Sustainable Fertilizer Level for Winter Wheat in Different Rainfall Regions on the Loess Plateau of China

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Abstract: Higher fertilization on winter wheat increased the fluctuation of winter wheat yield in different rainfall years and impacted the sustainable development of winter wheat production on the Loess Plateau. Based on the long term field experimental data at Chagnwu Agricultural Station, this paper evaluated the EPIC model. And this paper also suggested a sustainable fertilizer level for winter wheat, based on the analysis of simulation results in different rainfall regions. Results of this study indicated that: 1) The EPIC model simulated both winter wheat yields and soil water among different fertilizer levels well, with the mean R value of 0.91 and 0.89 respectively. 2) With the increasing of fertilizer, the value of IRFG (Increase Rate of Grain yield by Fertilizer) and WUEG (Water Using Rfficiency for Grain yield) became higher, when soil water in deep soil was not be used excessively; however, the value of IRFG became lower, when soil water in deep soil was used excessively. 3) In the semi-humid region, fertilizer for winter wheat should be from N_4 to N_5; in the semi-humid and drought-prone region and in the semi-arid region, it should be from N_3 to N_4; in the semi-arid and drought-prone region, it should be lower than N_3.

Key Words: The loess plateau; Winter wheat; Fertilizer; EPIC model

0. Introduction

Winter wheat is a major food and feed grain crop in the world. It occupies a large area (82%) of the Loess Plateau rain-fed region of china [1]. Wheat is mostly grown under dry land conditions, therefore, its growth, development and yield depended mainly on available water and fertilizer. An increase in fertilization can stimulate deeper rooting of winter wheat, making a greater quantity of stored soil-water available to the plant, thereby reducing potential water stress and harvesting more yields [2, 3]. With the spreading and applying of fertilizer, winter wheat yield on the Loess Plateau had increased from an average of 1696 kg/hm^2 for the period of 1980–1985 to 3438 kg/hm^2 for 1986–2010. However, larger above ground biomass and transpirational leaf area, stimulated by increased fertilizer, results in greater transpiration demands and amount of water loss from the crop canopy [4]. Therefore, this increased productivity had increase soil water depletion and reduced available soil water in deep soil [5]. Excessive consumption of soil water has become the key reason for soil desiccation and yield fluctuation in high-yield land farm [6]. It is urgently need to determine a sustainable fertilizer level for this region as well as the similar region in the world.

To carry out an experiment in different regions and in a long period may found out an answer for the sustainable fertilizer level in different rainfall regions. However, it is a long-term endeavor that is both expensive and time-consuming. An alternative approach is to use computer model to simulate soil water content and crop yield under different fertilizer levels in different rainfall regions based on local situations (soil, crop and climate etcetera). Several models have been developed to simulate soil water and crop yield [7-9]. One such model is the EPIC model that simulates the soil water and crop yield simultaneously with the help of its two sub-models (growth model and hydrology model) [10]. Wang and Li [11] evaluated EPIC model for crop yield and soil water content among different cropping systems (spring maize, winter wheat and alfalfa) on the Loess Plateau. They found that EPIC model estimate soil water and crop yield well with the new database built up for the Loess Plateau.

The primary objective of this study was to determine a sustainable fertilizer level for winter wheat in different rainfall regions on the Loess Plateau. The secondary objective was to evaluate EPIC model for crop yield and soil water among different fertilizer levels, using a long-term experimental data at Changwu Agricultural Station.

1. Materials and methods

1.1 Field experiment

The field experiment was carried out at Changwu Agricultural Station from 1985 to 2000. It consisted of three fertilization treatments (table 1) with three replications in 9 plots of 10.26×6.5 m (with a buffer zone of 1m between plots). Plots were arranged as a randomized complete block design. All fertilizers were mixed and applied at sowing, and winter wheat was sown at the rate of 19.5 kg/hm^2, using a no-till disk drill with the row space of 0.25 m. For grain yield determination, the plots were harvested manually. Soil samples were taken by core break method [12] in 0.1 m layers to the depth of 3 m soil. Soil water content was measured (gravimetrically) for each soil sample by the oven-drying method [13].

