Water Use Efficiency and Eco-Niche-Yield Prediction of Rainfed Wheat in China's Loess Plateau

Qianying Pan
Foreign Languages College, Anhui Polytechnic University
Wuhu 241000, Anhui, China
Food Crop Science Department, Cotton Research Institute
Shanxi Agriculture Science Academy, Yuncheng 044000, Shanxi, China

Xinglai Pan (Corresponding author) & Foyou Yang
Food Crop Science Department, Cotton Research Institute
Shanxi Agriculture Science Academy, Yuncheng 044000, Shanxi, China
Tel: 86-359-216-5899 E-mail: pxlwbig@126.com

Xuefei Wen & Fei Pei
Foreign Languages College, Anhui Polytechnic University
Wuhu 241000, Anhui, China

Sirui Pan, Tianyuan Pan & Yinhong Shi
Food Crop Science Department, Cotton Research Institute
Shanxi Agriculture Science Academy, Yuncheng 044000, Shanxi, China

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Abstract

A twenty-three year study of water use efficiency and related parameters on a 0.44 ha. rainfed wheat field resulted in the following new data: Yield averaged 2135.13±σ841.08 (minimum 810~maximum 3923 kgha^{-1}); Water Use Efficiency(Y/ET) = 6.23±2.06 (2.84~10.21 kgha^{-1}mm^{-1}); Precipitation during the fallow period = 301.7±107.6 (129.8~498.2 mm); Water storage in 5~210 cm soil layer at about sowing = 328.41±78.72 (177.3~453.8 mm); Soil evaporation during the fallow period = 195±60.14 (72.6~347.1 mm); Precipitation storage = 106.7±66.3 (-22~234.2 mm); Precipitation storage efficiency % = 32.61±16.22 (-16.9~53.3); Precipitation during the growing season = 234.6±57.39 (139.8~400.6 mm); Precipitation in May = 54.91±38.69 (8.8~142.1 mm); Water storage in 5~210 cm soil layer just after harvest averaged 220.35±46.15 (123.3~335.3 mm); EvapoTranspiration during the growing season averaged 342.6±84.29 (220.5~586.6 mm). WUE benchmarks were proposed for the first time to the region as follows: ≥5 kgha^{-1}mm^{-1} for very poor and poor years; ≥9 kgha^{-1}mm^{-1} for medium and good years; and ≥12 kgha^{-1}mm^{-1} for excellent years. A novel model using precipitation and soil parameters before sowing was well correlated with yields. Using the first digital clustered five eco-niche-yield types and based on the model predictions, management recommendations beforehand may help growers to approach the eco-niche-yield potentials with rational input.

Keywords: Draught stress, Soil moisture, Precipitation storage, Evapotranspiration, Decision supporting, Modeling

1. Introduction

Located on the first platform at the southeast end of the Loess Plateau, Yuncheng prefecture is believed to be the cradle of Chinese traditional agriculture civilization. Winter wheat-summer fallow has been the predominant rainfed staple food crop production system in this region for hundreds of years. Farmers in this region are considered as the best practitioners of careful and intensive cultivation that has the goal of maximum water infiltration and storage in drylands. Even though farmer's input level increasing steadily year by year, rainfed wheat yield varies significantly year from year. Draught stress is, of course, the greatest constraint on wheat yield in this region. According to the records of eight carved stone inscriptions (see two of them in Fig.1) and the disaster relief diary of Timothy Richard (Soothill, 1924), in 1877 an unprecedented deadly drought disaster occurred in this region. There was not even a drop of rainfall between March of 1877 and March (Chinese lunar calendar) of 1878. Although the drought was unusually severe, it is an indication of the potential rainfall variability in the region.

Farmers now grow about 200,000 ha rainfed wheat in this region. Farmer experience and scientific research indicate that the loess soils are deep and able to store large amounts of water and that the dryland winter-wheat crop relies heavily on use of water stored in the deep subsoil. But a number of important research questions remain for the region: a) How efficient is the soil storage of precipitation? b) How much water infiltrates into and stored in the soil, and how much is lost by evaporation from the soil and transpiration from the plant? c) How much of the available water stored in the soil is converted into wheat yield? And d) How can we predict the eco-niche-yield before sowing and/or any following key management stages, for successful planning and practicing?

We conducted a case study from 1982 to 2009 in a trial land at Beizhang village, Linyi County, Yuncheng prefecture, Shanxi province, China, with a number of goals. This report focuses on the water use efficiency and on the prediction of eco-niche-yield of rainfed wheat grown using the practices of local farmers. We try to develop a method that integrates modeling technic and local indigenous knowledge, to help farmers for input-efficient and high and stable yield in varying draught stress year-types.

2. Materials and Methods

2.1 Location

BeiZhang village is located at the cross section of about 34°42' N and 110°37' E, with the altitude about 530 m. The trial land was 220 m in length (E-W) and 20 m in width (S-N) = 4400 m^2 = 0.44 ha (approximately 6.6 Chinese *mu*) with a slope less than 2‰, and runoff occurring only when the rainfall intensity was greater than 100 mm hr^{-1}. The land has been cultivated for hundreds years and is a typical dryland. The soil is a light loess loam ("yuan huang lu tu" in Chinese). Soil profile bulk density ranged from 1.23 to 1.43 g cm^{-3} (Fig.2).

