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Characterization of Soybean Yield Variability Using Crop Growth Models and ^{13}C Discrimination

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Abstract. *During the past several years, crop models have successfully been used to test the hypothesis that water stress is the primary factor that causes spatial yield variability in soybean [Glycine max (L.) Merr.] fields. However, there have been few attempts to validate this hypothesis through direct temporal and spatial measurements of water stress during the season. Recently, a* *technique has been developed to relate plant tissue ^{13}C levels to the temporal water stress experienced by soybean plants. The purpose of this work was to compare the spatial yield loss simulated by a crop model with yield loss measured by ^{13}C discrimination (Δ) for a soybean field in South Dakota. The field was divided into 0.9-ha grids and the CROPGRO-Soybean model was calibrated to minimize error between simulated and observed yield in each grid over two seasons (1998, 2000). ^{13}C discrimination was measured at 50 points representing 23 of the grids used in the crop modeling analysis in 2000. Simulated yield loss in grids that encompassed each ^{13}C point in 2000 were compared to measurements of yield loss using the ^{13}C discrimination technique. Initially, the root mean square error and r^2 between simulated and measured yield loss was 259 kg ha^{-1} and 0.24, respectively. Upon closer inspection, it was observed that yield in 5 grids with the highest error likely were influenced by processes that are not represented in the crop model. Removing these values dramatically improved the agreement between simulated and observed yield loss, giving an RMSE of 216 kg ha^{-1} and r^2 of 0.81. Both ^{13}C discrimination and simulation results indicated that substantial yield loss occurred due to water stress in the summit/backslope areas of the field.*

Keywords. Spatial yield variability, CROPGRO-Soybean model, ^{13}C discrimination, water stress

Introduction

Water stress is one of the leading causes of yield loss for non-irrigated soybean production. Recently, produces and researchers have focused much attention on trying to quantify the effect of spatial water stress in creating spatial yield variability within fields. The working hypothesis is that if we can understand the magnitude of within-field variability of water stress, producers can likely capitalize on this information by changing production practices, which will lead to improved profits. Assessment of spatial yield variability within a field is necessary to be able to make better management decisions. Current agricultural research technologies offer tools for farmers in identifying different factors affecting yield variability.

The CROPGRO soybean growth model has proven to be a useful tool for identifying causes of spatial yield variability in soybean fields in the Midwestern United States. Through data collection and model analysis, researchers have verified that water stress is one of the leading contributors to spatial yield variability within soybean fields (Paz et al, 1998, 2001, 2002; Irmak et al, 2002a; Batchelor et al. 2002). In studies by Paz et al. (1998, 2002), the model was calibrated to fit measured historical soybean yield variability over several years in several non-irrigated fields in Iowa and Illinois. A limitation with crop models is that little work has been done to validate the underlying hypothesis used for model calibration, namely, that water stress is the primary cause of yield variability.

One way to verify model conclusions is to measure spatial water content at several sites during the season. Irmak et al. (2002b) investigated the variations in soil water content and the effect on soybean yield in 30 sites across a field. Water balance at each site was calculated in order to quantify water stress and timing of stress. Results of their study showed soybean yield was highly correlated to water stress.

An alternative approach is to use stable isotopic ^{13}C discrimination (Δ), which can be used as a diagnostic tool to evaluate nitrogen and water stress in wheat (Clay et al., 2001b), soybean (Clay et al., 2003), and corn (Clay et al., 2001a). In C_3 plants such as soybean, Δ can be used as an indicator of water stress because when the plant is not water stressed, the stomata are open, stomatal conductance is high, and CO_2 diffusion in and out of the leaf is relatively free. Under these conditions, ribulose bisphosphate carboxylase (RuBisCo) preferentially fixes $^{12}CO_2$ and the fixed CO_2 becomes depleted in ^{13}C. As water stress increases, plants reduce water loss by closing the stomata, which reduces CO_2 diffusion between the pore and the atmosphere. The net result of stomatal closure is increased $^{13}CO_2$ fixation by RuBisCo and decreased Δ of fixed C (Boutton, 1991; O'Leary, 1993).

