S_p-method: A Quantified Ecological Approach for Assessing Potential Crop Yield Breakthroughs

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Abstract

Understanding crop yield formation is important for agronomists to make a contribution to improved crop management. An analytical procedure, referred to here as S_p-method, is presented as a way to evaluate alternative ways to achieve yield advances, based on ecological theory and using regression techniques. The rationale of S_p-method is that the crop yield is the result of genetic potential performance under ecological pressure within field environments. Yield and its components are expressed as mathematical equations representing interacting ecological and management factors. Partial differentials of yield components and gradients for the factors assessed reveal which management tactics can best be exploited for higher crop yield. The application of this routine is illustrated with two examples, and some directions are pointed out for better applying and improving this method.

Keywords: Crop yield, Yield components, Field ecology, S_p-method, Super high-yield

1. Introduction

Higher crop yield is not only farmers' aspiration, but also something that most governments seek to promote. High yield is the focus of much agricultural research, especially in countries with large populations to feed such as China. In the past decades, new concepts of 'Super Rice' (Yuan 1977; Yang, 1987; Yang *et al.*, 2006) and 'Super Maize' have emerged as agronomists have worked hard to produce 'Super High-Yield Techniques'. Thresholds for super- high yield have previously been considered as 12 tons per hectare for rice, 9 tons per hectare for wheat, and 13.5-18 tons per hectare for maize (common considering, and web news, 2008), and various impressive achievements have been achieved in high-yield contests (Yang, 1987; Wang *et al.*, 1990; Wang *et al.*, 2000). A maize line DH3719 developed by Li Denghai, a famous Chinese farmer, has once recorded a yield of 21 tons per hectare (web news, 2006) and Kip Cullers recorded world soybean yield to 155 bushels in an acre(web news, 2007).

Meanwhile, the theoretical discussion of crop yield formation continues. Based on plant physiological theory,

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Zhao *et al.* (1995) summarized previous theories of the yield component (Engledow, 1923), photosynthetic characteristics (Blackman, 1919) and source-sink relationships (Mason & Maske, 1928), proposing a "three-combination structure model". This, however, is more conceptual than empirical. Some researchers seeking a more analytical route have used multiple-regression statistical analysis in their experimental design to explore various mathematic relationships between crop yield and crop management method. Their aim is to find optimum combinations of crop management measures. Several studies have employed (e.g., Lu *et al.*, 1990; Wang *et al.*, 1993; Akihito *et al.*, 1993; Wang *et al.*, 2000). However, they still have some systematic weaknesses on the physiological side and some mechanistic shortcomings in their regression designs. Based on ecological theory and certain regression design, Lu *et al.* (1997) established what they called the "S_p-method". A subsequent experiment was carried out using the S_p-methodology (Lu *et al.*, 2001). In this paper, we elaborate on those results and outline further this new approach.

2. The rationale

Crops grow and develop in a complex ecological environment having both artificial and natural elements. Such an environment supplies nutrition and energy for crop growth and development, while any inadequacy in the supplies of nutrition and energy restricts crops' growth and development and has an impact on ultimate crop yield. Such restrictions can be referred to as "the environmental pressure" and crop yield can be understood as the complex result of crops' genetic potential and its expression under the constraints of environmental pressure (Michael *et al*, 1986). Similarly, crop yield components were themselves restricted by environmental pressures. Such a conceptual formulation lends itself well to regression analysis, seeking to estimate optimal relationships under constraints.

The ecological environment includes many factors, among which the main ones are light, temperature and precipitation. In a specific geographical region, the main ecological factors are relatively constant, while agronomic factors such as irrigation, fertilizer applications, plant density and sowing date are changeable. To quantify the effects of agronomic factors on yield or yield components is very important for predicting or explaining yield.

Multiple regression statistical analysis and experimental design techniques can help to establish quantitative relationships affecting yield (or yield components) with specified agronomic factors considered as independent variables, as in:

$$Y = f\,(X_1, X_2 \ldots Xn),$$

Where Y stands for yield; X_1, X_2 …Xn stand for agronomic factors.

Usually, the above equation is regarded as a geometric surface or super-geometric surface with stationary points (Fig1), and the equation could be differentiable at any points within the factor space.