Table 1 Fertilizer treatments for the winter wheat at Changwu Agricultural Station from 1985 to 2000

Treatments	N (kg/hm^2)	P_2O_5 (kg/hm^2)
CK	0	0
N	120	
NP	120	60

1.2 EPIC model

EPIC is a widely tested and adopted process-based agro-ecological model originally built to quantify the effects of soil erosion on productivity [10, 14]. Currently the model has evolved into a comprehensive model capable of simulating photosynthesis, evapo-transpiration and other major plant and soil processes [15]. The model runs on a daily time step and needs daily weather data as well as information on soil properties, specific crop growth parameters and farm management practices [16].

Based on crop parameters and other related parameters, the EPIC model can calculate the uptakes of soil water and nutrients by crop, estimate the impacts of temperature, water, nutrients (N, P and k), air and salt stresses on crop biomass accumulation and crop yield by daily step [17]. For soil water, the EPIC model contains algorithms that allow for a description of the hydrological balance at the small watershed [18]. Calculated hydrological processes include snowmelt, surface runoff, infiltration, soil water content, percolation, lateral flow, water table change, and evapo-transpiration at a daily time step, details was given out by Sharply and Williams [19] and Williams et al. [15].

1.3 Methods

1.3.1 Evaluation of the EPIC model

In this study, six statistical values were used to evaluate the model performance as followings. Root Mean Square Error (RMSE), Relative Root Mean Square Error (RRMSE), Relative Error (RE), Model Efficiency (ME), Correlation Coefficient (R), Determination Coefficient (R^2), detailed information for these equations can found in Wang and Li [11] and Ko et al. [20].

1.3.2 Calculation for WUEG and FUEG

Water-use efficiency was calculated as equation 1 [21]:

$$\mathrm{WUEG} = \frac{\mathrm{GY}}{\mathrm{ET}} \qquad (1)$$

Where WUEG was water-use efficiency for the grain yield, GY was the grain yield and ET was the cumulative evapo-transpiration over the growing season which was calculated using the water balance equation (equation 2):

$$\mathrm{ET} = (P + I + \mathrm{C}) - (R + D) - \mathrm{D}S \qquad (2)$$

Where P was precipitation, I was irrigation, C was upward flow into the root zone, R was surface runoff, and D was downward drainage out of the root zone. DS was the change of available soil water in winter wheat field, which was calculated by equation 3.

$$\mathrm{DS} = \mathrm{ASP} - \mathrm{ASH} \qquad (3)$$

Where ASP was available soil water in 0-7 m soil when winter wheat was sown, ASH was available soil water in 0-7 m soil when winter wheat was harvested.

Since the experimental field was terraced, and located in the Loess Plateau, surface runoff was ignored. The groundwater table was very low, so the upward flow into the root zone and the downward drainage out of the root zone were negligible. Consequently, the soil water balance equation was reduced to equation 4.

$$\mathrm{ET} = \mathrm{P} - (\mathrm{ASP} - \mathrm{ASH}) \qquad (4)$$

Increase rate of grain yield for different fertilizer level was calculated by equation 5, 6 and 7.

$$\mathrm{IRFG} = \frac{\mathrm{DG}}{\mathrm{DN}} \qquad (5)$$

$$\mathrm{DG} = \mathrm{GN}_{m} - \mathrm{GN}_{m-1},\ 6 \geq m \geq 1 \qquad (6)$$

$$\mathrm{DN} = \mathrm{N}_{m} - \mathrm{N}_{m-1},\ 6 \geq m \geq 1 \qquad (7)$$

Where DG was increased yield from fertilizer level N_{m-1} to fertilizer N_m, DN was increased fertilizer of

N from fertilizer level N_{m-1} to fertilizer N_m; GN_m was grain yield of winter wheat under fertilizer level of N_m, GN_{m-1} was grain yield of winter wheat under fertilizer level of N_{m-1}; N_m was amount of N in fertilizer level of N_m, N_{m-1} was amount of N in fertilizer level of N_{m-1}.

