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Profitability of On-Farm Precipitation Data for Nitrogen Management Based on Crop Simulation

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Abstract. The purpose of this study was to determine the utility of on-farm precipitation measurement for nitrogen management decisions on an Indiana farm. Site-specific farming has led some producers to measure on-farm precipitation at multiple sites, but the profitability of such intense sampling for non-irrigated agriculture is not clear. The CERES-Maize model in Decision Support System for Agrotechnology Transfer (DSSAT) version 3.5 was used to simulate corn yield for a farm in east-central Indiana for 20 years of weather data from three precipitation data sources—an on-farm station, the nearest non-urban National Weather Service (NWS) station, and the weighted mean of the three nearest such stations. Stochastic dominance and descriptive statistics were used to compare simulated yield and profitability for four nitrogen strategies: variable-rate versus whole-field fertilizer application and split application (starter urea-ammonium nitrate mixture at planting and sidedressed ammonia 37 days later) versus sidedress application only. Off-farm data never led to a different choice of nitrogen strategy than on-farm data, but the ability to categorize a choice as risk averse or risk neutral depended on the precipitation data source used. This suggested that although on-farm precipitation measurement could be useful for risk management decisionmaking, it might not be profitable on average. The nearest NWS station would be the most profitable source of precipitation data, if it leads to the same management strategy as on-farm data.

Keywords: precipitation, weather data, variable-rate application, nitrogen fertilizer, profitability, stochastic dominance

Introduction

Precipitation variability is one of the reasons variable-rate nitrogen fertilization has so far not been shown to be conclusively profitable for Midwest farmers. Producers must make most fertilizer or nutrient application decisions at or near the beginning of the crop season. Farmers choose a strategy based on their goals, which may be as simple as maximizing the expected value of net profit from production or may also include avoiding risk in potentially low-yielding years. For this choice to be truly optimal for profit or yield, it must take into account the expected range of year-to-year precipitation variability. To measure precipitation at the highest possible resolution, dealers in weather monitoring equipment have been encouraging farmers to measure precipitation on their farm, even at multiple sites within the farm (Bechman, 1998), and some farmers have begun doing so (Dunn, 1997; Reetz, 1999).

The purpose of this study was to determine the utility of on-farm precipitation measurement compared to off-farm precipitation data sources, for improving profitability of nitrogen management decisions on a farm in eastern Indiana. Nitrogen management was used as an example economic management decision potentially impacted by precipitation variability, because nitrogen fertilizer efficiency depends in part upon precipitation after application. For this study, application decisions took place prior to each crop season based on past weather, rather than within the growing season.

In this study, the focus was on precipitation variability beyond the farm. A previous study (O'Neal *et al.*, 2001) examined variability of precipitation between fields for the same farm and found that it was not significant. Other small-scale precipitation research in flat rural areas also suggested that a contiguous area of less than 2.5–10 km^2 should have spatially uniform precipitation over the growing season (e.g., Huff, 1979; McConkey *et al.*, 1990).

Background

Nitrogen recommendations

Although farmers apply many nutrients based on soil tests, they usually apply nitrogen fertilizers independently of a soil test because of the difficulty of correlating soil tests with yield over changing weather and soil moisture conditions. Fertilizer recommendations that are independent of nitrogen soil tests typically base nitrogen needs on yield potential, previous crop, and relative increase in yield for a unit increase in soil nitrogen. One set of recommendations a Midwestern farmer is likely to use is the Tri-State Fertilizer Recommendations for Indiana, Michigan, and Ohio (Vitosh *et al.*, 1996), which use the relationship $N = a + by - c$ where N = nitrogen application amount (kg ha^{-1}), a = nitrogen base rate (67 kg ha^{-1}), b = ratio of nitrogen to corn yield potential (0.0243, from 1.36 lb N per bushel corn), c = nitrogen credit for previous crop (34 kg ha^{-1} after soybeans), and y = corn yield potential (kg ha^{-1}).

Although the recommendation amounts may be used for a single application, weather conditions may require more than one application. Farmers apply nitrogen at or before planting when they expect a high risk of nitrogen loss after planting or being unable to apply later in the season. Sidedress application allows nutrients to be supplied closer to the time of maximum crop need, but it is more risky. Vitosh *et al.* (1996) indicate, based on plot research from three states, that there should be no yield difference between preplant and sidedress application for medium and fine textured soils, and that sidedressing should produce higher yields than preplant application on sandy soils. In Indiana, however, studies have frequently shown starter nitrogen fertilizer to give a yield response for no-till corn (Mengel, 1996). The Tri-State Recommendations allow 22–45 kg ha^{-1} of nitrogen banded as sidedress for split applications. More risk-averse farmers may choose to apply half at planting and half at sidedress, while risk-takers may apply most or all at sidedress. Since the effects of starter and sidedressed nitrogen are specific to each location, the question may be asked whether it is profitable to apply all nitrogen in a single application or split between two applications, for a particular farm and its soils.

Variable-rate nitrogen application and precipitation variability

Field studies have shown that precipitation variability from year to year is an important factor in determining the profitability of variable-rate application. Snyder *et al.* (1998) found variable-rate nitrogen on corn to be profitable at two sites in a normal year, but at only one site in a year when excessive rainfall reduced yield. Long *et al.* (1996) found variable-rate nitrogen on wheat to be unprofitable one year and profitable the next year with three times as much precipitation.

Simulation models can account for precipitation variability over longer time scales. Braga *et al.* (1998) used 35 years of weather to examine profitability of variable-rate nitrogen application with a simulation model. Poor-yielding years gave the best advantage to variable-rate application. The authors found that yield response could cease above 175 kg ha^{-1} N, or yield could still be rising at 300 kg ha^{-1} N, depending on the weather year. Paz *et al.* (1999) demonstrated the usefulness of the same simulation model for optimizing variable-rate nitrogen fertilization, on the basis of profitability over 22 weather years, with optimal rates ranging from less than 60 to 220 kg ha^{-1}.

CERES-Maize

Modelers have incorporated sophisticated relationships among nitrogen, precipitation, air temperature, and yield into the CERES-Maize simulation model (Jones and Kiniry, 1986), which has become a module of the software package Decision Support System for Agrotechnology Transfer (DSSAT) version 3.5 (Hoogenboom *et al.*, 1999). Although questions have been raised about the model's ability to accurately predict the mean and variance of site-specific yield, because it was developed for larger scales (Sadler and Russell, 1997), CERES-Maize and DSSAT have been used in examining site-specific management, profitability, and yield for precision agriculture (e.g., Braga *et al.*, 1998; Corá *et al.*, 1998; Paz *et al.*, 1999), CERES-Maize simulates crop progress in nine growth stages based on daily precipitation, radiation, and air temperature, culminating in total yield. Genotype coefficients tie crop growth to weather, specifying rules by which air temperature and radiation affect growth during key intervals (Hoogenboom *et al.*, 1994).

Some research has raised questions about the plausibility of the yield response to nitrogen fertilization in CERES-Maize. Sadler *et al.* (2000) found yield response curves tended to level out at nitrogen rates lower than common empirically tested nitrogen recommendations. However, Braga *et al.* (1998) found yield responses up to 300 kg ha^{-1} N with the same crop. Although they used different versions of the model (3.5 versus 3.1), no major modifications were made to the soil water and nitrogen routines between the two versions (Hoogenboom *et al.*, 1999). Researchers have found precipitation effects in the model to be plausible (Sadler *et al.*, 2000).

Precipitation data

Farmers who want to capture spatial precipitation variability for crop simulation or yield map interpretation have a number of measurement options. One is to measure precipitation themselves, with a tipping bucket gauge and datalogger, or a plastic gauge read manually. Tipping bucket gauges cost $100 to $2000 and plastic gauges $25 to $60, but tipping bucket gauges have lower overall costs when labor is included. Another option is to purchase precipitation data from a local agricultural weather network, the National Weather Service (NWS), or services that sell 24-h cumulative precipitation estimates calculated from ground-based radar data. Still another is to obtain free precipitation data from university, state, or regional climate services on the Internet. These can include preliminary data from NWS stations that use electronic reporting; of all NWS stations in Indiana, for instance, about two thirds report electronically.