When maximum yield occurs at stationary points, its yield components do usually not occurs at to their own stationary points. The highest yield does generally not the combination of its highest components. For diagnosis a crop cultural technique, we can make difference at its coordinate point, in case of the technique is involved in this assessing. Thus, we have a chance to evaluate each individual agronomic factor "pressuring" on each individual component. From the partial derivatives of yield components, equations are derived as a series of slopes (or gradients).

$$f_x = \frac{\partial f}{\partial x} \quad \text{or, } Y` = \frac{\partial f}{\partial x}$$

The stationary points in agronomic terms represent the optimum yield or yield components; the slopes infer the relationship between genetic potential and environmental pressures. They can be indicated as S_p, i.e., the slope under certain environmental pressure. Significantly, a bigger S_p value corresponds to lower environmental pressure, and vice versa. Where environmental pressure is small, there can be a yield breakthrough. By comparing individual S_p's in a S_p series, the opportunities for breakthroughs to higher yield will become evident. In other words, management factors that have higher values of S_p warrant higher priority for manipulation to achieve super-high yields.

3. Operation samples

3.1 Choosing models for experiments and getting initial results

Using multiple regression statistical analysis and experimental response surface design, two field experiments were arranged with maize hybrid (Shendan 7) in Yuci, Shanxi Province (1994, 1995) and with two winter wheat lines (Pin 16, a big-ear genotype, marked as P, and 935031, a middle-sized ear genotype, marked as L) in Wuqiao, Hebei Province (1999-2000).

The factors, levels and codes that the model D-416 required and the treatments arrangement followed to the requirement of D-310 in these experiments are shown in Tables 1 and 2. In the maize experiment, 16 plots (each 66.7 m^2) with 3 replications were submitted to the model D–416A, and 10 plots(each 27 m^2) with 2 replications were assessed using the model D–310 for each wheat line. The experimental soils were all fertile, and the basic seedling densities of Pin 16 and 935031 were, respectively, 4.20 million and 2.24 million per hectare.

The crop plants were managed patiently and properly in the growing seasons. The ear/spike density and the yield and yield components were all investigated and measured carefully in the fields and labs. The results are presented in Tables 3 and 4.

3.2 To establish the regression equations

From the data in Tables 1-4, multiple regression equations of yield and its components with associated agronomic factors could be established by using SAS software. For the maize experiment,

$$S_{pikes} = -13478 + 5.24\ X_1 + 1.63\ X_2 + 219.74\ X_3 + 67.09\ X_4 - 4.13\times10^{-4}\ X_1^2 - 6.61\times10^{-5}\ X_1X_2 - 2.99\times10^{-4}\ X_2^2 - 0.02\ X_1X_3 + 0.03\ X_2X_3 - 7.71\ X_3^2 - 1.82\times10^{-3}\ X_1X_4 - 4.65\times10^{-3}\ X_2X_4 + 0.33\ X_3X_4 - 0.32\ X_4^2$$

$$Y_{grains} = -582.33 + 0.32\ X_1 + 0.19\ X_2 + 32.57\ X_3 + 5.89\ X_4 - 3.57\times10^{-5}\ X_1^2 - 2.32\times10^{-6}\ X_1X_2 - 2.58\times10^{-5}\ X_2^2 - 1.96\times10^{-4}\ X_1X_3 - 1.26\times10^{-3}\ X_2X_3 - 0.84\ X_3^2 - 7.81\times10^{-5}\ X_1X_4 - 1.99\times10^{-4}\ X_2X_4 - 0.03\ X_3X_4 - 0.83\ X_4^2$$

$$Y_{weight} = 42.82 - 4.31\times10^{-3}\ X_1 - 2.42\times10^{-3}\ X_2 - 0.07\ X_3 + 1.01\times10^{-3}\ X_4 + 1.97\times10^{-7}\ X_1^2 - 1.43\times10^{-7}\ X_1X_2 + 3.5l\times10^{-7}\ X_2^2 + 6.04\times10^{-5}\ X_lX_3 + l.78\times10^{-5}\ X_2X_3 - 5.68\times10^{-3}\ X_3^3 - 5.51\times10^{-7}\ X_1X_4 + 6.\ 5\times10^{-6}\ X_2X_4 - 1.8\times10^{-3}\ X_3X_4 + 1.25\times10^{-4}\ X_4^2$$

$$Y_{yield} = -1625.74 + 0.68\ X_1 + 0.2\ X_2 + 33.99\ X_3 + 0.71\ X_4 - 6.7\times10^{-5}\ X_1^2 + 1.82\times10^{-6}\ X_1X_2 - 3.31\times10^{-5}\ X_2^2 + 2.78\times10^{-3}\ X_lX_3 - 8.68\times10^{-4}\ X_2\ X_3 - 1.34\ X_3^2 - 5\times10^{-3}\ X_1X_1 - 1.55\times10^{-4}\ X_2X_4 - 0.05\ X_3X_4 - 0.05\ X_4^2$$

