African Journal of Agricultural Research Vol. 5(23), pp. 3251-3258, 4 December, 2010
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJAR10.589
ISSN 1991-637X ©2010 Academic Journals

Full Length Research Paper

Effectiveness of phosphorus application in improving regional soybean yields under drought stress: A multivariate regression tree analysis

Haifeng Zheng[1,2], Liding Chen[2]*, Xiaozeng Han[1,3], Yan Ma[2] and Xinfeng Zhao[2]

[1]Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences, Changchun, Jilin Province 130012, China.
[2]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, People's Republic of China.
[3]National Field Research Station of Agro-ecosystem in Hailun, Northeast Institute of Geography and Agro-ecology, Chinese Academy of Sciences, Harbin 150081, People's Republic of China.

Accepted 20 October, 2010

Scarcity of water often reduces the regional production of soybean (*Glycine max* (L.) Merr.) in many areas where it is grown. Contemporary climate change is characterized by increase in frequency and intensity of drought, yet little is known about the successful strategies of soybean cropping systems to drought stress at the regional scale. An effective way to improve the understanding is how to reduce the yields variability across regional fields and consequently increase total soybean production under drought conditions. In this study, using a series of household surveys and on-field trials conducted during a severe drought in 2007 provided data for 118 soybean fields throughout Hailun County of Northeast China, the triggers of regional yield variability and the relative importance of the determining factors were investigated. Regression trees analysis showed that regional soybean yield variability was mainly induced by soil available phosphorus and the amount of P applied, which explained 16.3 and 15.2% of the yield variation, respectively. Under drought stress, regional yields improvement could be accessed by altering P application rates. The productivity of soybean over the region did not increase when P application rate reached a threshold of 55.67 kg/ha. The results suggest that investing more P fertilizer was an effective management strategy for improving regional soybean production in Northeast China in such drought years and the level of effectiveness varied with the application rates.

Key words: Soybean, yield variability, phosphorus, drought, strategy, threshold.

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) was first domesticated in Northeast China, and has been adopted as a diet staple throughout many parts of the world. A major soybean-cropping region is located in Northeast China, including Heilongjiang, Jilin and Liaoning Provinces. The total soybean acreage of this region was around 4.5 million ha, which accounts for about 5% of the total soybean acreage in the world (Editorial Board for Agricultural Yearbook of China, 2008; FAO, 2009). During 2007, total soybean production in Northeast China was 5.3 million Mg (Editorial Board for Agricultural Yearbook of China, 2008). Soybean production in Northeast China contributes significantly to the economic structure of the worldwide food network and also plays an important role in global trade and international investment.

In 2007, one of the most extreme growing-season (May - September) droughts of the past few decades occurred in Northeast China. The growing season precipitation of the region totaled 350 mm, which was 110

*Corresponding author. E-mail: zhfdd@msn.com. Tel: +86-10-62943840. Fax: +86-10-62849104.

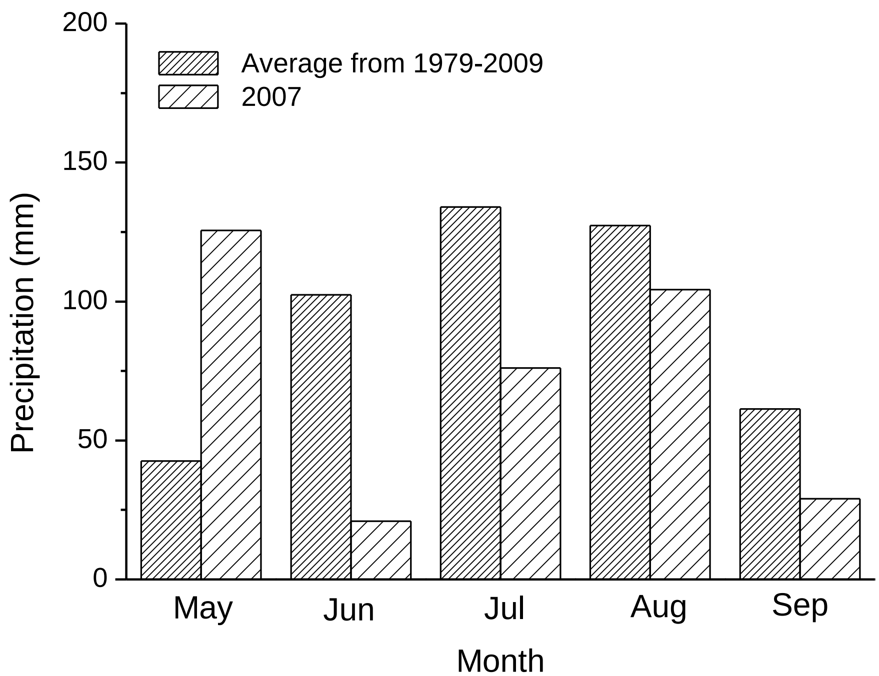

Figure 1. Monthly mean precipitation for growing season in 2007, and historical averages from 1979 to 2009.