One of the most accurate and widely accepted sources of precipitation data is the NWS. NWS offers data on its website (http://lwf. ncdc.noaa.gov/oa/ncdc.html) for around $10–$80 (depending on the product), and allows downloading of many decades of data at once. For NWS stations in Indiana, spacing ranges from 1.8 to 33.2 km with a mean of 17.7 km (O'Neal, 2000). A variety of ways exist to estimate precipitation data at a point located between stations (Tabios and Salas, 1985); one simple measure is the inverse distance-squared weighted mean, used by NWS (Serrano, 1997):

$$P_m = \frac{\sum \frac{P_i}{D_i^2}}{\sum \frac{1}{D_i^2}} \qquad (1)$$

where P_m = precipitation for the central unknown station, P_i = known precipitation for each of the surrounding stations, and D_i = the distance from the central station to each of the surrounding stations. It is preferable to have the points in more than one direction from the point being estimated, to avoid anisotropic effects, and to use non-urban data to estimate values for non-urban sites.

Precision agriculture profitability and variable-rate costs

Determining the profitability of precision agriculture methods relies strongly on cost assumptions. For variable-rate application of fertilizer inputs, a wide range of costs with different definitions have been used. For instance, Swinton and Lowenberg-

DeBoer (1999) assumed variable-rate spreading charges to be \$7.41 ha^{-1} higher than for uniform rates. In a three-year field study, an additional cost increment of \$17.59 ha^{-1} was incurred for variable-rate nitrogen application, which included GPS, variable-rate controller, and a laptop (Finck, 1998). Akridge and Whipker (1998), in a survey of 461 retail agronomy dealerships from 36 states, found an average cost of \$12.90 ha^{-1} for single controller-driven application. Casaday and Massey (1998) found \$3.71 ha^{-1} to be the average premium for variable-rate application with single product spreading among nine Missouri precision agriculture service providers. The sum of mapping and record keeping and single product variable-rate spreading from Lowenberg-DeBoer and Aghib (1999) gives a cost of \$20.88 ha^{-1}. English *et al.* (1998) used a blanket variable-rate application service cost of \$11.54 ha^{-1}. Swinton and Lowenberg-DeBoer (1999) used \$21.30 ha^{-1}, based on purchased planter, anhydrous ammonia controller, yield monitor, GPS, microcomputer, and printer.

Stochastic dominance

Given a choice among input application strategies, most farmers want to make the choice that will give the highest profit with least risk. Stochastic dominance is a standard economics tool that allows choice of a risk-preferable strategy, based on the cumulative probability distribution of a desired quantity (Hadar and Russell, 1969). It includes the concepts of first-degree stochastic dominance (FDSD), similar to maximizing profit at every step of the probability distribution, and second-degree stochastic dominance (SDSD), based on minimizing risk from the bottom of the distribution upward (Anderson, 1974). Determination of dominance relies on probability distributions. For any two strategies A and B, strategy A is FDSD-dominant over B if $F_A(R) \geq F_B(R)$ for all R from $\pi_{\min}$ to $\pi_{\max}$ (and they are unequal at least once), where $\pi_{\min}$ and $\pi_{\max}$ = the minimum and maximum profit values seen in the results, F_A and F_B = the cumulative probability functions of profit for the two strategies A and B, and R = each profit value (after Anderson, 1974). If neither strategy is FDSD-dominant, strategy A is SDSD-dominant over B if $\int_{\pi_{\min}}^{R} F_A(\pi)d\pi \leq \int_{\pi_{\min}}^{R} F_B(\pi)d\pi$ for all R from $\pi_{\min}$ to $\pi_{\max}$ (and they are unequal at least once) (Anderson, 1974).

Results of stochastic dominance comparisons can also be used to separate more than two strategies, by grouping them in terms of overall risk and profit desirability. Strategies fall into three categories—"dominated", "risk neutral", and "risk averse" (Hien *et al.*, 1997). An FDSD-"dominated" (and therefore SDSD-dominated) strategy is unacceptable to a rational decisionmaker, because it profits less at every probability level than another strategy. An SDSD-dominated, but not FDSD-dominated, strategy is acceptable only to a "risk neutral" farmer, because while average profits might be similar to the dominant strategy, the SDSD-dominated strategy always has a higher probability of low profit years. A strategy neither FDSD-dominated nor SDSD-dominated is acceptable even to a "risk averse" farmer, because it performs relatively well overall and also in the poorest years (Hien *et al.*, 1997).

Anderson (1974) gave a complete discussion and review of stochastic dominance in agricultural applications. Nagarajan *et al.* (1993) used stochastic dominance with SOYGRO, to compare soybean varieties under varying seasonal precipitation, and Lowenberg-DeBoer and Aghib (1999) used stochastic dominance to compare net profit from precision farming under different soil-sampling alternatives using empirical distributions estimated from on-farm trial data.

In a mean-variance sense, a strategy also dominates another strategy if it has both a higher mean and a lower variance. If two strategies have identical means, a risk-averse decisionmaker prefers the strategy with lower variance. If they have the same variance, the decision with the higher mean is preferred. This type of mean-variance analysis is easy to determine, but restricts the ordering of an alternative with both higher mean and higher variance, which might still be separated with stochastic dominance (Hadar and Russell, 1969).

Procedure

Research site

The research site was Davis–Purdue Agricultural Center, a 252-ha agriculture-forestry research center located in east central Indiana, in a region with relatively flat topography. Four fields (about 49 ha in area, which is typical for east central Indiana) were used for this study. Figure 1 shows a layout of the farm and the four fields used (M1, M2, N, P).

Precipitation data

Precipitation data were taken from four stations. A NWS Cooperative Observer station (labeled in Figure 1), consisting of a ground-mounted standard 8-in. (20.3 cm) metal gauge, is on the farm itself, and the same farm staff member has monitored it daily for 33 years, indicative of homogeneous high-quality records. The nearest NWS stations to the farm with electronic reporting that were in non-urban areas were Winchester (26.6 km away), Portland (27.4 km), and Hartford City (34.6 km). Figure 1 shows the stations nearest to the farm, including two excluded because they were in an urban area (Muncie). The three chosen stations all had daily records for 1980–1999, with the following number of missing days during the crop season (out of 3727 total): Winchester 26, Portland 5, Hartford City 665 (including a gap from May 1990 to April 1993). Data came from the National Climatic Data Center (NCDC, 1994), the Indiana State Climatologist's office, the Indiana Climate Page (http://shadow.agry.purdue.edu/sc.index.html), and the observer's handwritten sheets (on-farm data).

The inverse distance-squared weighted mean (Eq. 1) was used to estimate on-farm precipitation from the three nearest non-urban stations. When data were missing, the mean was based on the remaining one or two stations. The on-farm data were never missing during the 20-year period. Missing data for the nearest station were filled in with those from the farm.

