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METHOD TO USE CROP GROWTH MODELS TO ESTIMATE POTENTIAL RETURN FOR VARIABLE–RATE MANAGEMENT IN SOYBEANS

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ABSTRACT. *The objective of this study was to use a soybean crop model to estimate the difference in net return between variable–rate and uniform–rate management for soybean plant population and variety selection decisions. The CROPGRO–Soybean model was calibrated to fit three seasons of historical yield data in 77 grids within a 20–ha field infested with soybean cyst nematodes (SCN) in central Iowa. Procedures were developed to compute the net return and break–even cost for variable plant population density and variety selection for SCN management using 34 years of historical weather data. Implementing the best population (VRX) for each year produced higher net returns compared to using the 34–year average optimum rate (VRA) or using uniform management (UM). Achieving maximum possible net return under VRX may not be possible on a yearly basis due to uncertainties in weather condition. Risk–averse farmers, however, may opt to use the realistic 34–year average optimum rate (VRA) that provides favorable net return over the long term. Procedures were also developed to determine gross profit and break–even costs for switching SCN–resistant and susceptible varieties within an SCN–infested field. Using an SCN–resistant variety across the entire field resulted in significant net returns over that of a susceptible variety, and there appeared to be no economic advantage for variable variety selection compared to planting a uniform resistant variety across the field.*

Keywords. *CROPGRO–Soybean model, Potential return, Variable–rate management, Soybean cyst nematode.*

Precision agriculture is rapidly becoming a reality for soybean farmers in the Midwest. Much has been written in trade magazines about producer experiences in collecting and interpreting yield data and varying plant populations, fertility rates, and other inputs. Researchers have struggled to understand three basic aspects of precision agriculture: (1) how to attribute spatial variability of yield to underlying causes, (2) how to determine an optimum variable rate prescription, and (3) how to determine when it pays to move from single–rate to variable–rate management. Producers have begun to implement variable–rate technology without clear guidelines or estimates of economic consequences of variable–rate decisions.

In answer to question 1, techniques have recently been developed to use process–oriented crop growth models to identify causes of soybean yield variability. Crop growth models such as CROPGRO (Hoogenboom et al., 1994; Boote et al., 1998) are well suited for this because they account for daily spatial and temporal interactions affecting plant growth and yield (Batchelor et al., 1993). Paz et al. (1998, 2001) have recently developed procedures to use the CROPGRO model to separate interactive stresses and attribute spatial soybean yield variability to underlying factors. These techniques were tested on three fields in Iowa, where they explained 69%, 80%, and 88% of spatial yield variability over a 3–year period. These techniques have made it possible to separate the temporal and spatial effects of water stress, soybean cyst nematodes (SCN), and weed interactions and estimate the impact of each stress on yield variability.

Currently, soybean farmers can spatially vary population, variety, irrigation amounts, and fertilizer application rates across a field. At question is how to determine optimum prescriptions to maximize net returns and if it pays to move from uniform management to variable–rate management. Crop growth models have been used to compute the optimum prescription after the fact, accounting for the actual weather data that occurred during the season (Paz et al., 1999; Seidl et al., 2001). However, farmers must make these decisions at the beginning of the season, without knowledge of future weather conditions. A logical extension of previous work is to use crop models to estimate the potential economic return for variable–rate management (VRM) compared to uniform management (UM).

Two interesting comparisons that emerge are the differences in net return for VRM versus UM if: (1) perfect information about future weather is known, and (2) future weather is not known. The first question estimates the

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maximum potential benefit of VRM if perfect information is available (VRX). This is equivalent to always having the right prescription at the right time to match the weather that will occur during the season. While producers do not have *a priori* knowledge of weather, it is important for producers to understand the potential maximum benefit of VRM for different decisions. The second question provides a more realistic estimate of the benefit of VRM because producers never have prior information about future weather (VRA). This can be viewed as having the right prescription in place to maximize long–term profits when averaged over a large number of typical weather conditions. This strategy will not be the optimum prescription for any particular year, but over the long term, it will provide the greatest return with the minimum risk (Paz et al., 1999). It is important for producers to understand the potential and realistic profits that may result from moving from UM to VRM.

