, 1984; Zhang et al., 1997). In most cases, organic carbon in the surface layer of this region was generally below 5.8 g kg^{-1} (Xing et al., 2001) because low-quality manure are applied at rate of 30 t ha^{-1} and crop straws are taken out from field for feed or fuel.

Long-term fertilization experiments are valuable to follow yield and soil fertility trends with lapse of time, changes in yields and WUE, and risk management (Dawe et al., 2000; Regmi et al., 2002). Various long-term experiments were done to test effects of fertilization on yield and soil properties in the world (Jenkinson, 1991; Mitchell et al., 1991; Sandor and Eash, 1991; Brown, 1991; Bhandari et al., 1992). Although there have been many field trials on fertilizer yield responses in northwest China, however, most of these studies have been carried out within a short period of time and can provide only preliminary fertilizer recommendations, which need further calibration through multi-year field experiments. Long-term changes in soil fertility and yield are therefore not well documented in this region. The study reported here was began in 1979 at Pingliang, Gansu, China, and is the oldest running and exclusive experiment of annual cropping systems in the Loess Plateau. The study aimed to (1) examine yield and WUE trends for wheat and corn in annual cropping systems under long-term organic and inorganic fertilization and (2) monitor long-term effects of fertilization on soil properties.

2. Materials and methods

2.1. Experimental site

A long-term permanent plot experiment has been conducted since April 1979 at the Gaoping Agronomy

Farm, Pingliang, Gansu, China. The site is in the central part of the Shizi highland plateau (35°16′N, 107°30′E, 1254 m altitude) in Pingliang. Its dark loessial soils are Calcarid Regosols (FAO/UNESCO, 1988) with an average SOM of 9.1 g kg^{-1}, corresponding to about 5.3 g kg^{-1} of soil organic carbon (SOC). Soil texture of the 0–20 cm depth is silty loam (sand 231 g kg^{-1}, silt 432 g kg^{-1}, and clay 336 g kg^{-1}) with bulk density of 1.3 t m^{-3}. Based on the analysis of soil samples taken from the experimental area in October 1978, the top 15 cm of soil had the following characteristics: pH 8.2; SOC 6.15 g kg^{-1}; total N (TN) 0.95 g kg^{-1} (Black, 1965); total P (TP) 5.7 g kg^{-1} (Murphy and Riley, 1962); available P (AP) 7.2 mg kg^{-1} (Bray and Kurtz, 1945); and available K (AK) 165 mg kg^{-1} (Shi, 1986). SOM was analyzed by the Walkley–Black (WB) procedure (Allison, 1965; Walkley and Black, 1934) and the value divided by 1.724 to estimate SOC in g kg^{-1} 1 that was transformed into SOC in t ha^{-1} with a soil bulk density of 1.3 t m^{-3}. Groundwater level was at a depth of about 80 m below soil surface in the study area.

Under average climatic conditions, the area has an aridity index (P/PET: precipitation/potential evapotranspiration) of 0.39 and receives 540 mm precipitation, about 60% of which occurs from July to September. May to June is the driest period for crop growth and light precipitation is common during December and January. The mean monthly maximum and minimum temperatures for the wheat-growing period (October–June) are 21.1 and −12.9 °C, and 24.2 and 8.1 °C for the corn-growing season (April–September). The study area is representative of a typical rain-feed farming region completely dependent on precipitation.

2.2. Experimental design and treatments

The experiment began in 1979 with a corn crop on land that had been cropped to corn during previous year. There was one crop each year. Six fertilization treatments arranged in a randomized complete block design with three replications. Corn was grown in 1979 and 1980, wheat from 1981 to 1984, corn in 1985 and 1986, wheat from 1987 to 1990, corn in 1991 and 1992, wheat from 1993 to 1998, soybean (*Glycine max* (L.) *Merr.*) in 1999, sorghum (*Sorghum bicolor* (L.) *Moench*) in 2000, and wheat in 2001 and 2002. Data for the 16 years of wheat and 6 years of corn are presented in this paper (Table 1).

Table 1

Growing season precipitation (GSP), potential evapotranspiration (PET), estimated seasonal evapotranspiration (ET) and crop water stress index (CWSI = 1 − ET/PET), drought index (DI), and year's type classified by DI values in long-term (1979–2002) dryland fertilization experiment, Pingliang, Gansu, China

Years	GSP (mm)	ET (mm)	PET (mm)	CWSI	DI	Year's type
Winter wheat						
1981	191	191	1096	0.83	1.83	Dry
1987	316	316	965	0.67	0.74	Dry
1995	206	249	1190	0.79	1.58	Dry
2001	282	282	1006	0.72	1.07	Dry
1982	170	405	966	0.58	0.08	Normal
1988	367	431	887	0.51	−0.40	Normal
1993	380	380	862	0.56	−0.08	Normal
1994	290	397	980	0.59	0.14	Normal
1996	297	369	932	0.60	0.24	Normal
1997	197	339	941	0.64	0.50	Normal
1998	270	397	899	0.56	−0.08	Normal
2002	289	433	917	0.53	−0.30	Normal
1983	412	553	804	0.31	−1.85	Wet
1984	364	502	810	0.38	−1.36	Wet
1989	267	436	746	0.42	−1.10	Wet
1990	324	472	843	0.44	−0.92	Wet
Corn						
1986	309	333	1099	0.70	1.57	Dry
1992	354	374	935	0.60	0.60	Dry
1979	380	494	1075	0.54	0.00	Normal
1991	340	444	1011	0.56	0.21	Normal
1980	553	569	1000	0.43	−1.09	Wet
1985	465	550	967	0.43	−1.08	Wet

DI is defined as $(\mathrm{CWSI}_i - \overline{\mathrm{CWSI}})/\sigma$, where CWSI_i and $\overline{\mathrm{CWSI}}$ are crop water stress index for individual and average year for 16 years wheat and 6 years corn, and σ is the standard deviation for CWSI. Dry, normal, and wet year refers to $0.5 < \mathrm{DI} < 2$, $-0.5 \leq \mathrm{DI} \leq 0.5$, and $-2 < \mathrm{DI} < -0.5$, respectively.

The experimental layout was in a 0.44 ha area. Each plot was 16.7 m × 13.3 m with a buffer zone of 1.0 m between each plot. The six treatments were (1) CK, unfertilized control, (2) N, nitrogen fertilizer annually, (3) NP, nitrogen and phosphorus (P) fertilizers annually, (4) SNP, straw (S) plus N added annually and P fertilizer added every second year, (5) M, farmyard manure added annually, and (6) MNP, M plus N and P fertilizers added annually. Urea was the N source and was broadcast to supply 90 kg N ha^{-1}. Superphosphate was the P source and broadcast to supply 30 kg P ha^{-1}. M was added at rate of 75 t ha^{-1} (wet weight). Deep plowing of approximately 23 cm was performed in July after wheat harvest or in October after corn harvest except for the years in which wheat followed corn. In those years, shallow disk tillage was done after corn harvest and wheat was seeded immediately.