2.2 Weather

According to the Linyi county weather observatory station (55 km away from the site) records, the mean annual precipitation was 496.5 mm, with the maximum 849.8 mm in 1958 and the minimum 323.1 mm in 1977, with 52% of the precipitation occurring in July, August and September; the mean annual pan evaporation was 2116.9 mm; the mean annual sunshine hour was 2362 hr; the mean annual temperature was 13.5°C, with the maximum 42.8°C occurring in June, 1966, and the lowest -17°C occurring in January, 1967; with 224 mean annual frost free days.

2.3 Wheat cultivars

The wheat cultivars used for the experiment were Beijing 12057 from 1981 to 1989, Yun 78-2 from 1990 to 1994, Jinmai 47 from 1995 to 2005, and Linhan 536 from 2006 to 2009.

2.4 Management practices

In consideration of the protracted nature of the follow-up investigation, and the progress of the regional wheat productivity, we let the owner of the trial land do whatever the management practices as the farmers usually do in this region each crop year. Let him go with the flow. Planting dates occurred from the end of September to early October. Harvesting dates occurred from the end of May to early June.

2.5 Measurements

Precipitation was recorded from July 1978 to July 2010 using a rain gauge installed approximately 200 m away from the experimental field.

Soil gravimetric water content was measured in 10 cm increments from 5 cm to 100 cm depth and in 20 cm increments from 100 cm to 200 cm depth using gravimetric procedures. Soils were sampled a few days before planting in late September and just after harvest in early June of the following year.

Gravimetric water content (%) ≡ Gwc = ((weight of wet soil subsample - weight of dry soil subsample)/weight of dry soil subsample)*100.

Soil water storage content was determined to a depth of 210 cm because the wheat root system usually reaches to about such a depth and contributed much to the grain yield (Pan, 1982; Li, 1983; Pan et al. 1997a).

Storage **W**ater in 5~210 cm soil layer at **S**owing ≡ $\mathbf{S_{SW210}}$.

Storage **W**ater in 5~210 cm soil layer just after **H**arvest ≡ $\mathbf{H_{SW210}}$.

$\mathbf{S_{SW210}}$ **or** $\mathbf{H_{SW210}}$ = Sum of **Gwc***bulk density (gcm^{-3})*depth of sampling (cm) / 0.1 $gcm^{-2}mm^{-1}$

Soil Evaporation during the fallow period ≡ $\mathbf{E_F = P_F - (S_{SW210} - H_{SW210})_{CalendarYear}}$

Precipitation **S**torage during fallow ≡ $\mathbf{PS}_{mm} = (\mathbf{S_{SW210} - H_{SW210}})_{\mathbf{CalendarYear}}$

$\mathbf{PSE_{\%} = PS_{mm}/P_F}*100$

Evapo**T**ranspiration during growing season ≡ **ET** = $(\mathbf{S_{SW210} - H_{SW210}})_{\mathbf{CropYear}} + \mathbf{P_G}$

(Where $\mathbf{P_F}$ = **P**recipitation during the **F**allow period, $\mathbf{P_G}$ = **P**recipitation during the **G**rowing season)

Grain was harvested using either a traditional reaping and threshing procedure, or with a commercial combine. Grain was air dried in the sun to about 13% water content and weighed on a digital scale accurate to 500 g.

Yield = Total grain weight/0.44 ha.

Water Use Efficiency = Yield/ ET = $\mathbf{WUE}_{Y/ET}$ ≡ **WUE**

Strictly speaking, water use is the water used and transpired by the wheat itself during the growing season. We used soil and precipitation information to estimate ET, which includes both the water lost through evaporation from the soil and transpiration loss. Although this calculation includes the water that the wheat crop cannot access and thus underestimates the real water use efficiency, it provides a means to compare water use in different years.

3. Results

The measured data and calculated parameters with depth and/or with time are presented in Figures 2, 3, 4, 5 and Table 1.

1). About 52% of the annual precipitation occurred during the fallow period and the peak of annual precipitation was between July and September (Fig.2).

2). The average soil bulk density was 1.33 g cm^{-3}, with a slightly denser illuviation layer at about 50 cm depth (Fig.3), typical of region's soils (Soils in Yuncheng prefecture, 1986).

Using the data presented in Figures 3, 4, and 5, S_{SW210} and H_{SW210} were calculated. Although there was a large variation with depth and time, the average soil gravimetric water content (10~200 cm) for the 23 crop years was 13.7% at sowing, and 8.8 % after harvest. Rainfall greater than 100 mm in May could increase the soil gravimetric water content considerably to a depth of 60 cm such as in 2009 (142.1 mm), 1999 (106.6 mm), 1998 (140.5 mm) and 1983 (134.1 mm) (P_M in Table 1, arrowed years in Fig. 5). The critical growth stages of flowering, grain set, grain filling and maturing are all in the May, all need both rainfall and sunshine. Too much rain with low amounts of sunshine in May, not only reduces the yield through less evapotranspiration and photosynthesis, but also increases the swelling of roots in upper soils (Pan, 1982).

3). PS_{mm} ranged from -22 mm to 234.2 mm. $PSE_{\%}$ ranged from -16.9% to 53.2%. $PSE_{\%}$ Averaged 32.61%. It confirmed again that about 60% of precipitation during fallow period was lost through soil evaporation (runoff was estimated to be small during this time because the trial land is 30 cm high ridged at the 4 side edges). How to have the precious P_F got into the soil as faster and deeper as possible is a big challenge to the modern technology. Building "Nutrient Columns" (Pan et al., 1997b) and drilling "Soil Holes" (Xiao et al. 1986) demonstrated dramatic benefits but need mechanization. Increasing soil organic matter would certainly help because of its positive effects on soil structure and keeping soils more open to accept and maintain rainfall (Fred Magdoff, 1993).

