ANALYSIS OF WITHIN-FIELD GRAIN YIELD VARIABILITY: A COMPARISON OF YIELD MONITOR AND FIELD VERIFICATION DATA

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NOMENCLATURE

$\bar{d}$	Mean difference between paired values
N	Number of paired data values
R	Pearson's correlation coefficient
S_X	The standard deviation of X
S_Y	The standard deviation of Y
t_{mp}	Matched pairs t
σ	Standard error of the pair differences

CHAPTER 1

INTRODUCTION

Precision farming is a promising marriage of cutting edge technology and commonsense farm management practices. The intention of this marriage is an increase in farm efficiency and also the minimization of non-point source (NPS) pollution from farmlands. Briefly defined, precision farming is the management of soil and crop parameters on a sub-field, site by site basis. Until the last decade, almost all management practices addressed soil deficiencies, pests, tillage practices, and irrigation programs at the field level. With the arrival of accurate and affordable location tracking systems, variable-rate applicators, combine-mounted grain yield monitors, and the availability of PC-based farm software packages to display and analyze this spatial data, precision farming has gained acceptance among progressive producers.

The technological trends of the 80's and 90's have facilitated this shift of focus from the field level to a finer sub-field resolution. Variable rate controls are now widely available for spreaders and planters giving the farmer greater control over where he/she applies a product within a field. More importantly, the grower can control at what rate a given location in a field receives these inputs. This type of precision farming equipment sets the stage for the intelligent variation of management practices at a sub-field level.

However, to make educated decisions the producer or farm manager must have reliable information regarding the variability of soil and crop parameters. This information comes mainly from soil test data, soil maps, crop scouting, past cropping histories, and most recently, grain yield monitors. These data become a set of decision-making tools for the modern farmer who sees the logic of applying crop inputs only where needed and in quantities suitable for a given management goal. The promise behind this trend is that the farm manager will be able to minimize inefficiencies likely to occur when determining crop inputs based upon field averages. Inefficiencies are greatest when these averages come from highly variable data sets. Blanket spreading based on a highly variable data set may lead to significantly under- or over- application to areas within a field. Crops in these improperly treated areas do not fully benefit from the presence of the input and sub-optimal crop responses, and wasted product reduces the efficiency of the overall farm operation. Furthermore, underutilized nutrients are likely to become NPS pollutants in local waterways. Reduced efficiency and increased pollution are most likely in heterogeneous fields that are blanket-spread (Mulla 1993). This scenario contrasts with a blanket spread rate for a relatively homogeneous field. In this type of field, soil or crop parameters show little variance. Any given location within this field may return a value for the parameter of interest close enough to the mean value that a blanket spread rate is the most efficient. This concept of application based upon a suitable level of variability is equally relevant for pest management and irrigation programs.

Once a manager ascertains whether the variability within a field warrants site-specific management, he/she creates soil fertility and grain yield maps using one of several methods of estimation. The data used to create soil fertility maps come from a collection of discrete samples evenly or randomly located across a field. The data for grain yield maps are a stream of points collected by a grain yield monitor mounted on a combine that traverses the field during harvest. In both soil and yield data collection, analysts can estimate values for locations not sampled to create a surface map of soil or yield variability within a given field. Armed with these maps, the crop consultant or farm manager can vary crop inputs and other management practices across the field according to mapped variations in soil and crop parameters. If site-specific management proves superior to conventional field level management practices, the proof will be in increased efficiency. In other words, growers achieve the greatest grain yield per unit of input while at the same time minimizing pollution.

Before efficiency is evaluated, the accuracy of the given data must be proven. Using grain yield data to test the efficiency of a site specific management practice requires accurate site-specific yield results. Field average yield results collected over several growing seasons give a general indication of effectiveness. Unfortunately, these aggregated data do not indicate where in a given field yield was high or low. High yielding areas in a field are known to indicate reductions in soil nutrient levels over time due to plant nutrient uptake. Low yielding areas suggest that some limiting factor is already in place. Therefore, high yielding areas may need lower short-term inputs but eventually require higher levels of inputs than a blanket spreading operation will provide. Also, the lowest yielding locations are routinely under-spread when a farm manager uses a field average value to calculate a recommended rate. Without accurate site-specific yield data, the producer cannot use these data to predict where in his fields crop inputs are actually meeting or maintaining crop nutrient requirements. Inaccurate crop data, may lead to declining nutrient levels that limit future yields and reverse gains made in the past using site-specific management practices. Furthermore, aggregated yield results do not allow the grower to test grain yields for correlation with sub-field soil fertility. Poor knowledge of exactly where grain yield variations occur within a field impedes correlation testing of site-specific crop responses and site specific management practices (e.g., fertilizers, pesticides, tillage). The advent of differentially correct Global Positioning Systems (DGPS) with sub-meter accuracy, in tandem with a combine mounted grain yield monitor, has given crop producers a method of collecting site-specific yield data. These two technologies promise to provide accurate yield measurements for sub-field locations and accurate locational data for those same yield measurements.