The objective of this study was to compare spatial yield loss determined by ^{13}C discrimination with yield loss simulated by a soybean crop model to determine if model accurately represents spatial yield loss due to water stress.

Materials and Methods

Field Description

This research was conducted in an eastern South Dakota production field designated as Moody (65-ha). The site has a crop sequence of corn (*Zea mays* L.) followed by soybean and is located at 44° 10' N latitude and 96° 37'W longitude. Dominant soils were Cubden (Aeric Calciaquoll), Wauby (Aquic Hapludoll), Kranzburg (Calcic Hapludoll), and Vienna (Calic Hapludoll). Additional details about the soils at these sites are available in Clay et al. (2001a). Corn was planted in 1995, 1997, and 1999 and soybeans were planted in 1996, 1998, and 2000. Grain yield was measured with a calibrated yield monitor mounted in a combine equipped with differential corrected global positioning system (DGPS). Yield information was collected every second as the combine harvested the crop. Yield monitor data were removed from the database if the combine speed was lower than 1.78 m sec^{-1} or higher than 3.05 m sec^{-1} and if the flow rate exceeded ±3 standard deviations of the average flow rate.

Herbicides and fertilizers were applied to minimize or eliminate yield reductions due to pests and nutrient deficiency. Maintenance was conducted on the tile lines located in poorly drained areas of the fields (footslope area) between 1996 and 1997. Rainfall and air temperatures were measured at a weather station located near the research sites. Elevation at all sampling sites was measured with a carrier-phase DGPS. Gravimetric soil water contents were measured on soil samples (0-15 and 15-60 cm) collected from 50 sampling points on 7 June, 28 June, 18 July, 5 September, and 27 September. The 50 sampling points were located on 4 transects with each sampling point located every 30 m.

Grain samples collected from the sampling points were analyzed for oil and protein on a NIR S5000 Foss Tech (Silver Spring, MD). Grain samples were also analyzed for total N and the amounts of ^{13}C and ^{12}C in the sample on a 20-20 Europa ratio mass spectrometer (Europa Scientific Ltd., UK) (Clay et al., 2003). The ratio between C^{13} and C^{12} was the R value (O'Leary, 1993). The R value was used to calculate $\delta^{13}C$ using the equation:

$$\delta^{13}C = [R(sample)/R(standard)-1] \times 1000‰ \qquad [1]$$

where R(sample) was the $^{13}C/^{12}C$ ratio of the sample and R(standard) was the $^{13}C/^{12}C$ ratio of PDB, a limestone from the Pee Dee formation in South Carolina (O'Leary, 1993; Farquhar and Lloyd, 1993). Typically, $\delta^{13}C$ values for air, C_3, and C_4 plants are -8, -27, and -13‰, respectively. A negative sign indicates that the sample has a lower $^{13}C/^{12}C$ ratio than PDB. In many cases, it is convenient to report ^{13}C discrimination (Δ), which is calculated using the equation:

$$\Delta = (\delta^{13}C_a - \delta^{13}C_p)/(1+ \delta^{13}C_p/1000) \qquad [2]$$

where $\delta^{13}C_a$ is the $\delta^{13}C$ value of air(-8‰) and $\delta^{13}C_p$ is the measured value of the plant.

Model Calibration

The CROPGRO-Soybean crop model (Hoogenboom et al., 1994) is a process-oriented model that was developed to compute growth, development, and yield of soybeans on homogeneous units and has been demonstrated to adequately simulate crop growth at a field or research plot scale. This model requires inputs including management practices and environmental conditions. From this information, daily growth of vegetative, reproductive, and root components are computed as a function of daily photosynthesis, growth stage, and water and nitrogen stress.