4). WUE ranged from 2.84 to 10.21 $kgha^{-1}mm^{-1}$, averaged 6.23 kg ha^{-1} mm^{-1}. This is about 3.6 $kgha^{-1}mm^{-1}$ lower than the 9.8 $kgha^{-1}mm^{-1}$ estimated by Sadras's (2006) for the China loess plateau. The skewness (0.415) is also larger than Sadras's (0.16). There are probably two reasons for the differences: a) yields in this study were from a 0.44 ha grower's field rather than small experimental plots; and b) we used the actual measured ET instead of the reference ET.

Comparison between years indicates that while WUE was positively correlated with yields, higher yield did not always correspond to higher WUE. For example, in 1984 the yield was 1658 $kgha^{-1}$ and the WUE was 3.29, while the 2009 yield was only 960 $kgha^{-1}$, but with WUE was higher, 4.21; 1989 yielded 3263 $kgha^{-1}$ with WUE of 9.39, 2004 yielded 3563 $kgha^{-1}$ with lower WUE 6.07. It proves that WUE can also be used as a criterion for evaluating the degree of farmer skill at rainfed wheat production management. Here we set the benchmarking WUE as: ≥5 $kgha^{-1}mm^{-1}$ for poor eco-niche-yield years, ≥9 $kgha^{-1}mm^{-1}$ for medium and good eco-niche-yield years, and ≥12 $kgha^{-1}mm^{-1}$ for very good or excellent eco-niche-yield years, which will be useful for the region to guide and evaluate its wheat production in the coming years.

5). Using cluster analysis we identified five eco-niche-yield types as indicated in Fig.6. Yield less than 1500 kg ha^{-1} is a *very bad year*. Yield in between 1500~2250 $kgha^{-1}$ is a *bad year*. Yield in between 2250~3000 $kgha^{-1}$ is an *average or medium year*. Yield in between 3000~3750 $kgha^{-1}$ is a *good year*. Yield greater than 3750 $kgha^{-1}$ is a *very good or excellent year*.

6). Fig.7 shows calculated grain yield as a function of the P_F, S_{SW210}, E_F, and $PS_{mm.}$ We can use this model to predict the eco-niche-yield before sowing, it does have paramount importance for management planning and recommendations. For example, a) for a predicted poor eco-niche-yield, application of 100 $kgha^{-1}$ urea (or an equal amount of N from another source) would be suggested before sowing, if the precipitation from sowing to mid December is much better than the normal year, additional 35 $kgha^{-1}$ urea top dressing in late December with the traditional tillage practices will be suggested; b) for a good eco-niche-yield, 200 $kgha^{-1}$ urea (or equal N) before sowing will be suggested, if the precipitation from sowing to mid December is much better than the normal year, additional 50 $kgha^{-1}$ urea top dressing will be suggested again; c) for a predicted excellent eco-niche-yield, 230~250 $kgha^{-1}$ urea before sowing will be suggested. We are to be able in this way to reduce the growers input risks, because years' experiences have taught us that: too much nitrogen fertilizer in a bad year resulted haying-off (Angus et al., 2001) that not only wastes the fertilizers but also gives much less yield than less nitrogen fertilizer; while conservative application of nitrogen fertilizer in good years could not reach the attainable yield that of course lost the good chances.

4. Discussions

4.1 Twenty-three years' WUE and Three WUE benchmarks

Twenty-three years WUE ranged from 2.84 to 10.21 $kgha^{-1}mm^{-1}$, averaged 6.23 $kgha^{-1}mm^{-1}$. The three WUE benchmarks are: ≥5 $kgha^{-1}mm^{-1}$ for poor years; ≥9 $kgha^{-1}mm^{-1}$ for medium and good years; and ≥12 $kgha^{-1}mm^{-1}$ for the excellent years.

It is obvious that WUE depends on both the amount and the distribution of the rainfall itself. However, advisers can always make sure that if the WUE is smaller than the benchmark WUE in a given eco-niche-yield type, there must be some other constraint problems in addition to the given weather conditions. The results and the other new data may also serve as a case to be compared studies of other regions global rainfed agriculture.

4.2 Five eco-niche-yield year types and model prediction before sowing

Rainfed wheat yield varies year from year, even though farmer's input level increasing steadily year by year. A good forecast of the eco-niche-yield year type before sowing, is an important decision-making basis both for better output with rational input and for environment-friendship. Combining with the experienced-farmers' perceives, the experimental equation based on 23 year's data of the case study, had done very well for the past 3 years' eco-niche-yield predictions, for the ~200,000 ha rainfed wheat in YunCheng prefecture. Before sowing in 2006, the prototype of this model gave the expected yield for 2007, we changed the calculated yield value into a fuzzy value = average year type, combining with several experienced farmers' perceives, we predicted that 2007 would most likely be an average year to a bad year. And Yuncheng prefecture did have bad wheat yield in 2007. Then we incorporated all the data of the trial land already obtained in 2007 into the model, and had a revised model for prediction of 2008 as an average to good year type. Again the prefecture did have an average wheat yield in 2008. So we did for 2009 as a very bad year type, it did prove the fact once again. We are confident with this "exact-fuzzy-accurate" step-wise predicting method.