STATEMENT OF PROBLEM

With the ability of grain yield monitors to accurately record a field's total yield demonstrated through experimentation (Pringle et al. 1993; Auernhammer et al. 1993; Stott et al. 1993; Reitz and Kutzbach 1996), producers have the necessary data to create field level yield maps. If crop producers are to use these yield maps to make sub-field application decisions, they must be able to verify the ability of these maps to record yield variability. Only then may a producer rely on grain yield maps as inputs to a sub-field management decision making procedure. The process of sampling a corn field is relatively simple and several methods are currently in use by crop insurance agents and researchers. However, these methods normally involve broad generalizations in the case of crop insurance estimates or complete removal of entire plots in the case of researchers. The former methods do not provide the resolution needed to check yield data at the sub-field level. The latter methods utilize destructive processes over relatively large areas and researchers cannot return sampled material to the field for the actual harvest. Therefore, researchers and producers need a method of obtaining a set of control harvest data that provides the necessary resolution without influencing the grain yield monitor data. A systematic spot sampling scheme may prove feasible for the purpose of verifying the ability of grain yield monitors to record sub-field yield variability. No studies were found in which grain yield was spot sampled before the actual harvest and collection of monitor data.

Once the monitor collects the raw yield data and any bad data points are removed from the data set, the analyst can use various methods of estimation to create continuous surface grain yield maps for that field. These different methods can produce markedly different grain yield maps. A large number of articles exist addressing the pros and cons of these methods for yield surface estimation. However, because no pre-harvest yield data have been available, comparisons of methods have relied solely upon grain yield monitor outputs. It is therefore justifiable to ask the following question: If producers are to use these surface maps as decision making tools, are the source data for the estimates accurate? To investigate this question, it is necessary to compare grain yield monitor data to a subset of actual yield values tied to known locations. Once again, before researchers can address these questions, there is a definite need for a pre-harvest sampling methodology.

PURPOSE OF STUDY

It is the purpose of this study to investigate the capability of a combine-mounted grain yield monitor (AgLeader 2000®) in operation with a GPS receiver (OmniStar®) to accurately record the variability of grain yield in an Illinois corn field. The specific project goal was to evaluate the ability of grain yield monitor data to accurately reflect grain yield variability across a field by comparing grain yield monitor data to yield determined by hand sampling.

The accuracy of raw, corrected, and estimated grain yield data was evaluated using pre-harvest, hand-sampled grain yield estimates for known locations within the same field the combine harvested. Several methods of grain yield post-processing were utilized to determine which method(s) produced the best representation of variations in grain yield in the field as estimated by hand-sampling results. Specific objectives of this study included, but were not limited to the following:

1. Obtain a pre-harvest hand-sampled data set(s) to use as field verification.
2. Obtain grain yield monitor data for the same field at harvest time.
3. Correct the grain yield monitor data for transport delay inside the combine, GPS error, and normalize grain yield results based on variations in moisture content.
4. Analyze the hand sampled and monitor gathered data distributions for levels of skewness and kurtosis.
5. Create grain yield surface maps for each field using the following techniques: kriging, inverse distance weighted, and block averaging.
6. Use a matched pairs t-test to compare the pre-harvest samples and grain yield monitor data for difference.
7. Utilize Pearson's Product Moment correlation to estimate ability of the yield monitor data to accurately reflect the actual yield variability within a given field.

The null hypothesis for this study is:

H_o : $\delta = 0$, the hand sampled data and the yield monitor data represent the same population of

yield data, $\alpha = 0.05$.

H_a: $\delta \neq 0$, the hand sampled data and the yield monitor data do not represent the same

population of yield data, $\alpha = 0.05$.

JUSTIFICATION

As previously stated, precision farming strategies promise to increase efficiency while decreasing negative environmental impacts. The validity of the site-specific management paradigm hinges on the ability of the producer to create or obtain spatially accurate, representative data sets for soil and crop parameters. Since grain yield reflects the combined influence of a large number of underlying soil, crop, climate, and input parameters (Vansichen and De Baerdemaeker 1991), spatially accurate grain yield data is vital to a precision farming decision support system.

The farm manager must be able to link increases or decreases in yield directly to site specific management practices. Without this ability the manager cannot objectively make the decision to adopt or discard this crop management system. This study builds on past grain yield monitor research by testing the capability of a grain yield monitor-DGPS receiver combination to accurately estimate yield variability in an Illinois corn field at the sub-field, sub-pass level. Future researchers can modify the methodology presented here to test grain monitor data for spatial accuracy.