1.3.3 Description of the development of dry soil layer

In order to compare the development of dry soil layer among different fertilizer levels and different regions, parameters as following were considered in this study. 1) SMDDT Period, a Period in which soil water decreased and dry soil layers thickened continuously; 2) SSMD Year, a year in which steady dry soil layer built; 3) Max DSL, Maximum depth of dry soil layer occurred; 4) SSL Range, a depth range in which soil water content was stable after steady dry soil layer built; 5) SMC Range, a depth range in which soil water content was unstable after steady dry soil layer built; 6) SWU Depth, Maximum depth in which soil water was used; 7) DSLD Range, a depth range in which dry Soil Layers occurred; 8) SD Speed, dry soil layer building speed.

Parameters of SMDDT Period and SSMD Year described the time needed to building dry soil layer; Max DSL and DSLD Range presented the distribution depth of dry soil layer; SSL Range and SMC Range told us the stability of dry soil layer; SD speed indicated the building speed of dry soil layer.

1.3.4 Statistical method

Analysis of variance (ANOVA) was used to test the difference in grain yield, water-use efficiency and fertilizer-use efficiency among different treatments and different regions. Mean comparisons were made by the LSD (the least significant difference) method with $P < 0.05$ and $P<0.01$ respectively. The analyses were conducted using the SPSS program [22].

1.4 Design for the simulation

Mean annual rainfall at Luochuan and Changwu were 622 mm and 584 mm respectively; at Yan'an and Shouyang were 535 mm and 455 mm respectively. In this study, Luochuan and Yan'an were selected as the representation of semi-humid region and semi-arid region respectively; Changwu as the representation of semi-humid and drought-prone region; Shouyang as the semi-arid and drought-prone region on the Loess Plateau. Fertilizer treatments for each regions consisted of 7 fertilizer treatments as table 2.

Table 2 Fertilizer treatments for winter wheat in different rainfall regions on the Loess Plateau of China

Fertilizer	Luochuan (kg/hm^2)		Changwu (kg/hm^2)		Yan'an (kg/hm^2)		Shouyang (kg/hm^2)	
level	N	P	N	P	N	P	N	P
N_0	0	0	0	0	0	0	0	0
N_1	90	45	90	45	90	45	90	45
N_2	120	60	120	60	120	60	120	60
N_3	150	75	150	75	150	75	150	75
N_4	180	90	180	90	180	90	180	90
N_5	210	105	210	105	210	105	210	105
N_6	240	120	240	120	240	120	240	120

First, we input soil data, crop data, meteorological data and management data into the EPIC model for each selected region. Second we evaluate the EPIC model using the long-term experimental data at Changwu Agricultural Station. Third we run the EPIC model from 1961 to 2000, and out put the simulated winter wheat yield year by year and soil water day by day. At last we analyzed the fluctuation of crop yield and soil water during a long period, based on the simulation results. Considering the sustainable using of soil water and production of winter wheat, we pointed out a sustainable fertilizer level for different rainfall regions on the Loess Plateau.

2 Results

2.1Evaluation results of the EPIC model

2.1.1 Winter wheat yield

Measured mean annual winter wheat yield were 1.40, 2.28 and 2.98 t/hm^2; Simulated mean annual winter yield were 1.46, 2.30 and 2.77 t/hm^2 for CK, N and NP respectively. Table 3 showed that simulated winter wheat yield were slightly higher for CK and N treatment and were slightly lower for NP treatment, comparing with measured yield. Paired-t test demonstrated the difference between simulated and measured winter wheat yield for each treatment was not significant with P=0.05. EPIC model simulated mean annual winter wheat yield well, with the R vale of 0.91, 0.93 and 0.89 for CK, N and NP respectively.