Optimizing wheat production management within a small geo-ecological region of similar land attributes and soil properties is our base aim. However, optimum productivity is a continually moving target that requires step-wise moving methodologies because of the variations in climatic as well as technical and social features. We thought that 3 to 5 trial lands within an eco-niche range might give a much more accurate model. Therefore improved follow-up investigations have begun in 2009 for continually improvement of the model.

Anyway, varieties of tolerance and lower level of fertilizer input for very bad and bad years, varieties of stable yield and average level of fertilizer input for average and good years, varieties of higher yield potential and higher level of fertilizer input for good and excellent years, are all the best countermeasures to reach the highest water use efficiency. We hope more accurate model predictions can help farmers take a few simple precautions to increase their input/output ratios of rainfed wheat in a given eco-niche.

4.3 Logos for better crop production management

Drought disasters have a long history in China and elsewhere, Draughts cause more grain loss in China than any other type of natural disaster, and draught stress is still the biggest challenge in the 21^{st} century. Keeping this in mind, we sum up the logos for successful crop production in Chinese as shown in Fig.8.

We try to end this paper by translating the logos as following:

Crop production is to exploit and utilize all the available resources, take measures to increase the system's potential and decrease any possible losses, finally to sustainably obtain higher and healthier outcomes with less input and less environment-degradation.

Crop production rules should be: Observe the weather, Observe the soils, and Observe the living things; Knowing one's available production techniques and means, knowing their attributes and properties, and knowing the consequences of your practices; Ponder prudently, pre-plan carefully, and get everything ready and take measures beforehand; Use both general and local knowledge and your own sense to evaluate and re-evaluate your methods before and after the season; Following the appropriateness of the season to harmonize soils by focusing on manures and water; Utilize and/or adapt to your resources and carefully manage the crop/environment complex; Integrate perceptions of the agronomic truths while developing one's skillfulness; Pass down the farming arts (knowing, predicting, and operating) from generation to generation including your own innovations and sense and local indigenous knowledge.

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Table 1. Yield, Precipitation, Soil Water (5~210 cm depth), Evaporation, EvapoTranspiration, and Water Use Efficiency at BeiZhang village, 1983-2009

Crop year	Yield $kgha^{-1}$	[a]WUE $kgha^{-1}mm^{-1}$	[b]P_F mm	[c]S_{SW210} mm	[d]E_F mm	[e]PS mm	[f]PSE %	[g]P_G mm	[h]P_M mm	[i]H_{SW210} mm	[j]ET mm
1982~1983	1553	5.03	498.2	372.8	347.1	151.1	30.3	271.0	134.1	335.3	308.5
1983~1984	1658	3.29	423.8	453.8	305.3	118.5	28.0	298.8	51.5	248.5	504.1
1984~1985	2010	4.92	430.6	442.8	236.4	194.2	45.1	210.7	105	245.2	408.3
1985~1986	2625	7.17	389.3	430.8	203.6	185.7	47.7	204.0	35.8	268.8	366.0
1986~1987	900	3.99	129.8	246.8	151.8	-22	-16.9	228.4	52	249.6	225.6
1987~1988	2408	7.33	267.0	306.3	210.3	56.7	21.2	256.9	54.1	234.6	328.6
1988~1989	3263	9.39	409.7	392.6	251.7	158	38.6	183.2	24.7	228.3	347.5
1989~1990	1635	4.12	268.8	315.3	181.8	87	32.4	307.5	64.9	225.9	396.9
1990~1991	1748	5.32	207.8	287.3	146.4	614	29.6	273.9	44.3	232.9	328.3
1991~1992	1478	6.70	178.5	282.4	129.1	49.4	27.7	168.5	43.7	230.3	220.5
1993~1994	2858	10.01	261.2	301.1	237.7	23.5	9.0	230.9	3.4	246.6	285.4
1996~1997	3923	10.21	430.0	391.7	239.2	190.8	44.4	196.2	12.2	203.8	384.2
1998~1999	2325	5.71	368.3	434.9	179.6	188.7	51.2	225.2	106.6	253.0	407.1
1999~2000	3023	8.31	241.4	343.6	150.8	90.6	37.5	172.0	13.2	151.7	363.9
2000~2001	810	2.84	155.1	234.2	72.6	82.6	53.2	223.5	8.8	172.4	285.3
2001~2002	1718	5.45	275.0	292.4	155.1	120	43.6	233.1	93.7	210.6	314.9
2002~2003	2625	7.53	271.7	319.6	162.7	109	40.1	237.2	61	208.0	348.8
2003~2004	3563	6.07	486.8	442.2	252.6	234.2	48.1	400.6	61	256.3	586.6
2004~2005	1395	5.07	264.1	320.1	200.2	63.9	24.2	139.8	34.1	184.9	275.0
2005~2006	2085	6.26	201.9	227.8	159.0	42.9	21.3	275.7	65.2	170.6	332.9
2006~2007	1875	5.90	272.7	259.7	183.7	89	32.7	181.2	19.1	123.3	317.6
2007~2008	2670	8.41	322.1	278.0	167.4	154.7	48.0	192.3	32.5	152.9	317.4
2008~2009	960	4.21	185.2	177.3	160.8	24.4	13.2	285.6	142.1	234.6	228.3
n	23	23	23	23	23	23	23	23	23	23	23
mean	2135.13	6.23	301.70	328.41	195.00	106.7	32.61	234.62	54.913	220.35	342.68
s.d.	841.08	2.06	107.67	78.72	60.14	66.3	16.22	57.39	38.692	46.15	84.29
s.e.	175.38	0.43	22.45	16.41	12.54	13.83	3.38	11.97	8.0679	9.62	17.58
c.v.	0.3939	0.3305	0.3569	0.2397	0.3084	0.621	0.4974	0.2446	0.7046	0.2095	0.2460
skewness	0.3723	0.4157	0.3291	0.1308	0.6547	0.115	-1.3291	0.9727	0.8553	-0.0132	1.1479
kurtosis	-0.4511	-0.5353	-0.9688	-0.8943	1.0108	-0.73	2.6148	1.8031	0.1097	0.8871	2.3345