Similarly, equations for the wheat experiments were constructed, and their coefficients were summarized into Table 5.

3.3 Getting partial derivative equations

With the equations above, the effects of crop management factors on yield or yield components could be decomposed by their partial derivatives. For maize ear number, e.g., the partial derivative equations of X_1, X_2, X_3 and X_4 should be:

$$Y`_{X1} = -28.2850206 - 8.26\times10^{-4}\ X_1$$

$$Y`_{x2} = 1.441977542 - 5.98\times10^{-4}\ X_2$$

$$Y`_{x3} = 214.4725704 - 15.4323876\ X_3$$

$$Y`_{x4} = 50.05602 - 0.645388\ X_4$$

For the grain number per maize ear, the partial derivative equation should be:

$$Y`_{X1} = 0.32387 - 7.147\times10^{-5}\ X_1$$

$$Y`_{x2} = 0.I\ 6333 - 5.157\times10^{-5}\ X_2$$

$$Y`_{x3} = 25.7745 - 1.687086\ X_3$$

$$Y`_{x4} = 4.4077 - 1.66232\ X_4$$

For the weight of 100 maize grains, the partial derivative equation should be:

$$Y`_{X1} = -3\ 77894\times10^{-3} + 3.97x10^{-7}\ X_1$$

$$Y`_{x2} = -3.3441\times10^{-4} + 7.02\times10^{-7}\ X_2$$

$$Y`_{x3} = 0.121\ 91 + 1.1\ 358\times10^{-2}\ X_3$$

$$Y`_{x4} = -0.01\ 2937 + 2.5\times10^{-4}\ X_4$$

Similarly, the partial derivative equations from the wheat experiments could also be derived (not presented here for reasons of length).

From the equations in section 2.2, the maximum theoretic yields and their corresponding coordinates of independent variables at stationary points in the response surfaces could be estimated (Table 6).

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3.4 Finding the slopes

By substituting the coordinates in Table 6 for individual independent variables, the slopes of yield components to management factors could be derived and the S_ps are summarized in Table 7.

3.5 Analyzing the Sp table

First, just enhancing the application rate of calcium phosphate (X_3) could improve the number of ears for the maize cultivar Shendan 7 under experimental conditions, In contrast, increasing plant density (X_1) or the application rates of organic manure (X_2) and urea (X_4) should give negative effects on ear number. This indicates that achieving greater ear number is difficult. Second, for the grain number per ear, the pressures from plant density, application rates of urea and calcium phosphate are large at the stationary point of the maximum yield. Only organic manure has small positive effect, but near to zero value. Third, there is a great chance to promote grain weight if the application rate of urea is further increased.

In the big-ear genotype of wheat (Pin 16), calcium phosphate (X_p) could enhance all the three yield components, but X_N and X_K do not have positive effects on yield components. Among the three components, only grain weight has a little hope for being increased. For the middle-sized ear genotype (line 935031), the situation is somewhat more complex. X_P enhances the spike number, and X_N enhances grain number. The grain weight depends upon both of X_N and X_K. Breakthroughs for the two wheat lines would be in the area of grain weight, which is different from the conventional wisdom that the breakthrough for big-ear genotype lines lies in spike number.

3.6 Suggesting for improvements in crop management

From the facts and analysis above, the most promising breakthrough area for super-high yield is grain weight, similar with the already-known opinion of certain agronomists(Miao, 1994). Meanwhile, crop management suggestions could be: at the beginning of jointing stage, apply more urea to increase grain weight for Shendan 7; for big-ear genotypes in wheat, more calcium phosphate is needed and less urea and potassium sulfate; for middle-sized ear genotype one needs more calcium phosphate and potassium sulfate.