The difference between VRX and VRA for a particular variable–rate decision indicates the degree to which the benefit of a decision is dependent upon weather conditions. Large differences indicate that the decision is highly dependent upon weather, while small differences indicate little dependence upon weather. Large differences also indicate that the producers may only be able to realistically capture a small amount of the maximum potential benefit of the variable–rate decision. Likewise, differences between VRA and UM for a particular decision represent the potential benefit of moving from uniform management to variable–rate management. Large differences indicate that the move to VRM may be profitable. However, if the difference is small, then producers should weigh the benefits against the increased demands of more intensive management.

Currently, producers have few guidelines to estimate the benefits of moving to VRM. They must rely on results from strip trials or use anecdotal information to vary inputs. For instance, producers are using strip variety trials to directly compare variety performance across a field and then using that information to make site–specific variety decisions. These results, however, are subjected to weather patterns that occur during the on–farm trial and may not be reflective of long–term performance. Producers have also begun to adjust plant population across fields to achieve yield response to wet versus dry areas. However, the rates they select are not tied to a detailed economic analysis, and there is little research to support these decisions.

Modeling provides a way to examine different scenarios by predicting year–to–year response of crops within the field. This is unique because it allows users to determine break–even costs of different management strategies. The objective of this study was to use a soybean crop model to estimate the difference in net return between VRM and UM for plant population and variety selection decisions with and without prior knowledge of future weather information.

PROCEDURES

FIELD DESCRIPTION

The McGarvey field near Perry, Iowa, was selected as the field site for this study. In a previous project, the 20–ha field was divided into 100 grids, 0.2 ha in size, to study the effects of soil and pest interactions on yield variability (Paz et al., 2001). Yield data were collected from 1994 to 1999 using a yield monitor mounted on the farmer's combine. Relevant crop management (e.g., plant population and fertilizer rate) and pest levels (SCN egg count, weed density, and disease ratings) were collected in 1996–1999 for each grid. The field consisted of 7 soil types. Basic soil layer characteristics including soil texture and bulk density were available from the county soil survey report (Soil Conservation Service, 1981) and used to estimate model inputs. Soil nutrient levels (nitrogen, phosphorus, and potassium) were measured for each grid in 1997.

BASELINE MODEL CALIBRATION

In order to conduct this analysis, we used the baseline model calibrations discussed by Paz et al. (2001) for the McGarvey field. They calibrated the CROPGRO–Soybean model to fit measured historical yield variability over three years for the field. Their analysis included the effects of three yield–limiting factors, namely water stress, SCN stress, and weed pressure. Three model parameters, field tile drain spacing (FLDS), saturated hydraulic conductivity (KSAT), and root hospitality (RHRF), were calibrated using three years of yield and crop management data (1995, 1997, and 1999). They were able to explain 80% of the soybean yield variability (fig. 1), thus demonstrating that the model mimics historical yield variability adequately to proceed with an economic analysis.

PLANT POPULATION DECISION

Paz et al. (1998) demonstrated that soil water stress is a major factor causing spatial yield variability in soybeans. Variable plant population can be used as a VRM tool to take advantage of historically wet or dry locations within a field, conserving water to support pod addition and filling late in the season. Population has a significant effect on soybean node and pod numbers, leaf area index, plant growth rate, and total biomass. Parvez et al. (1989) found yield significantly increased with increasing plant population up to a threshold. Population also affects the soil water balance: high populations increase overall uptake of soil water, and low populations tend to conserve soil water. In this study, the CROPGRO–Soybean model was used to analyze VRM and UM practices using 34 years of historical weather data (1966–1999). The model was run for each grid using six different populations ranging from 247,000 to 370,000 pl ha^{-1} in increments of 24,600 pl ha^{-1}. Net return was computed for each combination as:

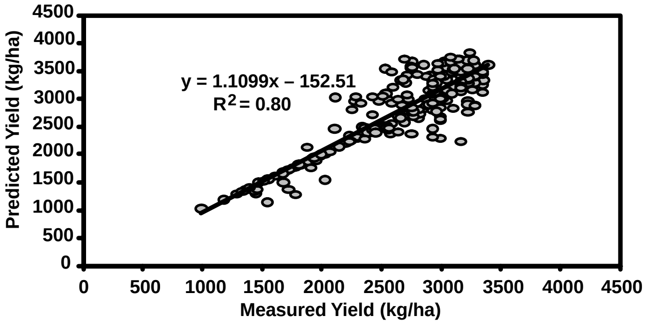

Figure 1. Measured and predicted soybean yield for 73 grids in the Heck McGarvey field over three years (source: Paz et al., 2001).

$$\mathrm{NR}(p)_n^t = Y(p)_n^t \times \mathrm{Pr} - \frac{p \times C}{B} \tag{1}$$

where

$\mathrm{NR}(p)^t_n$ = net return for population p, grid n, and year t (\$ ha^{-1})

$Y(p)^t_n$ = predicted yield for population p, grid n, and year t (kg ha^{-1})

Pr = selling price (\$ kg^{-1})

p = soybean population for grid n and year t at harvest (seed ha^{-1})

C = cost of seeds (\$ bag^{-1})

B = seeds per bag (assumed to be 308,642 sd bag^{-1}).

It was assumed that soybeans were valued at \$0.1833 kg^{-1}. Note that this equation does not consider the equipment or labor costs associated with the decisions.

The results of these model runs were compiled into a database and searched to compare UM vs. VRM practices. Net return for UM was defined as the population that maximized the field–level net return over all years. The average field–level net return for each of the six populations was computed over 34 years by:

$$\mathrm{UMNR}(p) = \frac{1}{N \times T} \sum_{n=1}^{N} \sum_{t=1}^{T} \mathrm{NR}(p)_n^t \tag{2}$$

where

$\mathrm{UMNR}(p)$ = field–level uniform management net return for population p (\$ ha^{-1})

N = total number of grids in the field

T = total number of years.

The net return associated with the population that maximizes $\mathrm{UMNR}(p)$ is considered the maximum average net return for UM:

$$\mathrm{UM} = MAX[\mathrm{UMNR}(p)] \quad (p = 1,2,\ldots,6) \tag{3}$$

For variable–rate management, two scenarios were considered: (1) the population that maximizes the average grid–level net return over 34 years of simulation (VRA), and (2) the population that maximizes grid–level net return in each year (VRX). Paz et al. (1999) defined VRA as a technique to determine the potential profit for VR when future knowledge of weather is not considered. The benefit of VRA was computed using a series of equations that compute profit for each grid and then average this over the field:

$$\mathrm{VRA}_n^p = \frac{1}{T} \sum_{t=1}^{T} \mathrm{NR}(p)_n^t \tag{4}$$

where

VRA_n^p = net return for population p and grid n (\$ ha^{-1})

T = total number of years for the analysis

t = year number

n = grid number.

Next, the net return associated with the population that maximizes the 34–year average net return for grid N (VRA_n) is computed by:

$$\mathrm{VRA}_n = MAX\left[\mathrm{VRA}_n^p\right] \quad (\mathrm{p} = 1,2,\ldots,6) \tag{5}$$

This procedure is repeated for each grid, and the net return for variable–rate management (VRA) over the whole field is computed by:

$$\mathrm{VRA} = \frac{1}{N} \sum_{n=1}^{N} \mathrm{VRA}_n \tag{6}$$

where N is the total number of grids.

The maximum potential net return (VRX) for variable–rate management is computed by determining the population that maximizes profits for each of 34 years in each grid. The average annual net return for each grid (VRX_n) is computed by:

$$\mathrm{VRX}_n = \frac{1}{T} \sum_{t=1}^{T} MAX[\mathrm{NR}(p)_n^t] \quad (p = 1,2,\ldots,6) \tag{7}$$

The term $MAX[\mathrm{NR}(p)^t_n]$ computes the maximum net return (\$ ha^{-1}) over all populations for grid n and year t. The average annual field–level net return (VRX, \$ ha^{-1}) is computed by:

$$\mathrm{VRX} = \frac{1}{N} \sum_{n=1}^{N} \mathrm{VRX}_n \tag{8}$$

Each of these profit indicators were computed and comparisons were made between UM, VRX, and VRA.