Note: [a]WUE = **W**ater **U**se **E**fficiency (Yield/ET) [b]P_F = **P**recipitation during the **F**allow period

[c]S_{SW210} = **W**ater **S**torage in 5-210cm soil layer at about planting

[d]E_F = Soil **E**vaporation during the **F**allow period [e]PS = **P**recipitation **S**torage during fallow period

[f]PSE = **P**recipitation **S**torage **E**fficiency

[g]P_G = **P**recipitation during the **G**rowing season [h]P_M= **P**recipitation in **M**ay

[i]H_{SW210}= **W**ater Storage in 5-210cm **S**oil layer just after **H**arvest

[j]ET = **E**vapo-**T**ranspiration during the growing season

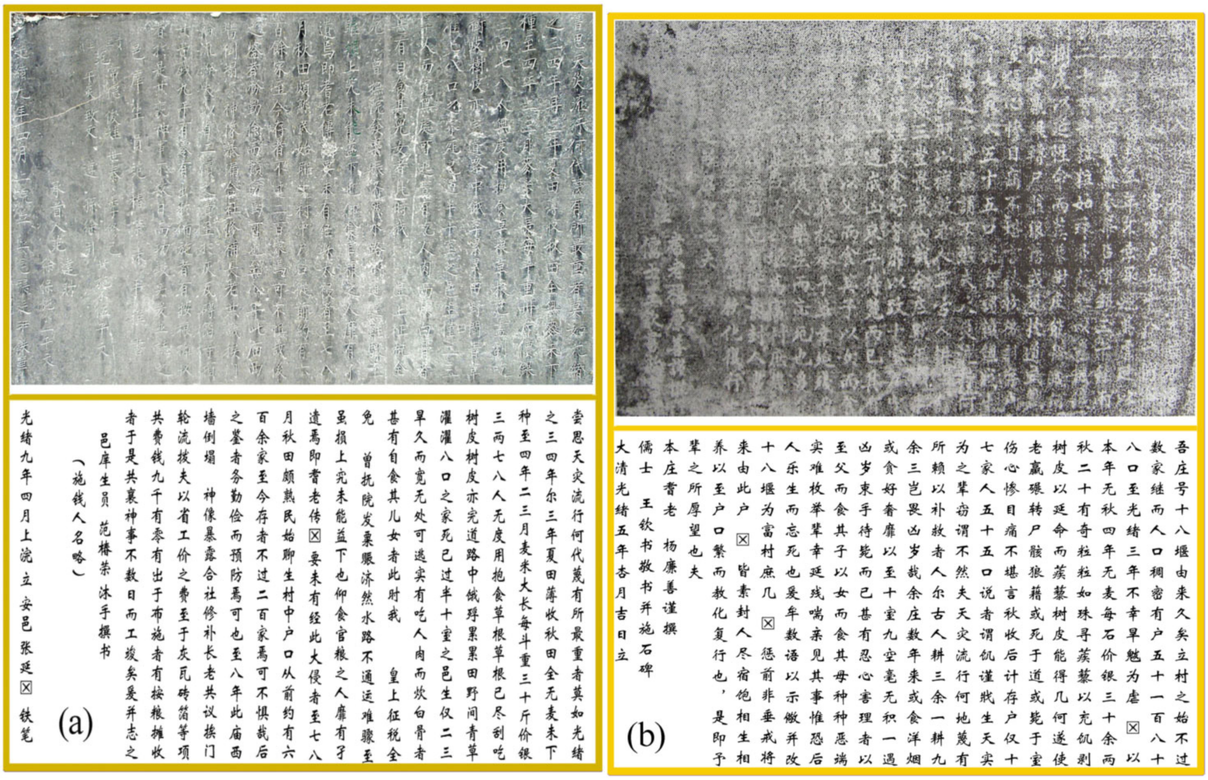

Figure 1. Village stone inscriptions carved following the famine of 1877~1878

(a) Ducun village, WanRong County, 1883 (more than 400 out of the total 600 households in the village died during the famine)

(b) Shibayan village, WenXi county, 1879 (133 out of the total 188 persons in the village died during the famine)

