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An Approach to Predict Land Production Potential for Irrigated and Rainfed Winter Wheat in Pinan County, China

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Summary

The methodology described in this paper provides land evaluators and land use planners with a tool to predict the land production potential for irrigated and rainfed winter wheat in Pinan County (China), taking into account environmental conditions and management practices of the local farmers.

The correlation between predicted yields and actual reported yields by local farmers suggests a close resemblance between the simulated production environment and the situation in which the farmers operate.

Incorporation in the model of quantified effects of limiting factors on crop performance allows estimation of inputs necessary to improve the actual yield level.

1 Introduction

Agriculture may be defined as the human activity that produces useful organic material by means of plants and animals, with the sun as source of energy. The minimum number of resources is small: sun, water, land and labor (Van Keulen & Wolf 1986).

The surface of arable land in China is only 7% of the world's total, but it has to feed about 22% of the world's population. This implies that if the increasing non-farming population has to be sustained, the yield has to be much higher than its subsistence level. In this context, quantitative information on land production potential and on the major constraints to agricultural production are extremely important for further land use planning and development.

Climate and soil are fixed properties for a given region and, in combination with management, characterize the land quality level. For a given land quality level, the production potential can be considered as fixed for a fairly long period of time, and may, therefore, be calculated with reasonable accuracy (Van Keulen & Wolf 1986).

This paper presents an approach to predict the land production potential for irrigated and rainfed winter wheat in Pinan County, China, taking into account the environmental conditions and management practices of different farmers operating in this area. The methodology considers three hierarchically ordered production situations.

The simplest or highest hierarchical production situation is a winter wheat cropping system in which the production

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Climatic characteristics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean max. temperature (°C)	2.8	5.1	12.6	20.2	27.5	32.3	31.8	30.4	26.4	20.4	11.9	4.7
Mean min. temperature (°C)	-8.6	-6.5	0	7.1	13.3	18.8	22.0	21.2	14.9	8.3	0.6	-5.8
Mean relative humidity (%)	60	61	59	57	55	58	78	81	73	70	69	65
n (sunshine hours)	6.0	6.3	7.4	7.5	9.2	9.6	7.6	7.5	7.6	7.3	6.3	5.8
Wind speed (m/s)	2.1	2.4	2.9	3.3	2.9	2.5	2.0	1.6	1.8	2.1	2.2	2.0
Rainfall (mm)	3.3	6.7	7.4	36.1	29.0	58.4	198.6	153.6	49.6	29.0	14.6	3.7

Tab. 1: *Climatic data for Pinan County (recorded over the period 1957–1989).*

potential depends on one land quality only; the other qualities and land characteristics are assumed not to be limiting the production potential. As temperature and radiation regimes during the crop cycle cannot normally be manipulated, these factors determine, within the physiological capacity of the winter wheat, the "potential production" level in the area. The yield of winter wheat is then only determined by its physiological characteristics, the prevailing level of irradiance and the temperature regime (RPP: Radiation-thermal Production Potential).

If one or more of the land characteristics or qualities that were supposed nonconstraining in the potential production situation is sub-optimal in the considered crop system, the production that can be realized falls short of the radiation-thermal production potential. It is then necessary to identify the limiting quality or characteristic and to quantify its effect on crop performance.

In addition to availability of water (especially limiting in the rainfed crop system), soil nitrogen status, level of management, land slope and effective soil depth were found to be the main factors limiting winter wheat production in the area (Jiang 1989).

For the second hierarchical production situation, the influence of moisture availability on transpiration and crop production is taken into account (CPP: Climatic Production Potential) while it is assumed that all other factors are still optimal.

The effects of nitrogen status, management level, land slope and effective soil depth on climatic production potential are considered in the third hierarchical production situation (LPP: Land Production Potential). With respect to soil nitrogen status, special emphasis has been given to nitrogen, because of the large quantities of N-fertilizer required each year, its cost and its mobility in the soil-plant-atmosphere system.

2 Materials and methods

2.1 Materials

Pinan County covers approximately 1,420 km^2, and is located in the northwest of Shangdong Province (China) between 37°13′ to 37°37′ NL and 116°21′ to 116°57′ EL. Its altitude is approximately 53 m above mean sea level and it is characterized by a cool dry steppe climate, the Bsk-type following Köppen's classification. Average annual rainfall is 591 mm (records from 1957 to 1989) and the mean monthly temperature ranges from -3.4 to 26.7°C. More detailed climatic data are given in tab. 1.