SOYBEAN CYST NEMATODE MANAGEMENT DECISION

The Heck McGarvey field contains SCN, which has been identified as reducing yields up to 475 kg ha^{-1} in locations across the field. Planting an SCN–resistant or moderately resistant cultivar is a common practice for managing SCN populations and maintaining high yields. Producers must incur the cost of soil sample collection and processing (at least 10 cores per sample) to identify the problem. SCN cannot move on its own but instead is disseminated by anything that moves soil, including tillage operations. Consequently, SCN infestations typically are aggregated and spatially variable. Once SCN is identified in any part of a field, the entire field typically is planted with a resistant or moderately resistant cultivar. Although SCN usually is widespread throughout infested fields, the question is whether it is economically and biologically advantageous to utilize variable–rate technology for site–specific placement of resistant and susceptible cultivars in an infested field.

Two management scenarios involving susceptible and resistant soybean cultivars were evaluated. For each soybean cultivar, the model was used to predict yields in each grid using 34 years of historical weather data (1966–1999). Grid–level SCN egg count and plant population data, measured in 1997 and used in the model calibration (Paz et al., 2001), were used as a baseline for the analysis. Methods to simulate the effect of SCN damage in the CROPGRO model were outlined by Fallick (1999). It was assumed that the SCN population would stay constant throughout the simulation period (1966–1999). Net return for a susceptible cultivar provided a baseline for the comparison of economic gain or loss of using a resistant cultivar.

The predicted gross profit for the baseline scenario of planting a uniform SCN–susceptible cultivar over the entire field is computed by:

$$\mathrm{UMS}=\frac{1}{N\times T}\sum_{n=1}^{N}\sum_{t=1}^{T}Y(vs)_n^t\times \mathrm{Pr} \qquad (9)$$

where

UMS = average annual gross profit for planting SCN–susceptible cultivar v (\$ ha^{-1})

$Y(vs)_n^t$ = predicted yield for susceptible cultivar v, grid n, and year t (kg ha^{-1}).

The predicted gross profit for planting a resistant cultivar uniformly across the field (UMR, kg ha^{-1}) was computed by:

$$\mathrm{UMR}=\frac{1}{N\times T}\sum_{n=1}^{N}\sum_{t=1}^{T}Y(vr)_n^t\times \mathrm{Pr} \qquad (10)$$

where $Y(vr)_n^t$ is the predicted yield for resistant cultivar v in grid n and year t (kg ha^{-1}). Finally, the predicted gross profit for planting the best variety (susceptible or resistant) in each grid (VRMSR, kg ha^{-1}) was computed by:

$$\mathrm{VRMSR}=\frac{1}{N}\sum_{n=1}^{N}MAX\left(\frac{1}{T}\sum_{t=1}^{T}Y(vs)_n^t,\frac{1}{T}\sum_{t=1}^{T}Y(vr)_n^t\right)\times \mathrm{Pr} \qquad (11)$$

The differences in gross profit for UMS, UMR, and VRMSR were computed and compared, and the maximum fixed cost associated with a variable–variety planter and soil sampling was estimated.

RESULTS AND DISCUSSION

PLANT POPULATION DECISION

Figure 2 shows an example of the predicted response of net return to population for grid 53 for selected years of weather data. Although the curves appear flat, the optimum population for each year (i.e., VRX scenario) is dramatically different and depends on water stress and rainfall patterns during the year, while the 34–year optimum population (i.e., VRA scenario) is near 296,200 pl ha^{-1} for this grid.