Generally, the farmyard manure was a mixture of about 1:5 ratio of manure to loess soils and so its nutrient content was quite variable from year to year. The N, P, and K contents of manure taken in 1979 were 1.7, 6.8, and 28 g kg^{-1} in dry weight, indicating that manure is very low in N, and high in P and K. Although the specific amounts of nutrients added with manure each year were not determined, an application of approximately 75 t ha^{-1} (wet weight) supplied roughly 40 kg N ha^{-1}, 200 kg P ha^{-1}, and 840 kg K ha^{-1} in manure annually to crops. For SNP treatment, 3.75 t ha^{-1} of wheat straw approximately 10 cm in length was returned to the soil prior to plowing, and P fertilizer was added every 2 years. There was very little wheat straw or corn residue on the other treatments because all crops were harvested at soil surface and removed from the plots before thrashing the grain. Treatment 4 was the only treatment that had residue returned to the plots. The carbon (C) content of the straw was 42.9%, so there was approximately 1.6 t C ha^{-1} added each year to this treatment.

Winter wheat (Qingxuan 8271, Longyuan 935, and Ping 93-2) was seeded in rows 14.7 cm apart at rates of 165 kg ha^{-1} on about 20 September each year when wheat followed wheat, and in early October when wheat followed corn. Corn was seeded about 20 April each year that corn was grown and Zhongdan 2 was seeded by hand in clumps every 33 cm in rows 66.5 cm apart. About 3 weeks after seeding, corn plants were thinned to one plant per clump. Later, if tillers developed, they were removed to avoid competition. Hand weeding was done to control weeds and plant protection measures were applied when needed. Crops were harvested manually close to the ground and all harvested biomass was removed from the plots. Grain yields were determined by harvesting 20 for wheat and 40 m^2 for corn at centers of the plots. Grain samples were air-dried on concrete, threshed, and oven-dried at 70 °C to a uniform moisture level, and then weighed.

2.3. Soil sampling and analysis

Eighteen soil samples of three replicates of six treatments were collected annually during 1979–1991 and 1996–1998 at 15 days after harvest. Each sample was a composite of three random 2 cm diameter cores per plot. A 5 cm internal diameter auger was used to sample the 0–15 cm soil depth to determine the effect of fertilizations on soil nutrient contents by the methods listed earlier. The entire volume of soil was weighed and mixed thoroughly and a subsample was taken to determine dry weight. The fresh soil was mixed thoroughly, air-dried for 7 days, sieved through a 2.0-mm sieve at field moisture content, mixed, and stored in sealed plastic jars for analysis. Representative subsamples were drawn to determine TN, TP, AP, AK, and SOM by the methods listed earlier. TP, AP, and AK were not determined in the samples taken in 1996.

2.4. Seasonal evapotranspiration and crop water stress index

Monthly precipitation was measured using a rain gauge at a weather station close to the experimental farm, and potential evapotranspiration (PET) was derived simultaneously from a Class A Evaporation Pan located on the station (FAO, 1998). Generally, seasonal evapotranspiration (ET) values are calculated by summing seasonal soil water depletion amounts with the growing season precipitation (GSP) amounts. For this study, soil water amounts at seeding and harvest were not measured and so ET values could not be determined for each plot. However, ET amounts were estimated by assuming fallow efficiency (FE) values based on reported studies and authors experience (USDA, 1974; Freebairn and Glanville, 1994; Shangguan et al., 2002; Nielsen and Anderson, 2002). The FE values used were 35% for the 3-month fallow period when wheat followed wheat, 30% for the 6-month fallow period when corn followed corn, and 25% for the 9-month period when corn followed wheat. A null FE value was assumed when wheat followed corn because there was no fallow period and the corn had used most or all of the soil water available to plant. Although these FE values are somewhat arbitrary, we think they provide reasonable estimates of water used from stored soil water and allow estimates to be made of seasonal ET values. For the 24-year study, there were 16 wheat crops and 6 corn crops. Three of the wheat crops followed corn and one followed sorghum (calculations for sorghum were same as for corn), and 12 wheat crops followed wheat. Of the six corn crops, three followed corn and three followed wheat. Seasonal ET amounts were estimated by: ET = (FE × fallow season precipitation) + GSP (growing season precipitation). Growing season precipitation for wheat was October–June, and April–September for corn. Surface runoff was not considered because individual plots were surrounded with border dikes. Drainage was assumed negligible because of semi-arid conditions.

The methodology used resulted in all fertilization treatments having the same amounts of seasonal ET each year. Although in reality there were probably some differences, the amounts are believed relatively small because water was generally limiting so all treatments extracted most or all of the plant available water from the soil profile. Viets (2001) stated that under arid and semi-arid conditions fertilizers often had no effect on ET. He concluded whether fertilizers increase consumptive use not at all or only slightly, all evidence indicates that water-use efficiency can be greatly enhanced if fertilizers increase yield. Huang et al. (2003) showed little or no differences in seasonal ET values for various fertilizer treatments during a 15-year study in Shanxi Province relatively with similar soil and climatic conditions to those in our study.

The crop water stress index (CWSI) is defined as being equal to 1 − (ET/PET) (Jackson et al., 1988; Olufayo et al., 1996) and was used in this study to assess the relationship between it and crop yield. Mean seasonal CWSI values for wheat and corn each year were calculated using estimated seasonal ET and derived PET from the weather station. A CWSI value of 1 would indicate full water stress and a value of 0 would indicate no stress. At the same time, assuming that the 24 years of record closely represent the climate of the region, probability values, expressed by the relative frequency from the 24 years (1979–2002), of 75, 50, and 25% for CWSI and ET in the above four annual cropping systems, were calculated based on monthly PET records and estimated ETs, respectively. Therefore, grain yields corresponding to these probabilities can be predicted by using the functions of ET and CWSI related to yield as presented in this study.

2.5. Data analyses

Analysis of variance (ANOVA) for the randomized complete block design was done to determine main and interactive effects of treatment and year on wheat and corn yield and WUE using PROC GLM (SAS Institute, 1991), and the fertilization treatment by year mean square was used as the error term to test for treatment and year effects in the 16 years of wheat and the 6 years of corn. There were significant interactions between treatments and years, so means separation tests for 16 years wheat and 6 years corn were not conducted. One-way ANOVA was therefore made for individual years, and mean separation tests among fertilizer treatments were conducted using the least significant difference (LSD) procedure at the 0.05 probability level only when F was significant. Linear regression analyses were done using each plot data to follow trends (slopes) of grain yield and WUE, and using composite soil data from three replicate plots to assess trends of various soil parameters over the years. Linear regression analyses were also used to identify the impact of seasonal ET, and CWSI on both wheat and corn grain yield. The P-values ($P > t$) of the slopes were used to test whether the observed changes were significantly different from 1.