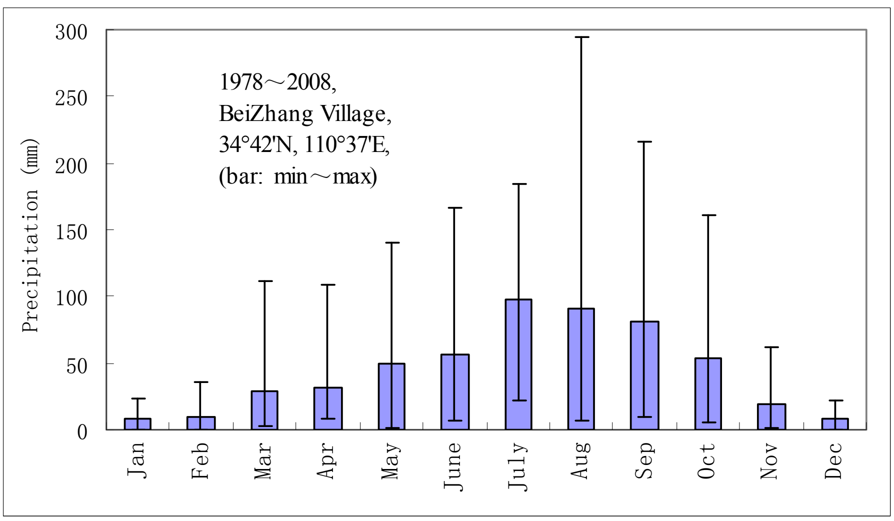

Figure 2. Average (column), maximum and minimum (line with bars) monthly precipitation during 1978 to 2008 at the study site