In order to use the model to estimate the soybean yield loss due to water stress, specific model parameters were calibrated. The technique outlined by Paz et al. (2001) was used to calibrate the model. In calibration, the field was subdivided into 70 0.9-ha grids. Two model parameters which could not be measured, saturated hydraulic conductivity (KSAT), and root hospitality (RHRF), were calibrated to minimize the root mean square error (RMSE) between simulated and observed yields for each grid over the 2 seasons of data, resulting in a unique set of parameters for each grid. These model parameters primarily affect water movement and rooting depth, which creates water stress condition mirroring the degree of water stress that the soybean plant is subjected to in the field. After calibration, the maximum soybean yield in each grid was determined by the running the model with the water stress option turned off. The yield loss due to water stress in 2000 was calculated by subtracting the estimated yield in each grid from the maximum potential yield.

Results and Discussion

Field Results

Clay et al. (2003) showed that water stress was responsible for yield losses of between 25 and 60%, and that ^{13}C discrimination could be used as an index for water stress in soybean (Figure 1). Based on this relationship, Δ estimated yield losses due to water stress (CYL) were calculated using the equation: CYL= 3300- (-5230+387Δ). In transects 1 and 2 there was an elevation change of approximately 15 m. Soil water content in the highest elevation areas were less than soil water content in low elevation areas. Yield was negatively correlated to elevation and positively correlated to CYL (Fig. 1 and 2). In high elevation areas, adding water increased yield and Δ. Based on Δ information, low, moderate, and high water stressed areas in the field were identified. Soybean plants growing at low elevation sampling points had low water stress, while plants growing at high elevation sampling points had high water stress.

Model calibration

The CROPGRO-Soybean model was calibrated in Moody field in Brookings, South Dakota for 1998 and 2000. We found that predicted soybean yields were in good agreement with measured yield (r^2 = 0.81) after calibrating two model parameters (Figure 3). The root mean square error (RMSE) indicates the degree of variation of predicted yields with respect to the measured yield; and low RMSE value is desirable. The RMSE value was low for Moody (161 kg ha^{-1} or 2.8 bu ac^{-1}). In examining yield prediction in all grids for each year, results show that in 1998, errors between simulated and measured yields in 58 out of 70 grids (83%) were within ±10%, and in 2000, yield estimates in 65 out of 70 grids (93%) were within ±10% of the measured yield (Table 1). These findings provide strong evidence that water stress is the dominant factor affecting yield variability in Moody field. Further, this allows the calibrated model to be used in determining the magnitude and spatial distribution of soybean yield loss across the field.

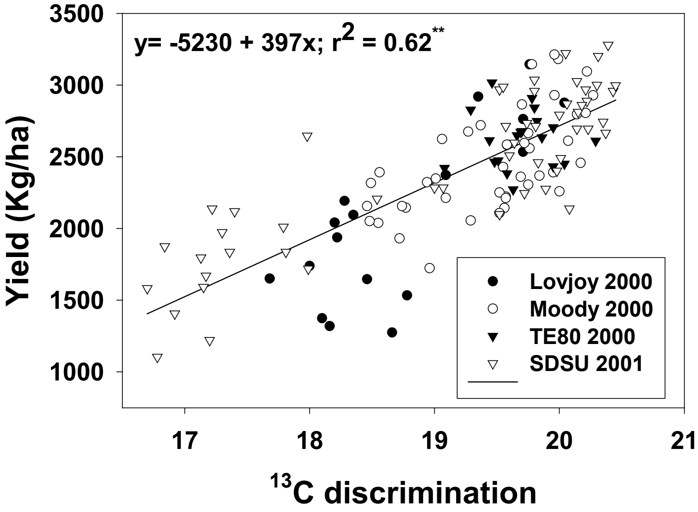

Figure 1. Relationship between yield and ^{13}C discrimination using data points at several fields in South Dakota.