Tab. 3 Comparison of simulated and measured winter wheat yield for different fertilizer levels at Changwu Agricultural Station

	Annual mean yield(t/hm^2)		RE	R	RMSE	RRMSE
	Measured	Simulated	(%)		(t/hm^2)	(%)
CK	1.40	1.46	4.4	0.91**	0.41	29
N	2.28	2.30	1.2	0.93**	0.53	23
NP	2.98	2.77	-7.1	0.89**	0.86	28

Little difference between ME and R^2 value (figure 1) presented the variance of winter wheat yield in different years was simulated well by EPIC model with the RRMSE value of 29 %, 23 % and 28 % respectively (table 3). Comparing with that for NP, winter wheat yield was simulated better with a higher value of R^2 for CK and N (figure 1).

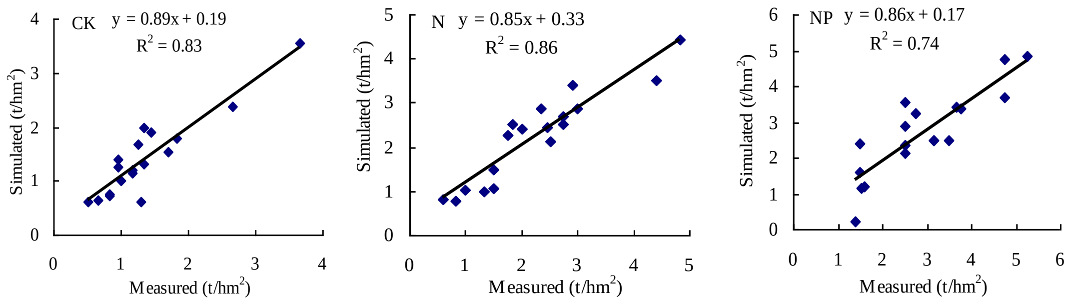

Fig.1 Comparison of simulated and measured winter wheat yield for different fertilizer levels at Changwu Agricultural Station

2.1.2 Soil water

Measured mean available soil water in 0-3 m soil were 120, 96 and 85mm for CK, N and NP respectively; simulated mean value were 113, 97 and 92 mm respectively. The value of mean available soil water estimated by EPIC model was slightly higher than that of simulated for N and NP, and slightly lower for CK (table 4). Paired-t test indicated the difference between simulated and measured available soil water in 0-2 m soil for each treatment was not significant with the P value of 0.05. EPIC model estimated mean annual available soil water well, with the R vale of 0.90, 0.96 and 0.81 for CK, N and NP respectively.

Tab. 4 Comparison of simulated and measured available soil water in 0-3m soil for different fertilizer levels at Changwu Agricultural Station

	Annual available soil water (mm)		RE	R	RMSE	RRMSE
	Measured	Simulated	(%)		(mm)	(%)
CK	120	113	-5.8	0.90	22.38	19
N	96	97	1.0	0.96	16.44	17
NP	85	92	8.2	0.81	18.37	23

Little difference between ME and R^2 value (figure 2) showed the variance of available soil water in different years for each fertilizer level was simulated well by EPIC model with the RRMSE value of 19%, 17% and 23% respectively (table 4). Comparing with that for NP, available soil water in 0-3 m soil was simulated better with a higher value of R^2 for CK and N (figure 2).