Table 1 shows that the optimum population for the field under UM was 247,000 pl ha^{-1}, giving an average annual net return of 226.77 \$ ha^{-1}. The average annual net return for VRX was \$231.58 ha^{-1}, and the optimum population varied for each grid and year. The average annual net return for VRA was \$227.32 ha^{-1}, and the optimum population varied by grid, but was the same for a grid over all 34 years of historical weather data. The difference between VRX and UM was \$4.79 ha^{-1}, which indicates the upper boundary of estimated net return based on the premise that future weather is known. The difference between VRA and UM was \$0.54 ha^{-1}, which is an estimate of the potential net return that can be realized by this producer for this field, since the VRA strategy does not rely upon *a priori* knowledge of weather information. It should be noted that this analysis does not consider the additional fixed cost associated with equipment and training for VRM.

Figure 3 shows a comparison of the annual net return (averaged over 34 years) for UM, VRA, and VRX for different soybean prices. The curve for VRA is very close to that of UM. As expected, VRX provided the highest return, and there were small differences between VRA and UM, which is a realistic estimate of the net return realized by the producer. All net returns increased with soybean price, and the slopes of the VRX and UM lines were nearly the same, indicating that the economics are not very sensitive to soybean price. The difference between the VRX and VRA curves indicates the potential net return for variable–rate management that is dependent upon *a priori* knowledge of future weather. In this case, most of the value of moving to variable–population management is dependent upon *a priori* knowledge of future weather, and thus is not easily captured by the producer.

The fixed cost (equipment, training, etc.) associated with moving from UM to VRM is different for each producer. Figure 3 was modified to show the fixed cost defining the break–even point for moving from UM to VRM for this field. At a soybean price of \$211 ton^{-1}, the predicted break–even fixed cost associated with moving from UM to VRX is \$5.00 ha^{-1}, while the difference between UM and VRA is \$0.50 ha^{-1} (fig. 4). Figure 4 shows that soybean price has a linear effect on the break–even cost. Higher soybean prices allow for higher fixed costs to support a move to VRM.

An alternative way to analyze the field data is to determine how much profit the producer sacrifices if UM practices are continued. Figure 5 shows an example of the predicted loss

Table 1. Annual net return for UM, VRA, and VRX for soybean population decisions (Soybean price \$0.1833 kg^{-1}).

Management practice	Population (pl ha^{-1})	Annual net return (\$ ha^{-1})
UM	247,000	226.77
VRA	Variable by grid and year	227.32
VRX	Variable by grid and year	231.58

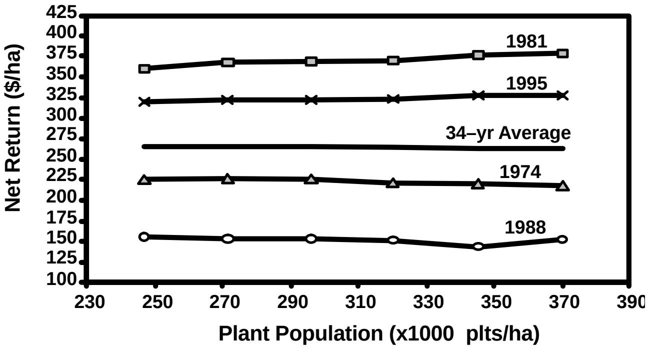

Figure 2. Predicted response of net return to population for grid 53 for selected years of weather data.

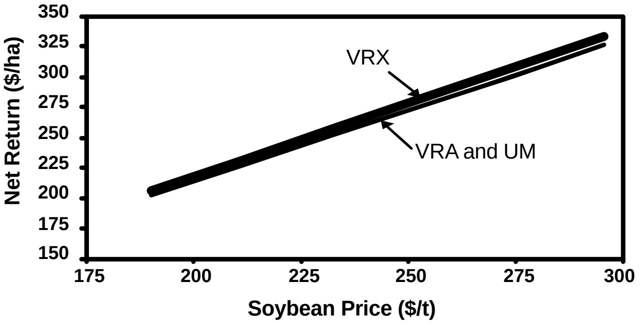

Figure 3. Annual net return for UM, VRA, and VRX.