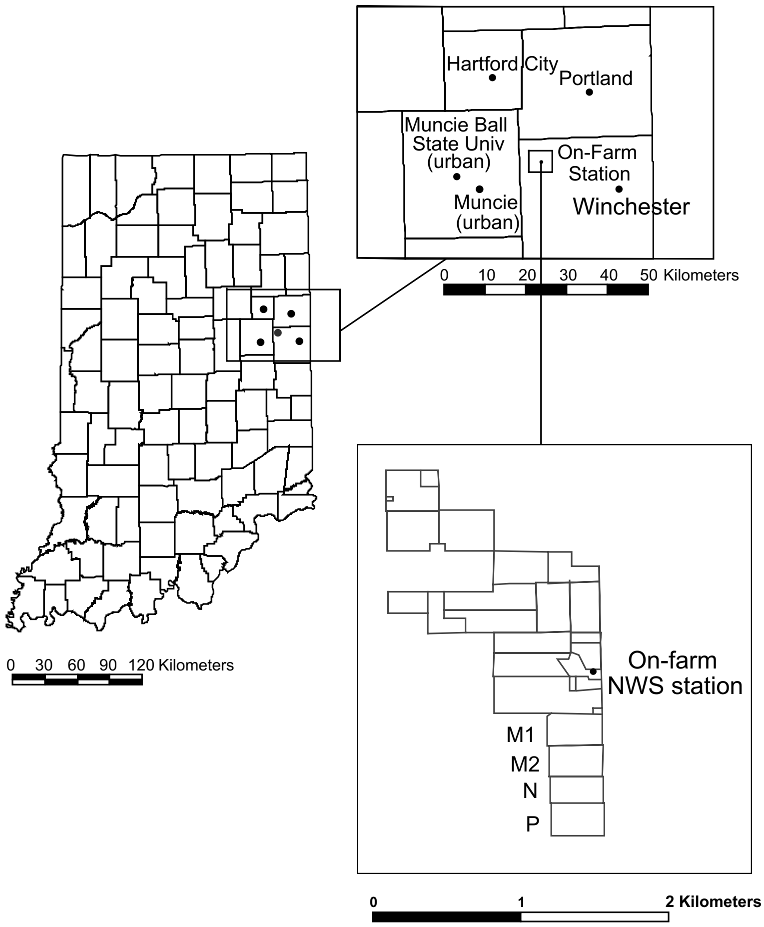

Figure 1. Location of NWS stations in east central Indiana, and fields used at Davis–Purdue Agricultural Center for this study.

Data were converted to daily precipitation readings by completely assigning the observation to the previous day if the observation time was before noon, or to the same day if noon or later. Maximum air temperature was similarly assigned according to observation time. This was done to limit biases caused by 24-h averaging times, as noted by Andresen (1987). On-farm data were assigned explicitly by each day's observation time, while off-farm station data were all treated as if they had morning observation times, based on recent years' data.

Median monthly and seasonal precipitation for the three precipitation data sources is in Table 1. The within-season difference in precipitation among precipitation data sources is plotted in Figure 2, as the percent difference between each source and the mean of all three data sources. Differences of more than 50% occur in

Table 1. Median monthly and seasonal precipitation by data source (April 1980–October 1999)

Month Data Source	1980–1999 median		
	On-farm data	Nearest station	Three-station mean
April	110	105	104
May	101	105	95
June	102	109	107
July	113	109	119
August	78	71	83
September	58	57	62
October	52	69	61
Season[a]	638	637	624

All values in millimeters.
[a]Different from sum of months because of variable monthly totals within each season.

extreme months, and no data source appears to be consistently higher or lower than another, even within the same season.

Nitrogen application

Four strategies were considered for nitrogen application, based on two scales of application and split application versus sidedress-only. The two scales of application were whole-field (a single rate for each field based on that field's yield potential) and variable-rate (a potentially different rate for each 1-ha grid cell based on that grid cell's yield potential). The Tri-State Fertilizer Recommendations equation was used to determine the application amount for corn after soybeans.

Yield potential was estimated as the average of yield monitor data for the whole field, or for each grid cell. Five years of yield monitor data were available, split among corn and soybeans, as shown in Table 2. Yield potential was the mean of all available corn years, excluding drought (1996), plus 5% (Wilson, 1997; Taylor, 1998).

Yield monitor data came from a model 1640 Case-International Axial Flow[1] combine equipped with an AgLeader 2000 yield monitoring system. The algorithm used to convert the processed data to kilograms per hectare at standard moisture accounted for a number of yield monitor and GPS errors and smoothed the data with an 11-point moving average, to reflect the expected spatial resolution of yield data (O'Neal *et al.*, 2000). Field boundaries were digitized to encompass GPS-recorded yield monitor data locations, and within these boundaries each field was divided into 12 approximately 1-ha grid cells. Yield was determined as kilograms divided by either the header width × distance traveled, or by a maximum limit of cell area (1.214 ha), whichever was smaller. Yield potential, derived from multiple years of processed data, ranged from 5566 to 9211 kg ha^{-1}.

From the Tri-State Recommendations equation, calculated variable-rate application rates ranged from 67 to 156 kg ha^{-1} among grid cells. Calculated whole-field nitrogen application ranged from 89 to 123 kg ha^{-1}. The resulting nitrogen

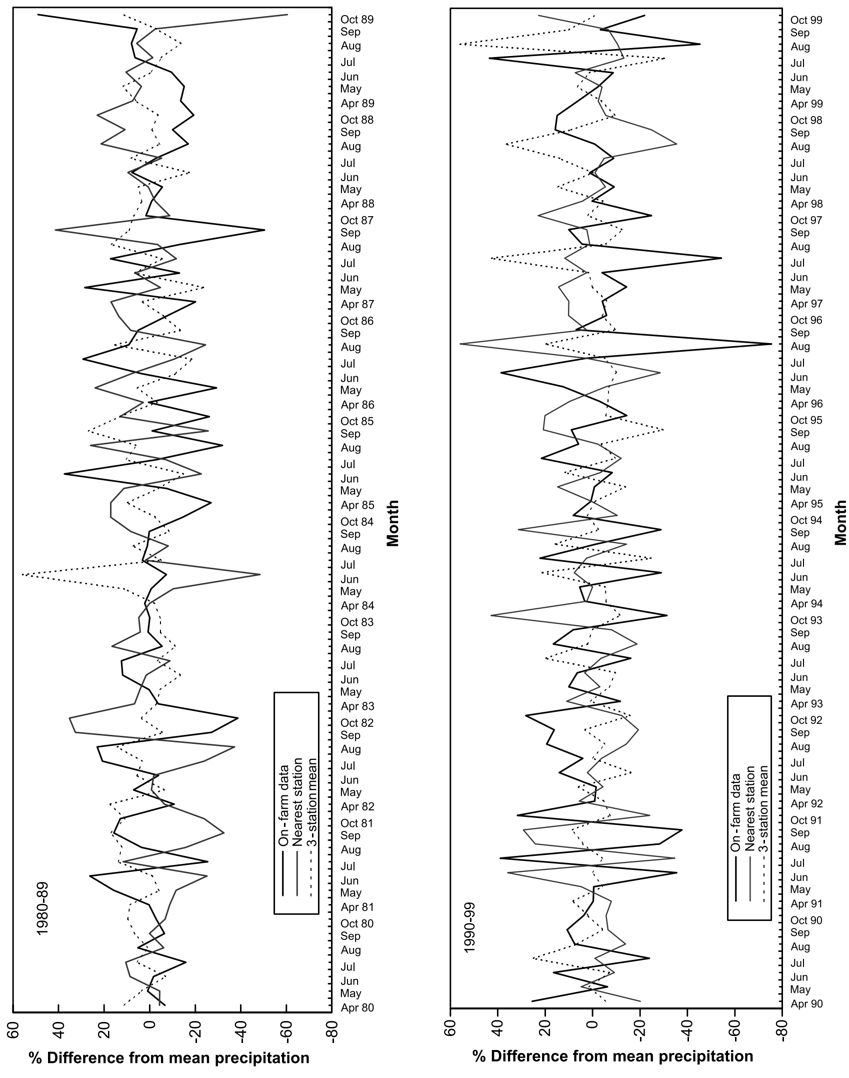

Figure 2. Percent difference in monthly precipitation, each data source minus the mean of all three data sources, 1980–1999.

Table 2. Yield monitored crops in each field, 1995–1999, at research site

Field	1995	1996	1997	1998	1999
M1	Corn	Soybeans	Corn	Corn	Soybeans
M2	Soybeans	Soybeans	Corn	Corn & soybeans	Corn
N	Corn	Soybeans	Corn	Corn	Soybeans
P	Soybeans	Corn	Corn	Soybeans	Corn

application maps are in Figure 3. Variable-rate application resulted in slightly increased applied nitrogen overall, from 5088 to 5123 kg.