To analyze further treatment effects on yield in response to years with different rainfall, drought index (DI), defined as $(\mathrm{CWSI}_i - \overline{\mathrm{CWSI}})/\sigma$, where CWSI_i and $\overline{\mathrm{CWSI}}$ are crop water stress indexes for individual and average year for wheat and corn, and σ is the standard deviation for CWSI, was calculated. Xing et al. (2001) used DI to distinguish among wet $(-2 < \mathrm{DI} < -0.5)$, normal $(-0.5 \leq \mathrm{DI} \leq 0.5)$, and dry $(0.5 < \mathrm{DI} < 2)$ years.

3. Results

3.1. Crop water stress index

There were large differences in the amounts and distribution patterns of GSP, fallow period intervals, and PET and CWSI values for the various annual cropping systems (Table 1). For the 16 years of wheat, the average GSP, estimated seasonal ET, PET, and CWSI values were 289 mm, 384 mm, 929 mm, and 0.57, respectively. The coefficients of variance (CV) for ET, PET, and CWSI were 24.9, 24.5, 12.0, and 24.6% in the same respective order. The CWSI was highly negatively correlated with ET ($r = -0.98$) and positively correlated with PET ($r = 0.92$), which indicates crop water stress increases with ET decreases or PET increases. The highest CWSI value was 0.83 in 1981 when the seasonal ET was only 191 mm and the PET was 1096 mm. This was the year with the lowest amount of seasonal precipitation during the wheat growing season, and also a year when wheat was seeded immediately following corn. The lowest CWSI was 0.31 when wheat followed wheat in the wet year of 1983. During that year, seasonal ET was 553 mm and the PET was 853 mm compared to the 16 years average values of 384 and 929 mm, respectively. The calculated DI values for the 16 years of wheat ranged from −1.85 to 1.83. Four years, 1981, 1987, 1995, and 2001, had DI values ranging from 0.74 to 1.83, were classified as dry years and had an average CWSI of 0.75. Four years, 1983, 1984, 1989, and 1990, were wet with DI values ranging from −0.92 to −1.85 with an average CWSI of 0.39. The remaining eight years of wheat, 1982, 1988, 1993, 1994, 1996, 1997, 1998, and 2002, were classified as normal years with DI values ranging from −0.40 to 0.50 with an average CWSI of 0.57.

For the 6 years of corn, the GSP, ET, PET, and CWSI values were 400 mm, 461 mm, 1015 mm, and 0.54, respectively. The CVs were 23.0, 20.6, 6.1, and 18.8% in the same respective order. The CV for CWSI as a function of ET was −0.97 and it was 0.47 as a function of PET. Compared to wheat, CWSI for corn is more dependent on ET than PET, which means a decrease in ET will in serious water stress. The highest and lowest values of CWSI for corn, 0.70 and 0.43, occurred in 1986 and 1980 (and 1985), respectively, when corn followed corn. The estimated ET for 1986, the dry year, was 333 compared to 569 for 1980, the wet year (Table 1). The difference in PET values, however, differed by only 65–935 mm compared to 1000 mm. The DI values for the 6 years of corn ranged from −1.09 in 1980 to 1.57 in 1986. Two years, 1986 and 1992, were classified as dry. Two years, 1979 and 1991, were classified as normal and the remaining two years, 1980 and 1985, were classified as wet. The mean CWSI values were 0.65, 0.55, and 0.43 for the dry, normal, and wet years, respectively. The ranges of DI values were from 0.60 to 1.57 for the dry years, from −0.00 to 0.21 for the normal years, and from −1.09 to −1.08 for the wet years.

From data in Table 1, it is worthy of note that if an exceptional dry year of 1981 was not included, the estimated ET for 15 years of wheat had declined with amounts of 6.8 mm per year at the 0.04 probability level. For 6 years of corn, the estimated ET declined at amounts of 10.8 mm per year at the 0.1 probability level. This indicated that water stress gradually increased through the experimental periods.

3.2. Grain yield

Statistical analyses of each of the 16 years of wheat grain yields and 6 years of corn grain yields showed that fertilization treatments impacted grain yields significantly, but yields were still highly influenced by precipitation and its interaction with fertilization which represented by high significant effect of years in the ANOVA (Table 2). For each year, there were significant effects due to fertilization treatments using LSD (data not shown) for both wheat and corn. Yields in fertilized plots were generally higher than those in the unfertilized control plots. The highest yields in wheat and corn were always highest with the MNP, lowest for the CK, and the N was always lower than the M or others that received P fertilizer along with the N fertilizer.

The average yields of wheat for all over the 16 growing seasons were 1.29, 2.36, 3.54, 4.15, 3.87, and 4.71 t ha^{-1} for the CK, N, M, SNP, NP, and MNP treatments, respectively (Table 2). During the study period, the wheat yield declined with lapse of time except CK and MNP treatments (Table 2), indicating yield when manure was added with the chemical fertilizers could arrest the yield decline, and low yield without any nutrients added fluctuated highly at a CV of 40% among years. In the NP and SNP, the yield declines of 57 and 61 kg ha^{-1} $year^{-1}$ were significant at the 0.05 probability level, but mean yield for the SNP was 7% higher than the NP. In contrast, the N and M showed yield reductions of 77 and 81 kg ha^{-1} $year^{-1}$ that were significant at 0.01 probability level and accounted for 16–20% of the yield variability. Although these differences in yield reduction were similar, the N-only treatment had a CV of 55% that was the highest among all treatments. The M treatment CV was only 35% that compares closely

Table 2

Grain yield and water-use efficiency (WUE) changes, significance of yield and WUE change ($P > t$) over years, regression coefficient (R^2), and analysis of variation (ANOVA) in the long-term (1979–2002) dryland fertilization experiment, Pingliang, Gansu, China

Treatments (T)	Wheat								Corn							
	Grain yield				WUE				Grain yield				WUE			
	Mean (t ha^{-1})	Change (t ha^{-1} year^{-1})	$P > t$	R^2	Mean (kg m^{-3})	Change (kg ha^{-1} year^{-1})	$P > t$	R^2	Mean (t ha^{-1})	Change (t ha^{-1} year^{-1})	$P > t$	R^2	Mean (kg m^{-3})	Change (kg ha^{-1} year^{-1})	$P > t$	R^2
Control	1.29 (40%)	−0.021	0.0935	0.07	0.32 (26%)	−0.003	0.1766	0.04	2.29 (52%)	−0.185	0.0001	0.66	0.47 (36%)	−0.028	<0.0001	0.70
N	2.36 (55%)	−0.077	0.0054	0.16	0.57 (38%)	−0.014	0.0036	0.17	3.02 (45%)	−0.186	0.0006	0.54	0.63 (29%)	−0.027	0.0002	0.60
NP	3.87 (34%)	−0.057	0.0382	0.08	0.99 (18%)	−0.007	0.049	0.06	4.75 (32%)	−0.250	0.0004	0.56	1.00 (14%)	−0.030	0.0001	0.62
SNP	4.15 (30%)	−0.061	0.0234	0.11	1.08 (16%)	−0.008	0.034	0.09	4.75 (29%)	−0.160	0.005	0.40	1.02 (9%)	-0.010	0.0177	0.30
M	3.54 (35%)	−0.081	0.0014	0.20	0.91 (16%)	−0.014	<0.0001	0.33	4.39 (38%)	−0.181	0.0018	0.46	0.94 (20%)	−0.017	0.0009	0.51
NPM	4.71 (28%)	−0.050	0.1054	0.07	1.22 (12%)	−0.004	0.2298	0.03	5.61 (35%)	−0.249	0.0021	0.46	1.19 (16%)	−0.026	0.0008	0.52
LSD (0.05)	0.067	0.019	0.148	0.032												