CHAPTER 2

REVIEW OF LITERATURE

PRECISION AGRICULTURE

Precision agriculture is the practice of varying management practices (inputs, tillage, seeding rates, irrigation, etc.) according to the variability of crop and soil parameters across a farm and within the boundaries of each field. Currently, the standard program utilizes three major technologies: Variable rate applicators, a positioning system for gathering spatial data, and a computer based management system for storing and manipulating the data (Schnug et al. 1993). The actual management program involves a sequence of activities (Fig. 1). The cycle of events begins with the gathering of basic spatial data concerning a farm or field. These basic data include field boundaries, soil type maps, and some times, remotely sensed imagery. Once the farm manager obtains the basic spatial information, he/she evaluates within-field variability of key soil variables and maps these variables according to soil test samples taken from known positions within a field. From the soil test results, soils maps, yield history, and remotely sensed data, the farm manager makes recommendations for crop inputs or seeding rates and sends them to a variable rate applicator or planter. The manager monitors crop growth and health

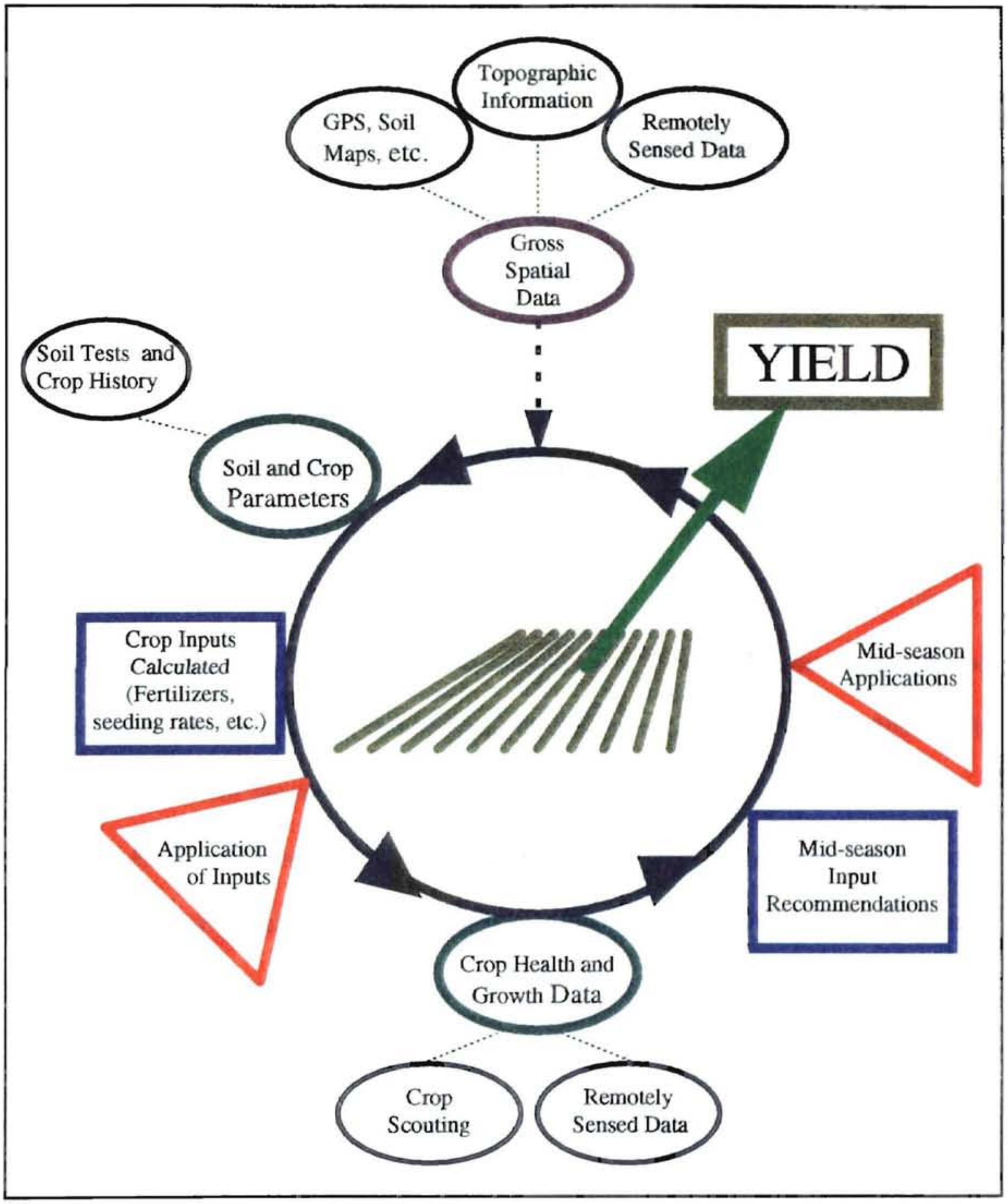

Figure 1. LOOP OF PRECISION FARMING ACTIVITIES

throughout the season at a sub-field level and applies necessary inputs where needed. Finally, the grower harvests the crop and the grain monitor collects data as the harvesting equipment moves across a field. Following harvest, the producer performs further soil testing to estimate plant uptake and determine possible application strategies. The manager analyzes the final yield, all inputs, and the post-harvest soil test results for each field to determine the effectiveness of the season's sub-field management strategy. If the initial analysis suggests that precision management boosted profits, the manager makes any adjustments to the basic farm spatial data (for example, boundary changes) and the process of sub-field management continues. This cycle will likely continue for several growing seasons before the farm manager can make final judgment concerning the overall effectiveness of precision farming of a given field or farm (Blackmore 1994; Lowenberg-DeBoer and Swinton 1995).