The soils in the study area are mainly Ochrepts (Soil Survey Staff 1990), inten-

Crop development stage	Length (days)	kc*	Growing periods	Length (days)	ky**
Initial stage	25	0.35	Establishment (0)	15	
Dormancy	90			90	
Development stage	40		Vegetative (1)	85	0.2
Mid-season stage	65	1.15	Flowering (2)	20	0.6
Late season stage	40		Yield formation (3)	35	0.5
At harvest		0.20	Ripening (4)	15	0.2
Total growing cycle	260		Total growing cycle	260	
Crop sowing date:			decade 2, October		
Harvest index:			0.45		
Moisture content of the grain:			13%		
Leaf area index:			4.0		
Maximum crop rooting depth (cm)			125		

* kc: Crop coefficient (Doorenbos & Pruitt 1977)
** ky: Yield response factor (Doorenbos & Kassam 1979)

Tab. 2: *Crop data for winter wheat relevant to the study area (Zhang 1990).*

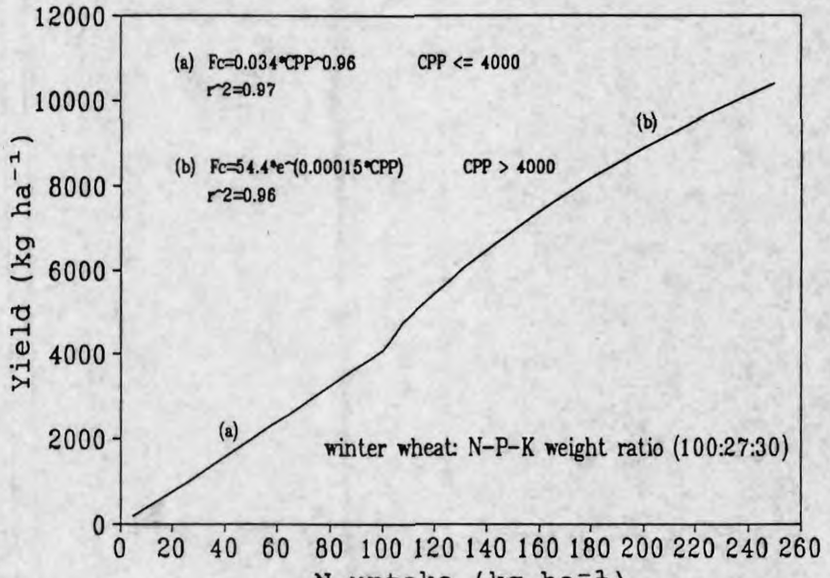

Fig. 1: *Yield response of winter wheat to N-uptake in the study area (Yang et al. 1989).*

sively used for the cultivation of winter wheat, one of the most important food crops. Information about phenological development of the winter wheat in the study area as well as other crop data are given in tab. 2.

For this study, 20 farmers cultivating rainfed winter wheat and another 20 applying irrigation to the same crop were selected. Selection of these farmers was based on differences in management and in soil nitrogen status, slope and effective soil depth of the cultivated plots.

Based on field investigations, the different management practices were classified in three groups, each with a different influence on crop performance:

1. **high management level:** most field activities (ploughing, sowing and harvesting) are carried out mechanically, farmers have good knowledge of modern farming techniques, high input of fertilizers and adequate phytosanitary care;
2. **intermediate management level:** some field activities (ploughing and sowing) are done mechanically, farmers have some knowledge of modern farming techniques, intermediate input level of fertilizers and necessary phytosanitary care;
3. **low management level:** only ploughing is carried out mechanically, farmers have poor knowledge of modern farming techniques, low input of fertilizers and phytosanitary care is poor.

Data on land slope and soil depth were collected during the soil survey. The amount of nitrogen needed to achieve an optimal level (economically and technically) has been determined by considering separately the relationship between the amount of nitrogen taken up by the crop and yield, and that between this uptake and the amount of fertilizer applied. The recovery fraction of applied N-fertilizer has been estimated at 0.75 (Yang et al. 1989). Yield response to N-uptake (fig. 1) was derived from field experiments in the study area (Yang et al. 1989).

Information on management level, soil nitrogen status, land slope, soil depth and N-fertilizer application as well as the yields for the year 1989 by the different farmers, are presented in tab. 3 and 4 for irrigated and rainfed winter wheat, respectively.

2.2 Methods

The methodology for the calculation of the land production potential (or the prdicted yield) for winter wheat is diagrammatically presented in fig. 2.