	Grain yield			WUE			Grain yield			WUE		
ANOVA	d.f.	F	$P > F$	d.f.	F	$P > F$	d.f.	F	$P > F$	d.f.	F	$P > F$
Year (Y)	15	31.78	<0.0001	15	6.59	<0.0001	5	58.01	<0.0001	5	19.31	<0.0001
T	5	111.52	<0.0001	5	123.36	<0.0001	5	40.46	<0.0001	5	64.55	<0.0001
Y × T	75	24.94	<0.0001	75	19.73	<0.0001	25	13.74	<0.0001	25	8.43	<0.0001

$P > t$: probability value for testing slopes (change) different from 1 was calculated using each plot data by years; values in parentheses are coefficient of variance; N: nitrogen; NP: nitrogen (N) and phosphorus (P) added annually; SNP: a 3.75 Mg ha^{-1} wheat straw plus N added annually and P fertilizer added every second year; M: manures, a mixture of cattle manure with loess soil (1:5); MNP: M plus N and P fertilizers added annually.

to the CV of 28% found in the MNP that showed the greatest stability of all treatments. These results indicated that depletion of other nutrients limited wheat yield. In addition, yield differences between treatments were also influenced by how dry or wet the growing season was. For the 4 years classified as dry by the DI, the average CWSI was 0.75. The CK had an average grain yield of only 0.60 t ha^{-1} compared to 1.75 t ha^{-1} for the 4 years classified as wet having an average CWSI of 0.37. In comparison, an average yield for the N-only treatment was 0.86 t ha^{-1} for the dry years and 4.22 t ha^{-1} for the wet years. The yields of the N were still low in the normal and wet years when compared to treatments receiving fertilizer P in addition to N or when organic materials were added, but they were much greater than the CK. The MNP produced the greatest yields and averaged 3.1 t ha^{-1} for the dry years and 6.2 t ha^{-1} for the wet years. These results show the importance of adequate soil fertility even in the dry years because the average yield of wheat from the MNP was about 5 times greater than the yield of the CK for the same years.

Like wheat yields, corn yields were also significantly influenced by treatments, and the mean yields for the 6 years were 2.29, 3.02, 4.39, 4.75, 4.75, and 5.61 t ha^{-1} for the CK, N, M, SNP, NP, and MNP treatments, respectively. However, unlike wheat, the corn yield declines over that periods were highly significant for the all treatments, and the declined amounts ranged from 181 to 250 kg ha^{-1} $year^{-1}$ that were much higher than in wheat and explained 40–66% of the yield variability that were also substantially greater than those for wheat (Table 2). The yield declines among the CK and N and M did not differ, but mean yields increased by 32% for the N and 92% for the M compared to the CK. The yield decline for the NP was similar to that for the MNP. These obvious yield declines for wheat and corn were likely due to both negative change in soil fertility and amounts of precipitation. As suggested earlier, the water stress gradually increased for both crops because the estimated ETs were showing a downward. The years of 1984 for wheat and 1985 for corn were wet, and the highest yields were recorded for the MNP plots. Grain yields were 7.0 t ha^{-1} for wheat and 7.9 t ha^{-1} for corn in the MNP. These comparable yields between corn and wheat in the MNP suggest that N was limiting for corn growth. This was because that a amount of 90 kg N ha^{-1} in chemical fertilizer added annually was usually plentiful for wheat but may have been deficient for corn, particularly in years receiving normal or higher precipitation. The yield changes for dry, normal, and wet years were similar to those of wheat, but the year effect was greater for corn.

More importantly, the mean wheat yield for the 16 years in the SNP was 0.28 t ha^{-1} higher than that in the NP. There was no difference, however, for corn yield between these two treatments, and the yield decrease in the SNP was only 160 kg ha^{-1} $year^{-1}$ that was smallest in all treatments. Both wheat and corn yields from the M were consistently greater than the N. These results (Table 2) clearly showed a positive impact of annual application of organic materials such as straw and manure on these dryland crops. However, it is not clear whether the impact was due to improved water relationships resulting from increased soil organic matter or improved fertility, particularly potassium, as will be discussed later.

3.3. Water-use efficiency

The linear regression lines between grain yields and seasonal water supply were statistically significant for all treatments for both wheat (16 years) and corn (6 years) (Table 3). The linear regression slopes ranged from 1.15 to 1.27 kg m^{-3} for wheat and from 1.34 to 2.03 kg m^{-3} for corn across treatments except for the CK, in which the slopes were 0.51 and 1.15 kg m^{-3}, respectively. The slopes for the CK were low presumably because plant nutrients were often more limiting than water for crop production. The slopes for the fertilized wheat in this study were similar to the value of 1.22 kg m^{-3} reported by Musick et al. (1994) for wheat grown in the semi-arid U.S. Southern Great Plains. The slope values for the fertilized corn were closer to the values of 2.05 kg m^{-3} reported by Musick and Dusek (1980) and 1.53 kg m^{-3} by Tolk et al. (1998) in the U.S. High Plains.

WUEs, grain yield per unit of estimated seasonal ET, varied greatly between crop years and treatments, ranging from 0.12 kg m^{-3} for the unfertilized wheat in the dry year of 1995 to 1.42 kg m^{-3} for the plot fertilized with the MNP in the normal year of 1982. Similarly, the values ranged from 0.31 kg m^{-3} for the unfertilized corn in the dry year of 1986 to 1.44 kg m^{-3} for the MNP in the wet year of 1985.

Table 3
Fitted linear slopes and y-intercepts for the relationship between grain yield and seasonal ET in the long-term (1979–2002) fertilization experiment, Pingliang, Gansu, China

Treatment	Wheat					Corn				
	Slopes		y-Intercepts		R^2	Slopes		y-Intercepts		R^2
	kg m^{-3}	$P > t$	t ha^{-1}	$P > t$		kg m^{-3}	$P > t$	t ha^{-1}	$P > t$	
CK	0.0051	<0.001	−0.657	<0.001	0.85	0.0115	<0.001	−3.003	<0.001	0.79
N	0.0127	<0.001	−2.523	<0.001	0.82	0.0134	<0.001	−3.128	<0.001	0.86
NP	0.0124	<0.001	−0.884	0.045	0.74	0.0184	<0.001	−3.745	<0.001	0.94
SNP	0.0115	<0.001	−0.269	0.510	0.73	0.0139	<0.001	−1.640	0.003	0.93
M	0.0112	<0.001	−0.769	0.055	0.74	0.0145	<0.001	−2.306	<0.001	0.93
NPM	0.0125	<0.001	−0.097	0.787	0.80	0.0203	<0.001	−3.759	<0.001	0.94

$P >$ t: probability value for testing slopes and y-intercepts different from 1, and zero, respectively; R^2: linear regression coefficient. CK: unfertilized control; N: nitrogen; NP: nitrogen (N) plus phosphorus (P); SNP: a 3.75 Mg ha^{-1} wheat straw plus N added annually and P fertilizer added every second year; M: manures, a mixture of cattle manure with loess soil (1:5); MNP: M plus N and P fertilizers added annually.