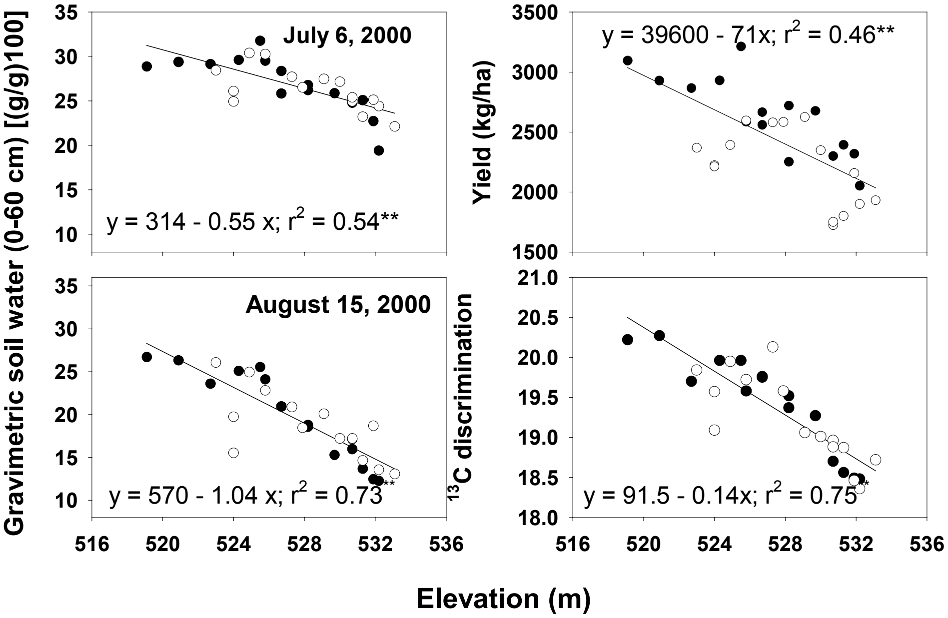

Figure 2. The relationships between elevation, yield, ^{13}C discrimination, and gravimetric soil water content at Moody field.

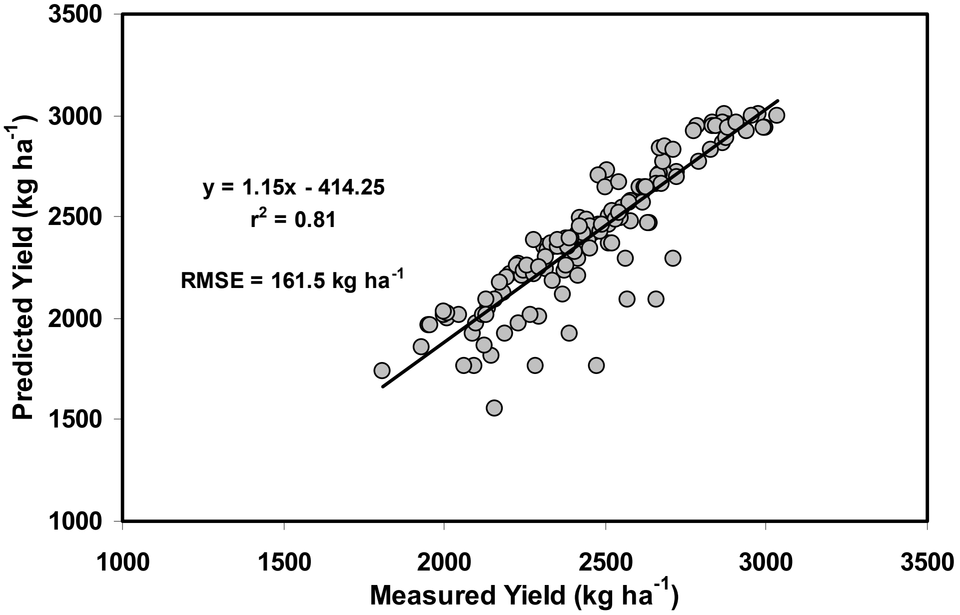

Figure 3. Comparison of measured and predicted soybean yield at Moody field after calibrating the CROPGRO-Soybean model and using two years (1998, 2000) of yield data.