mm below the 30 years average. June precipitation was only 25 mm, 80% below the long-term average (Figure 1). As a consequence of the 2007 drought, soybean yield in Northeast China fell to its lowest level since 1990s. The biggest soybean producer, Heilongjiang Province, achieved average soybean yields of only 1.1 t/ha (Editorial Board for Agricultural Yearbook of China, 2008).

Within the global warming perspective, drought is expected to increase in frequency and intensity over wide areas of the world (Meehl and Tebaldi, 2004; IPCC, 2007). Northeast China has experienced severe and prolonged dry periods since the late 1980s, with a drying trend rate of 31.8% per decade (Zou et al., 2005). Future increase in the frequency and intensity of drought could thereby have dramatic impacts on soybean production. There is therefore a pressing need to conduct new studies investigating how soybean yields in Northeast China can be increased on the large spatial scales under severe drought conditions (Figure 1).

Soybean is an economical and agronomical crop because of its high ability to assimilate atmospheric N_2 into forms that plants can use. However, symbiotic N_2 fixation in soybean has been shown to be highly sensitive to soil moisture (Sinclair and Serraj, 1995; Serraj et al., 1999) and dry soil conditions result in both decreased N accumulation and soybean yield. In a glasshouse pot experiment in Northeast China, Han et al. (2003) found that drought stress sufficient to result in a decline in grain yield was likely to occur at any stage of soybean growth. Xie et al. (1994) demonstrated that both early maturity and late maturity soybean cultivars commonly grown in Northeast China suffered yield reduction when drought stress occurred during flowering or seed-filling periods. The effects of drought stress differ with growth stages of soybean plants. Stress during early reproductive growth could affect soybean yield by reducing number of pods and seeds per unit area (Frederick et al., 2001; Liu et al., 2004; Zhao et al., 2006), whereas stress during seed filling accelerated leaf senescence, which shortened the seed-filling period and resulted in smaller seeds (Desclaux and Roumet, 1996; Egli and Bruening, 2004).

A large number of the studies have been conducted to examine soybean adaptations to drought conditions. However, most studies to date considered physiological and molecular aspects (Sinclair et al., 2000; Streeter et al., 2001; Oya et al., 2004; Hufstetler et al., 2007; Sinclair et al., 2007; Manavalan et al., 2009). The effectiveness and opportunities for farm management-level strategy has received relatively little attention in the literature. A key question for this study is to investigate which management factors exert a critical role in maintaining soybean production at the regional scale under severe drought conditions.

To answer this question, the relative importance of all the soil and management variables in determining regional variability of soybean yields were examined in the drought year, 2007. The approach to solving the multivariate analyses was based on regression trees, which are robust and suitable for predicting agricultural yield variability responses to variations of abiotic, biotic and associated crop management constraints (Lobell et al., 2005; Tittonell et al., 2008; Zheng et al., 2009).

Table 1. Summary of soil variables for selected survey fields.

Variables	Maximum	Minimum	Mean	CV	IQR*
OM (%)	11.28	1.044	4.634	0.316	1.391
TN (g/kg)	0.486	0.08	0.235	0.261	0.07
TP (g/kg)	3.19	0.48	0.894	0.438	0.32
TK (g/kg)	31.76	17.16	21.423	0.091	1.52
pH	8.21	5.27	6.45	0.101	0.67
EC (Ds/m)	930	74.2	181.419	0.653	111.00
AP (mg/kg)	78.83	3.76	17.55	0.80	11.99
AK (mg/kg)	611.09	80.1	195.329	0.378	56.01

*IQR, the distance between the 75th percentile and the 25th percentile.

MATERIALS AND METHODS

Site description

The study was conducted in Hailun County (47°N, 126°E) of Heilongjiang Province in Northeast China, an agricultural region that is characterized by high levels of management intensity. It comprises roughly 270,000 ha of cultivated land, with 45 - 65% of this area typically planted with soybean each season. The elevation range of the study area is from 150 to 290 m above sea level. The climate in Hailun County is a temperate continental monsoon. Rainfall ranges from 300 to 700 mm annually and is mostly distributed in the soybean growing season period (May - September). Daily mean temperature during the soybean growing season averages 17.8°C. The region has very fertile soils with organic matter content over 3%. Most of the soils are predominantly vertisols. Fragmentation of landholdings is a common feature of the agricultural systems of small farmers in the region. The length of the farm is large (200 - 800 m), but the width is very small (10 - 30 m). Average field sizes range from 0.2 to 1.0 ha. The term “field” here refers to the one farmer’s land, which is managed independently, but is not separated from adjacent fields by fences or other physical barriers. The landscape of many fields is fairly flat. No irrigation was applied to the soybean fields in this region during the growing season. Most farmers usually apply NPK compound chemical fertilizer to soybean farms at a rate over 250 kg/ha per year. The application rates of N, P and K varied over years and among individual farmers.