Similar to the ANOVA results for grain yields, WUE values of both crops were significantly affected by treatments, years, and their interactions (Table 2). For each year, effects of fertilization were statistically significant as assessed by LSD (data not showed). Average WUE values for the 16 years of wheat were 0.32, 0.57, 0.91, 0.99, 1.08, and 1.20 kg m^{-3} for the CK, N, M, NP, SNP, and MNP treatments, respectively. For the 6 years of corn, WUEs averaged 0.47, 0.63, 0.94, 1.0, 1.02, and 1.19 kg m^{-3} for the same respective treatments. In all years, the MNP had the highest WUE value, the CK had the lowest value, and the N-only treatment value was lower than all treatments except the CK. Compared to yield data, CVs for WUE values were consistently low for all treatments, particularly for the M, NP, SNP, and MNP treatments where the CVs (Table 2) were about half of those for yield, suggesting that WUE values were relatively stable from year to year. For wheat, when both M and NP were used simultaneously, it is particularly noteworthy that lowered grain yields during dry years did not concomitant to substantially lowered WUE values. Moreover, the increased yields during normal and wet years did not find attributed to increased WUE values much compared to the dry years. Similar findings occurred for corn in the dry and wet years.

Similar to yield declines discussed earlier, wheat WUEs over years showed significant downward trends for all treatments except for the CK and MNP treatments. For corn, WUE declined linearly and the change was significant in all treatments (Table 2). The relative declines in WUE were greater for corn than for wheat.

For the SNP and MNP, mean values of WUE for four dry wheat years were 1.02 and 1.17 kg m^{-3}, and for two dry corn years were 0.95 and 1.01 kg m^{-3}, respectively. The WUE values for these two treatments were consistently higher than those for other fertilized plots, indicating that the combination of NP and organic materials resulted in the most efficient use of water. This was possibly linked to increased soil organic matter that resulted in a higher water-holding capacity in the soil profile as shown by others (Bauer and Black, 1994; Martin Diaz-Zorita et al., 1999; Merckx et al., 2001).

3.4. Crop water stress index and grain yield

As already discussed, CWSI was found strongly correlated with seasonal ET and PET with a direct relationship between ET and grain yield. Grain yields were therefore correlated with CWSI values. These relationships were statistically significant with declining regression slopes for both wheat and corn as presented in Table 4. The declining linear regression slopes ranged from 3.2 to 8.7 t ha^{-1} per unit increase in CWSI for wheat, and from 9.7 to 18.2 t ha^{-1} for corn across all treatments. Theoretically, the CWSI can vary from 0, zero stress, to 1, total stress. During the 24 years study, CWSI values ranged from 0.31 to 0.83. The downward slopes were almost double for corn as compared to wheat, suggesting that corn response to water stress is more pronounced, highly

Table 4
Fitted linear coefficients (slopes) and y-intercepts for the relationship between grain yield vs. crop water stress index (CWSI) in the long-term (1979–2002) dryland fertilization experiment, Pingliang, Gansu, China

Treatment	Wheat					Corn				
	Slopes		y-Intercepts		R^2	Slopes		y-Intercepts		R^2
	kg CWSI^{-1}	$P > t$	t ha^{-1}	$P > t$		kg CWSI^{-1}	$P > t$	t ha^{-1}	$P > t$	
CK	−3.19	<0.001	3.11	<0.001	0.79	−9.70	0.040	7.56	0.01	0.70
N	−8.04	<0.001	7.35	<0.001	0.91	−11.54	0.020	9.30	0.007	0.76
NP	−8.45	<0.001	8.47	<0.001	0.74	−16.06	0.010	13.48	0.002	0.84
SNP	−7.49	<0.001	8.43	<0.001	0.73	−12.50	0.005	11.54	0.008	0.87
M	−7.52	<0.001	7.84	<0.001	0.78	−13.07	0.006	11.49	0.001	0.87
NPM	−8.77	<0.001	9.44	<0.001	0.82	−18.20	0.001	15.50	0.006	0.88

$P > t$: probability value for testing slopes and y-intercepts different from 1, and zero, respectively; R^2: linear regression coefficient; CK: unfertilized control; N: nitrogen; NP: nitrogen (N) plus phosphorus (P); SNP: a 3.75 Mg ha^{-1} wheat straw plus N added annually and P fertilizer added every second year; M: manures, a mixture of cattle manure with loess soil (1:5); MNP: M plus N and P fertilizers added annually.

suggesting that the same magnitude of water stress can lower corn yields more than do with wheat yields.

Yields of both wheat and corn increased as CWSI values decreased, but this differed with treatments. The greatest yield increases occurred with the MNP and NP, followed closely by the SNP and N and M. The increase for the CK was constrained by lack of nutrients, so increased available water seemed not efficiently utilized. Based on the data presented in Table 4, there is a necessity of having adequate soil content of nutrients needed for adequate crop performance even when water conditions are limited. Even when the CWSI values approached 0.83 for the driest year of the wheat cropping, the observed yields were still about 2 t ha^{-1} for the adequate fertilized plots (MNP and SNP), but only 0.4, and 0.7 t ha^{-1} for the CK, and N treatments, respectively.

3.5. *Yield prediction based on probabilities of ET or CWSI*

Dryland farming is greatly impacted by seasonal precipitation variations both in amount and distribution, making risk assessment is necessary and important farm decision tool. In this study, probabilities of various seasonal CWSI and ET values for the four cropping systems were determined based on the 24 years of precipitation and PET records. Assuming that the 24 years of record closely represent the climate of the region, probabilities of different amounts of grain yields can be estimated by using the functions of ET and CWSI related to yield as presented earlier in Tables 3 and 4. The probabilities of producing various amounts of wheat and corn for different cropping sequences and different fertility treatments are calculated at the same time, respectively. For example, when wheat follows wheat, there is a 50% probability that the CWSI during the growing season will be 0.59 or greater and the estimated grain yield without fertilization area will be about 1.2 t ha^{-1} or less. In contrast, for an area of high fertility like the MNP plot, the grain yield would be expected to be about 4.5 t ha^{-1} or less. For the same treatments, there is a 75% probability that the yield of the CK would be about 1.4 t ha^{-1} or less, but a high fertility area would likely yield about 5.1 t ha^{-1} or less. The lowest wheat yields would be expected when wheat follows corn because there is essentially no fallow period for storing soil water. In that case, there is a 50% probability that the grain yield of wheat will not be more than about 1 t ha^{-1}, but even in this case, a high fertility area would be expected to yield about 3.6 t ha^{-1}. All these probabilities can be considered giving that soil fertility and adequate micronutrient supply is in the range that will not be limiting to plant growth and crop performance. This clearly shows the importance of good soil management for reducing risk in dry years. Similar trends when seasonal ET values are considered rather than CWSI values.

