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Field-Scale Variability of Soybean Yield and Its Relations with Soil Fundamental Fertility

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Abstract: By the methods of geostatistics combined with traditional statistics, the spatial variability of soybean yield and its relations with soil fundamental fertility was examined within a site-specific long-term experimental field at the Shenyang Experimental Station of Ecology, Chinese Academy of Sciences (a 30 m × 42 m plot was divided into 7 m×5 m subplots, with 49 sampling sites). The results showed that the isotropic variogram for soybean yield fitted a spherical model, with R^2 being 0.838 and significant at the 0.01 level. The distribution map of soybean yield was spatially dependent and the directional variability mainly occurred in the 45° and 0° directions. Soybean yield was significantly correlated with the number of seeds per m^2 ($R = 0.945$, $p<0.01$), with the number of pods per plant ($R = 0.353$, $p<0.05$) and with soil pH ($R = 0.515$, $p<0.01$), exchangeable calcium concentration ($R = 0.386$, $p<0.01$) and cation exchange capacity ($R = 0.387$, $p<0.01$). However, the soil fundamental fertility index, i.e., soil organic carbon, nitrogen and phosphorus, exhibited no contributions to soybean yield. Soil water content was considered as the most limit factor that affecting soybean yield within the field-scale. It is suggested that soil fundamental fertility alone or other single factors be not enough to explain the observed spatial variability of soybean yield and hence, more factors should be taken into account to diagnose causes of poor plant growth and to improve the management of site-specific farming.

Key words: Soybean (*Glycine max* L.), yield, spatial variability, soil fertility, site-specific farming

INTRODUCTION

Crop yields integrate the accumulated effects of many spatially-variable factors such as soil properties, fertilization, topography and infestations of weeds, insects and diseases; therefore, a yield map is one of the most important pieces of information for precision farming. It not only helps identify within-field spatial variability for variable rate applications, but also enables a farmer to evaluate the economic returns of different farming management strategies[1,2]. It is generally accepted that high crop yields cannot be obtained without Nitrogen (N), Phosphorus (P) and potassium (K) applications, it is also accepted that soils with high fundamental fertility tend to yield higher production[3,4]. Site-Specific Farming (SSF) has the potential to revolutionize crop production by increasing profit margins through improved efficiency in the management of field variability[5]. Soil fertility is one of the key factors for SSF[2], however, its adoption is lagging and its profitability is questionable, because fertilizer alone or other single factors have not been able to explain the observed spatial variability in crop yields[5,6]. We hypothesized that within the field-scale, areas with high soil fertility could yield more production than those with low soil fertility if the cultivation and fertilization conditions were similar and soil fundamental fertility might be the key factors to influence crop yields. The objectives of this study were to describe the field-scale variability of soybean yield and related biological characters, to map the spatial distributions of these variables at a site-specific long-term experimental field in the Shenyang Ecological Experimental Station of Ecology, Chinese Academy of Sciences and to explore the potential relations between soybean yield and soil fundamental fertility. The results to be obtained may be helpful to the management of site-specific farming.

MATERIALS AND METHODS

The experimental plot (30 m×42 m) is a long-term soil properties observatory field at the Shenyang Ecological Experimental Station of Ecology, Chinese Academy of Sciences. This Station was established in 1990 and is a member of the Chinese Ecosystem Research Network (CERN), which is situated at the Lower Reaches of Liao River Plain in Northeast China (41°31′ N, 123°22′ E), with continental temperate monsoon climate (dry and cold in winter and warm and wet in summer). The annual temperature is 7.0-8.0 °C, annual precipitation is 650-700 mm and annual non-frost period is 147-164 days. The soil is classified as aquic brown soil. The field was fertilized with 225 kg N, 60 kg P and 112 kg K per hectare annually,

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and rotated with maize (*Zea mays* L.) and soybean [*Glycine max* L.] for about 10 years. Before 1990, this field was planted with paddy rice (*Oryza stativa* L.) for dozens of years. The test soybean variety was Tiefeng 29.

The experimental field was divided into 7 m×5 m subplots, with 49 sampling sites. Soil samples were collected before soybean sowing (April, 2004). Soil samples were collected at the depth of 0-20 cm from each subplot, air-dried and sieved for subsequent chemical analyses. The soybean samples were collected during harvest (October, 2004) at the same field where soil samples were collected, within 50 cm×90 cm area for each sample.

Collected soybean plants were taken to laboratory to investigate yield and related biological characters. Soil chemical properties and soil water content were determined according to Page *et al.*[7].