Field design and sampling

A total of 118 representative fields uniformly distributed across the study region (Hailun County) were selected for analysis. The surface of each selected field was characterized by flat plain topography. Before sowing, all the fields were confirmed to be used for planting soybean in the current year. A transect with width of 9 m perpendicular to the direction of tillage was established across the middle of each field. Nine soil samples from top-soil (0 - 20 cm) were collected with a manual soil coring tube in an S-shaped pattern along the transect line in each field. The nine samples were bulked to form one composite sample for each field making a total of 118 soil samples for the study.

The fresh soil of each soil sample was air-dried and sieved and stored for subsequent analysis. Soil samples were analyzed using procedures of the standard soil test methods (Lu, 1999). Soil organic matter (SOC) was measured by the $K_2Cr_2O_7$ titration method after digestion. Soil pH was determined in water using a 1:2.5 soil/solution ratio. Soil electrical conductivity (EC) was measured using Mettler Toledo Delta-326 conductivity meter (Mettler Toledo, Shanghai, China). Soil total nitrogen (TN) was determined according to the semi-micro Kjeldahl method. Available nitrogen (AN) was determined by the Cornfield method (alkaline hydrolysable nitrogen). Total phosphorus (TP) was determined by colorimetrically after wet digestion with H_2SO_4 plus $HClO_4$. Total potassium (TK) was analyzed using atomic absorption spectrometer. Available phosphorus (AP) and available potassium (AK) were measured by ICP-AES after samples were extracted with 0.03 $(NH_4)_2CO_3$ solution. Statistics for the measured soil variables across all the regional fields were presented in Table 1.

At maturity, nine plant subsamples were hand harvested from each field. Each subsample consisted of 1 m segments from each of the two rows adjacent to where the soil subsample was taken. Plants were cut and then grain was collected and stored in a labeled bag. Row space of all the studied fields was measured by tapeline for subsequent calculation of soybean yields. The partitioned seed samples were oven-dried at 70°C to a constant weight. Dried grain from each soybean field was weighed and adjusted to 125 g/kg moisture for final yield calculation.

Household surveys

A survey was conducted with the 118 households of the selected fields from April to October of 2007. Household heads or their spouses for all the various fields were chosen as the interviewees because they are usually the decision-makers of household affairs. A subset of the information obtained is given in Table 2. Farm management information included variety of soybean, sowing rate, planting date, crop rotations, type of tillage, methods of soil preparation before sowing, type and amount of insecticide and herbicide applications, whether or not farmyard manure (FYM) was added to fields and type and total amount of fertilizer (including N, P and K) applied. Application rates of N, P and K in each field were calculated from their respective percentages as written on the fertilizer bags and the bulk application rate reported by the interviewee. In addition, socio-economic information were collected, such as age and education level of the selected heads of the household, family structure, cropland area, mean household income and sources of income.

Statistical analysis

Classification and regression tree analysis (CART; Breiman et al., 1984) was used to predict or explain the response of regional soybean yields to soil parameters and field management practices. CART is a nonparametric statistical approach that partitions the data to find increasingly homogeneous subsets based on independent variable splitting criteria using variance minimizing algorithms. Homogeneity of partitioned groups was assessed by the least

Table 2. Agronomic management variables used in the CART analysis.

Variables	Unit	Description	Mean	S.D.	Maximum	Minimum	IQR*
N	Kg/ha	Fertilizer N applied	39.89	0.87	75	22.5	11.4
P	Kg/ha	Fertilizer P applied	40.18	1.1	73.67	18.92	14.55
K	Kg/ha	Fertilizer K applied	33.55	0.78	59.33	11.60	11.24
DTPL	Days	Planting date (days after 15 April)	22	0.53	31	2	5
SR	Kg/ha	Sowing rate	58.01	0.65	75	35	7
FYM	None	Farmyard manure addition (0 = non-manured, 1 = manured)	0	0	0	0	0
CROP	None	Crop planted last year (0 = soybean, 1 = corn)	0.34	0.16	1	0	1
INSECT	None	Insecticide applied (0 = no, 1 = yes)	1	0	1	1	0
HERBICID	None	Herbicide applied (0 = no, 1 = yes)	1	0	1	1	0
VAR	None	Variety (fourteen varieties in total, coded from 0 to 13)	3.58	0.27	13	0	4
TT	None	Tillage traction (0 = horse power, 1 = tractor power)	1	0	1	1	0
TILL	None	Tillage practice: autumn ploughing (coded 0), spring ploughing followed by spring secondary tillage (coded 1) or no ploughing (coded 2)	0.75	0.08	2	0	1

*IQR, the distance between the 75th percentile and the 25th percentile.