4. Discussion

Although the concept of “environmental pressure” (Miao, 1994) is not new, and the principle that “crop yield is the complex result of crops’ genetic productivity and the environmental pressure” is easily understood, quantifying “environmental pressures” is a new undertaking. By using the S_p method, it is possible to measure these indirectly, at least to compare the pressures on different yield components, and to assess the recommendations of previous analysis. Furthermore, it could guide the technologic improvement in crop management.

Meanwhile, there is further work requirement to be done to refine this approach of S_p. An advanced model that better reflects the relationship of yield and its components to agronomic factors and more technical proficiency for decreasing the operating errors in experiments are the main areas for advance.

To use the S_p method, one must: (1) choose a model and independent variables (e.g., plant density, fertilizer application rate) that allow the experiment to produce a better response and to decrease the disturbing factors of weaknesses in mechanisms; (2) design new research techniques which are always based on the high-yield crop culture techniques – it is important to set the technique measurements to a 0 level or very nearby of codes and be able to narrow the variables’ ranges in response to surface designs; and (3) keep physiological routines in mind when making decisions.

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Table 1. Factors, levels, and codes in D–416A design in Yuci, Shanxi (1994, 1995)

level			-1.685	-1	0	1	1.685
factor	X_1	Density (plants/666.7m^{-2})	3000	3810	5000	6190	7000
	X_2	Organic fertilizer (Kg/666.7m^{-2})	0	1016	2500	3984	5000
	X_3	Urea (kg/666.7m^{-2})	0	6.5	16	28.4	32
	X_4	Calcium phosphate (kg/666.7m^{-2})	0	26.8	97.8	150	
code			-1.949	-0.908	0.644	1.784	

(Organic manure, phosphate, and 1/2 urea as basal fertilizer, 1/2 urea as side-dressed fertilizer at the jointing stage of maize life cycle)

Table 2. Treatment arrangement in D–310 design in Wuqiao, Hebei (1999-2000; Kg/666.7m^2)

Plot No.	Autumn			Spring	Plot No.	Autumn			Spring
	X_N (urea)	X_P (Potassium sulfate)	X_K (calcium phosphate)	urea		X_N (urea)	X_P (Potassium sulfate)	X_K (calcium phosphate)	urea
1	0.00	0.00	0.00	0.00	6	29.80	0.00	59.60	14.90
2	50.00	0.00	0.00	25.00	7	29.80	29.80	0.00	14.90
3	50.00	0.00	100.00	25.00	8	17.80	50.00	100.00	8.90
4	0.00	0.00	100.00	0.00	9	50.00	17.78	100.00	25.00
5	0.00	29.80	59.60	0.00	10	50.00	39.50	35.43	25.00

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Table 3. Yield and yield components of Shendan 7

Plot code	Yield (kg / 666.7m^2)	Ear number (ears / 666.7m^2)	Grain number per ear	Weight of 100 grains (g)	Plot code	Yield (kg / 666.7m^2)	Ear number (ears / 666.7m^2)	Grain number per ear	Weight of 100 grains (g)
1	715.3	5336	647.5	23.7	9	608.6	5043	691	23.3
2	772.1	4882	673.9	23.5	10	734.9	4669	538.9	26.3
3	700.1	5256	677.3	28	11	751.2	5496	540.4	20.4
4	688.1	6296	568.5	22.8	12	561.3	3255	717.9	27.5
5	735.4	3468	735	26.3	13	759	4589	677.3	22.9
6	746.6	5416	686.7	20.1	14	666.1	3735	544.6	27.7
7	611.9	3735	669.6	24.5	15	602	3308	564.6	22.4
8	735.7	5203	568	22.2	16	559.4	4802	547.6	21.0

Table 4. Yield and yield components of Pin 16 (P) and 935031 (L)