Classical statistical parameters were solved by using SPSS 10.0 software and the isotropic and anisotropic semivariances of obtained data were calculated by using GS+ geostatistical software[8]. Semivariance $\gamma(h)$ is defined in Eq.

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[z(x_i)-z(x_i+h)\right]^2 \qquad (1)$$

where N(h) is the number of sample pairs at each distance interval h and $z(x_i)$ and $z(x_i+h)$ are the values of variable x at any two places separated by distance h. The semivariogram is the plot of the semivariance against the distance and its shape indicates whether the variable is spatially dependent. Experimental semivariograms were fitted by theoretical models with well-known parameters nugget C_0, sill C_0+C, and range of spatial dependence a[9-12].

The F test of models' coefficient of determination was calculated with Eq.

$$F=\frac{R^2}{1-R^2}\times\frac{N-k}{k-1} \qquad (2)$$

where N is the number of sampling sites£¬k is the number of independents and R^2 is the coefficient of determination[12].

Block kriging was used before constructing contour maps to provide enough estimated data. The contour maps of soybean yield and selected biological characters were constructed by using GS+ software.

RESULTS AND DISCUSSION

Summary statistics for soybean yield, biological characters and soil properties: The summary statistics for the data sets of soybean yield, biological characters and soil chemical properties (Table 1) indicated that the number of pods per plant had the highest coefficient of variation, while the weight of 100 seeds had the lowest coefficient of variation among the test variables of soybean yield and related biological characters. Of the test soil chemical properties, available P had the highest C.V., while available N had the lowest C.V. The median values were close to mean values for most of the variables, but the ranges between the minimum and maximum values were large for most of the variables.

Spatial variability of soybean yield and related biological characters: Like many other regionalized variables, the distributions of soybean yield and related biological characters within field-scale may vary in different directions with quite different ways and as a consequence, variograms are often two-dimensional functions. Table 2 showed that all variables of soybean yield and related biological characters fitted linear models, except for plant height which fitted exponential. All variable had the $C/(C_0+C)$ values larger than 70% and the F-test showed that the anisotropic variogram models for all the variables were significant at the 0.01 level (Table 2).

Models for isotropic variograms fitted spherical or exponential, with the $C/(C_0+C)$ values between 59.8% and 69.6%. The spatial dependence ranges were same for soybean yield as for the number of seeds per m^2. The F-test for the isotropic variogram models of soybean yield and related biological characters were significant at the 0.05 and 0.01 levels, respectively (Table 3).

Spatial distribution map of soybean yield via kriging: Contour maps were constructed via block kriging for soybean yield and related biological characters (Fig. 1). Distribution map of soybean yield was similar to that of the number of seeds per m^2, but different from those of the number of pod per plant and the weight of 100 seeds. The directional variability of soybean yield and the number of seeds per m^2 mainly occurred in the 45° and 0° directions, while the number of pods per plant in the 90° and the weight of 100 seeds in the 0° and 90° directions (Fig. 1).

Correlations of soybean yield with related biological characters and soil properties: The observed soybean yield was spatially dependent within the field-scale. However, the spatial variability of soybean yield was not in line with those of the soil organic carbon, total and

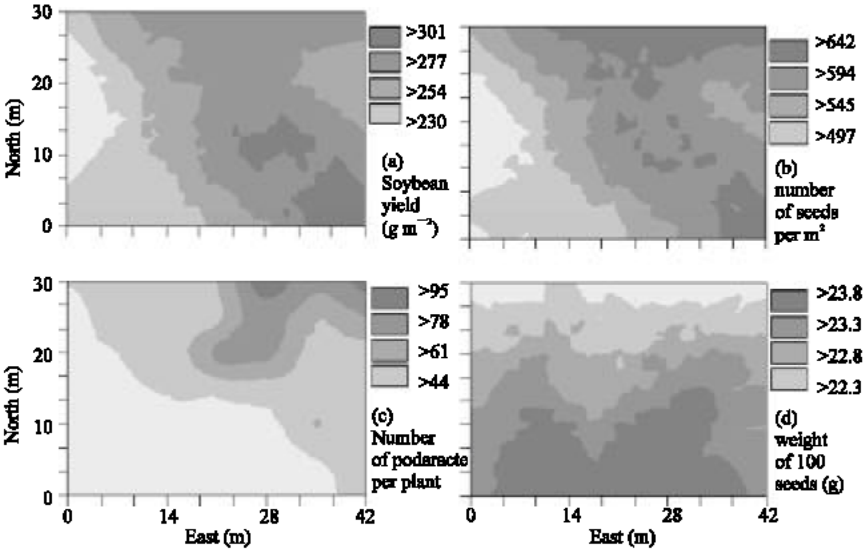

Fig. 1: Distribution maps of soybean yield and related biological characters

Table 1: Summary statistics for data sets of soybean yield, biological characters and soil properties