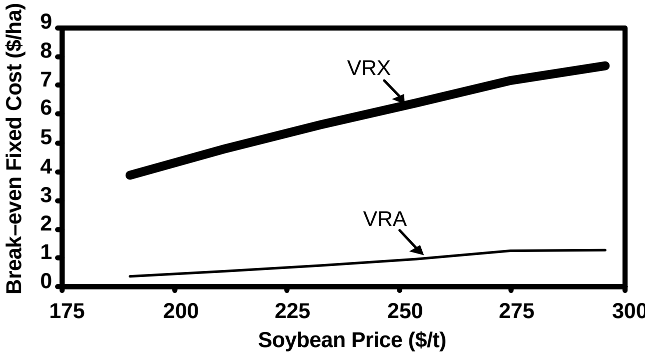

Figure 4. Predicted break–even for fixed costs associated with moving from UM to VRA or VRX.

in net return for grids 10 and 13 if a uniform population (UM) is applied each year, compared to the population that maximizes the 34–year profit (VRA). For example, in grid 10, the optimum population that maximizes the 34–year average yield is 247,000 to 272,000 pl ha^{-1}. If the producer continues to plant 370,000 pl ha^{-1}, then he will lose \$4.33 ha^{-1} compared to variable–rate management (VRA).

Table 2 shows the difference in VRX and VRA compared to different fixed populations over the entire field. For this field, VRA always gives a higher return compared to UM, when fixed costs are not considered. For instance, if this producer always plants 370,000 pl ha^{-1}, then VRA will provide a benefit of \$2.84 ha^{-1} compared to UM. Alternatively, the break–even fixed cost of switching to VRM is \$2.84 ha^{-1} for this producer and field. The economic decision of switching from UM to VRM is dependent upon the population that the farmer normally plants. In this field, the optimum uniform population that maximizes the field–level net return is 247,000 pl ha^{-1}. The higher the uniform rate, the more economical it appears to switch to VRM. If the producer normally plants the optimum uniform rate, then the net return for moving to VRA is only \$0.54 ha^{-1}, thus reducing the maximum allowable fixed cost associated with VRM. Table 2 also shows the difference between VRX and VRA to be about \$4.25 over all fixed uniform population levels. This return is not available to the producer without *a priori* knowledge of weather, and the amount is not sensitive to the producer's current UM practices.

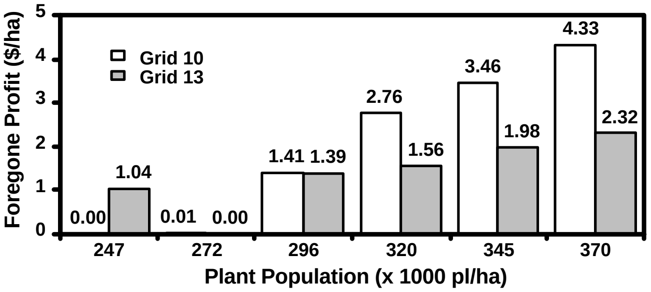

Figure 5. Predicted forgone profit due to UM instead of VRA for grids 10 and 13.

Some of the model limitations and assumptions for this analysis should be noted. First, the model assumes that the population is uniformly distributed. Thus, the yield response to population is relatively flat in the model over the range of populations tested. In reality, as populations decrease, the uniformity of plants tends to increase, leaving gaps in the canopy and resulting in yield loss. Second, the model does not predict lodging or the effects of lodging on yield. Lodging can occur under high populations, as soybean plants become very tall to compete for light with neighboring plants. In reality, lodging can have a significant effect on yield by reducing harvesting efficiency.

SOYBEAN CYST NEMATODE MANAGEMENT DECISION

Table 3 shows the predicted field–level gross return averaged over 34 years when the field is uniformly planted with SCN–susceptible (UMS) or resistant (UMR) cultivars. The model predicted the benefit of moving to UMR to be \$30.68 ha^{-1}. This benefit was expected since most of the field contains SCN populations.