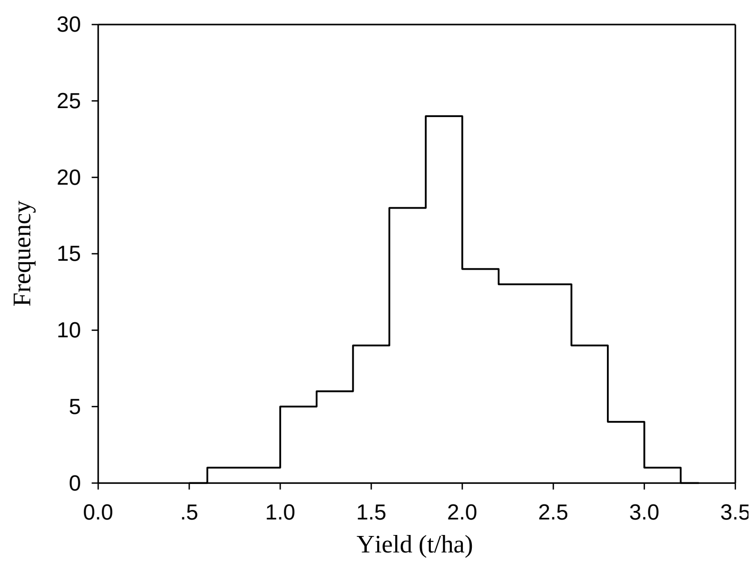

Figure 2. Histogram of soybean yields at the regional scale.

squares as the loss function with a minimum proportional reduction of error (PRE) at any split of 0.05 and minimum of five objects allowed in any node. For regression tree, the PRE is equivalent to the multiple R^2. As a popular data mining technique, CART model has recently been widely used for detecting crop yields variability in the agricultural field (Roel et al., 2007; Tittonell et al., 2008; Zheng et al., 2009; Ferraro et al., 2009).

CART in the “TREES” model of SYSTAT statistical software version 12 (Systat, 2007) were implemented. All the soil and management predictor variables used in analyses were shown in Tables 1and 2, respectively.

RESULTS

Yield variability

Figure 2 showed the distribution in soybean grain yield at the regional scale; the variability was surprisingly high (CV = 0.24). Across the 118 fields, soybean grain yield varied from 0.7 to 3.1 t/ha, with a mean of 2.0 t/ha and a standard deviation of 0.49 t/ha. Yields were distributed normally and above 85% of the fields attained yields ranging from 1.4 to