Besides varying nitrogen application rates, timing of application was also varied. The typical practice at the farm was to apply a 19% N urea/ammonium nitrate solution at planting, then apply anhydrous ammonia as sidedress. The midrange of timing for sidedressing was 37 days after planting. Splitting the Tri-State Recommendations amount of nitrogen between planting (urea/ammonium nitrate) and sidedress (anhydrous ammonia) formed one strategy, while the other strategy was to apply only sidedress nitrogen (100% of recommendations, as ammonia) with none at planting. In some years the farm could not sidedress because of weather or field conditions. Accordingly, sidedress application was set to zero for the simulations of those years.

DSSAT input data

Over 100 variables and options could or must be specified in DSSAT. Site and management information specific to each grid cell were mostly used whenever available. Otherwise, inputs were assigned default values, based on the manuals (Hoogenboom *et al.*, 1994; Jones *et al.*, 1994; Hoogenboom *et al.*, 1999) or other literature or files provided with the software.

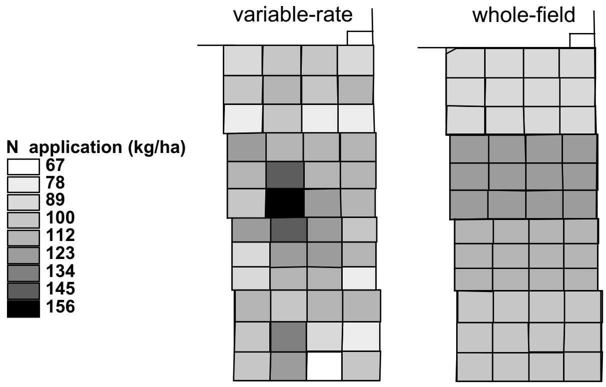

Figure 3. Nitrogen application rates for corn (kg ha^{-1}), by whole field and by 1-ha grid cells, based on yield potential and the Tri-State Recommendations equation.

The four fields included four soil types (Blount silt loam, Glynwood silt loam, Morley clay loam, Pewamo silty clay loam). Soil information was taken from the county Soil Survey (Neely, 1987), on-farm soil samples, and the DSSAT soil application program (Hunt *et al.*, 1994). Ranges of values among the grid cells and within soils for specific soil properties are shown in Table 3. The only site-specific soil test data used were pH in water and pH in buffer, which varied from grid to grid; other parameters were assigned by soil type. The range of variation in soil properties was moderate for most parameters, with the greatest difference being in organic carbon content. The inability to account for more site-specific variation in soil drainage properties could have led to some underestimation of the precipitation-induced yield differences.

Crop inputs, including planting dates, came from field records, crop literature, and agricultural statistics. Further details of inputs and initial conditions are available in O'Neal (2000).

Weather input data included precipitation, air temperature, and solar radiation. Precipitation data sources were described earlier. Air temperature data were taken from the on-farm NWS station (which had no missing values), and long-term average daily solar radiation for each month came from Indianapolis (98 km to the west), via US Department of Energy data. The WeatherMan program (Hansen *et al.*, 1994), which included an adaptation of the WGEN weather generator (Richardson and Wright, 1984), was used to simulate solar radiation on individual days. Using latitude and longitude, WeatherMan generates radiation according to the mean and standard deviation of radiation on wet and dry days plus a response to the previous day's air temperature (Richardson and Wright, 1984). These were the only

Table 3. Soil properties used in CERES-Maize simulations

Soil property (for values that differ by soil layer, only the value for the surface layer is shown)	Blount silt loam	Glynwood silt loam	Morley clay loam	Pewamo silty clay loam
Clay (< 0.002 mm) content (%)[a]	24.5	21.5	31.0	33.5
Coarse (>2 mm) fraction (%)[a]	0	1	0	0
Drained upper limit of soil moisture (cm^3 cm^{-3})[b]	0.282	0.266	0.298	0.320
Lower limit of soil moisture (cm^3 cm^{-3})[b]	0.145	0.131	0.174	0.184
Moist bulk density (g cm^{-3})[a]	1.55	1.50	1.60	1.55
Organic carbon content (g kg^{-1})[a]	25	20	17.5	65
pH in buffer[c]	6.3–7.0	6.6–7.0	7.0	6.4–7.0
pH in water[c]	5.7–7.9	5.8–7.2	7.0	5.8–7.8
Saturated hydraulic conductivity (cm h^{-1})[d]	3.3	3.3	1.0	3.3
Saturated upper limit of soil moisture ($cm^3 cm^{-3}$)[e]	0.486	0.486	0.390	0.432
SCS (Soil Conservation Service) runoff curve number[f]	85	85	85	87

[a]Determined from county Soil Survey.
[b]Calculated by DSSAT soil utility from % sand-silt-clay, moist bulk density, organic carbon, and coarse fraction >2 mm.
[c]Measured from soil sample.
[d]Determined from permeability from county Soil Survey.
[e]Determined from effective porosity from Rawls *et al.* (1982).
[f]Row crops, straight row, good hydrologic condition assumed.

stochastically simulated daily weather data used in the analysis. Although simulated radiation varies based on whether there is precipitation, median monthly radiation for the off-farm data sources varied by a maximum of 2.9% from on-farm data, which was small compared to precipitation differences.

For calibration and validation only, fertilization information was from field records. As many as four nitrogen applications occurred in a season, in the form of anhydrous ammonia, urea, and ammonia sulfate. Nitrogen content of fertilizer came from existing field records and use of chemical conversions from Hignett (1985) and Rauschkolb and Hornsby (1994). N amounts ranged from 1 to 5 kg ha^{-1} per application for ammonia sulfate and 34 to 211 kg ha^{-1} for other types of nitrogen.

CERES-Maize calibration, validation, and simulation

Corn yield was calibrated in CERES-Maize with DSSAT according to the genetic potential of corn varieties in the form of genotype coefficients. These coefficients were calibrated for each grid cell, for actual 1995–1999 growing conditions. Calibration for CERES-Maize followed a sequence of variables suggested by the CROPGRO sequence described in the DSSAT manual (Boote, 1999). The years with fewest crop stresses (1995 and 1998, except when corn yield data were not available) were used for calibration. The remaining years were used for validation. Further details of the calibration and validation are in O'Neal *et al.* (2002).

After calibration and validation, CERES-Maize was used to simulate corn yield for the four nitrogen application strategies, for each of the three precipitation data sources. Soybeans were assigned as the previous crop, to represent a 2-year corn-soybean rotation. Fertilizer incorporation/application depth was set to 5 cm for starter and 15 cm for ammonia injection. Start date of simulation was January 1. Files used actual planting dates; if a field did not have corn, planting date came from a nearby field, or else the surrounding crop district from state statistics. DSSAT produced output values of dry matter yield. Values were divided by 0.85 to convert them to 15% standard moisture for the analysis.