Table 1. The number and percentage of grids in Moody field within different yield prediction error categories over two years of data.

Year	Prediction Error		
	±10%	±15%	±20%
1998	58 (83%)	64 (91%)	67 (96%)
2000	65 (93%)	67 (96%)	69 (99%)

Estimating Yield Loss Due to Stress

The maximum potential soybean yields at Moody (2000) were estimated by running the calibrated model with no water stress (Figure 4). We assumed that there were no other stresses due to soybean cyst nematode (SCN) and weeds. This was a good assumption because scouting of the field showed that SCN was not present and weed populations were low to non-existent. Average crop model estimated yield loss due to water stress was 710 kg ha^{-1}.

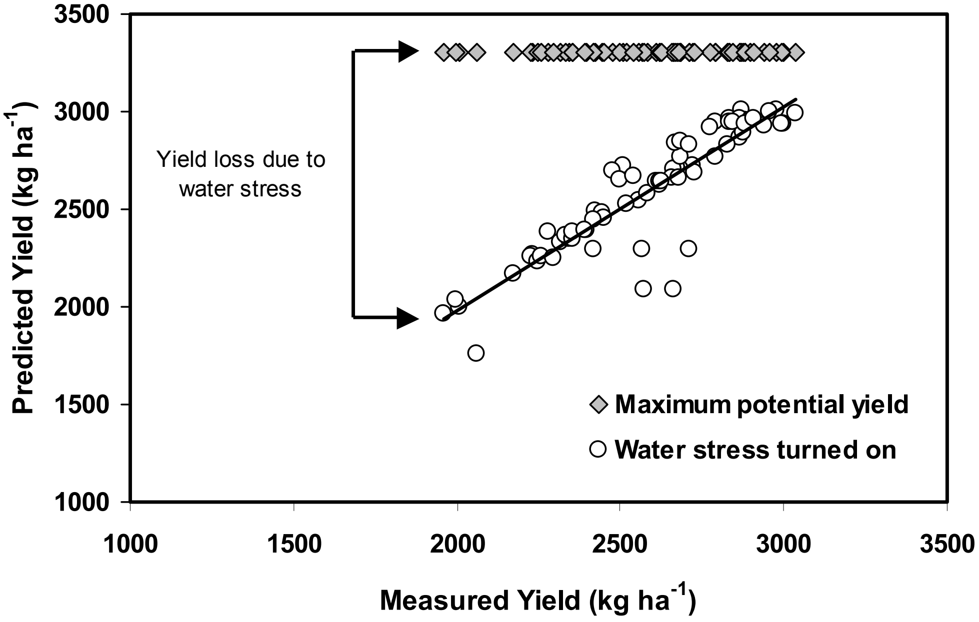

Figure 4. Maximum potential soybean yield in Moody Field (2000) and variations in predicted soybean yield due to water stress.

The locations of the ^{13}C sampling points were superimposed on a digital elevation model of the Moody field that was generated using ArcView geo-processing extension (Figure 5). This information helped identify topographic characteristics of individual grids especially those with high yield loss due to water stress. Spatial distribution of soybean yield loss in grids and C-13 sampling points are shown in figure 6. Grids with high yield loss (> 750 kg ha^{-1}) were located in the summit/backslope areas.

The relationship between yield loss computed by the Δ technique and yield loss estimated by the model was examined using grids with ^{13}C sampling points. In order to do this analysis, the grid layout used for the crop model calibration was superimposed on top of the ^{13}C point locations using ArcView, and the subsequent intersected layer yielded 23 grids containing 50 ^{13}C sampling points. It is important to note that the layout of grids used for model calibration was made without regard to the location of the ^{13}C sampling points. Hence, a grid may contain one or more ^{13}C data points. For grids with two or more sampling points, the average value of Δ and yield loss was computed.