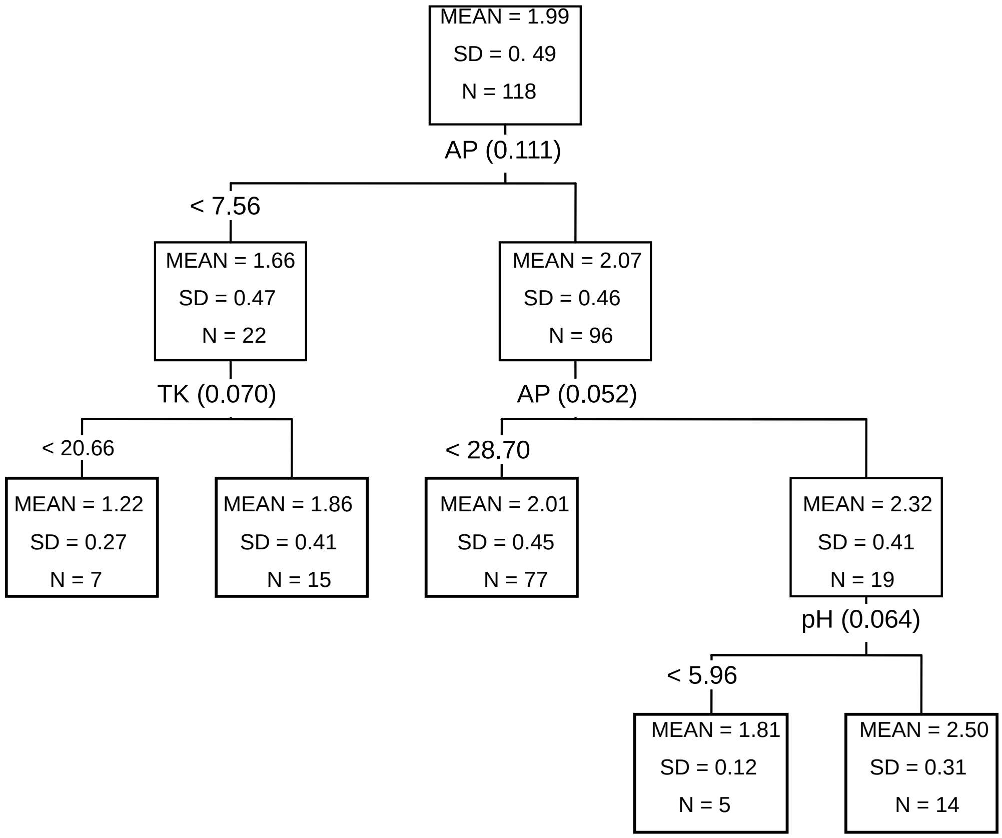

Figure 3. Regression tree predicting soybean yields from soil variables (PRE = 0.29). Each node (square) is labeled with average yield (Mean), standard deviation (S.D.) and the number (n) of fields in that group. The model is read from top down until terminal nodes appear. Partial PRE values are presented in parentheses at each root node to split.

2.6 t/ha. The large differences in soybean grain yield between regional fields were attributed to the large range in both soil properties (Table 1) and field management practices (Table 2) within the study site (Figure 2).

Multivariate regression tree for soybean yield versus soil properties

The regression tree model suggested that soybean grain yield varied as a function of selected soil variables (Figure 3). The model explaining the largest amount of variation in soybean yield (0.30) was a regression tree pruned to five terminal nodes by three soil variables. In the tree, yield variability estimations were first split by soil available phosphorus (AP), indicating that AP was the most dominant measured soil variable influencing soybean yield. This split produced two relatively homogenous groups of data: one had 22 fields with soil AP content less than 7.56 mg/kg achieving a mean yield of 1.66 t/ha and the other had 96 fields with AP greater than 7.56 mg/kg achieving a mean yield of 2.07 t/ha. The first data partition accounted for nearly 0.111 of the variation in the original dataset. Each of these two groups was further subdivided according to total potassium (TK) and AP class, respectively. In the left-hand branch, fields with low soil TK (< 20.66 g/kg) had smaller yields than those with high soil TK. No additional splits were performed in the left hand branch after the split on soil TK. In the right-hand branch, fields with soil AP more than 28.7 mg/kg had superior grain yield (mean = 2.32 vs. 2.01 t/ha). There was an increase of a 15% in the yield of soybean with high AP as compared to the low AP. At the third level in the hierarchy, the group with high soil AP was split based on soil pH (pH = 5.96), which accounted for 6.4% of the yield variation. The low pH showed that fields were considered to be threatened from soil acidification. The dominant factor governing soybean yield in this drought year was soil AP with higher soybean yields in fields with higher AP (Figure 3).

Multivariate regression tree for soybean yield versus management practices

A regression tree to explain the relationship between soybean grain yield and management practices was

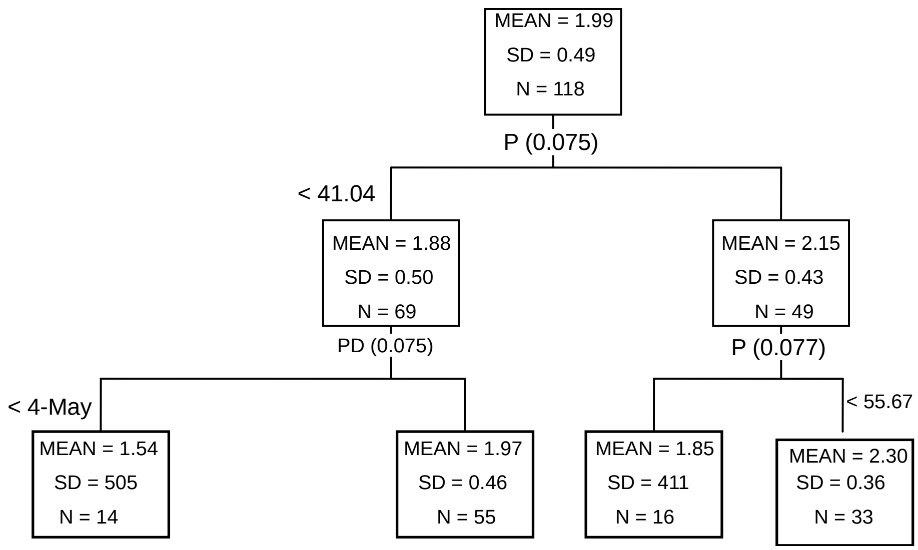

Figure 4. Regression tree predicting soybean yield from agronomic management variables (PRE = 0.23).