A key goal of precision farming is to improve yield either by increasing yield per acre or decreasing inputs while maintaining comparable yields (Blackmore 1994). The economic benefits of precision agriculture may not prove themselves for some crops or locations. Uncontrolled variables such as microclimates or soil differences may mask or confound positive or negative changes in yield, thus, making assessment of management practices untenable (Lowenberg-DeBoer and Swinton 1995). Colvin and Karlen (1996a) calculated partial budgets for a precision farming operation for 224 sites in an Iowa field based upon seven years of historic yield data. Results of their study revealed that for any given year 30% of the field would have shown negative returns. Furthermore, they found that for each year 5-10% of this field should not have been farmed at all. With results such as these, farm managers will need several seasons of yield results to make even tentative judgment on the benefit of precision agricultural practices on a particular parcel of land or crop type. In contrast, the profitability of precision farming for high value crops is already being reported, and bulk commodity crops may begin to gain similar advantages as technology and precision management skills improve (Lowenberg-DeBoer and Swinton 1995).

Although increased profitability is the most obvious goal of precision management practices, being able to maintain these profits while meeting the stringent requirements of a local or federal environmental agency is another strong incentive for implementing this type of farm management. Researchers have found actual and simulated reductions in surface and groundwater pollution when they used site-specific application techniques (Horsley 1995)

Precision agriculture is not a new idea. But it was the advent of variable rate equipment and controllers, the completion of United States' NAVSTAR satellite network (the Global Positioning System), and powerful PC-based mapping and GIS software packages that made large-scale precision farm management economically promising (Schueller 1992). High equipment costs, however, reduce its appeal to smaller producers who cannot justify the risk of not being able to recoup the high initial costs of precision farming and management equipment. Furthermore, yield monitoring equipment exists mostly for grains and similar row crops. Most specialty crop growers do not have access to suitable yield monitors at this time. Growers and researchers are currently testing several specialty crop yield monitors (Lowenberg-DeBoer and Swinton 1995 and Walter et al. 1996).

One appealing aspect of precision farm management tools are their ability to allow the farm manager the opportunity to conduct on-farm research at the sub-field level (Reetz 1996). With accurate GPS equipment, soil and yield data, and a GIS, managers and research cooperators can plan farm-based research projects designed to investigate the spatial and temporal variability occurring in their own fields. Results from these field-scale tests should be more applicable to the evaluation of local management practices than traditional plot studies. Researchers usually conduct plot studies at locations other than an operating farm so they can control or reduce the effects of soil and crop variability on the results.

YIELD VARIABILITY

For years, crop producers have noted yield variability within their field boundaries. Agriculturists and researchers frequently list soil properties, in relationship with soil water holding capacities, as the key limiting variables to predicting crop yield. Recent work concerning prediction of grain yields supports these observations (Sudduth et al. 1996). Researchers report that soil depth and elevation are two variables with a consistent effect on soybean yields. Furthermore, they cite difficulty in detecting significant correlation between soil fertility and yield. They attributed the lack of correlation to a complex, non-linear relationship between yield and soil properties. Conversely, Missotten et al. (1996) report "good correlation" between yield monitor data and soil fertility, soil texture, and especially soil water relations.

Lark and Stafford (1996) found regions of consistent high grain yield associated with soil series. These findings led the researchers to conclude that soil moisture was a possible major limiting factor on yield in these regions. After comparing seven years of yield data with a single season's soil test data, Cambardella et al. (1996) found similar results for an Iowa corn-soybean field. They state that, "...aggregate size distribution contributed significantly to yield variability seven out of seven years." They emphasized the importance of aggregate size and distribution as it defines water relationships in the plant-soil system. Aggregate size refers to the clumping of soil particles into distinct shapes.

The factors affecting yield vary spatially and temporally, and, although findings of correlation between grain yield and soil-crop parameters do not seem consistent at this time, predicting corn yield according to soil productivity indices has shown positive results in at least one regional study (Khakural et al. 1996b). However, applying a landscape level prediction method at the field or sub-field level may prove difficult considering the findings of several investigators concerning yield stability at these scales.

After collecting yield data from 1991 to 1995 on two experimental plots of continuous corn or corn in rotation with soybean, Lamb et al. (1996) found little yield stability between years. Because they had managed the fields intensively and uniformly for the duration of the study, they concluded that, without knowledge of the parameters controlling this variability the short term yield maps they produced were not sufficient for predicting fixed yield goals or documenting changes in yield potential on these sites. Colvin et al. (1996b) reached similar findings for a field in Central Iowa. Following a review of six years worth of yield data, the researchers found only a few points in the field that showed consistent yield patterns.

Given that crop yield may vary greatly depending upon the spatial and temporal variability of a large number of manageable and unmanageable variables, the accuracy of yield monitor data must not be assumed without thorough testing of the yield data produced. In designing these tests, a knowledge of the functionality and operation of yield monitor equipment is a necessity.

YIELD MONITORS

Grain yield flow monitors gather instantaneous yield measurements as the crop harvesting equipment moves across a field. Monitors normally measure grain yield on a one second interval resulting in a unit per second value termed "flow". Along with the flow data, moisture, grain density, swath width, combine speed, load number, and combine position are usually recorded. These additional measurements are necessary for data corrections and processing as well as accurate grain yield mapping (Reitz and Kutzbach 1996).