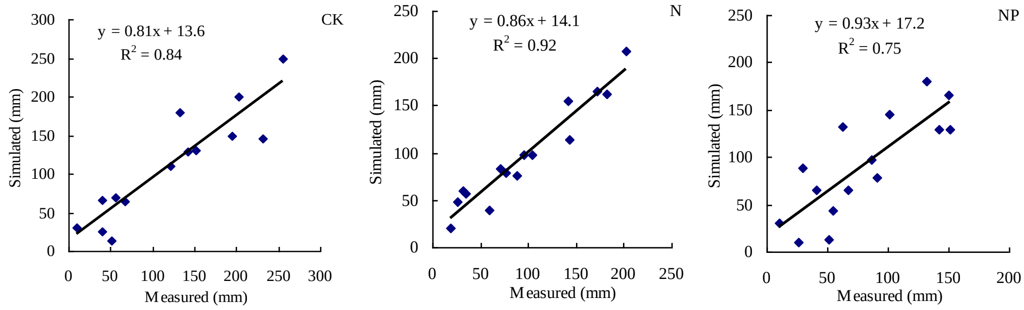

Fig. 2 Comparison of simulated and measured annual mean available soil water in 0-3m soil for different fertilizer levels at Changwu Agricultural Station

2.2 Simulation results of winter wheat yield and soil water

2.2.1 Winter wheat yield

The difference of mean annual winter wheat yield was highly significant (P=0.01) in different rainfall regions (table 5). Mean value of annual winter wheat yield were 2.77, 2.70, 1.97 and 1.00 t/hm^2, with standard deviation of 1.52, 1.59, 1.40 and 0.84 t/hm^2. With the increase amount of precipitation, more winter wheat yield was founded at Luochuan and Changwu.

The difference of winter wheat yield among N_0, N_1, N_2, and N_3 fertilizer level was significant (table 5). The difference of winter wheat yield between N_5 and N_6 fertilizer level was not significant. Before N3 fertilizer level, winter wheat yield increased with the increase amount of fertilizer application; after N4 fertilizer level, the impact of fertilizer on winter wheat was different in different rainfall regions (table 5).

Table 5 Difference of winter wheat yield among different fertilizer levels in different rainfall regions on the Loess

Plateau of China

Fertilizer level	Luochuan	Changwu	Yan’an	Shouyang
N_0	1.20 a	1.44 a	0.96 a	0.53 a
N_1	1.83 b	1.94 b	1.36 b	0.69 b
N_2	2.53 c	2.45 c	1.76 c	0.90 c
N_3	3.00 d	2.87 d	2.08 d	1.07 d
N_4	3.44 e	3.24 e	2.43 e	1.22 de
N_5	3.59 f	3.38 ef	2.54 ef	1.25 ef
N_6	3.78 f	3.56 f	2.67 f	1.33 f

The correlation between winter wheat yield and precipitation over growing season was highly significant (P=0.01); and it was found significant (P=0.05) between winter wheat yield and precipitation over growing year (table 6). Table 6 showed that winter wheat yield was highly significant correlated with the available soil water in 0-3 m soil before sowing. This indicated that available soil water in 0-3 m soil before sowing and precipitation in growth period was the key impact factors to influence winter wheat yield on the Loess Plateau. Since the correlation index between winter wheat yield and available soil water in 0-7 m soil before sowing was significant (P=0.05), soil water in 0-7 m soil should be considered when to determine a sustainable fertilizer level for the winter wheat on the Loess Plateau.

Table 6 Winter wheat yield, precipitation and available soil water in different rainfall regions on the Loess Plateau of China

Fainfall region	Mean annual yield (t/hm^2)	Correlation index between yield and			
		Precipitation over (mm)		Available soil water before sowing in (mm)	
		Growing season	Growing year	0-3 m soil	0-7 m soil
Luochuan	2.77 a	0.66**	0.42*	0. 81**	0.57*
Changwu	2.70 b	0.63**	0.38*	0. 78**	0.60*
YanAn	1.97 c	0.80**	0.43*	0. 80**	0.70*
Shouyang	1.00 d	0.51**	0.34*	0. 79**	0.68*

Growing season of winter wheat was from September to June; growing year was from September to August.