Figure 6 shows the predicted differences in gross return for both UMS and UMR for different soybean prices. The gross return for UMS provided a baseline for the current management practices of the producer. The difference between the gross returns for UMS and UMR indicates the benefit of moving from SCN– susceptible to resistant varieties. Conversely, this can be viewed as the break–even cost associated with moving from uniform to variable–rate cultivar selection (fig. 7). Break–even cost ranges from \$27 to \$43 per hectare for a soybean price range of \$190 to \$296 ton^{-1}. For a typical soybean price of \$250 ha^{-1}, this producer can spend approximately \$35 ha^{-1} to identify and manage SCN populations. The seed cost for SCN–resistant and susceptible varieties are the same. However, the soil sampling and processing required to identify SCN eggs costs at least \$10 per sample.

An analysis was conducted to determine the benefit of moving from a uniform variety to optimizing placement of resistant and susceptible varieties across the field. In the model, it was assumed that the genetic yield potential for an SCN–resistant variety was the same as an SCN–susceptible variety under no SCN pressure. Thus, the gross return for variable–rate management using a mix of susceptible and resistant varieties (VRMSR) was the same as planting a resistant variety across the field (table 3). The break–even costs for VRMSR and UMR are the same as well (fig. 7). In this case, however, the producer must factor in the cost of soil sampling and processing to identify SCN populations as well as the cost of a planter capable of switching varieties across the field. Figure 8 shows the predicted susceptible and resistant variety placement across the field following the VRMSR strategy. The model indicated that only 13 of the

Table 2. Annual net return (\$ ha^{-1}) for VRA and VRX compared to different uniform populations averaged over 34 years.

Management practice	Uniform plant population (pl ha^{-1})					
	247,000	271,600	296,200	320,800	345,400	370,000
VRX	4.79	4.89	5.41	5.80	6.40	7.09
VRA	0.54	0.64	1.14	1.56	2.15	2.84
VRX – VRA	4.25	4.25	4.27	4.24	4.25	4.25

Table 3. Predicted gross return for uniform and variable–rate management of soybean cultivars resistant and susceptible to soybean cyst nematodes.

Management practice	Predicted profit ($ ha^{-1})
UMS	255.81
UMR	286.49
VRMSR	286.49
UMR – UMS	30.68
VRMSR – UMS	30.68

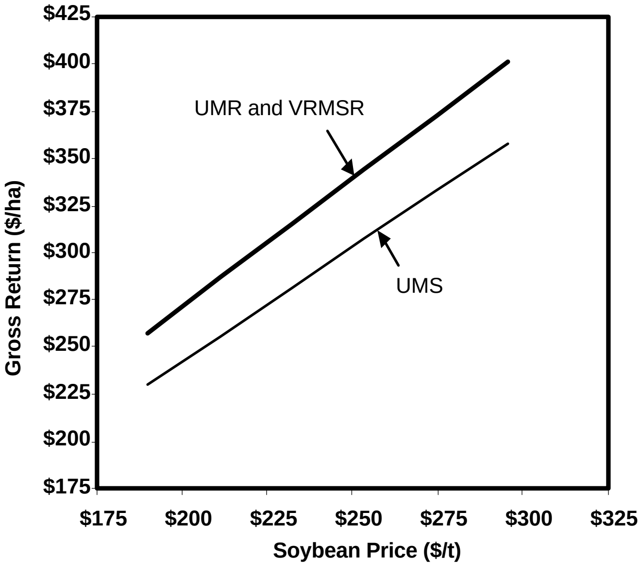

Figure 6. Predicted gross return for using uniform and variable–rate variety selection for SCN management.

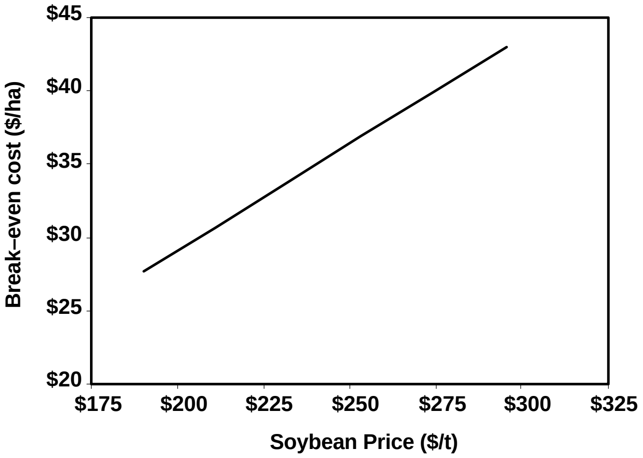

Figure 7. Predicted break–even for fixed costs associated with moving from uniform to variable–rate cultivar selection to manage SCN populations.