There are several types of error generated by the combine, yield monitor sensors, and the positioning system used (Searcy et al. 1989; Schueller 1992; Reitz and Kutzbach 1996; Stafford et al. 1996). At a gross scale, monitor-GPS systems often generate some spurious data. Grain yield monitors generally record yield on a continuous basis once the combine operator turns the monitor on and lowers the combine header into position. While the system is in this mode, the monitor gathers yield points regardless of the location of the combine within the field. The monitor may continue to gather yield points if the operator fails to shut off the monitor when the combine moves across previously harvested areas or while the machine sits idle during transfer of grain to grain trucks. The operator may also raise the header bar above the shut off point to clear obstacles in the field or to maneuver slopes. When shutoff occurs, the monitor records no data for these locations. Combine speed also influences harvest efficiency (Reitz and Kutzbach 1996).

Monitors incorrectly estimate yield data at the ends of the field, a short distance into the field, and a short distance before and after internal transitions across barren areas because harvest efficiency drops off at lower speeds (Stott et al. 1993). Another less mentioned source of yield data error is the loss of grain from the combine (Blackmore and Marshall 1996; Skotnikov and McGrath 1996). Skotnikov and McGrath (1996) report that grain losses may range between 5-16% of total yield. Although these losses do not affect the efficiency of the yield monitor at predicting the weight of the grain at the truck scale, the inability of most monitors to estimate this loss may render yield data less useful for judging the effects of a particular management practice. This invalidation of yield data for statistical comparisons is possible if grain loss is variable across a given field.

Although yield monitor equipment is relatively new on the market, the accuracy and precision of several models for estimating total grain yield from a field or test strip has been demonstrated (Searcy et al. 1989; Wagner and Schrock 1989; Stafford et al. 1991; Stott et al. 1993; Auernhammer et al. 1993; Stafford et al. 1996). There are currently two basic types of grain flow sensors available (Borgelt and Sudduth 1992). The first type collects volumetric data as the grain moves through the combine. The second type takes a mass reading.

Volumetric sensors are further subdivided according to the actual measuring devices used. These methods rely on either a hopper, paddle wheel, or bin equipped with an optical or mechanical level sensor. Due to variations in grain bulk densities across a field, the data produced by volumetric monitors is imprecise. Therefore, either the monitor or the data analyst must adjust the values according to the output of a grain density measuring device (Stott et al. 1993; Reitz and Kutzbach 1996).

Mass flow sensors also use a variety of methods and technologies to accomplish their task. These sensors measure the mass of harvested material flowing through the combine using one of a variety of sensors. The sensor used depends upon the system installed. Currently, these sensors monitor crop flowing through the combine with one of the following methods (Borgelt and Sudduth 1992):

1) The monitor estimates mass as material strikes a piezo electric device mounted at the top of the clean grain elevator.
2) The monitor uses changes in gamma ray absorption to calculate changes in the mass of material flowing through the combine auger.
3) Capacitive sensors measure dielectric changes to estimate the amount of grain flowing past the monitor.
4) The monitor measures the displacement of a metal plate as it is struck by grain flowing out of the clean grain elevator and into the grain bin to estimate the mass of the material striking the plate at a given instant in time.
5) The monitor uses changes in auger speed and torque as material moves through the grain auger to estimate the mass creating the changes.
6) The monitor uses a changing signal from a load cell to estimate the mass of material.

Although changes in grain bulk density do not reduce the accuracy of mass flow sensors, it remains necessary to adjust mass data for moisture content.

Both types of grain yield flow monitors require data correction to take into account the redistribution of grain as it moves through the combine between the header and the monitor. There are two types of error generated by this transport delay. The first is simply the amount of time the grain takes to reach the monitor after it enters the combine header. The second, more complicated error, arises as the harvested grain spreads out through the combine before it reaches the monitor. These transport delays mean that the combine spreads the actual yield at a given location across yield points for several locations. Therefore, each flow value contains only a portion of the actual yield information from the location attributed to it by the GPS receiver. Each raw yield measurement is an aggregation of partial yields across an undetermined area. In short, uncorrected yield does not accurately reflect actual yield at the location of the combine when the monitor records flow. Several researchers and research groups have conducted studies to evaluate procedures for correcting crop lag delays (Searcy et al. 1989; Wagner and Schrock 1989; Stafford et al. 1996). The goal of these procedures is to link measurements recorded at the yield monitor with the position of the header in the field when the measured material was actually harvested (Stott et al. 1993 and Birrell et al. 1996a).

POSITIONING SYSTEMS

Researchers and equipment manufacturers have utilized several methods of positioning to record a combine's location inside a field while harvesting. Ground based triangulation, dead-reckoning, and Global Positioning Systems have all been used to provide locational information for yield monitor data (Searcy et al. 1989 and Borgelt and Sudduth 1992). Each system has its strengths and weaknesses.