developed. In the tree analysis, soybean yields were remarkably predictable as a function of management variables and the full model explained 22.7% of the variation in the original dataset (Figure 4). The branching sequence of the regression tree indicates that P application rate and planting date were the most important predictors of yield. The primary split into two different sized groups occurred when the amount of applied P was 41.04 kg/ha. This single split explained nearly 8% of yield variation. Soybean yield was inferior in the fields receiving low P application. Average yield was 1.88 t/ha (S.D. = 0.50) for the 69 fields receiving P rate less than 41.04 kg/ha compared to 2.15 t/ha (S.D. = 0.43) for the 49 fields receiving more than 41.04 kg/ha applied P. The data low applied P were further grouped into two terminal nodes on the basis of planting date. Fields that were planted before 4th May obtained lower average yield. The remaining cases (49 fields) in the high P rate group (> 41.04 kg/ha) were again split into two branches according to P application rate, which explained 7.7% of yield variability. It should be noted that fields with the highest P rate (> 55.67 kg/ha) experienced yield reduction. In contrast, those fields receiving lower P rate (41.04 - 55.67 kg/ha) had the highest average yield (mean = 2.3 t/ha). To summarize, P application rate was the most important management variable for soybean cropping system under drought conditions, but there was a critical upper threshold (55.67 kg/ha) above which yield was suppressed (Figure 4).

DISCUSSION

The analysis carried out by CART model showed that soil and management variations between fields drove a large part of yield variability observed at the regional scale. It is commonly assumed that yield variability is mostly caused by the existence of soil spatial heterogeneity within smallholder farmlands. However, CART models showed that the importance of management variables in determining soybean yield variability were nearly equal to soil variables (Figures 3 and 4). In fact, a few recent studies have shed some light on the significance of management differences in determining crop yield variability (Lobell et al., 2002, 2005; Tittonell et al., 2008; Zheng et al., 2009). According to these findings, management practices, as opposed to soil properties, explained the majority of observed yield variability (from 51 to 93%). The importance of field management practices as explanatory factors for yield varied with crop and site. On the other hand, the relative contribution of soil properties and crop management variables to yield variation was dependent on the spatial scale. In the study area, the previous experiment at the village scale (many fields managed by different farmers in a village) in the same region detected that soil and management explained roughly 81% of the variability of soybean yield and management variables alone explained roughly 76% of yield variability (Zheng et al., 2009). In this study at the regional scale, the results indicated that management differences accounted for roughly 22.7% of the variation in soybean yield with the same number of variables at the village scale. These results presented above imply that the contributions of management practices to yield variability become less as the spatial scale is increased from the village to the region. The reduction in the importance of management effects for yield variability might stem from the increase in unmeasured sources of yield variability such as spatial distribution of micro-climate and plant diseases or insect pests. Essentially, the above observation has the important implication that remarkable soybean yield increases appear possible both at the village scale and the regional scale by adopting appropriate management practices. The difference in variability explained by management at the village and regional scales implies that appropriate management practices may be different in different parts of the region, possibly influenced by differences in climate, topography etc. (Lobell et al., 2002, 2005). For example, localized rain showers could cause considerable regional variability, particularly in a drought year. Thus, identification of management strategies for improving crop yields should consider climate variability between years.

During the 2007 growing season, the overall results obtained in this study indicated that soil AP content and P application rate played a substantial role in determining soybean yields (Figures 3 and 4). This suggests that more applications of P tended to narrow the differences in soybean yields across all the fields and improve regional soybean production under drought conditions. In soils with low soil test P levels, P application ameliorated the negative effects of drought on relative water content, net photosynthetic rate, carbohydrate metabolism and soluble protein content in pulse crops (Garg et al., 2004). Recent research also found that application of P could improve root morphology and P uptake of different soybean cultivars when the water deficiency occurred at either the R1 or R4 stage (Jin et al., 2005). In addition, recent work showed that increased P application stimulated higher nitrogen fixation rates (Ogoke et al., 2003; Rotaru and Sinclair, 2009). As a result of larger water and nutrients uptake, higher P rates were able to alleviate the drought-induced soybean yield reduction.