Profitability

Profitability, calculated on an annual basis, was based on simulated yield, for the four nitrogen management strategies. The equation used to calculate profitability was as follows, built upon Braga *et al.* (1998)'s equation:

$$\pi = \frac{1}{A}\left[\sum_{i=1}^{n} a_i \cdot \left(p_G Y_i - \sum_j r_{N_j} N_{ij} - r_H Y_i\right)\right] - F - r_A - I \qquad (2)$$

where π = profitability (\$ ha^{-1}), A = total area (ha), n = number of management units, a_i = area of management unit i (ha), p_G = grain price (\$ kg^{-1}), Y_i = crop yield in management unit i (kg ha^{-1}), N_{ij} = amount of nitrogen applied in management

Table 4. Prices used to compute cost and profitability

Item	Units	Price
Fixed costs	\$ ha^{-1}	\$195.00
Harvest cost	\$ kg^{-1}	\$0.0055
Information and analysis cost	\$ ha^{-1}	
On-farm data		\$2.38
Nearest station		\$0.13
Three-station mean		\$0.17
Corn price	\$ kg^{-1}	
Default		\$0.11
Maximum		\$0.19
Minimum		\$0.08
Application costs	\$ ha^{-1}	
Whole-field anhydrous ammonia		\$19.10
Variable-rate ammonia: Default		\$31.93
Varying costs (\$4 ha^{-1} and \$8 ha^{-1} above and below the default variable-rate cost)		\$23.93, \$27.93, \$35.93, \$39.93
Nitrogen cost	\$ (kg N)$^{-1}$	
Ammonia		\$0.39
Default		
Maximum		\$0.44
Minimum		\$0.28
Starter (10-34-0):		\$1.48
Default		
Maximum		\$1.51
Minimum		\$1.46

unit i in each application j (kg ha^{-1}), r_{Nj} = nitrogen cost for each form of fertilizer applied (\$ kg^{-1}), r_H = harvest cost (\$ kg^{-1}), F = fixed costs (\$ ha^{-1}), r_A = application costs (\$ ha^{-1}), and I = information and analysis cost (\$ ha^{-1}). Costs and prices used for calculating profitability are in Table 4.

Fixed costs and harvest cost followed those of an early online version of Braga *et al.* (1998), and the default corn price was the average monthly January 1995–June 1999 price from IASS (1995–1999). The default nitrogen cost was the average 1995–1999 price of ammonia or a nitrogen–phosphorus mix from IASS (1995–1999).

The information cost for on-farm precipitation data was based on a datalogging tipping bucket gauge purchased for \$250 with a 5-year lifetime and 12.5% opportunity cost of capital, plus 1 h week^{-1} unskilled labor (data collection) plus \$25 year^{-1} for cleaning, repair, and maintenance. The information cost for data from the nearest NWS station with electronic reporting, obtained from the Internet, consisted of a \$10 download fee each year, plus 8 h skilled labor (computer/Internet work) the first year and 1 h each subsequent year. The cost for the 3-station-mean was the same as nearest-station data plus 2 h skilled labor the first year (an additional calculation program and having to process two other stations' data), 1/2 h each subsequent year, for 10 years. For all three sources, the cost of labor was \$6.25 hr^{-1} unskilled, \$8.75 hr^{-1} skilled, after Benson *et al.* (1996).

Whole-field application cost of sidedressed anhydrous ammonia followed Benson *et al.* (1996), based on a 10-year depreciation and 12.5% interest, readjusted to a tillable farm area of 185 ha. Variable-rate application cost was \$12.83 ha^{-1} more than conventional application. This additional increment consisted of a \$5000 package including planter/anhydrous ammonia controllers, electronics, and an in-cab computer, with a 3-year useable lifetime, after Swinton and Lowenberg-DeBoer (1999), adjusted to 12.5% opportunity cost of capital and 185 ha, and no additional labor or fuel costs. The farm was assumed to already have a yield monitor. The assumption of already owning a yield monitor implied that the farmer was already making yield maps but had not yet made the decision to apply variable-rate. This would underestimate the additional cost of yield data and total cost of variable-rate application if the decisionmaker were a first-time user new to precision farming. However, the economic comparison of this study could not be performed unless the farmer already had yield monitor data for the crop model.

Sensitivity analysis of the profitability of variable-rate and sidedress-only application was also performed. This involved recalculating profitability with eight scenarios: maximum and minimum corn price (for January 1995–June 1999), maximum and minimum nitrogen (urea/ammonium nitrate and anhydrous ammonia) prices (1995–1999), and four different costs of variable-rate application (\$4 ha^{-1} and \$8 ha^{-1} higher and lower than the default). Values used for these scenarios, and default values of costs and prices, are in Table 4.

Choice among nitrogen strategies

The choice among nitrogen application strategies was based on profit, using stochastic dominance. The determination of stochastic dominance involved the area under (to the right of) cumulative probability curves of profit (π, Eq. 2) and their relative position along the profitability axis. Strategies were further separated into categories of "dominated", "risk neutral", and "risk averse", in terms of risk and profit desirability, based on the stochastic dominance results (Hien *et al.*, 1997). The Kolmogorov–Smirnov (K–S) two-sample D^+ test was used as suggested by Hien *et al.* (1997) to test if the distributions were statistically different.

Choice among precipitation data sources

After making choices between paired nitrogen strategies for each precipitation source, it was possible to make a choice among the three precipitation data sources. The most accurate source was presumably on-farm data, since it measured the precipitation closest to the place where the crops were grown. Thus, the correct choice between paired nitrogen fertilization strategies was the one selected using on-farm data, if one dominated another with first or SDSD. If off-farm data led to one or more incorrect choices, and the additional cost of on-farm data was less than the increase in profit from the correct choice, then on-farm data would be profitable. If the profit difference was less than the extra cost of on-farm precipitation measurement, then on-farm data might be useful, but unprofitable, and using NWS station data would be more efficient than measuring precipitation on-site, for a site-specific farmer in east central Indiana, for such a decisionmaking scenario.

Results

CERES-Maize calibration and validation

The calibration of CERES-Maize using the 1-ha grid cell yield gave an r^2 of 0.742 for regression of simulated yield versus yield monitor data, with 65.3% of the simulated grid cell yields within 10% of yield monitor data (O'Neal *et al.*, 2002). The slope of the regression was 0.73. Yield error on the field scale in 1995 and 1998, the two main calibration years, ranged from 0.3% to 9.1%.

The validation of 1-ha grid cell yield gave an r^2 of 0.330 and regression slope of 0.555. Although low, the r^2 statistic was within the range of values found by other CERES modelers including the r^2 of 0.160–0.441 found by Jagtap *et al.* (1999) with plot-level corn prediction and $r^2 = 0.57$ from Paz *et al.* (1999) for within-field corn yield variability (552 m^2 grid cells). However, it was much lower than the $r^2 = 0.80$ which Booltink *et al.* (2001) were able to obtain for yield of 0.2-ha grid cells with CROPGRO-Soybean, by calibrating water stress, pests, and weeds rather than genetic coefficients. Of predicted yields on a field basis, two thirds were within 25% of observed. The regression slopes suggested more random error in calibration and more systematic error (under-prediction) in validation. Further details of calibration and validation are in O'Neal *et al.* (2002).

The coefficient of variation for observed grid cell yield was 1.22 times that of simulated grid cell yield. The model underestimated high yields and overestimated low yields, showing a reduction from the variation seen in observed data. Thus, the model underestimated the variance relative to the mean. This characteristic of the model would tend to show less significant differences in yield between different precipitation sources and different nitrogen strategies.

CERES-Maize simulation

The spatial patterns of simulated yield were similar among treatments for each precipitation source, but varied among precipitation sources, as shown in Figure 4 for the year 1997. Over the 20-year period, Figure 5 shows how variable the simulated yield was from year to year and between data sources, for one strategy, based on the precipitation differences which are shown in Figure 2. The extreme difference in yield between data sources in 1996 and its relationship to precipitation differences are discussed in O'Neal *et al.* (2002). Determining the accuracy of simulated yields was not possible because of the use of fixed values for inputs each year versus the actual year-to-year variable inputs. The 20-year average of predicted corn yield for each of the 12 combinations for the 49-ha area ranged from 5282 to 6103 kg ha^{-1}.