77 grids in this field should be planted to a susceptible variety, while most of the grids should be planted to a resistant variety. When equipment cost is factored in, it is likely that UMR would be the best option for this field.

Caution must be taken in choosing a variable variety selection for SCN over uniform management. SCN population densities will inevitably increase over time if an SCN–susceptible variety is grown in a field rather than an SCN–resistant variety. Over time, nematode populations would likely spread into areas where an SCN–susceptible variety is planted in the field. The data that are presented do not account for such temporal changes. Consequently, the uniform management with a resistant variety (UMR) likely would be even more profitable than uniform management with a susceptible variety (UMS) if changes in SCN population densities were considered.

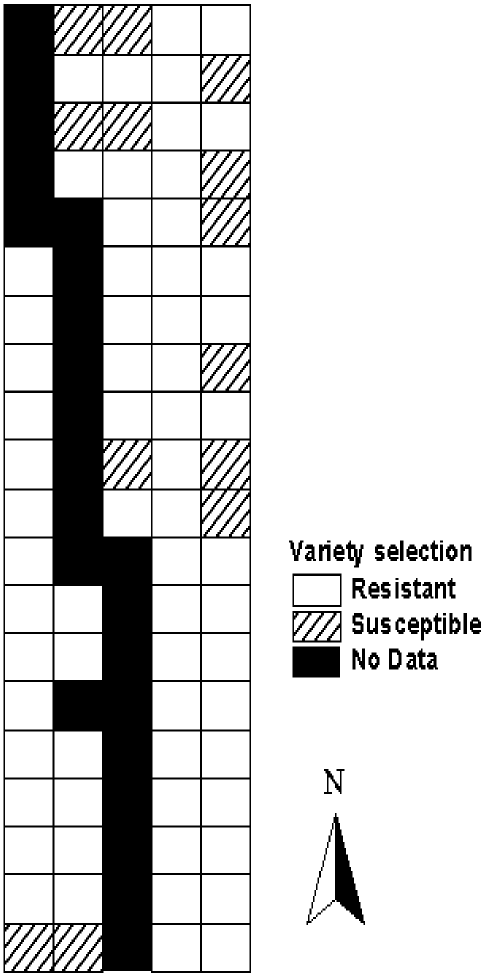

Figure 8. Variable cultivar prescription to maximize net profit to manage SCN.

CONCLUSIONS

The CROPGRO–Soybean model was used to evaluate the economic consequences for moving from uniform– to variable–rate management for soybean population and variety selection to manage the effects of soybean cyst nematodes. Techniques were developed to evaluate the potential return with and without *a priori* knowledge of future weather, and to determine the potential profit that cannot likely be recovered by the producer due to uncertain information about future weather. The value of switching from single– to variable–rate population management was estimated to be approximately $4.81 ha^{-1}, of which only $0.55 ha^{-1} could be captured without *a priori* knowledge of weather conditions. Curves representing the break–even cost of moving from uniform management to variable–rate management were also developed. Under the most favorable prices ($175 t^{-1}), the break–even cost must be less than $1.00 ha^{-1} for a move to variable–rate management to be profitable over the long term.

The net return for selecting SCN–resistant or susceptible varieties was not sensitive to *a priori* knowledge of future weather. Thus, the producer can capture all of the potential value of moving from uniform to variable–rate management, without regard to consequences of future weather. In general, a resistant variety produced higher grid–level soybean yields than a susceptible variety in this SCN–infested field. There were no economic differences between planting an SCN–resistant variety across the field and variably applying SCN–resistant and susceptible varieties based on SCN populations in the field. The break–even cost for moving to a resistant variety (either uniform or variable–rate management) was also the same, and was much higher than the break–even cost for managing populations.

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