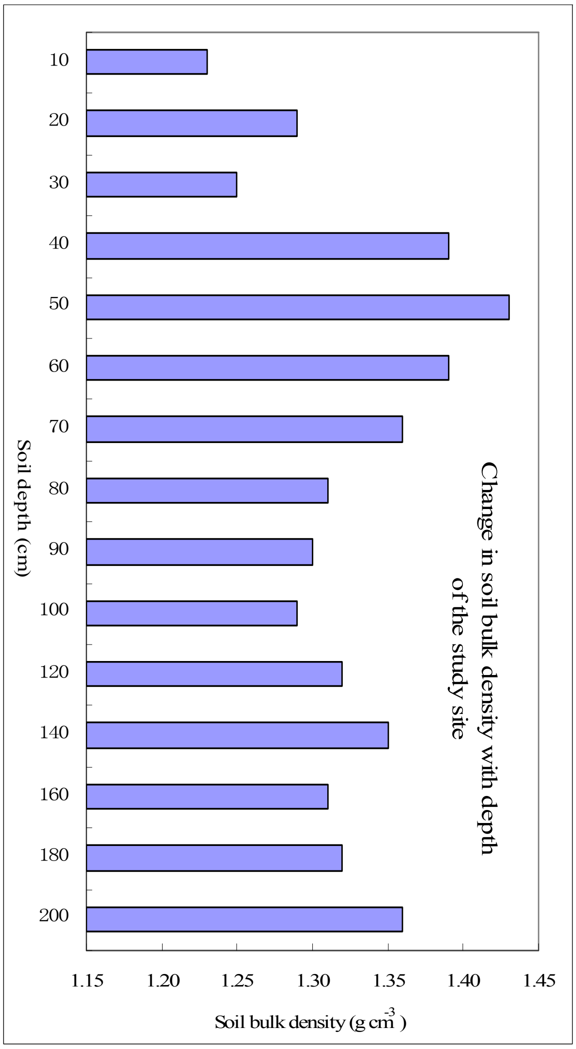

Figure 3. Change in soil bulk density with depth of the trial land

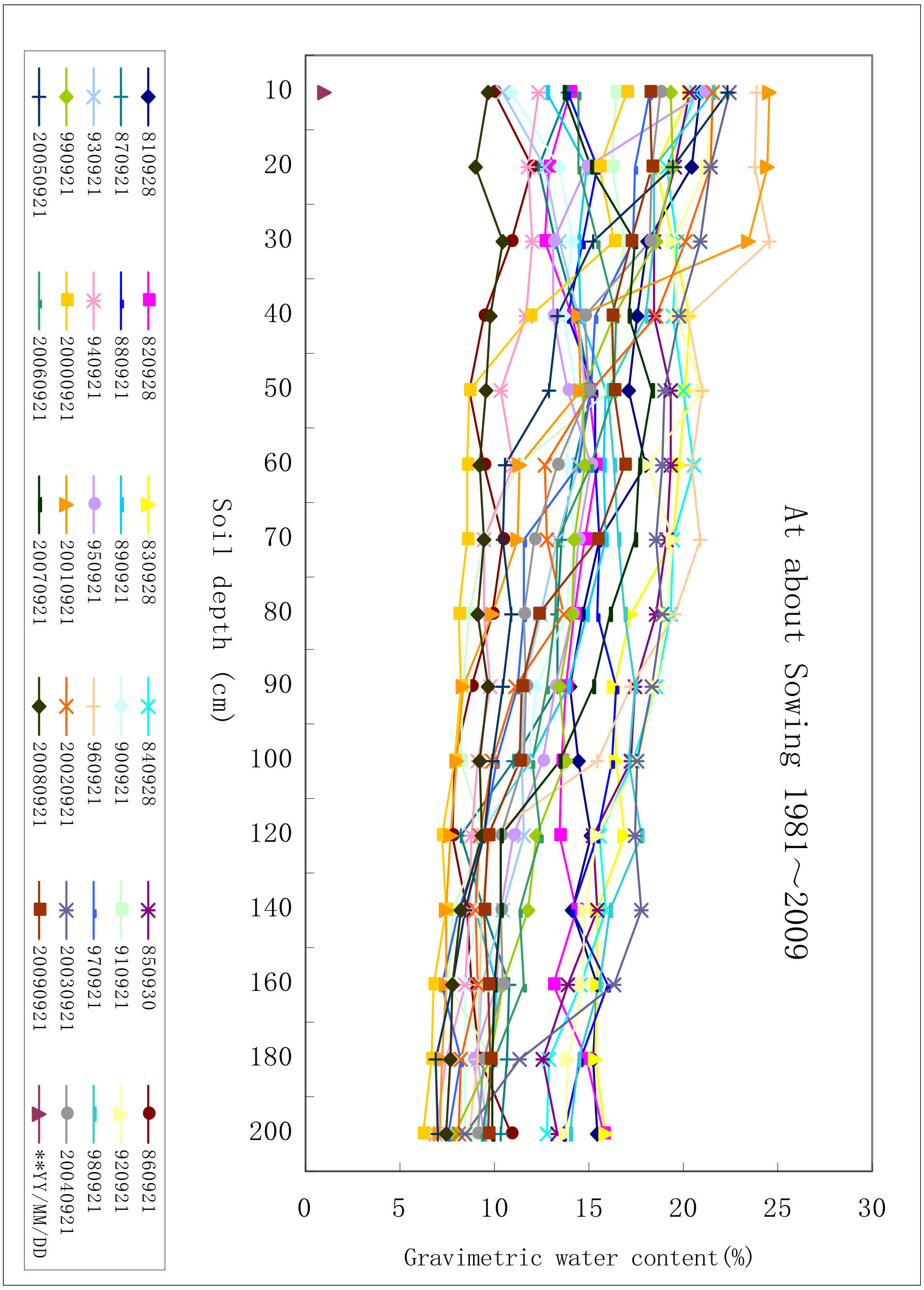

Figure 4. Change in gravimetric water content (%) with depth of the trial land at about sowing (1983~2009)

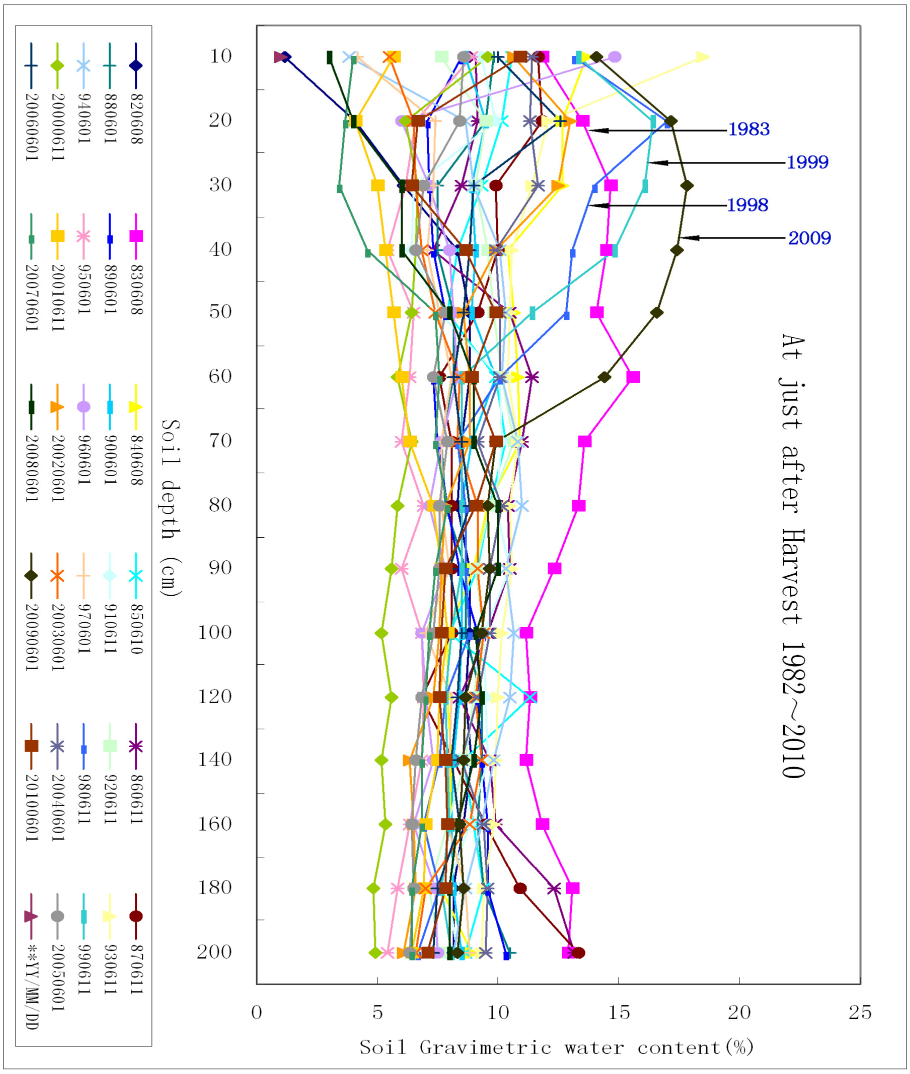

Figure 5. Change in gravimetric water content (%) with depth of the trial land at just after harvest (1983~2009)