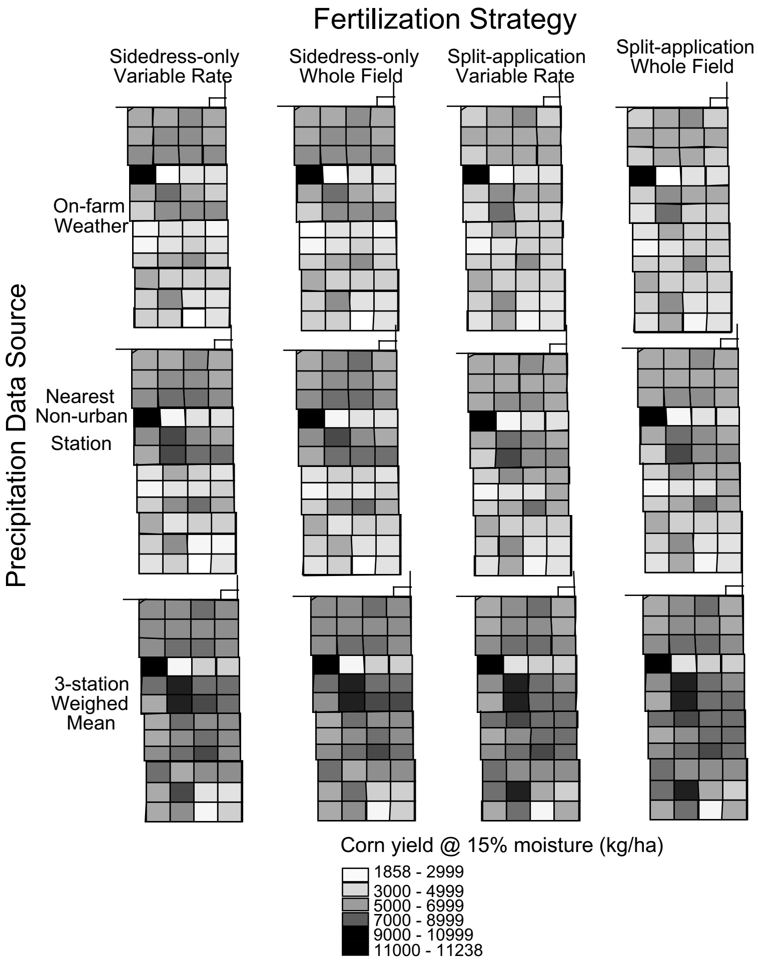

Figure 4. Simulated corn yield, 1997, based on three precipitation data sources and four nitrogen strategies.

Choice among nitrogen strategies

Cumulative probability graphs (Figure 6) did not show one strategy to be more profitable than another for every data source, over the distribution of profits. For large portions of the distribution, but not throughout the entire range of profitability, sidedress-only had higher profit, due to the relatively large cost savings of sidedressed ammonia compared to urea/ammonium nitrate starter. Whole-field application had higher profit than variable-rate application more often than the reverse, but this was not clear for every data source. On-farm data showed a greater difference between distributions in the center of the probability range than did the other data sources.

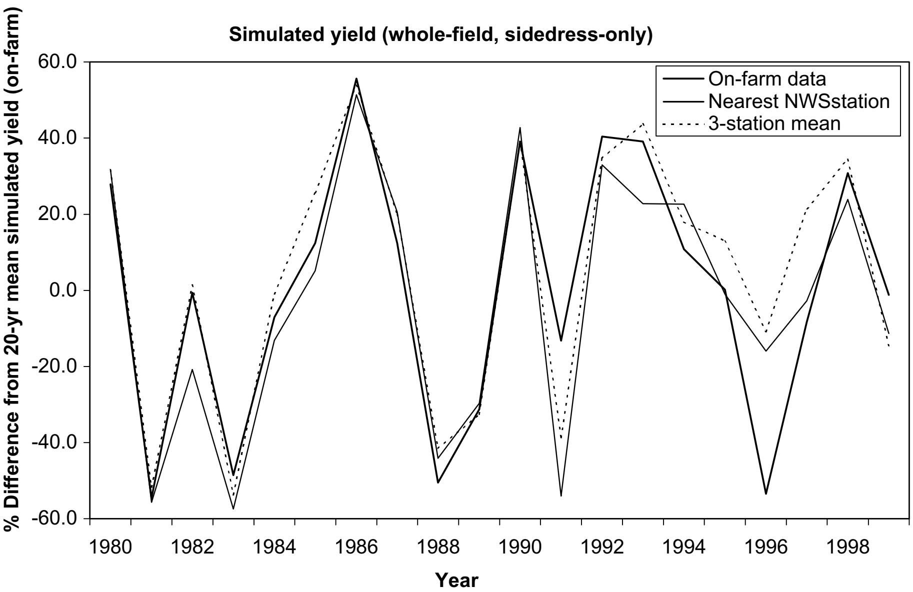

Figure 5. Simulated corn yield summed over a 49 ha area, for three precipitation data sources, 1980–1999, for one management strategy (sidedress-only, whole field N application), percent difference from the 20-year mean simulated yield of on-farm data.

If maximizing overall mean profit was the criterion of choice, descriptive statistics of profitability (Table 5) showed that sidedress-only was more profitable on average than split application, and whole-field application was slightly more profitable than variable-rate, for all three data sources. Nearest-station data showed lower minimum profit and the 3-station mean showed higher minimum profit compared to on-farm data. Both off-farm sources underestimated the maximum profit.

Sensitivity tests indicated that the ranking of sidedress-only as more profitable than split application remained for all three sources even if nitrogen prices increased or decreased to the 1995–1999 maximum or minimum or corn prices decreased to the 5-year minimum; however, at the maximum corn price, split application became more profitable. The extra yield of high-value corn from split application in some weather years was then sufficient to offset the additional nitrogen cost.

The slight advantage of whole-field management over variable-rate management appeared with maximum and minimum corn and nitrogen prices also, for all three data sources. Even when variable-rate application cost was lowered by \$8 ha^{-1} from the default, whole-field application still had a higher mean profit. The general principle illustrated here is that variable-rate application would be more profitable with higher cost inputs. Ammonium nitrate is usually much more expensive than anhydrous ammonia, so variable-rate application would make more sense when using ammonium nitrate. However, since the ammonium nitrate was applied with the planter, variable-rate application occurred only with the anhydrous ammonia, and therefore whole-field application remained more profitable.

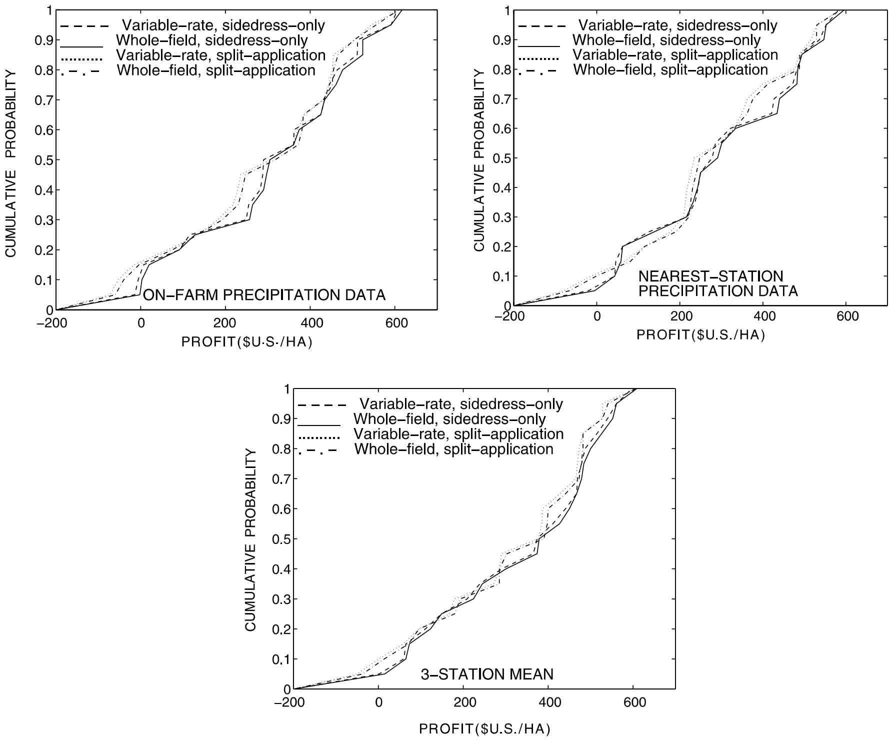

Figure 6. Cumulative distributions of profitability, 1980–1999, based on simulated corn yields.