2.2.2 Soil water

2.2.2.1 Available soil water in 0-7 m soil

With the increase amount of precipitation, more available soil water was founded in winter wheat field at luochuan and Changwu. Mean value of monthly available soil water in 0-7 m soil were 740, 558, 512 and 412 mm, with standard deviation of 102, 140, 137 and 99 mm, at luochuan, Changwu, Yan’an and Shouyang respectively. Considering among different rainfall regions, precipitation was one of the key factors to impact the available soil water in winter wheat field.

The value of DS in different rainfall regions was different significantly. Table 7 showed more soil water decreased at Changwu and Yan’an, with the mean DS value of 113 and 114mm respectively. Comparing with that in Shouyang, more precipitation and less DS value was founded at Changwu and Yan’an. Analysis of the winter wheat growth indicated the leaf area index (LAI) of winter wheat at Shouyang was significantly less than that at Changwu and Yan’an. It means that less trans-evaporation at Shouyang, comparing with that at Changwu and Yan’an. A highest value of LAI and precipitation was found at Luochuan. Though higher trans-evaporation (indicated by the high value of LAI) took place and may be decreased soil water, more precipitation added more water to the soil and decreased the DS value at Luochuan.

Comparing with N_1, N_2 and N_3 fertilizer level, a higher value of DS was founded in N_4, N_5 and N_6 fertilizer level. This indicated that more soil water decreased under the higher fertilizer level in winter wheat field on the Loess Plateau.

Table 7 Mean value of decreased available soil water from winter wheat was sowed to winter wheat was harvested

	N_0	N_1	N_2	N_3	N_4	N_5	N_6
Luochuan (mm)	61	71	78	82	91	93	94
Changwu (mm)	85	99	109	116	125	126	130
Yan'an (mm)	86	100	111	111	127	128	131
Shouyang (mm)	76	86	93	99	104	106	111

2.2.2.2 Development of dry soil layer in 0-7m soil

Fertilizer and rainfall were two key factors to effect the development of dry soil layer in winter wheat field on the Loess Plateau of China. Table 5 indicated that higher fertilizer level increased the winter wheat yield; at the same time increase the SD speed and the thickness of dry soil layer (table 8). Highest value of SD speed and highest SSL range were founded in N6 fertilizer level at four selected regions. With the increase amount of fertilizer applied to winter wheat, the value of SD and Max DSL increased (table 8). With the increasing amount of fertilizer level, more soil water was depleted and soil desiccation degree increased. More rainfall resulted in lower SD speed and SSL range in Luochuan and Changwu, comparing with that in Shouyang and Yan'an.

Table.8 Statistical value of soil water distribution in 0-7 m soil in winter wheat field under different fertilizer levels in different rainfall regions on the Loess Plateau

Rainfall region	treat ment	SMDDT Period	SSMD Year	Max DSL (m)	DSLD Range (m)	SSL Range (m)	SMC Range (m)	SD Speed (m/a)	SWU Depth (m)
Luochuan	N_0	1960～1968	1968	3	1～3	2～3	0～1	0.38	2～3
	N_1	1960～1968	1969	3	1～3	2～3	0～2	0.33	2～3
	N_2	1960～1967	1971	4	1～4	2～4	0～2	0.36	>4
	N_3	1960～1967	1970	4	1～4	2～4	0～2	0.4	>4
	N_4	1960～1969	1971	5	1～5	2～5	0～2	0.42	>5
	N_5	1960～1968	1971	5	1～5	2～5	0～2	0.45	>5
	N_6	1960～1968	1970	5	1～5	2～5	0～1	0.5	>5
Changwu	N_0	1960～1968	1969	3	1～3	2～3	0～2	0.33	2～3
	N_1	1960～1967	1968	3	1～3	2～3	0～2	0.38	2～3
	N_2	1960～1967	1971	4	1～4	2～4	0～2	0.36	>4
	N_3	1960～1968	1970	4	1～4	2～4	0～2	0.4	>4
	N_4	1960～1966	1972	5	1～5	2～5	0～2	0.45	>5
	N_5	1960～1966	1971	5	1～5	2～5	0～1	0.45	>5
	N_6	1960～1966	1970	5	1～5	2～5	0～1	0.5	>5
Yan'an	N_0	1960～1966	1967	3	1～3	2～3	0～2	0.43	2～3
	N_1	1960～1966	1967	3	1～3	2～3	0～2	0.43	2～3
	N_2	1960～1966	1969	4	1～4	2～4	0～2	0.44	>4
	N_3	1960～1965	1968	4	1～4	2～4	0～2	0.5	>5
	N_4	1960～1965	1969	5	1～5	2～5	0～2	0.56	>5
	N_5	1960～1965	1968	5	1～5	2～5	0～1	0.63	>5