However, the availability of the P from the applied P varied with soil test available P content. A study in Nigeria has shown that the effect of P application was significant when soil available P levels were below 7.0 mg/kg, whereas when soil available P levels exceeded 16.2 mg/kg, P application did not significantly increase soybean yield (Ogoke et al., 2003). Also, in the Black Soil of Northeast China, researchers found that increased P application did not significantly increase soybean yield when soil available P supply was higher than 26 mg/kg (Dong, 2000). The results presented above suggest that there were thresholds for P application either in the fields with low soil available P content or in the fields with high soil available P content. In the control plots of the study area, Wang et al. (2006) found that the thresholds of P application ranged from 49.1 to 65.5 kg/ha when soil available P content was about 4.1 mg/kg. In the present study, the results demonstrate that a maximum threshold of 55.67 kg/ha for P application exists across the soybean fields on the regional scale (Figure 4). This maximum threshold of P application was within the threshold range detected by Wang et al. (2006). The thresholds of P application and P availability may vary with year and environment conditions. Under the severe drought conditions during 2007, the threshold effect of P application was observed for soybean systems in Northeast China, but further studies are required to assess the threshold of P application for soybean in different climatic conditions.

The results presented here provide evidence that increased P application was the most effective strategy of soybean cropping system in Northeast China to increase regional yields under drought conditions. One of the most striking results observed in this research, however, was that a threshold point of the P application occurred at the regional scale. This suggests that the effectiveness and constraints must be considered carefully in developing possible strategies for soybean cropping systems under drought conditions. In soybeans, drought stress results in a decline in symbiotic N_2 fixation activity and consequently a reduction in yield (Serraj et al., 1999). Through breeding programs, it may be possible to reduce the sensitivity of N_2 fixation to drought stress. Accordingly, there is a pressing need for scientists and plant breeders to select and develop suitable genotypes associated with N_2 fixation drought resistance in soybean. Significant scientific effort and government support is required to devise appropriate strategies to adapt soybean production systems to inevitable increase in drought conditions accompanying global warming to ensure sustainability of the important food production region in Northeast China.

In conclusion, the present study indicates that P application is a key determinant of regional soybean yields in such severe drought year. Increases in P application rates can dramatically minimize the large variation in soybean yields among fields and achieve higher total regional soybean production. However, this management strategy should only be applied to fields with low available P as the effectiveness was greatly reduced when the application of P rates reached a maximum threshold (55.67 kg/ha). It is proposed that improving P availability is the foremost concern for soybean cropping systems of the study region under drought stress.

ACKNOWLEDGEMENTS

The authors thank all of the people involved in the experiments. This work was supported by the National Science Fund for Distinguished Young Scholars of China (40925003), the Knowledge Innovation Program of NEIGAE, Chinese Academy of Sciences (KZCX3-SW-NA09-10), and National Natural Science Foundation of China (41001053).

REFERENCES

Breiman L, Friedman JH, Olshen RA, Stone CJ (1984). Classification and Regression Trees. Chapman and Hall (Wadsworth, Inc.), New York, NY USA, 254 p.

Desclaux D, Roumet P (1996). Impact of drought stress on the phenology of two soybean (*Glycine max* L Merr) cultivars. Field Crop Res., 46: 61-70.

Dong Z (2000). Soybean yield physiology. China Agriculture Press, Beijing, 157 pp. (in Chinese).

Editorial Board – China Agriculture Press (2008). China Agriculture Yearbook 2008. China Agriculture Press, Beijing (in Chinese).

Egli DB, Bruening WP (2004). Water stress, photosynthesis, seed sucrose levels and seed growth in soybean. J. Agr. Sci., 142: 1-8.