The CWSIs and seasonal ET amounts shown in Tables 3 and 4 were calculated using the 24 years of weather records and the fallow efficiency assumptions discussed in Section 2. If actual available soil water amounts for plants at seeding time are

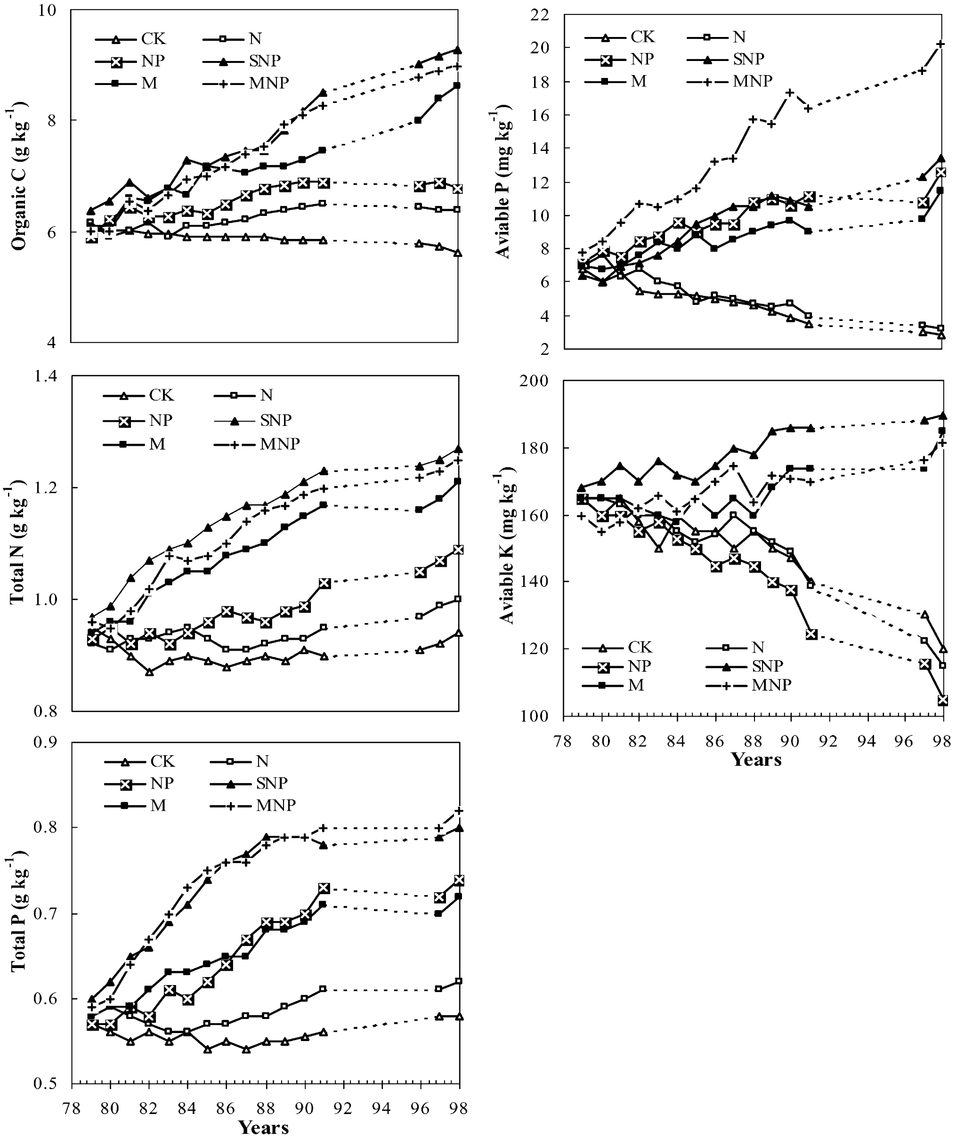

Fig. 1. Trend changes of soil fertility in long-term fertilizers experiment, Pingliang, Gansu, China. Data showed here were continuous from 1979 to 1991 and 1996 to 1998; soil samples for 1992–1995 were not analyzed (dashed lines), and total P, available P, and available K for 1996 were not determined except total N and soil organic matter.

known, they should be used along with probabilities of seasonal precipitation to possibly improve the risk assessment.

These results clearly show that wheat following wheat, corn following corn, and corn following wheat are all well-adapted systems for the Loess Plateau of China. However, the importance of high soil fertility levels cannot be over-emphasized because the risk of low yields is exceedingly high when nutrients are limited. The risk of low yields when wheat follows corn is considerably greater because of limited stored soil water, but even this sequence is fairly dependable when soil fertility and soil organic matter are maintained at a high level.

3.6. Soil properties

3.6.1. Soil organic carbon and total nitrogen

Levels of SOC and TN were greatly affected by the various treatments during the study period. The SOC at the beginning of the study in 1979 was 6.1 g C kg^{-1}, which was about 12.2 t C ha^{-1} in the 0–15 cm depth based on the measured soil bulk density of 1.30 t m^{-1}. From 1979 to 1998, SOC increased for all treatments except the CK, but the greatest increases occurred for the plots receiving organic materials (Fig. 1). The slopes of the SOC trend lines presented in Table 5 indicate that 165.0, 157.3, and 118.7 mg C kg^{-1} year^{-1} were accumulated each year for the MNP, SNP, and M treatments, respectively. The NP and N treatments also increased SOC levels but at much slower rates of 44.3 and 20.9 mg C kg^{-1} year^{-1}, respectively. SOC decreased in the CK plots at an indicated rate of 18.3 mg kg^{-1} year^{-1}. The values of 165.0, 157.3, and 118.7 mg kg^{-1} year^{-1} for the treatments including organic materials are equivalent to 0.33, 0.31, and 0.24 t C ha^{-1} year^{-1} and compare favorably to values of 0.2–0.3 t C ha^{-1} year^{-1} for fertilized maize (Lal, 2000), and the 0.31 t C ha^{-1} year^{-1} value (Jenkinson, 1991). Taking into account the inputs of C from straw in SNP treatment, it can be estimated that about 15% of the total C added were converted into SOC each year. Rasmussen and Collins (1991) conducted a literature review for semi-arid regions and reported that soil organic C levels typically increase at a rate of 10–25% of the amount of added C. Therefore, the SOC accumulation rates found in this study came in accordance with previous studies that residues can result in significant increases in SOC in dryland farming areas, especially for annual cropping systems composed of high residue crops such as wheat and corn.