	N_6	1960～1965	1968	5	1～5	2～5	0～2	0.63	>5
Shouyang	N_0	1960～1966	1966	3	1～3	2～3	0～1	0.5	2～3
	N_1	1960～1965	1966	3	1～3	2～3	0～2	0.5	2～3
	N_2	1960～1965	1968	4	1～4	2～4	0～2	0.5	>4
	N_3	1960～1965	1967	4	1～4	2～4	0～2	0.57	>5
	N_4	1960～1965	1968	5	1～5	2～5	0～2	0.63	>5
	N_5	1960～1965	1967	5	1～5	2～5	0～2	0.71	>5
	N_6	1960～1965	1967	5	1～5	2～5	0～1	0.71	>5

2.2.3 WUEG and IRFG

Table 9 showed the value of WUEG increased, with increase application of fertilizer to winter wheat field. Mean value of WUEG among different regions for N_0, N_1, N_3, N_2, N_4, N_5 and N_6 fertilizer level were 2.76, 3.80, 4.83, 5.57, 6.32, 6.59 and 6.92 t/(hm^2 mm) respectively. Among different rainfall regions, WUEG increased with the increasing of annual rainfall at Luochuan, Changwu, Yan'an and Shouyang (table 9).

From N_1 to N_4 fertilizer level, the value of IRFG increased with the increase of fertilizer applied to the winter wheat field (table 9). From N_4 to N_5 fertilizer level, a contrary changing trend was founded for the value of IRFG. The value of IRFG became lower, when the fertilizer was more than 180 kg/hm^2. Among different rainfall regions, the value of IRFG was the highest at Luochuan, it was the second at Changwu, and the lowest value was at Shouyang (table 9). Annual rainfall was one of the key factors to influence fertilizer using efficiency on the Loess Plateau of China.

Table 9 Comparison of WUEG among different fertilizer levels and different rainfall regions on the Loess Plateau of China

Rainfall regions	items	N_0	N_1	N_2	N_3	N_4	N_5	N_6
Luochuan	WUEG (t/(hm^2 mm))	3.14	4.73	6.37	7.22	8.38	8.76	9.19
	IRFG (t/(hm^2 kg))	--	0.70	1.11	1.20	1.24	1.14	1.08
Changwu	WUEG (t/(hm^2 mm))	3.53	4.61	5.63	6.50	7.24	7.55	7.93
	IRFG (t/(hm^2 kg))	--	0.56	0.84	0.95	1.00	0.92	0.88
Yan'an	WUEG (t/(hm^2 mm))	2.67	3.66	4.58	5.33	6.07	6.35	6.66
	IRFG (t/(hm^2 kg))	--	0.43	0.67	0.75	0.82	0.75	0.71
Shouyang	WUEG(t/(hm^2 mm))	1.71	2.20	2.73	3.23	3.58	3.70	3.91
	IRFG (t/(hm^2 kg))	--	0.18	0.30	0.36	0.38	0.34	0.33

3 Discussions

3.1 Fertilizer, dry soil layer and rainfall

Nitrogen fertilizer stimulated the winter wheat root to develop into the deeper soil, and using more deep soil water [23]. However, once dry soil layer built in deep soil, it was difficult to recover on the Loess Plateau [24]. Therefore, the use of high fertilization rates has been found to increase the thickness of dry soil layer [25] and resulted the fluctuation of winter wheat yield in different rainfall years on the Loess Plateau [6]. This paper showed that more soil water in deep soil depleted and the SD speed (soil desiccation speed) increased, with the increasing application of fertilizer for winter wheat.