The calculation procedure covers three hierarchically ordered production situations:

2.2.1 Radiation-thermal Production Potential (RPP)

Calculation of the radiation-thermal production potential is based on the crop growth model of the "FAO Agro-Ecological Zones Project" (FAO 1979) and is derived using the following equation:

$$RPP = 0.36(Bgm * KLAI * Hi) / (1/L + 0.25ct)$$

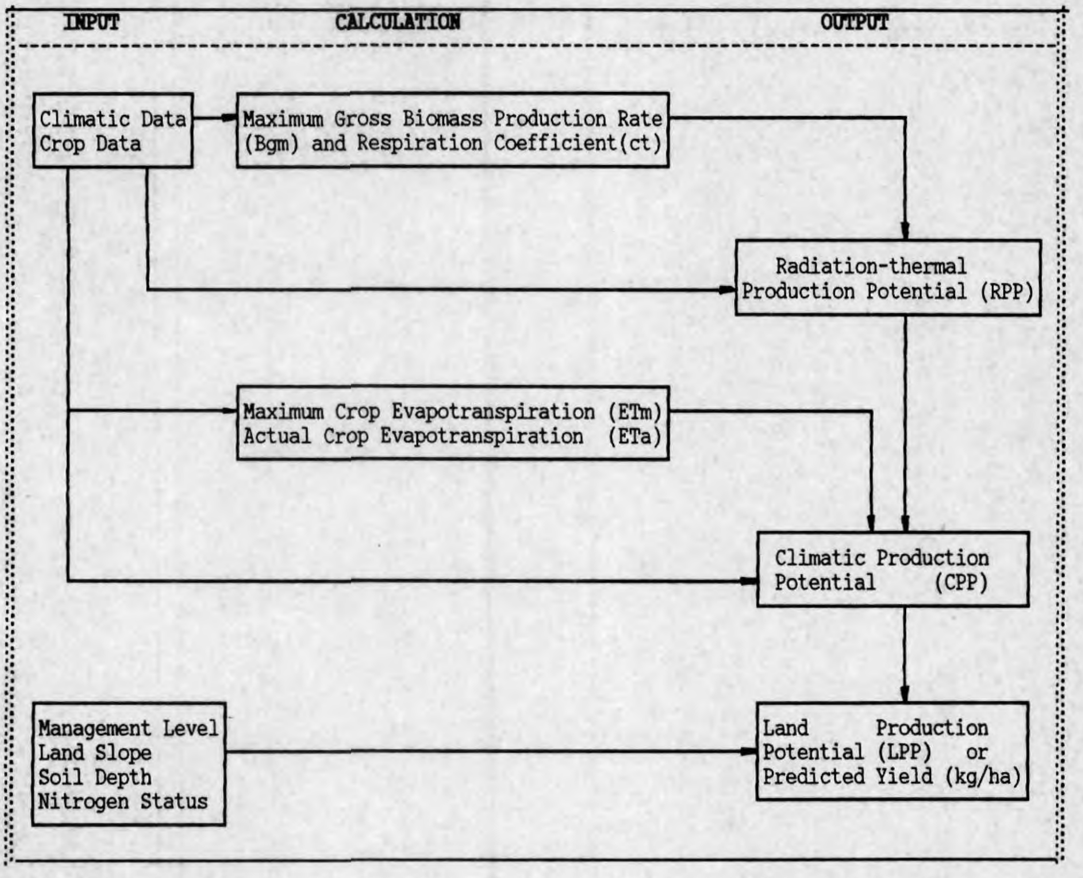

Fig. 2: *Diagrammatic representation of the calculation procedure of the land production potential for winter wheat.*

where

RPP	= radiation-thermal production potential (kg dry matter ha^{-1})
Bgm	= maximum gross biomass production rate (kg CH_2O ha^{-1} hr^{-1}) (FAO 1979)
KLAI	= maximum growth rate ratio (correction factor for a leaf area index (LAI) of less than 5 m^2/m^2) (FAO 1979)
Hi	= harvest index, fraction of the total net biomass that is economically useful (FAO 1979)
L	= number of days that the crop takes to reach maturity
ct	= respiration coefficient [ct = 0.0208 * (0.044 + 0.00297 + 0.001 * t^2) with t being the mean daily temperature (°C)]

A detailed description of the variables, their values as well as the calculation procedures are given in FAO (1979).