Table 5

Slopes (mg kg^{-1} year^{-1}) of the linear regression vs. time for each soil property, significance of soil properties change ($P > t$ values), and R^2 of the different soil properties in a long-term dryland fertilizer (1979–2002) experiment, Pingliang, Gansu, China

Treatments		Soil properties				
		SOC	TN	TP	AP	AK
Control	Slope	−18.3	0.7	0.6	−0.20	−2.06
	P-value	<0.001	0.519	0.354	<0.001	<0.001
	R^2	0.92	0.03	0.06	0.95	0.88
N	Slope	20.9	3.6	1.9	−0.22	−2.44
	P-value	0.006	<0.001	0.013	<0.001	<0.001
	R^2	0.44	0.63	0.39	0.88	0.88
NP	Slope	44.3	8.4	10.1	0.25	−2.95
	P-value	<0.001	<0.001	<0.001	<0.001	<0.001
	R^2	0.73	0.90	0.89	0.85	0.96
SNP	Slope	157.3	14.6	10.4	0.38	1.18
	P-value	<0.001	<0.001	<0.001	<0.001	<0.001
	R^2	0.97	0.89	0.74	0.91	0.83
M	Slope	118.7	13.5	7.5	0.19	0.98
	P-value	<0.001	<0.001	<0.001	<0.001	<0.001
	R^2	0.95	0.91	0.88	0.85	0.58
MNP	Slope	165.0	15.6	11.6	0.67	1.18
	P-value	<0.001	<0.001	<0.001	<0.001	<0.001
	R^2	0.98	0.90	0.77	0.94	0.80

SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; CK: unfertilized control; N: nitrogen; NP: nitrogen (N) plus phosphorus (P); SNP: a 3.75 Mg ha^{-1} wheat straw plus N added annually and P fertilizer added every second year; M: manures, a mixture of cattle manure with loess soil (1:5); MNP: M plus N and P fertilizers added annually.

Similarly, TN contents increased over the life of the study for all treatments except the CK that remained almost stable. The slopes of the trend lines (Table 5) ranged from 3.6 mg kg^{-1} year^{-1} for the N-only treatment to 8.4, 13.5, 14.6, and 15.6 mg kg^{-1} year^{-1} −1 for the NP, M, SNP, and MNP treatments, respectively. As evidenced for SOC accumulations, the accumulations of N were higher when manure or straw was added along with NP fertilizers. This may have been partially due to a slow release of N from manure and straw, resulting in smaller losses of N as suggested by Bhandari et al. (1992). Organic fertilizers used as manure are also known to stimulate biological N-fixation (Roper and Ladha, 1995). In addition, the MNP and SNP treatments produced higher amounts of crop biomass and therefore likely had more extensive root systems that may have contributed to increased N levels. The consistent SOC and TN trends illustrate the importance of long-term additions of organic materials to soil for maintaining SOC and sustaining land productivity.

Wheat yields for the NP, MNP, and SNP treatments for different years were analyzed in relation to seasonal ET (mm) and SOM (t ha^{-1} to 15 cm depth based on soil bulk density of 1.30 t m^{-3}) to gain some insights regarding the effect of SOM. All the selected treatments received the same amount of NP fertilizer but the SOM was considerably higher in the MNP and SNP plots than in the NP plots (Fig. 1). Grain yield ($t\ ha^{-1}$) was related to ET and SOM as follows:

$$Y_w = -1.538 + 0.0124\mathrm{ET} + 0.0429\mathrm{SOM}$$
$$(R^2 = 0.77,\ n = 30,\ P < 0.001)$$

where Y_w is the grain yield of wheat, ET the mm seasonal evapotranspiration, and SOM the %SOC × 1.724. The ET coefficient ($1.24\ kg\ m^{-3}$) is similar to values by Musick et al. (1994). The SOM contribution of $42.9\ kg\ ha^{-1}$ is, however, larger than the $15.6\ kg\ ha^{-1}$ that Bauer and Black (1994) found for Typic Agriborlls in the U.S., but almost similar to the $40.7\ kg\ ha^{-1}$ reported by Martin Diaz-Zorita et al. (1999) in the semi-arid Argentine Pampas. The increased grain yield with increasing SOM in this study is perhaps a combination of increased fertility and increased soil physical properties that improved water-use efficiency which implies that a decline in SOM will result in decreased yields as a consequence of both loss of fertility and decreased soil water-holding capacity which, in turn, reduce water availability to plants.

3.6.2. Total phosphorus and available phosphorous

TP values increased significantly with lapse of time through the experimental course for all treatments except the CK, in which trend lines showed no change (Fig. 1 and Table 5). There were large differences, however, among the treatments. Great grains for TP occurred ranging from 7.5 to $11.6\ mg\ kg^{-1}$ for the treatments receiving manure or combinations of NP and organic materials, but litter increase of $1.9\ mg\ kg^{-1}$ for the N (Table 5). Slopes of the trend lines for AP (Table 5) indicated declines of about $0.20\ mg\ kg^{-1}\ year^{-1}$ for the CK and only N treatments, but increases of 0.19, 0.25, 0.38, and 0.67 for the M, NP, SNP, and MNP treatments, respectively. In 1998, the 20th year of the study, the TP in the MNP was 114% of the TP in the M, and the AP was 189% of that in the M. This shows that inputs of P with M combined with inorganic fertilizer exceeded plant needs and resulted in a substantial build-up of both soil TP and AP. As estimated earlier, about $200\ kg\ P\ ha^{-1}$ was applied annually as part of the manure.

3.6.3. Available potassium

In contrast to AP, AK showed significant yearly declines from a beginning level of $160\ mg\ kg^{-1}$ for treatments that did not receive manure or straw (Fig. 1). Trend lines for AK (Table 5) showed yearly decline rates of 2.06, 2.44, and $2.95\ mg\ kg^{-1}\ year^{-1}$ for the CK, N, and NP treatments, respectively. This is contrary to the general belief that most soils of the Loess Plateau in China are high in K and that K is a rare limiting factor (Su, 2001). However, Liu et al. (2000) and Liu and Yao (2003) also showed similar declines in northwest China, and Krauss (2001) reported AK declines in arid/semi-arid climatic conditions in West Asia and North Africa. In contrast, AK levels increased with time at rates ranging from 0.98 to $1.18\ mg\ kg^{-1}\ year^{-1}$ for plots receiving manure or straw. This demonstrates that inputs of K with organic materials resulted in a build-up of soil AK because manure or straw generally contains high amounts of K as mentioned early. This study clearly showed that high levels of production resulting from the use of inorganic N and P fertilizers and removal of aboveground biomass greatly reduced the level of AK. The extent of K deficiency in this study, if any, is not clear although yields of the SNP treatment were significantly higher than the NP treatment, particularly in the latter years when the AK levels were greatly reduced.

4. Discussion

The search for reasons to explain the yield decline in this dryland field experiment was difficult because soil properties were changing both negatively and positively depending on the fertilization treatment, but the gradual dry weather should be a major reason because grain yields are highly correlated with ET and CWSI as discussed earlier. Nonetheless, the yield declines observed may also be considered as an indication for a reduction in soil fertility and unbalanced nutrient supply resulting from annual continuous rotations of wheat and corn. More importantly, results showed that adding only N or NP fertilizers may result in a deficiency of other nutrients and a decline in soil chemical, biological, and physical properties and that addition of organic materials along with inorganic fertilizers is necessary for sustainable production of intensive dryland agriculture in the northwest China. It was hypothesized that perhaps the yields of the MNP would increase with lapse of time as SOM increased, but this could not be detected from the yield and WUE values.