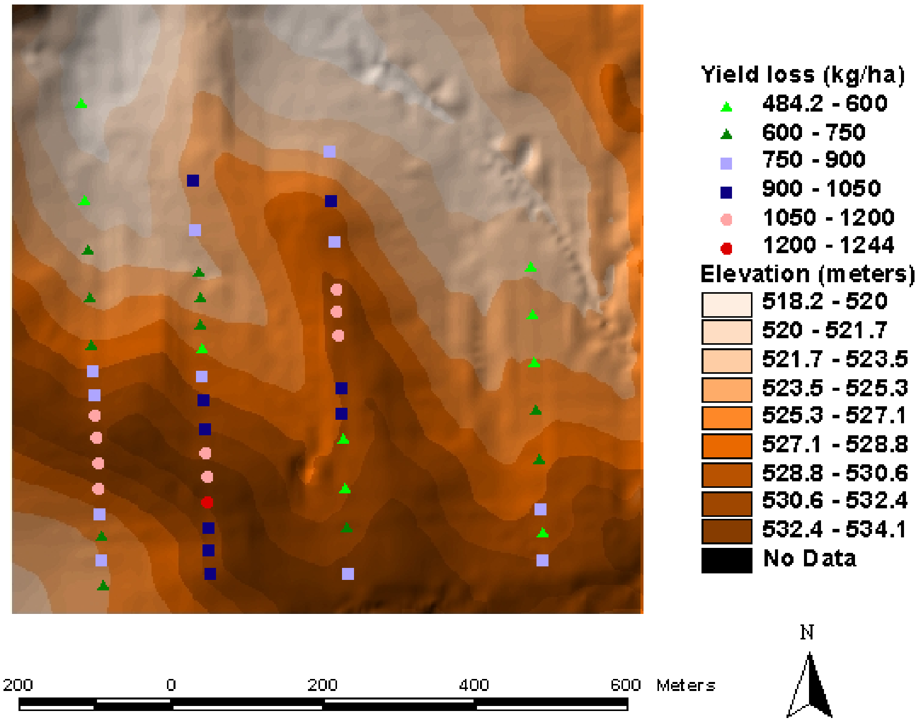

Figure 5. Elevation map and location of ^{13}C sampling points in Moody field.