2.2.2 Climatic Production Potential (CPP)

The equation used to compute the climatic production potential has been derived from the relationship between relative yield decrease and relative evapotranspiration deficit (Doorenbos & Kassam 1979):

Farmer	Management level	Land slope (degree)	Soil depth (cm)	Mineralized N* (kg/ha)	N fertilizer applied (kg/ha)	Observed yield (kg/ha)
a	high	0	120	35	96	5273
b	intermediate	1	90	32	76	3921
c	intermediate	0	150	24	83	4500
d	high	0	150	37	108	6155
e	intermediate	2	85	28	78	3320
f	intermediate	0	150	21	73	3456
g	high	0	110	34	116	6127
h	high	0	150	31	91	4860
i	intermediate	1	150	27	85	4110
j	high	0	120	47	119	6645
k	high	0	120	39	108	6498
l	high	0	150	35	96	5120
m	intermediate	1	150	33	89	4500
n	intermediate	2	110	25	87	3678
o	high	0	120	46	128	7459
p	high	0	150	37	99	5422
q	high	0	150	38	110	6140
r	high	0	110	37	104	5612
s	high	0	150	31	108	5905
t	intermediate	1	130	29	89	4569

* The mineralization rate of soil organic N has been estimated at 2.5% during the crop growing cycle (Yang et al. 1989)

Tab. 3: *Management level, land slope, soil depth, nitrogen status and yield in the year 1989 for 20 farmers cultivating irrigated winter wheat.*

Farmer	Management level	Land slope (degree)	Soil depth (cm)	Mineralized N* (kg/ha)	N fertilizer applied (kg/ha)	Observed yield (kg/ha)
a1	low	1	150	20	36	1736
b1	low	7	150	19	37	1658
c1	low	3	150	25	40	2190
d1	low	4	100	21	31	1260
e1	low	8	90	16	23	905
f1	low	1	120	11	33	980
g1	low	5	110	17	30	1189
h1	low	6	150	27	37	1726
i1	low	9	90	11	27	940
j1	low	4	100	14	25	1008
k1	low	1	85	17	26	923
l1	low	8	75	12	28	610
m1	low	1	110	14	37	1427
n1	low	4	150	20	30	1389
o1	low	6	75	12	27	712
p1	low	7	90	13	30	1208
q1	low	4	120	18	27	1100
r1	low	2	150	17	35	1478
s1	low	6	95	15	25	995
t1	low	7	100	14	26	1173

* The mineralization rate of soil organic N has been estimated at 2.5% during the crop growing cycle (Yang et al. 1989)

Tab. 4: *Management level, land slope, soil depth, nitrogen status and yield in the year 1989 for 20 farmers cultivating rainfed winter wheat.*

$$CPP = RPP - [ky * RPP * (ETm - ETa)]/ETm$$

where

CPP	= climatic production potential (kg dry matter ha^{-1})
ky	= yield response factor (Doorenbos & Kassam 1979)
ETm	= maximum crop evapotranspiration (mm/crop cycle) = $Kc * ETo$
kc	= crop coefficient (Doorenbos & Pruitt 1977)
ETo	= Penman's reference evapotranspiration (Doorenbos & Kassam 1979)
ETa	= actual crop evapotranspiration (mm/crop cycle)

Actual crop evapotranspiration has been calculated from rainfall and irrigation water applied taking into account soil water storage as related to texture (Baier & Robertson 1972). The relationship, between relative evapotranspiration and available soil moisture, presented in fig. 3 is used in the calculation.

If crop water requirements are fully met, ETa=ETm, and maximum yield is obtained. When available soil moisture decreases, ETa remains equal to ETm until a critical moisture content (p) is attained. Below this critical value ETa<ETm and yield is reduced. The degree of reduction depends on the crop species, the crop growing cycle and the soil.

Rijtema & Aboukhaled (1975) formulated this relationship as follows:

$$ETa = [(St * D)/(1 - p) * Sa * D] * ETm = [-d(St * D)]/dt$$

where

$St * D$	= available soil moisture (mm) at time t over the rooting depth (D)
$Sa * D$	= maximum available soil moisture (mm) over the rooting depth (D)
p	= fraction of easily available soil water

2.2.3 Land Production Potential (LPP)

The land production potential has been calculated using an equation in which the effects of climate (radiation, temprature and water), management level, land slope, soil depth and soil nitrogen status on crop yield have been combined:

$$LPP = CPP * (My * Sy * Dy * Ny)$$

where

LPP	= land production potential (kg dry matter ha^{-1})
My	= relative yield decrease due to management level
Sy	= relative yield decrease due to land slope
Dy	= relative yield decrease due to effective soil depth
Ny	= relative yield decrease due to soil nitrogen status

- **Management level:** the influence of management level on the relative yield decrease is estimated to range from 0 to 20%. The values of My are accordingly 1.0, 0.9 and 0.8 for high, intermediate and low management level respectively.