Although the causes of yield decline are not separated from weather effect and soil improvement, low input of N and declining soil fertility should be of much concern. Currently recommended N levels are 145 kg N ha^{-1} for wheat and 180 kg N ha^{-1} for corn in the study region. But as mentioned earlier, about 130 kg N ha^{-1} annually that included only 90 kg N ha^{-1} from chemical fertilizer and the remaining 40 kg N ha^{-1} from manure was basically adequate for wheat but may have been deficient for corn, particularly in wet years.

Yield declines from the first 8 years to the last 8 years for wheat, and from the first 3 years to the last 3 years for corn were arbitrarily used to try to separate the contribution of climate and soil properties to the decline. Actual yield decline observed in each treatment included many factors, but most were believed due to changes in climate or soil properties. Yield declines due to climate differences were predicted based on the CWSI-yield formulas determined in this study. The results show that actual yield declines were higher than predicted in all treatments (Fig. 2), suggesting that soil fertility or other factors aside from climate differences were involved in the deterioration process. The big gaps for both wheat and corn yield declines occurred in the CK, N, and M treatments believed due to a gradual depletion and imbalance of one or more nutrients. The yield decline for the M is mainly attributed to a lower N content in manure. However, actual and predicted yield decline gaps in the SNP, MNP, and NP are of greater concern. These can be possibly attributed to N insufficiency, or added N immobilized for decomposition of straw in the case of the SNP treatment. Potassium could possibly have become limited in the NP treatment, but there is no data available to support this conjecture. The gaps for the corn are similar to those for wheat for the same treatments.

A gradual decline of available nutrients would certainly explain a decline in yields with proceeding through the experimental period, but this was inconsistent with the build up of SOM and the macronutrients N and P in the M, NP, SNP, and MNP.

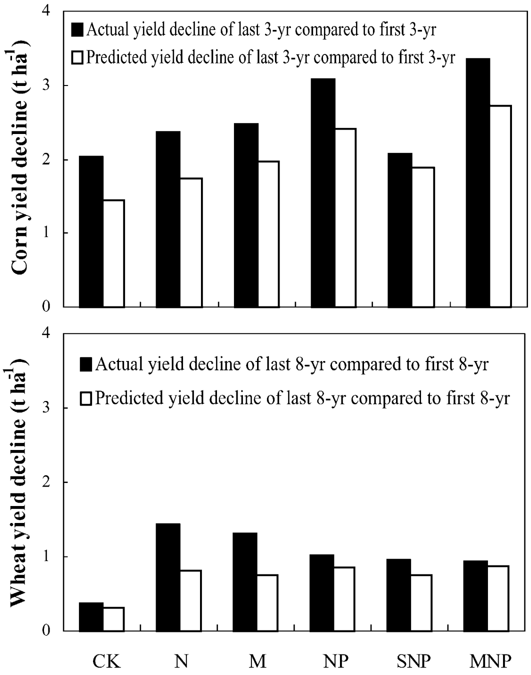

Fig. 2. Comparison between actual yield declines observed and predicted yield decline based on CWSI-yield formula showed in Table 4 for each fertilization treatment. Actual yield decline observed, which was influenced by many factors such as soil and climate changes, etc., was calculated by average yield in last 8 years minus that in first 8 years for wheat, and in last 3 years minus in first 3 years for corn, respectively. Predicted wheat yield decline, which was considered climate contribution to yield decline, was determined by yield estimated with mean CWSI of last 8 years in the formula subtract from that with mean CWSI of first 8 years, and predicted corn yield decline follow similar methods.

However, one of the most striking findings of the study is that the combination of organic and inorganic fertilization markedly enhanced the accumulation of SOC, which is considered an indicator of soil quality and enhancement in water retention. So the more precipitation can be retained in the soil and improve the sustainability of the system. SOC increased at a rate of about 0.30 t ha^{-1} $year^{-1}$ when the manure or straw was added to the soil in combination with NP fertilizers. At this rate, the SOM of the surface 15 cm of soil can be increased about 0.4% in 25 years. Soil available K decline without straw or manure in this study should also be paid great attention to intensive annual cropping system in Loess Plateau China. For long, application of K by farmers in the region is typically rare, and they are not aware of soil K deficiency when high amounts of NP fertilizer are added to improve grain yield and think the soil is usually high in K.

5. Conclusions

The objectives of this study were to follow yield and WUE trends for wheat and corn in annual cropping systems under a 24-year dryland fertilization experiment, and monitor long-term effects of fertilization on soil properties. Results showed that the addition of organic materials and inorganic fertilizers significantly enhanced grain yields, water use, and soil properties if compared to no additives or addition of only inorganic nitrogen and phosphorus. Overall, the yields and WUEs for both wheat and corn crops showed downward trends over the study period, with the exception of MNP and CK treatments for wheat. Comparatively, the decline amounts in corn are much higher than in wheat. Unlike yield, soil nutrients showed a gradual build-up of SOC, TN, and TP. But, there was a gradual depletion of soil nutrients for the CK plots and for the plots receiving only inorganic fertilizers with lapse of time. The study concludes the importance of returning straw to the soil, or adding manure in cases where the straw is removed. Particularly, returning straws to the soil should be recommended to farmer of this dryland area. This will help them towards better land-use, minimize of production input costs, improved agricultural economy, and better work abilities and also environmental soundness. These results also suggest that CO_2 emissions from agricultural soils could be decreased with improved practices and may in the long run have a significant effect on controlling greenhouse gases believed to be a major factor in global climate change. In order to meet the food demands of a rising population in this area, considerable fossil fuel inputs are required to grain production in this dryland region. But results, from this long-term fertilization experiment under cereals crop rotation system of wheat and corn, demonstrate nutrients depletion and deteriorate soil fertility as well as yield declines will be inevitable when only chemical fertilizer add or without nutrients or low amount of N. Therefore, the government should encourage farmers to manage the nutrient and soil fertility based on a balanced approach and organic combined with inorganic to increase crop productivity, agricultural sustainability, and more environmental healthiness, as it is difficult to build up soil N, P, and K once they are depleted. A legume crops such as soybean and green manure, well known as soil betterment crops, need to be contained in this or similar experiments in the future to arrest soil fertility and yield decline from a beneficial turnover effect of rotation containing legumes. Conversion from sole cereals crop rotation to cereals and leguminous plants rotation should be considered as the other effective method for increasing the water availability and maintaining high yields.

More importantly, considering this long-term experiment, researchers and farmers and government should come together in research, extension, evaluation, and dissemination of technologies to fully meet the objectives. Thorough activities like regular meetings, lectures, and field days, a feed and feedback information system between scientists and farmers should be recommended to let farmers have to be given access to the most appropriate and cost-effective technologies for their particular circumstances in nutrient and soil fertility management.

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