The significant difference was between sidedress-only and split application. Figure 7 shows the profit distributions for split application versus sidedress-only, for variable-rate application. The effect of the higher nitrogen cost for starter fertilizer was apparent throughout most of the distribution, especially for on-farm data. All three data sources showed sidedress-only more profitable in the lowest-profit years—suggesting that the savings in nitrogen cost outweighed the decrease in yield.

A yield-maximizing criterion would have favored split application, as it yielded higher than sidedress-only for all precipitation data sources. Weather risk could give an additional advantage if in some years sidedress nitrogen application was impossible because of weather and surface moisture. For the research site, according to farm records, no sidedress application occurred in 6 of the 20 years, due to rain and field conditions. The simulations were set up to exclude sidedress application in those same years. Therefore, for 30% of the growing seasons, nitrogen fertilizer at planting was all that the simulated crop received, with split-application, or none at all, with a sidedress-only strategy. This represents an extreme scenario.

Risk categories of profitability

Stochastic dominance comparisons showed that the whole-field sidedress-only strategy was in the risk averse category for all three precipitation data sources

Table 5. Descriptive statistics for net profit over the 49 ha by strategy, 1980–1999, simulated from three precipitation data sources

	Net profit by treatment ($ ha^{-1})			
	Whole-field sidedress-only	Whole-field split-application	Variable-rate sidedress-only	Variable-rate split-application
On-farm data				
Average	$322.05	$297.15	$313.45	$289.60
Standard deviation	$188.44	$193.91	$188.95	$196.75
Minimum	−$2	−$60	−$14	−$72
Maximum	$617	$609	$606	$611
Nearest-station data				
Average	$309.65	$294.40	$302.90	$285.30
Standard deviation	$183.14	$176.35	$182.63	$178.58
Minimum	−$5	−$66	−$20	−$79
Maximum	$595	$586	$582	$586
Three-station mean				
Average	$350.15	$330.50	$341.65	$321.35
Standard deviation	$182.06	$183.97	$182.16	$185.82
Minimum	$15	−$37	$2	−$50
Maximum	$609	$607	$598	$607

(Table 6). This strategy was therefore the most desirable from both profit and risk standpoints. This result held for all sensitivity tests. However, the Kolmogorov–Smirnov test did not show this strategy to have a significantly different distribution than any other strategy at the 95% confidence level, based on any precipitation source, for the default costs. Since the K–S test is based only on the maximum difference between entire cumulative distributions, more detailed analysis (FDSD and SDSD) is appropriate to determine whether smaller differences within distributions can still separate them in terms of risk and profit. Unless otherwise noted, the outcomes in Table 6 apply to all sensitivity tests (corn price, nitrogen price, VR application cost, dropping each weather year from the distribution).

At least one variable-rate strategy was always dominated (undesirable even to a risk neutral farmer), for each data source. Whole-field split application was always in the risk-neutral category, for the default values; it would be desirable to a risk-neutral farmer for overall profit, but not to a risk-averse farmer because some other strategy (whole-field sidedress-only) would perform better in the lowest-yielding years. With sensitivity tests, for on-farm data, whole-field split application ranged from dominated (totally undesirable) to risk averse (most desirable), depending on corn price. The advantage of having at least some nitrogen application in years when sidedressing is impossible depended strongly on the economic value of the additional yield. Off-farm data showed an advantage for split application when corn prices were high but no disadvantage when corn prices were low.

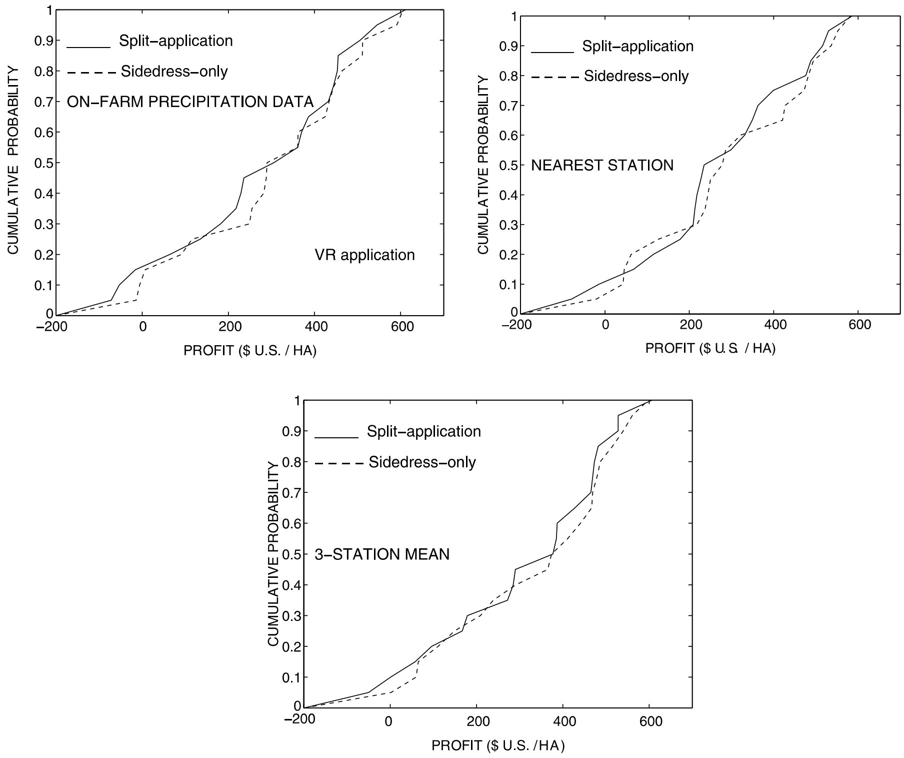

Figure 7. Cumulative probability of profitability over the 49 ha, based on three sources of precipitation data and simulated corn yield, for split application versus sidedress-only, with variable-rate application.

Stochastic dominance

Using the on-farm data, whole-field application with sidedress-only was FDSD over variable-rate sidedress-only for the defaults and every sensitivity test, and FDSD-dominant over all other strategies for minimum corn price. The 3-station mean, however, failed to show FDSD for the lowest variable-rate application fee, and the nearest-station data showed FDSD in only three of the sensitivity tests. Split application and sidedress-only were not separable with FDSD except at minimum corn price. Overall, neither of the off-farm data sources consistently showed FDSD for the same comparisons as on-farm data, although the 3-station mean agreed more frequently than the nearest-station data.

For the defaults, the K–S two-sample test was relevant for only two FDSD comparisons: whole-field sidedress-only versus variable-rate sidedress-only, and whole-field split application versus variable-rate split application. For the on-farm data, the K–S test gave a D^+ value (maximum vertical difference in probability) of 0.10 for the variable-rate versus whole-field comparison with sidedress-only. The same comparison for the 3-station mean gave a value of 0.05. For nearest-station

Table 6. Risk categories for the objective of maximizing profit, tested with CERES-Maize corn simulations, 1980–1999, by nitrogen application strategy and precipitation data source

Precipitation data source	Whole field sidedress-only	Whole field split-application	Variable-rate sidedress-only	Variable-rate split-application
On-farm data	Risk averse	Risk neutral[a]	Dominated	Risk neutral[b]
Nearest non-urban NWS station	Risk averse	Risk neutral[c]	Risk neutral[d]	Dominated
3-station weighted mean	Risk averse	Risk neutral[e]	Dominated[f]	Dominated

[a]Risk averse for maximum corn price; dominated for minimum corn price.
[b]Dominated for minimum corn price.
[c]Risk averse for maximum corn price and dropping 1981, 1984, 1988, 1989, or 1999.
[d]Risk averse for \$8 ha^{-1} lower VR application cost; dominated for minimum corn price, \$8 ha^{-1} higher VR application cost, and dropping 1996.
[e]Risk averse for maximum corn price.
[f]Risk averse for \$8 ha^{-1} lower VR application cost.

and 3-station-mean data, the comparison of whole-field versus variable-rate for split application gave a D^+ of 0.15. None of the values were significant at even a 75% significance level, based on a critical D^+ of 0.20 for sample size $n = 20$.