Dead-reckoning requires the use of a heading and distance traveled. It is the least expensive but the risk of a large accumulated error may outweigh the cost benefit. If the equipment operator takes an erroneous heading in a large field, the combine begins to propagate a location error. This error continues to grow until the operator corrects the discrepancy. The other two methods are more expensive in terms of equipment purchases. However, the accuracy of these methods is normally consistent.

Triangulation systems use two transmitters at fixed locations and a third receiver mounted on the combine to calculate the equipment's position at a given moment. This system may employ radio-waves, micro-waves, or lasers to transmit between transponders. Triangulation has met with mixed success and needs more study (Borgelt and Sudduth 1992).

The third type of positioning system that has received research attention is the Global Positioning System (GPS) consisting of a set of satellites in fixed orbit around the earth linked to the equipment via a receiver mounted in the cab of the equipment. This system uses triangulation but uses the receiver to simultaneously receive signals from three or more of the 24 NAVSTAR satellites. The receiver calculates its coordinates from the position of each satellite it is in contact with as a function of time. The receiver utilizes the actual time the receiver picks-up the signals and the transit time of each signal as calculated by the receiver. With this information the receiver can determine the receiver's position at a given time using a simple three-dimensional geometric computation (Tyler 1993). Original designers of the system did not require great accuracy for military needs and the best error correction produced errors of five meters at best making the system useless for precision agricultural applications (Tyler 1993). In addition to the inherent error in the system, the U.S. government introduced a degree of intentional error termed Selective Availability (SA). Selective availability allows restricted access to the full accuracy of the system to authorized users (Parkinson 1996). With SA in place, accuracy of the uncorrected signal drops to approximately 100 meters. The system user can overcome this intentional error in part by adjusting the output of the receiver with a correction factor calculated from the output of a fixed receiver with known coordinates. The fixed receiver (base station or satellite) is either a second receiver in proximity to the roving receiver or a satellite in a geosynchronous orbit. However, if the mobile receiver loses the signal from one of its visible satellites, the mobile unit must recalculate the correction factor or large amounts of output error begin to propagate. Without a new correction factor prolonged drifting of the output coordinates will occur. If signal lock remains problematic during harvest, the error compromises the spatial accuracy of the resulting yield data. Barring signal loss, today's agricultural GPS receivers claim that sub-meter accuracy is consistently possible with a differential correction (DGPS) factor calculated from the output of a fixed antenna at a known location.

Depending upon the system used, there is a certain amount of signal lag generated between the receiver, the GPS constellation, and the differential tower or satellite. To offset this signal lag, the yield monitor-GPS system must either anticipate the location of the combine at the end of the signal lag time or recalculate previous positions based upon lag time. The system used for this study performs the latter operation.

Positioning systems for agriculture require location precision greater than most GPS users require (Larsen et al. 1991). Auernhammer and Muhr (1991) suggest that a level of accuracy of plus or minus one meter is necessary for variable rate machinery to react within 10 meters of changes in levels of a variable. Therefore, if farm managers use yield data to drive input recommendations, GPS receivers used during harvest must be able to maintain sub-meter accuracy throughout the harvest. The GPS receiver must be able to re-calculate the correction factor promptly after the receiver loses one or more of the satellite signals. The system must also be able to automatically correct for signal lag or provide enough information to do so. A system that is unable to perform these necessary operations will produce spatial data with a higher margin of error than data gathered by systems with these abilities.

The NAVSTAR constellation of 24 satellites now provides a free signal that allows real time position determinations with one centimeter accuracy (Larsen et al. 1991). The actual degree of accuracy is a result of equipment specifications, signal stability, and user familiarity with GPS operation and data collection techniques. Saunders et al. (1996) have designed a simple series of tests to evaluate the effectiveness of a GPS receiver for agricultural application. GPS features required for an agricultural application are accuracy (static and dynamic), stability, repeatability, and acceptable response to horizon changes and signal losses. Note that, even with the best equipment, improper data collection techniques or inappropriate display procedures can render the GPS output of little value to the producer's decision making process.

Once the monitor has collected the yield data, the person handling the data puts it into a mapping or GIS software package as a set of point features with yield information attributed to each point. The manager then uses the resulting point theme to create maps of crop variability (for example, dry yield or percent moisture). The grower or crop consultant compares these maps statistically with maps of soil edaphics and soil nutrient levels to identify any correlation between soil and crop parameters. If a determinant correlation exists between a manageable variable and crop yield, that variable becomes the focus of management strategies that seek to optimize yield.

YIELD MAPPING AND POST-PROCESSING TECHNIQUES

"Yield maps are retrospective data on the accumulated effects of many spatially variable factors" (Lark and Stafford, 1996). The factors that Lark and Stafford refer to are biotic, abiotic, manageable, unmanageable, ephemeral and persistent. A single two-dimensional yield map integrates variables such as soil type, soil structure, soil depth, topography, climate, moisture regime, crop response, and etc. for an entire growing season into a single variable tied to spatial coordinates. Producers use this map as a tool to help them make precision farm management decisions concerning future tillage practices, crop inputs needed, soil sampling schemes, crop performance evaluations, etc.