Item	Mean	S.D.	C.V. (%)	Median	Minimum	Maximum
Soybean yield (g m^{-2})	270.49	58.02	21.45	273.00	155.00	434.00
Number of seeds per m^2	587.40	134.64	22.92	599.00	333.00	899.00
Number of pods per plant	50.25	29.03	57.76	40.20	21.20	154.50
Plant height (cm)	50.14	7.86	15.68	48.70	30.80	73.70
Weight of 100 seeds (g)	23.14	1.55	6.71	23.35	19.54	25.68
Number of seeds per pod	1.79	0.16	8.75	1.80	1.38	2.16
Soil pH	5.20	0.42	8.14	5.15	4.59	6.68
Soil organic C (g kg^{-1})	10.50	0.77	7.36	10.44	9.35	12.53
Total N (g kg^{-1})	1.07	0.09	8.03	1.06	0.92	1.27
Available N (mg kg^{-1})	98.64	5.15	5.22	98.75	86.35	110.31
Total P (g kg^{-1})	0.40	0.04	10.72	0.38	0.32	0.55
Available P (g kg^{-1})	15.50	7.38	47.58	13.11	6.55	35.73
Exchangeable Ca (g kg^{-1})	2.54	0.16	6.36	2.51	2.30	3.03
Exchangeable Mg (g kg^{-1})	0.33	0.03	9.91	0.33	0.26	0.41
Exchangeable K (g kg^{-1})	84.82	18.88	22.26	81.71	46.90	125.97
CEC (cmol kg^{-1})	15.93	1.06	6.64	15.74	14.35	19.21
Soil water content (%)	21.95	1.48	6.74	21.86	18.67	25.68

Table 2: Parameters of the best-fitted semivariogram model for anisotropic variogram

				Effective range					
Item	Model	Nugget C_0	Sill C_0+C	A_1 (m)	A_2 (m)	C/(C_0+C) (%)	Model R^2	RSS	F-test
Soybean yield (g m^{-1})	Linear	1802	7528	94.2	94.2	76.1	0.441	$1.242x10^7$	5.52**
Number of seeds per m^2	Linear	10140	42029	108.6	78.7	75.9	0.638	$2.174x10^8$	12.34**
Number of pods per plant	Linear	753	4576	497.2	183.3	83.6	0.615	$1.298x10^7$	11.18**
Plant height (cm)	Exponential	19.5	126.3	43.6	43.6	84.6	0.452	9773	5.77**
Weight of 100 seeds (g)	Linear	1.73	6.38	168.6	59.7	72.9	0.548	7.227	8.49**
Soil water content (%)	Exponential	1.39	4.65	95.7	51.8	70.1	0.560	4.965	8.91

***,** F test significant at the 0.01 levels

available nitrogen and total and available phosphorus concentrations[10-12]. Correlations of soybean yield with soil fundamental fertility also testified the disagreement (Table 4). Xu *et al.*[13] have examined that sward dry matter yield was patchy and temporally unstable within the field-scale and found it was not correlated with soil N and other nutrients. In this study, both soybean yield and the number of seeds per m^2 were significantly correlated with soil pH, exchangeable Ca and cation exchange capacity (Table 4). These variables may have a direct yield effect by themselves, but interaction with N, P and K may also be expected[2]. Manu *et al.*[3] and Cox *et al.*[14] have observed that soil pH value and Ca and Mg levels were correlated with, or had significant effects on crop yields. A better understanding of the most important soil chemical complexities and their operating mechanisms seems essential to reliably match site conditions with fertilizer technologies in SSF.

Table 3: Parameters of the best-fitted semivariogram model for isotropic variogram

Item	Model	Nugget C_0	Sill C_0+C	C/(C_0+C) (%)	Range A(m)	Model R^2	RSS	F-test
Soybean yield/g•m^{-2}	Spherical	1940	5669	65.8	91.0	0.838	4.513×10^5	36.21**
Number of seeds per m^2	Spherical	10940	30250	63.8	91.0	0.898	6.948×10^6	61.63**
Number of pods per plant	Exponential	310	985	68.5	10.9	0.289	$2.180\times10^5$2.85*	
Plant height/cm	Spherical	22.8	75.0	69.6	33.8	0.787	305	25.86**
Weight of 100 seeds/g	Exponential	1.82	4.53	59.8	80.5	0.411	0.6574.88**	
Soil water content/ (%)	Exponential	1.62	3.23	50.0	41.9	0.704	0.11616.65	