- **Land slope:** the relative yield decrease due to land slope has been quantified (Wu 1989), assuming that a land slope of 25° is the maximum limit for crop production (FAO 1980, Salyuino 1964) and that slopes below 5° and 1° have no influence on rainfed and on irrigated winter wheat yields, respectively (Sys et al. 1991, Wu 1989, Yang et al. 1989).

Rainfed farming:

$Sy = e^{(0.2565-0.0513*LS)}$ $5° < LS < 25°$

$Sy = 1$ $LS \leq 5°$

Irrigated farming:

$Sy = e^{(0.118-0.12*LS)}$ $1° < LS < 25°$

$Sy = 1$ $LS \leq 1°$

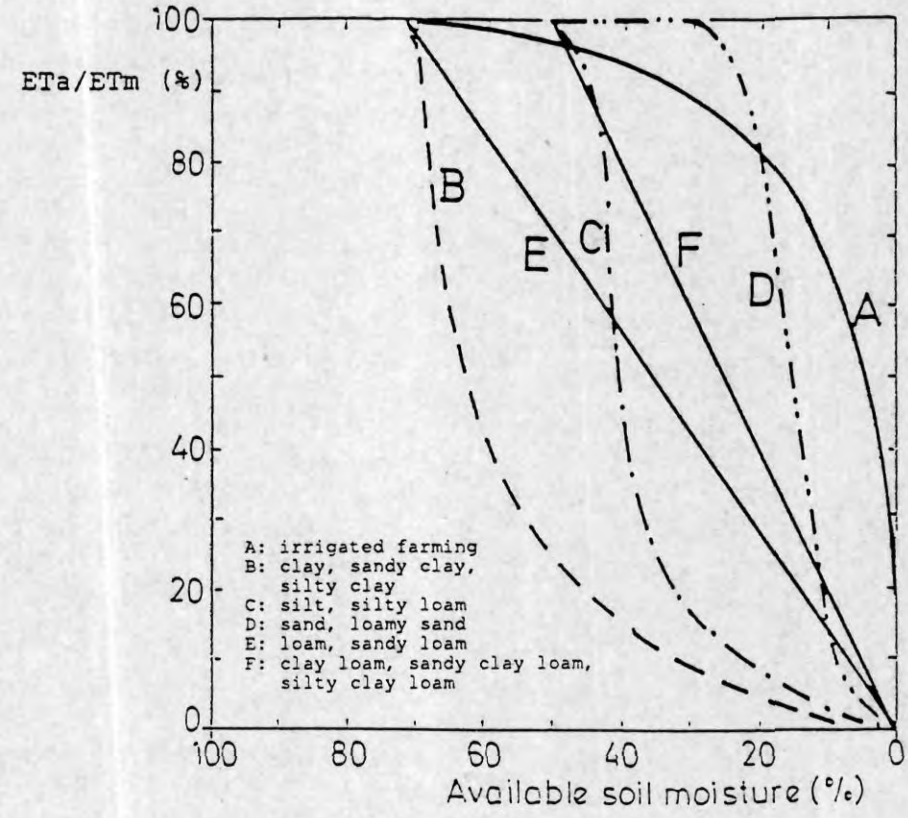

Fig. 3: *Relationship between relative evapotranspiration and available soil moisture (Baier & Robertson 1972).*

where
Sy = relative yield decrease due to land slope (fraction)
e = 2.7183
LS = land slope (in degree)

- Soil depth: a relationship between relative yield decrease and effective soil depth has been estblished by Wu (1989):

$$Dy = 1 - e^{(-0.027*SD)} \quad SD < \text{crop rooting depth}$$
$$Dy = 1 \quad SD \geq \text{crop rooting depth}$$

where
Dy = relative yield decrease due to soil depth (fraction)
SD = effective soil depth (in cm)