It is obvious that a yield map produced from inaccurate yield data has the potential to adversely affect site specific management decision making and the economic return from a field. Inaccurate recommendation rates calculated from a combination of erroneous yield data and soil fertility data are an example of the poor management decisions that might result from invalid yield maps. Error in a yield map can originate from a variety of sources. These error sources include GPS error, variations in transport delay time as the grain moves through the combine, surging grain through the combine, measurement errors resulting from poorly calibrated yield monitors and moisture meters, and grain loss from the harvesting equipment (Blackmore and Marshall 1996).

For several decades, researchers have used a variety of interpolation methods to estimate values for non-sampled locations (Hosseini et al. 1994). Agronomists and soil scientists have limited the application of interpolation techniques in the past to soil test data. The increased availability of yield monitor data has prompted the natural migration of interpolation techniques to yield monitor data. Previous yield studies have made comparisons between yield monitor data for the same field from several seasons (Stafford et al. 1996, Stott et al. 1993). Once again, the researchers made no pre-harvest estimates of yield variability. The comparisons addressed the precision of the interpolation techniques and not the accuracy of the resulting yield surfaces when compared to actual yield in the field.

Birrell et al. (1996b) found that the interpretation of grain yield results varied according to the methods used to correct data for lag and the methods of interpolation. Furthermore, Reitz and Kutzbach (1996) found that post-processing methods that factor in swath width and grain moisture enhance the quality of wheat yield data. The analyst must correct and reconstruct the spatial components of yield monitor data to optimize mapping accuracy (Reitz and Kutzbach 1996). Nolan et al. (1996) found quite unsurprisingly that, raw yield data are inappropriate for mapping yield. They also found that they could not adequately remove striping in their processed map data. Striping is the offsetting of locational data created by a combination of grain lag and the alternating direction of the combine. Furthermore, these researchers concluded that a single lag time was insufficient for correcting grain lag when yield data came from a topographically variable landscape where transport delay times ranged from 5-32 seconds. Skotnikov and McGrath (1996) also cited map distortion due to variable transport time.

Investigations of nutrient maps and the recommendation maps created from them have found variations in accuracy that point to the danger of accepting grid maps at face value without knowing how the data were collected and how the maps were created

(Birrel et al. 1996, Gotway et al. 1996). It is highly likely that the estimation methods used in soil fertility mapping will generate a new set of inaccuracies when data analysts apply them to yield monitor data. One potential source of error propagation that has proven difficult to eliminate from yield data is variation in the length of grain lag associated with a given yield value (Blackmore and Marshall 1996). This same paper also emphasized the importance of matching the interpretation of yield data to the intended use of those data. Inappropriate interpretation may result in an unsuitable management decision. Larscheid and Blackmore (1996) suggest that proven mapping methodologies are rare. They suggest that the creators of agricultural maps should base these maps upon a manager's understanding of variability, his/her information technology capability, and the equipment he/she uses. They also report that future software development for precision farming must take into consideration the personal nature of farm management and decision making.

If gridding of yield data is a requirement for application mapping, Missotten et al. (1996) suggest a grid size based on the equipment used for the operation and the inherent error in the yield data collected by the yield monitor. Specifically, they found increasing error with decreasing cell size ($120m^2$ - $2000m^2$) for peas, wheat, barley, and corn yield. On a 20m x 20m cell size, they found a 5% error in yield and a 2.5% error in combine speed for a total of 7.5% combined error. The overall error for the entire field was 1.7%.

SUMMARY

Precision agriculture seeks to increase the efficiency of crop inputs as a means of increasing profitability and/or increasing environmental compliance. One important phase of the precision farming loop is to collect sub-field level yield data as a means of evaluating past management strategies and determining future ones. Unfortunately, current research findings concerning the lack of yield stability within several study locations make the acquisition of accurate and useful yield data questionable. This spatial and temporal variability is the result of a combination of soil conditions modified by climate, pest interactions, disease, and management actions (Cambardella et al. 1996). However, with a properly calibrated monitor and DGPS, a yield monitor can accurately estimate the total yield or the yield per load (Wagner and Schrock 1989; Pringle et al. 1993; Birrell et al. 1996a; Stafford et al. 1996). Despite these successes, the yield variability as reflected in yield monitor output has not been proven accurate below the scale of a single pass. It is the purpose of the study reported herein to test the ability of post-processed yield monitor data to accurately reflect the spatial variability in yield at a finer scale than previously investigated.

CHAPTER 3

METHODS AND ANALYSIS

STUDY SITE

The study site for this project is a 37 acre field in southeastern Illinois (Fig. 2). The study site is part of Gray Farms, Inc. located in the northwest corner of Lawrence County, IL. The field dimensions are 2500 feet east-west and 650 feet north-south. The terrain is generally flat with an average elevation of approximately 500 feet above mean sea level. The landscape matrix is agriculture interspersed with clusters of farm related structures, small patches of hardwoods, fence rows and windbreaks.

After flooding destroyed the first planting, the field owner replanted the field on June 17, 1996 in ZimmermanZ62 food-grade white corn. The farm owner planted the corn with a row spacing of 32 inches and plant spacing within rows of approximately 9 inches. Cool and moist fall conditions kept the crop moisture content well above the optimal harvest level of twenty-six percent. The high moisture content of the corn delayed harvest until November 14, 1996. Past grain yields from this field indicate that a source of moderate yield variability exists within this field (personal communication 1996).