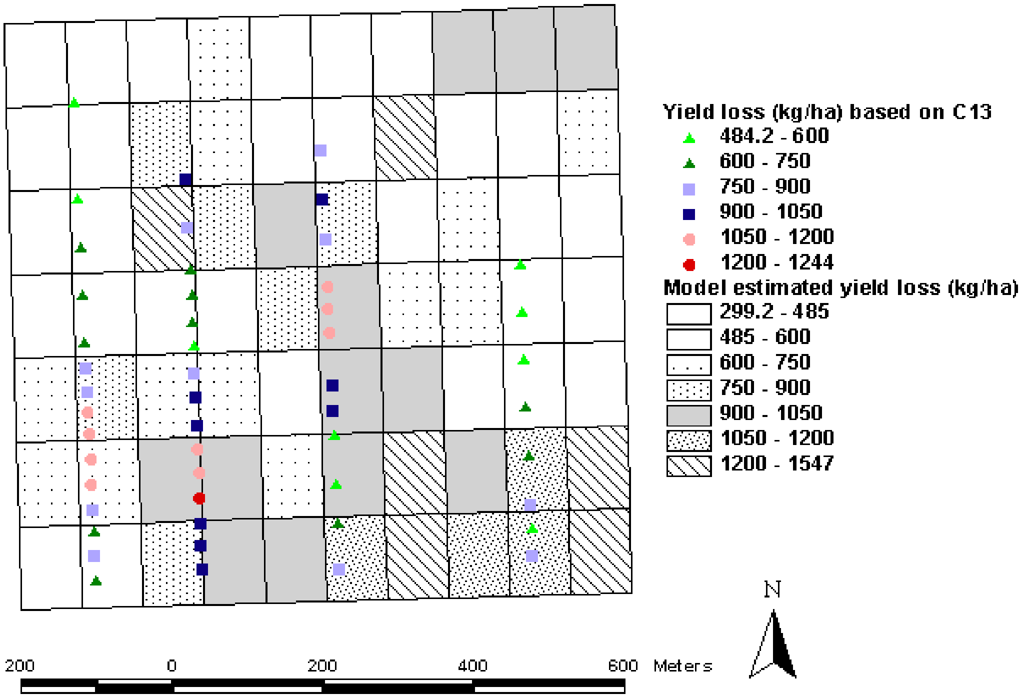

Figure 6. Estimated soybean yield loss due to water stress in Moody Field using ^{13}C discrimination and CROPGRO-Soybean model.

The relationship between yield loss computed by the crop model and ^{13}C resulted in an r^2 of 0.24 and RMSE of 259 kg ha^{-1} (Figure 7). These findings may suggest a weak relationship between these two techniques, however it is important to note that (a) while results of model calibration were very good, yield variability may be attributed to factors other than water stress; and (b) the Δ and calculated yield loss based on Δ is not a 1:1 relationship. Based on field notes of the different ^{13}C sampling points in 2000, 5 points were removed from the analysis. These points were removed because the water flow at these sites was not well defined which resulted in either Δ values, measured yields, or crop model estimates that were outliers relative to the surrounding values. Subsequent removal of these points resulted in significant improvement of r^2 value (0.81) between yield losses computed using Δ and the model estimated yield loss, and lower RMSE (216 kg ha^{-1}) (Figure 8). These findings support the results of previous model-based analysis (Paz et al. 1998; Batchelor et al., 2002) of soybean yield variability in non-irrigated fields. More significant is that these results show: (a) two mutually exclusive techniques came to the same conclusion – that water stress is a dominant factor responsible for soybean yield variability; (b) the CROPGRO-Soybean growth model and Δ can be used to determine the magnitude of soybean yield loss due to water stress; and (c) one technique can be used to cross-check the results of the other technique.

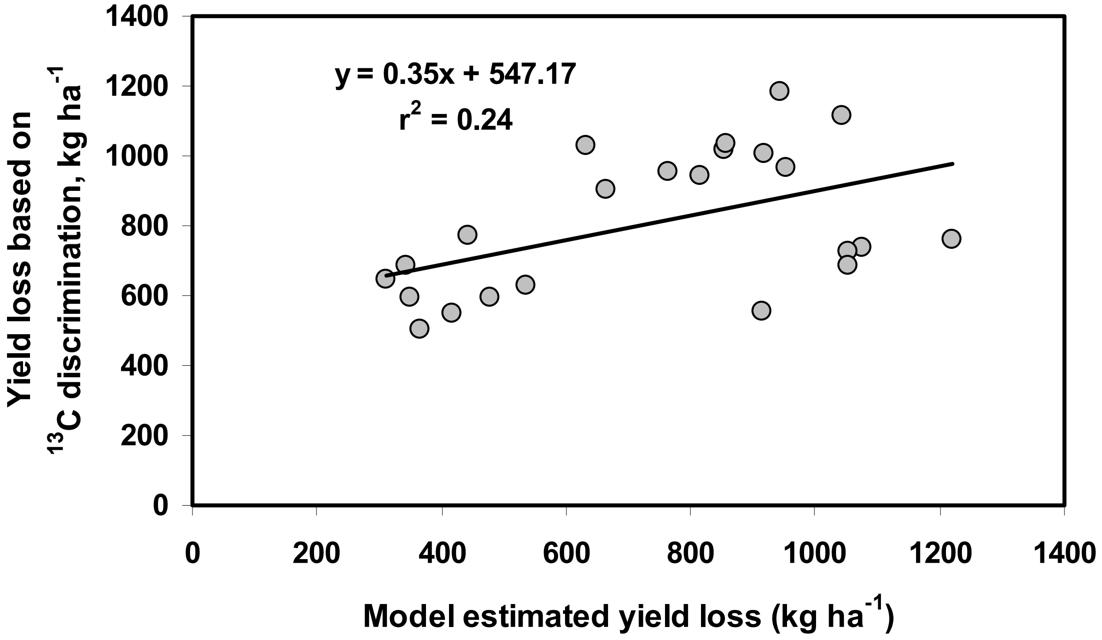

Figure 7. Yield loss due to water stress computed using ^{13}C discrimination and the CROPGRO soybean growth model.