FAOSTAT (2009). Statistics Database. http://faostat.fao.org/default.aspx (verified 23 June 2009).
Ferraro DO, Rivero DE, Ghersa CM (2009). An analysis of the factors that influence sugarcane yield in Northern Argentina using classification and regression trees. Field Crop Res., 112: 149-157.
Frederick JR, Camp CR, Bauer PJ (2001). Drought-stress effects on branch and mainstem seed yield and yield components of determinate soybean. Crop Sci., 41: 759-763.
Garg BK, Burman U, Kathju S (2004). The influence of phosphorus nutrition on the physiological response of moth bean genotypes to drought. J. Plant Nutr. Soil Sci., 167: 503-508.
Han XZ, Qiao YF, Zhang QY, Wang SY, Song CY (2003). Effects of various soil mosture on the yield of soybean. Soybean Sci., 4: 269–272 (in Chinese).
Hufstetler EV, Boerma HR, Carter TE, Earl HJ (2007). Genotypic variation for three physiological traits affecting drought tolerance in soybean. Crop Sci., 47: 25-35.
IPCC (2007). Climate change 2007: The Physical Science Basis. In: Trenberth, K.E., Jones, P.D., Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge.
Jin J, Wang GH, Liu XB, Pan XW, Herbert SJ (2005). Phosphorus application affects the soybean root response to water deficit at the initial flowering and full pod stages. Soil Sci. Plant Nutr., 51: 953-960.
Liu FL, Jensen CR, Andersen MN (2004). Drought stress effect on carbohydrate concentration in soybean leaves and pods during early reproductive development: its implication in altering pod set. Field Crop Res., 86: 1-13.
Lobell DB, Ortiz-Monasterio JI, Addams CL, Asner GP (2002). Soil, climate, and management impacts on regional wheat productivity in Mexico from remote sensing. Agric. For. Meteorol., 114: 31-43.
Lobell DB, Ortiz-Monasterio JI, Asner GP, Naylor RL, Falcon WP (2005). Combining field surveys, remote sensing, and regression trees to understand yield variations in an irrigated wheat landscape. Agron. J., 97: 241-249.
Lu RK (1999). Methods for Soil and Agriculture Chemistry Analysis. Chinese Agricultural Science and Technology Press, Beijing (in Chinese).
Manavalan LP, Guttikonda SK, Tran LSP, Nguyen HT (2009). Physiological and Molecular Approaches to Improve Drought Resistance in Soybean. Plant Cell Physiol., 50: 1260-1276.
Meehl GA, Tebaldi C (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. Science, 305: 994-997.
Ogoke IJ, Carsky RJ, Togun AO, Dashiell K (2003). Effect of P fertilizer application on N balance of soybean crop in the guinea savanna of Nigeria. Agric. Ecosyst. Environ., 100: 153-159.
Oya T, Nepomuceno AL, Neumaier N, Farias JRB, Tobita S, Ito O (2004). Drought Tolerance Characteristics of Brazilian soybean cultivars - Evaluation and characterization of drought tolerance of various Brazilian soybean cultivars in the field. Plant. Prod. Sci., 7: 129-137.
Roel A, Firpo H, Plant RE (2007). Why do some farmers get higher yields? Multivariate analysis of a group of Uruguayan rice farmers. Comput. Electron. Agric., 58: 78-92.
Rotaru V, Sinclair TR (2009). Interactive influence of phosphorus and iron on nitrogen fixation by soybean. Environ. Exp. Bot., 66: 94-99.
Serraj R, Sinclair TR, Purcell LC (1999). Symbiotic N_2 fixation response to drought. J. Exp. Bot., 50: 143-155.
Sinclair TR, Purcell LC, King CA, Sneller CH, Chen PY, Vadez V (2007). Drought tolerance and yield increase of soybean resulting from improved symbiotic N_2 fixation. Field Crop Res., 101: 68-71.
Sinclair TR, Purcell LC, Vadez V, Serraj R, King CA, Nelson R (2000). Identification of soybean genotypes with N_2 fixation tolerance to water deficits. Crop Sci., 40: 1803-1809.
Sinclair TR, Serraj R (1995). Legume Nitrogen-Fixation and Drought. 378: 344-344.
Streeter JG, Lohnes DG, Fioritto RJ (2001). Patterns of pinitol accumulation in soybean plants and relationships to drought tolerance. Plant Cell Environ., 24: 429-438.
SYSTAT 2007 SYSTAT, 2007. SYSTAT, version 12.0. SYSTAT Software, Inc., Richmond, CA.
Tittonell P, Shepherd KD, Vanlauwe B, Giller KE (2008). Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya - An application of classification and regression tree analysis. Agric. Ecosyst. Environ., 123: 137-150.
Wang JG, Li ZL, Li WB, Xu YL, Li CJ (2006). Application of phosphorus in relation to soybean yield and quality. Syst. Sci. Compr. Stud. Agri., 1: 55-57.
Xie FD, Dong Z, Sun YH, Wang XG (1994). Influence of drought on growth and yield of soybeans at different growth stages. J. Shenyang Agric. Univ., 25: 13-16 (in Chinese).
Zhao HW, Li QZ, Wei YX (2006). Effect of drought at different growth stages on main physiological parameters and yield in soybean. Soybean Sci. 3: 329-332 (in Chinese).
Zheng HF, Chen LD, Han XZ, Zhao XF, Ma Y (2009). Classification and regression tree (CART) for analysis of soybean yield variability among fields in Northeast China: The importance of phosphorus application rates under drought conditions. Agric. Ecosyst. Environ. 132: 98-105.
Zou XK, Zhai PM, Zhang Q (2005). Variations in droughts over China: 1951-2003. Geophys Res Lett., 32, L04707, doi:10.1029/2004GL021853.