When the choice was unclear between whole-field and variable-rate application or between sidedress-only and split application, as occurred frequently, profit alone (FDSD) was insufficient to determine a better strategy, so finding the best balance of risk and returns (SDSD) became the criterion of choice.

In 29 of the 30 cases when SDSD was necessary for off-farm data, and was not necessary for on-farm data, the result was the same choice that FDSD led to for on-farm data. The difference was that a choice now appeared to be better only from a risk perspective, when actually it was also better from a profit perspective. In a single case (lowest VR application fee, nearest-station data), the choice still could not be made with SDSD.

In all 29 cases when SDSD was not necessary for off-farm data (showed a FDSD choice) but was necessary for on-farm data (no FDSD), on-farm data led to the same choice for SDSD. The choice was better from the risk perspective, but not from the profit maximization perspective (as off-farm data mistakenly showed).

In the cases where SDSD was necessary for all precipitation data sources, off-farm data either led to the same choice as on-farm data or showed that no strategy was SDSD-dominant. The three precipitation data sources never led to a disagreement about which choice was better, but rather about the sense in which the choice was better.

The differences in FDSD and SDSD meant that the precipitation data sources affected the risk category of the strategy, as shown in Table 6. For instance, with the defaults, on-farm data showed variable-rate sidedress-only to be the only strategy in the dominated (most undesirable) category, while for the nearest-station data, variable-rate split-application was the only such strategy, and for the 3-station mean, two strategies were dominated.

Choice among precipitation sources

The differences in expected value and variance of profit between the four different strategies for on-farm data were associated with the profitability of correct and incorrect choices. Expected value is a measure of overall profitability, while variance is a measure of the riskiness of profit. Off-farm data sources are not used for this determination because they do not represent the actual farm conditions. The difference in profit between the correct strategy and some other choice is the cost of making that wrong choice, and it contrasts with the additional cost of having on-farm data to make the right choice. Based on the on-farm data simulations, split application cost an extra \$24–25 per hectare in profits compared to sidedress-only, while whole-field and variable-rate application were more similar in profitability.

The cost differential between on-farm and off-farm data, \$2.38 ha^{-1} versus \$0.13–0.17 ha^{-1}, gave a baseline against which to compare profitability of decisions made with the data. Even if off-farm data had led to an incorrect choice of strategy, the additional profit from the correct strategy would need to have covered the information/analysis cost of on-farm measurement for it to be truly profitable. Any of the wrong choices in this case would have cost more than the additional on-farm measurement cost. However, the three data sources typically led to the right choice, although the profit and risk characteristics of that choice varied among data sources with FDSD and SDSD.

Since all three data sources led to the same best choice, the most profitable precipitation data source would be the least expensive. The nearest-station data and 3-station mean both had comparable costs (\$0.13 and \$0.17 ha^{-1}), a great deal less than that of on-farm measurement (\$2.38 ha^{-1}). Given the additional time and management needed to use three files instead of one, the most profitable information source appeared to be data from the nearest station, via the Internet. Also from a climatological standpoint, the nearest station was preferable, because the weighted average of three stations smoothed over zeroes, causing apparent increased precipitation values and frequency.

Summary and conclusions

Precipitation data from on a farm led to the same choice, of whole-field or variable-rate nitrogen application with all at sidedress or split between starter and sidedress, as either the nearest non-urban NWS station or the inverse distance-squared weighted mean of the three nearest such stations. However, the choice varied in terms of whether a nitrogen fertilization strategy was acceptable in terms of risk, with stochastic dominance. Sensitivity testing with extreme historical values of prices/costs and years of weather data showed that the on-farm data results were relatively robust, while stochastic dominance comparisons changed frequently with nearest-station data, and less so with the 3-station mean. For instance, the three precipitation data sources each gave a different answer in terms of which strategy was in the "dominated" (unacceptable) category, and in one case the three data sources showed the same strategy to be in three different risk categories (dominated, risk averse, and risk neutral). In several cases, off-farm data showed one comparison to be ambiguous in terms of profit maximization, when on-farm data showed one strategy to dominate throughout the distribution of profitability.

The cumulative probability curves of profitability for sidedress-only and split application were not easily separable with stochastic dominance. The higher nitrogen cost of split application outweighed the increased yield, even though sidedressing could not be performed in some weather years. For whole-field versus variable-rate application, the extra cost of variable-rate application equipment favored whole-field application, as yield differences between the two were small.

A limitation of the current study is with the calibration of the crop simulation model. It would have been better to calibrate to soil properties and drainage, as done by Paz *et al.* (1999), rather than to genotype coefficients, to characterize site-specific yield variability. Corn yield variability in Midwest fields is likely to come from water stress associated with the highly variable soil properties and drainage characteristics found across the field, as assumed by Paz *et al.* (1999), while crop genotype characteristics are relatively homogeneous within fields.

The crop model, as calibrated, also underestimated variance relative to observed yields, which made frequency curves more similar and could give fewer significant differences between nitrogen strategies and between precipitation data sources. A more precise calibration and model would allow more complete frequency distributions of yield and profitability with more extended tails for the extremes, and in turn permit a more accurate economic determination of best profit risk for nitrogen management strategies.

This study is based on simulated yield and profit, but the most important determinant of making profitable management decisions from weather data is what happens in the field. Under-prediction of actual yield values with simulated yield, and a small simulated yield response to nitrogen in the crop model, could have reduced the overall yield differences among precipitation data sources. Nevertheless, simulated information is the best possible, and most likely to be used for decisions of this sort. Testing the value of on-farm precipitation data with field trials and actually applying nitrogen in different strategies over multiple years with different weather would be inefficient for research, so a modeling approach is clearly preferable, despite the shortcomings of the model being used.

Since the average farmer is unlikely to have on-farm weather records going back very far, using existing long-term stations nearby is desirable. The farm in this study was within 27 km of an off-farm NWS station with electronic reporting. Most farmers in the state of Indiana have a NWS station this close or closer from which to obtain data. Missing data, however, might require finding a station farther away.

The analysis of sidedress nitrogen choice constrains the results to a management decision made before the beginning of the season. The result of this study further depends on geographic precipitation patterns, which are different in regions with more varied topography than the flat glaciated areas of east central Indiana. Larger field sizes could also change the results, if there was more spatial variability within each field, for the relative profitability of whole-field application.

The conclusion drawn from this study is that having precipitation data on the farm, or at scales smaller than the NWS network, may be useful for this type of management decision, but may not be profitable for nitrogen application choices. Decisionmaking is enhanced with on-farm precipitation data, via more accurate risk assessment, but profitability is not. Nitrogen application strategies chosen based on inexpensive precipitation data from the NWS would be the same as those based on relatively expensive recording at the farm, although in sensitivity testing on-farm data sometimes results in clearer distinctions between strategies. Better decisionmaking may have other sociological or economic impacts not directly addressed, such as stability of management over time, confidence about future decisions, and more efficient land management and use of time and resources. With precision farming, on-farm management requires the best available data, so it can be argued that on-farm data are desirable for reasons other than profitability. However, if profitability is what matters, then using NWS data from the nearest station, via the Internet, would be more profitable than on-farm data because of its lower cost.

Note

1. Throughout this text, the use of specific company and/or product names is in no way an endorsement by the authors or by Purdue University.

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