Plot code	Spike number (10^4 /666.7m^2)		Grain number per spike		Grain weight of 1000 grains (g)		Theoretic yield (kg/666.7m^2)		Harvested yield (kg/666.7m^2)		Harvest Index	
Var.	P	L	P	L	P	L	P	L	P	L	P	L
1	27.75	29.73	36.7	33.4	37.98	42.6	386.80	423.01	351.8	441.6	0.475	0.430
2	28.8	30.2	38.2	35	33.83	40.65	372.18	429.67	330.1	408.2	0.457	0.490
3	26.93	28.27	34.9	35.2	32.17	40.65	302.35	404.51	295.4	394.9	0.456	0.485
4	28.33	30.67	41.1	33.6	34.41	43.66	400.66	449.92	341.5	424.3	0.480	0.498
5	27.07	31.33	38.2	38.3	37.01	40.93	382.71	491.14	353.8	476.8	0.478	0.444
6	27.27	30.27	40.6	34.1	34.69	40.83	384.07	421.45	374.1	408.3	0.470	0.424
7	30.13	35.2	36.3	28.8	34.74	36.9	379.96	374.08	413.2	442.8	0.481	0.469
8	27.87	31.6	40.8	31.3	37.01	38.29	420.84	378.72	398.7	376.3	0.478	0.462
9	30.67	30.93	44.4	38.4	34.81	39.95	474.02	474.49	405.3	412.8	0.466	0.507
10	28.53	31.2	36.8	35.6	34.13	38.43	358.33	426.85	318.1	376.6	0.464	0.489

Table 5. Yield and yield component equation coefficients for the wheat (Pin 16 and 935031)

Var.	item	intercept	X_N	X_P	X_K	X_N^2	X_P^2	X_K^2	X_PX_K	X_NX_K	X_NX_P
Pin 16	spike	29.42	1.15	0.71	-1.10	-0.99	1.59	-3.18	1.03	1.24	-0.61
	grain	43.56	2.01	5.67	-4.98	-3.17	-0.07	-7.57	5.40	3.20	-1.93
	weight	36.3	-1.10	0.51	-0.11	-0.30	-0.36	-1.17	1.82	0.50	0.48
	yield	459.1	24.38	72.21	-64.71	-46.43	17.92	-129.8	86.20	52.61	-20.92
935031	spike	33.32	-0.10	-0.49	0.30	-2.07	1.32	-2.56	-0.24	0.38	-0.72
	grain	35.28	0.59	2.44	-2.15	3.68	-3.29	-3.51	2.34	-0.22	0.001
	weight	38.92	-0.77	0.91	-1.98	1.48	-0.58	0.69	0.65	0.47	-0.27
	yield	456.8	-2.28	35.83	-44.54	35.45	-32.26	-77.70	35.39	7.41	-13.02

Table 6. Coordinates of independent variables at the stationary points of yield equations

Var.	Max. theoretical yield (kg/666.7m^2)	X_1 or X_N	X_2 or X_P	X_3 or X_K	X_4
Shendan 7	1026.2	5257	2684	15.864	70.14
Pin 16	448.4	1.066901	0.899667	3.55306	
935031	468.4	1.654994	5.786803	3.43235	

Table 7. S_p values of yield components to agronomic factors at yield stationary points

Cultivar		Shendan 7			Pin 16			935031		
Component		spike	grain	weight	spike	grain	weight	spike	Grain	weight
Factor	X_1 or X_N	-32.63	-0.047	-40.51	-5.09	-18.80	-2.252	-527.316	25.466	8.6121
	X_2 or X_P	-0.16	0.025	1.55×10^{-3}	2.47	2.42	3.495	11.9036	-31.764	-9.022
	X_3 or X_K	-30.21	-0.983	1.92	-2.56	-4.91	-0.426	-8.26545	-0.991	5.65
	X_4	4.79	-112.18	4.60×10^{-3}						

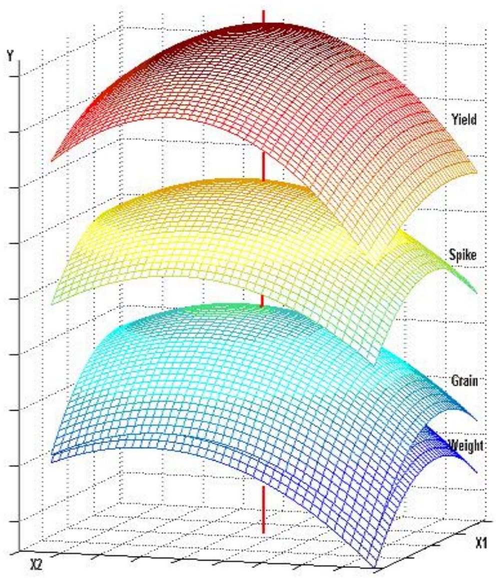

Figure 1. Sketch map of yield and its components surface (Protracted by Wang Yong)