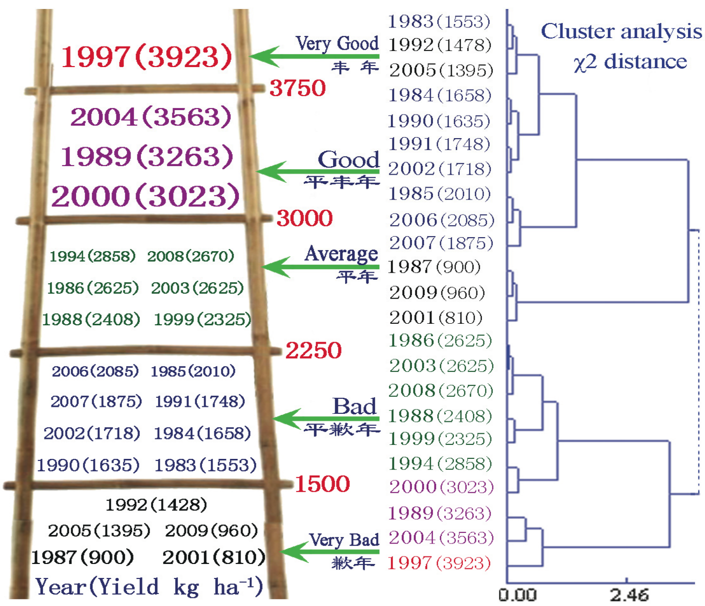

Figure 6. Cluster analysis and classification of the eco-niche-yields

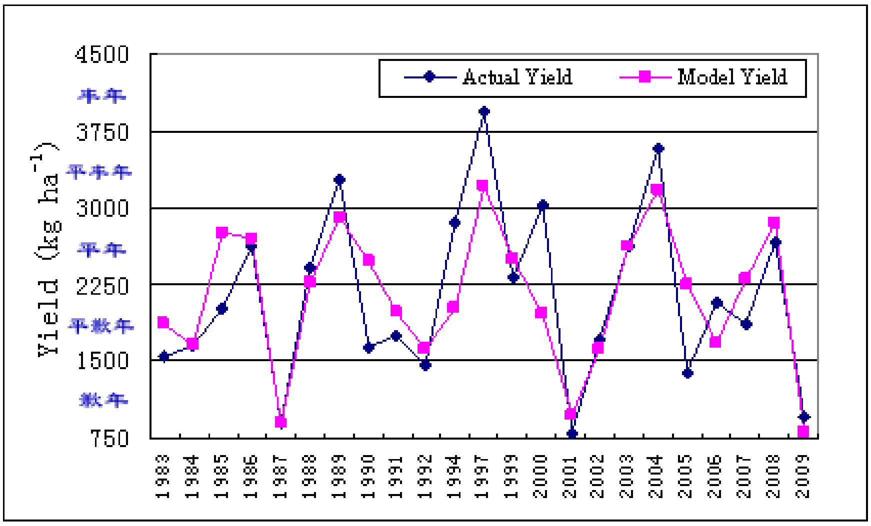

Figure 7. Yields estimated by regression equation model and measured yields

$$\mathbf{Y} = 43.04\mathbf{S}_{\mathbf{SW210}} + 41.02\mathbf{P}_{\mathbf{F}}^{2} - 0.1301\mathbf{S}_{\mathbf{SW210}}^{2} + 0.1295\mathbf{P}_{\mathbf{F}}{*}\mathbf{S}_{\mathbf{SW210}} - 41.09\mathbf{P}_{\mathbf{F}}{*}\mathbf{E}_{\mathbf{F}} - 41.06\mathbf{P}_{\mathbf{F}}{*}\mathbf{PS} - 4681.7$$

$(R = 0.8148, R^2 = 0.6639, p = 0.0036)$

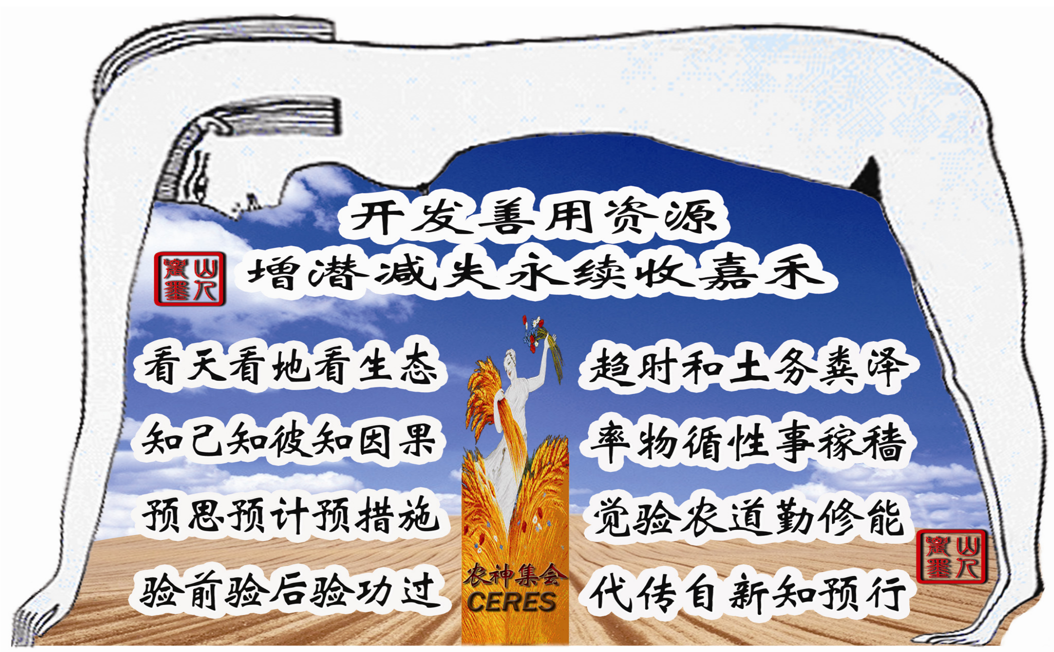

Figure 8. Chinese characters for crop production logos