The amount of annual rainfall impacted the develop speed of dry soil layers in different regions. Comparing with Luochuan and Changwu, higher value of SD speed was founded at Yan'an and Shouyang.

3.2 Fertilizer, WUEG and IRFG

The increasing use of deep soil water during critical crop development stages increased the value of WUEG (water use efficiency for grain yield) for high fertilizer winter wheat [5]. Various study found that water and fertilizer related and impacted each other [26-27]. This study indicated higher value of IRFG and WUEG in higher fertilizer level field, when no dry soil layer build in deep soil; while lower IRFG value in higher fertilizer level field, when dry soil layers had been built in deep soil.

3.3 Sustainable fertilizer level for winter wheat field

At Luochuan, the difference of winter wheat yield for N_5 and N_6 fertilizer level was not significant; there was not significant difference between winter wheat yield for N_5 and N_6 at Changwu and Yan'an, and also for N_4 and N_5 fertilizer level was not significant; At Shouyang, there was no significant difference between winter wheat yield for N_5 and N_6, N_4 and N_5, N_3 and N_4. These statistical results indicated that fertilizer level should not be higher than N_5, N_4, N_4 and N_3, at Luochuan, Changwu, Yan'an and Shouyang respectively.

When dry soil layers develop to more than 5 m depth, it will become more difficult to recover [28] on the Loess Plateau of China. Table 8 showed that the depth of dry soil layer was deeper than 5m for N_4, N_5 and N_6 at Luochuan and Changwu; for N_3, N_4, N_5 and N_6 at Yan'an and Shouyang. Therefore, considering on the recovery of dry soil layers, fertilizer level for winter wheat should not be higher than N_4 at Luochuan and Shouyan; and it should not be higher than N_3 at Yan'an and Shouyang. Table 9 indicated the value of IRFG became lower when the fertilizer level was higher than N_4 for winter wheat field, either at Luochuan and Changwu or at Yan'an and Shouyang. This result indicated the fertilizer using efficiency decreased when fertilizer level was higher than N_4 for winter wheat field.

Considering on the sustainable production of winter wheat and the sustainable using of soil water, the fertilizer level for the different rainfall regions on the Loess Plateau should as followed. 1) In the semi-humid region (Luochuan), fertilizer level should be from N_4 to N_5; 2) in the semi-humid and drought-prone region (Changwu) and in the semi-arid region (Yan'an), it should be from N_3 to N_4; 3) in the semi-arid and drought-prone region (Shouyang), it should be lower than N_3.

4 Conclusions

The EPIC model simulated the variance of winter wheat yield among different fertilizer levels well, with the mean R value of 0.91; and it estimated mean annual available soil water well, with the mean R vale of 0.89, on the Loess Plateau of China.

Soil desiccation speed increased with the increasing of fertilizer applied to winter wheat field; and it decreased with the increasing of annual rainfall in different rainfall regions on the Loess Plateau of China.

With the increase application of fertilizer, the value of IRFG and WUEG became higher, when soil water in deep soil was not be used excessively; the value of IRFG became lower, when soil water in deep soil was used excessively.

Sustainable fertilizer levels for winter wheat on the Loess Plateau were different for different rainfall regions. 1) In the semi-humid region (Luochuan), it should be from N_4 to N_5; 2) in the semi-humid and drought-prone region (Changwu) and in the semi-arid region (Yan'an), it should be from N_3 to N_4; 3) in the semi-arid and drought-prone region (Shouyang), it should be lower than N_3.

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