- Soil nitrogen status: the influence of soil nitrogen status on yield has been calculated using the equation:

$$Ny = (Na + Nb) / Nc$$

where
Ny = relative yield decrease due to soil nitrogen status (fraction)
Na = amount of N fertilizer applied (kg ha^{-1})
Nb = calculated amount of mineralized nitrogen (kg ha^{-1})
Nc = N-uptake level necessary to reach the climatic production potential (N kg ha^{-1}) (fig. 1)
Nc = $0.034 * CPP^{0.96}$ (CPP $\leq$ 4000 kg ha^{-1})
Nc = $54.40 * e^{0.00015*CPP}$ (CPP > 4000 kg ha^{-1})

Farmer	CPP (kg/ha)	Fraction of CPP My	Sy	Dy	Ny	LPP (kg/ha)
a	7120	1.0	1.00	0.96	0.83	5673
b	8130	0.9	1.00	0.91	0.73	4861
c	6142	0.9	1.00	1.00	0.78	4312
d	7876	1.0	1.00	1.00	0.86	6773
e	6014	0.9	0.91	0.90	0.79	3463
f	5816	0.9	1.00	1.00	0.72	3709
g	8081	1.0	1.00	0.95	0.87	6679
h	6837	1.0	1.00	1.00	0.80	5470
i	7410	0.9	1.00	1.00	0.75	5002
j	8920	1.0	1.00	0.96	0.89	7621
k	7561	1.0	1.00	0.96	0.88	6725
l	7196	1.0	1.00	1.00	0.82	5900
m	6948	0.9	1.00	1.00	0.79	4940
n	7468	0.9	0.91	0.95	0.73	4242
o	9120	1.0	1.00	0.96	0.91	7967
p	7890	1.0	1.00	1.00	0.82	6470
q	7862	1.0	1.00	1.00	0.85	6683
r	8258	1.0	1.00	1.00	0.81	6689
s	7400	1.0	1.00	1.00	0.84	6216
t	6890	0.9	1.00	1.00	0.77	4775

Tab. 5: *Climatic production potential, fractions of climatic production potential for management level, land slope, soil depth and soil nitrogen status, respectively and land production potential of irrigated winter wheat cultivated by different farmers.*

Farmer	CPP (kg/ha)	Fraction of CPP My	Sy	Dy	Ny	LPP (kg/ha)
a1	2980	0.8	1.00	1.00	0.75	1788
b1	3166	0.8	0.91	1.00	0.72	1641
c1	3037	0.8	1.00	1.00	0.87	2378
d1	2974	0.8	1.00	0.93	0.71	1650
e1	3015	0.8	0.86	0.91	0.53	1001
f1	2972	0.8	1.00	0.96	0.60	1369
g1	2966	0.8	1.00	0.95	0.65	1631
h1	3055	0.8	0.95	1.00	0.85	1974
i1	3175	0.8	0.81	0.91	0.49	917
j1	3064	0.8	1.00	0.93	0.59	1345
k1	3037	0.8	1.00	0.90	0.57	1246
l1	2989	0.8	0.86	0.86	0.54	955
m1	2942	0.8	1.00	1.00	0.70	1648
n1	3100	0.8	1.00	1.00	0.66	1761
o1	2996	0.8	0.95	0.86	0.52	1018
p1	3018	0.8	0.91	0.91	0.57	1384
q1	3112	0.8	1.00	0.96	0.58	1386
r1	2935	0.8	1.00	1.00	0.71	1668
s1	3004	0.8	0.95	0.92	0.54	1134
t1	3127	0.8	0.91	0.93	0.52	1101

Tab. 6: *Climatic production potential, fractions of climatic production potential for management level, land slope, soil depth and soil nitrogen status, respectively and land production potential of rainfed winter wheat cultivated by different farmers.*

3 Results and discussion

As a first step in the proposed model, the radiation-thermal production potential or the potential yield of winter wheat in the study area was calculated at 9,494 kg (dry matter) per hectare.

The calculated climatic production potential, considering the influence of moisture availability at the selected sites, shows yields ranging from 5,816 to 9,120 kg (dry matter) per hectare (tab. 5) for the farmers applying different quantities of irrigation water and yields ranging from 2,935 to 3,175 kg (dry matter) per hectare (tab. 6) for rainfed winter wheat. As these yield levels are considerably lower than the potential, "availability of water" seriously constrains the production potential showing that the irrigation is not fully controlled.

Average annual rainfal in the area is 591 mm, but only about 170 mm falls during the winter wheat growing period, resulting in water stress during part of the crop growth cycle hampering assimilatory activity of the crop and rducing the production potential (De Wit 1965).

The calculated water-limited yield levels are still considerably higher than the yields actually obtained by the local farmers (tab. 3 and 4). This suggests that the actual production potential can not be explained by water shortage alone.