** *,** F test significant at the 0.05 and 0.01 levels, respectively

Table 4: Correlations of soybean yield with related biological characters and soil properties

	(A)	(B)	(C)	(D)	(E)	(F)
(A) Soybean yield (g m^{-2})	1.000					
(B) Number of seeds per m^2	0.945**	1.000				
(C) Number of pods per plant	0.353*	0.462**	1.000			
(D) Plant height (cm)	-0.062	-0.029	0.266	1.000		
(E) Weight of 100 seeds (g)	-0.044	-0.361*	-0.389**	-0.105	1.000	
(F) Number of seeds per pod	0.256	0.265	0.080	-0.385**	-0.054	1.000
Soil pH	0.515**	0.470**	0.190	0.291*	0.024	0.041
Soil organic C (g kg^{-1})	-0.035	0.056	-0.011	0.049	-0.250	0.038
Total N (g kg^{-1})	-0.016	0.106	0.075	-0.013	-0.375**	0.029
Available N (mg kg^{-1})	-0.085	0.027	0.181	0.103	-0.301*	-0.218
Total P (g kg^{-1})	-0.367**	-0.329*	-0.062	0.131	-0.057	-0.231
Available P (g kg^{-1})	-0.444**	-0.449**	-0.198	0.108	0.107	-0.345*
Exchangeable Ca (g kg^{-1})	0.386**	0.325*	0.023	0.204	0.094	-0.001
Exchangeable Mg (g kg^{-1})	0.251	0.251	-0.064	0.061	-0.031	0.141
Exchangeable K (g kg^{-1})	0.163	0.233	-0.003	-0.079	-0.229	0.006
CEC (cmol kg^{-1})	0.387**	0.343*	0.017	0.187	0.052	0.034
Soil water content (%)	0.340*	0.488**	0.499**	0.365**	-0.382**	0.120

*, ** Correlations are significant at the 0.05 and 0.01 levels, respectively

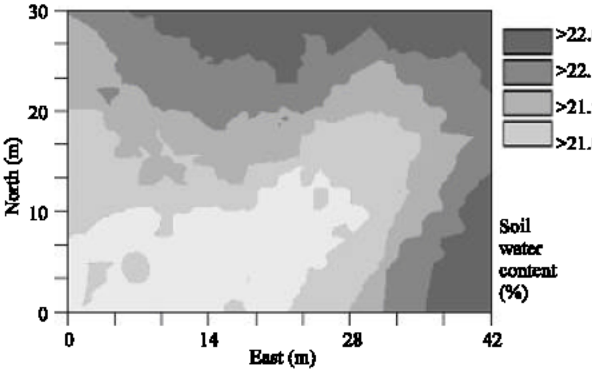

Fig. 2: Distribution maps of soil watercontent in April 2004

Soil water content in April, 2004 was significantly correlated with soybean yield and the number of seeds per m^2 (Table 4), this suggests that soil water may have played important role in the soybean growing season. Figure 2 showed that the spatial pattern of soil water content was similar to that of the soybean yield and the number of seeds per m^2 (Fig. 1). In the early summer of 2004, the study field received little rainfall and hence the soybean might have undergone drought stress during the growing season. However, to the east of the soybean field, there is a paddy field which could have supplied water to the soybean field through infiltration (Fig. 2 also testified the infiltration status of the field in April, 2004). The effect of water on crop yields is more significant when it is hot and dry during crop growing season. Machade *et al.*[6] found that the effect of soil NO_3^--N on crop yield was positive when soil water was abundant and under high water treatment, but was negative when soil water was limiting and under the low water treatment. Unfortunately, the temporal variability of the soil water was not examined during the growing season, but it is deducible that when the soybean underwent drought stress, the contribution of soil fundamental fertility to yield was limited and hence, the spatial pattern of soybean yield was not in line with that of the fundamental fertility such as SOC, N and P.

CONCLUSION

The within field study showed that soybean yield was spatially dependent. The spatial pattern of soybean yield was similar to those of soil pH, exchangeable Ca, cation exchange capacity, but not in line with soil organic matter, nitrogen and phosphorus concentrations. Soil water content might have played important contribution to soybean yield and the drought stress might have inhibited soybean to absorb nutrients during the growing season. There are a lot of factors that influence crop yield within the field-scale. These may include but not limited to soil fundamental fertility such as organic matter, cation exchange capacity, N, P, K and other soil nutrients. To this end, more work is needed to identify factors and relationships among factors influencing crop yield variability. Understanding these factors is the key to diagnosing causes of poor plant growth and improving the management of site-specific farming.

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