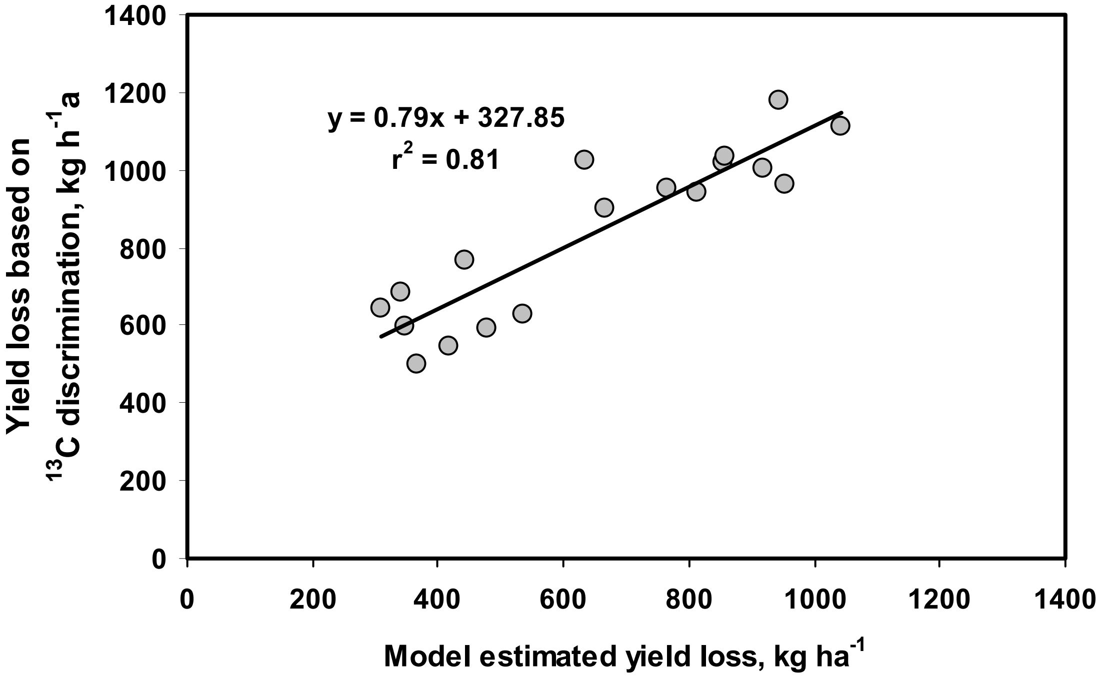

Figure 8. Yield loss due to water stress computed using ^{13}C discrimination and the CROPGRO soybean growth model after removing five data points from the analysis.

Summary

Two techniques, Δ and crop growth model were used to determine the effects of water stress on soybean yield loss in Moody field in Brookings, South Dakota. The calibrated model was used to estimate the soybean yield loss due to water stress in each of 70 0.9-ha grid in the field. Isotopic ^{13}C discrimination of grain samples from 50 sampling points were determined from a field experiment in 2000, and used in computing yield loss to water stress. Grids with high yield loss (> 750 kg ha^{-1}) were located in the summit/backslope areas. Similar results were obtained for estimated yield loss based on Δ. Relationship between yield loss due to Δ and model estimated yield loss due to water stress was examined using grids with ^{13}C sampling points. Results of this study provide strong evidence that water stress is a dominant factor responsible for soybean yield variability, and these techniques can be used to determine the magnitude of soybean yield loss due to water stress.

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