The limiting effect of soil nitrogen status, management, slope, soil depth on production potential has been quantified and the results are given in tab. 5 and 6, for irrigated and rainfed winter wheat, respectively.

Incorporation of these yield reducing effects in the calculation of the production potential results in a production estimate (land production potential) which pertains to a more complex simulated production environment.

The estimated land production potential for the selected farmers ranges from 3,463 to 7,967 kg (dry matter) per hectare for irrigated winter wheat (tab. 5) and from 917 to 2,378 kg (dry matter) per hectare for rainfed winter wheat (tab. 6).

Comparison between these predicted yields (land production potential) and the reported yields for winter wheat in the year 1989, graphically illustrated in fig. 4 and 5 for irrigated and rainfed winter wheat, respectively, shows fairly good agreement. This suggests that the simulated production environment closely resembles the situation in which the selected farmers actually operate.

The yield of a crop is limited by the least favourable land characteristic or quality, however the degree of limitation depends on the interaction of land characteristics and qualities which are not optimal for crop growth (Riquier 1972, McRae & Burnham 1981, Samir 1986). This interaction can be quantified by using the multiplicative procedure (Storie 1976, Strzemski 1972, Sys et al. 1991). Jiang (1989) stated that availability of water, soil nitrogen status, level of management, land slope and effective soil depth are the main factors limiting winter wheat yield in the study area. The yield level of rainfed winter wheat could be considerably increased, by 3 to 5 tons per hectare, by irrigation and by 1 to 2 tons per hectare through improved nitrogen availability and management level. The yield of irrigated winter wheat could also be increased by 1 to 2 tons per hectare through fully controlled irrigation, and by 1 to 2 tons per hectare through improved fertilizer use and better management.

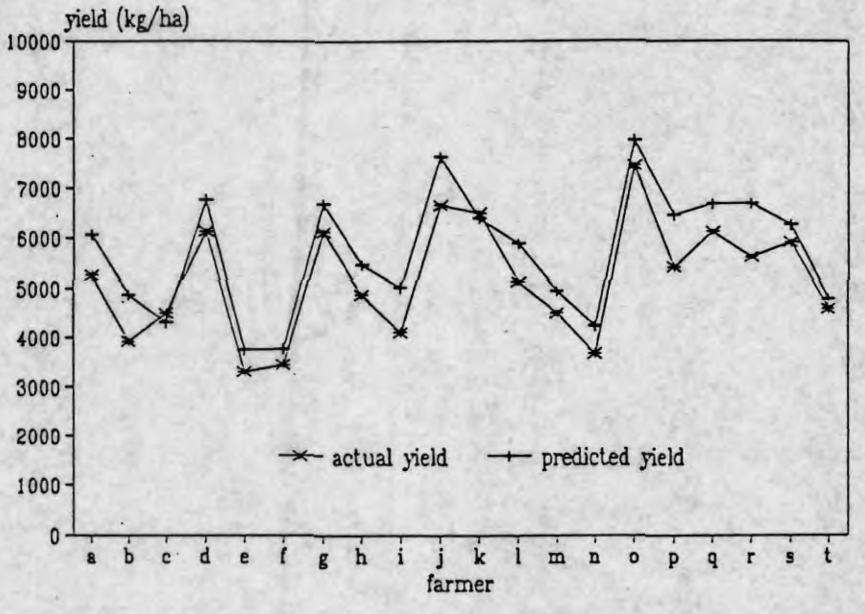

Fig. 4: *Graphic comparison of predicted and observed irrigated winter wheat yield (1989) for different farmers.*

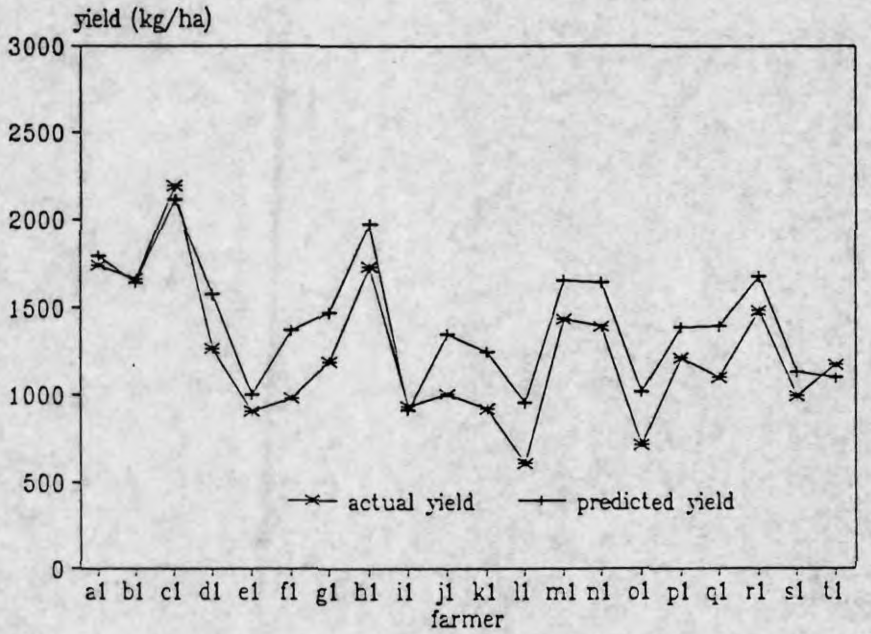

Fig. 5: *Graphic comparison of predicted and observed rainfed winter wheat yield (1989) for different farmers.*

4 Conclusions

The approach described in this paper provides land evaluators with a tool to quantify the land production potential of winter wheat in an agro-ecological zone of China, taking into account soil conditions and management practices of local farmers. Quantification of the major constraints allows estimation of the required inputs to increase the production potential necessary for feeding an increasing non-farming population.

References

BAIER, W. & ROBERTSON, G.W. (1972): Soil moisture estimator program system. Technical Bulletin **78**. Agrometeorology ection, Research branch, Canada Department of Agriculture, Ottawa.

DE WIT, C.T. (1965): Photosynthesis of leaf canopies. Agric. Res. Rep. **663**. Pudoc. Wageningen.

DOORENBOS, J. & PRUITT, W.O. (1977): Crop water requirements. FAO irrigation and drainage paper **24**, FAO, Rome.

DOORENBOS, J. & KASSAM, A.H. (1979): Yield response to water. FAO irrigation and drainage paper **33**, FAO, Rome.

FAO (1979): Report on the agro-ecological zones project. Vol. **1**. Methodology and results for Africa. World soil resources report **48**, FAO, Rome.

FAO (1980): Land resources for populations of the future. FAO, Rome.

JIANG, G. (1989): A quantitative methodology for land evaluation. Natural Resources (Beijing, China) **1**, 43–49.

McRAE, S.G. & BURNHAM, C.P. (1981): Land evaluation. Clarendon Press, Oxford.

RIJTEMA, P.E. & ABOUKHALED, A. (1975): Crop water use. In: Research on Crop Water Use, Salt Affected Soils and Drainage in the Arab Republic of Egypt. FAO Regional Office for the Near East, 5–61.

RIQUIER, J. (1972): A mathematical model for calculation of agricultural productivity in terms of parameters of soil and climate (AGL/MISC/72/14), FAO, Rome.

SALYUINO, T.A. (1964): The land capability map of Portugal. Trans. 8th Intern. Congr. Soil Sci. **5**, 837–845.

SAMIR, H.K. (1986): A statistical approach in the use of parametric system applied to the FAO framework for land evaluation. Unpublished Ph.D. dissertation, Ghent Univ., Belgium.

SOIL SURVEY STAFF (1990): Keys to Soil Taxonomy. SMSS Technical Monograph **19**, Fourth Edition.

STORIE, R.E. (1976): Storie soil index rating. Spec. Publ. Div. Agric. Sci., Univ. Calif. **3203**.

STRZEMSKI, M. (1972): Awarding points in land classification. Pam. Pulawski **55**, 199–210.

SYS, C., VAN RANST, E. & DEBAVEYE, J. (1991): Land evaluation, part I: Principles in land evaluation and crop production calculations. ITC, University of Ghent, Belgium.

VAN KEULEN, H. & WOLF, J. (Eds.) (1986): Modelling of Agricultural Production: Weather, Soils and Crops. Simulation Monographs, Pudoc, Wageningen.

WU, L. (1989): Methodology of evaluating winter wheat productivity and its application. Ph.D. dissertation, Beijing Agricultural University, Beijing.

YANG, H., ZHOU, K. & LI, S. (1989): Soil fertility status in Pinan County. Regional Study (Beijing, China) **1**, 65–73.

ZHANG, Y. (1990): Modelling of winter wheat production. Regional Study (Beijing, China) **4**, 42–51.

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