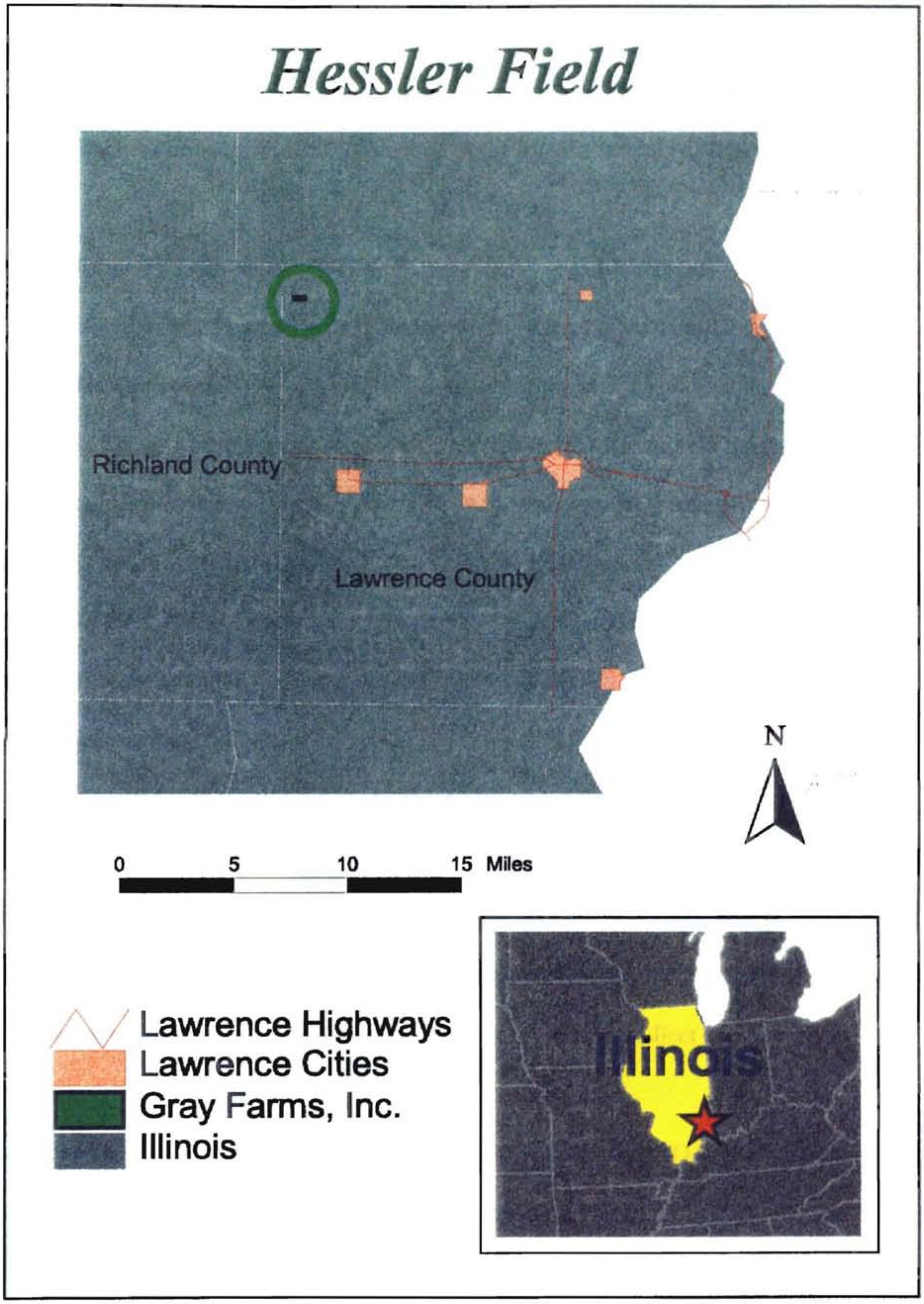

Figure 2. The Study Site in Lawrence County, Illinois.

A fence row of trees and shrubs bounds the study site on its southern edge. These features, of approximately 30 feet maximum height, are the only terrestrial obstructions at the site likely to interfere with GPS reception or the satellite emitted differential correction signal.

DATA COLLECTION

The grower prepared the field for harvest five days before hand sampling took place. The farm owner removed eight rows of corn from both the north and south sides of the field. The grower removed the equivalent of sixteen rows from both the narrower east and west ends of the field (Fig. 3). The practice of removing the standing crop from the east and west ends of the field allows the combine to make smooth turns during the harvest of the remainder of the crop. The removal of the standing crop along the north and south edges facilitated the movement of a truck mounted GPS receiver through the field while taking boundary coordinates.

After the author collected the boundary coordinates, the field owner removed two eight row swaths from the field along an east-west orientation. The purpose of these two strips was to facilitate sample collecting throughout the field. Pin flags were placed at 30 meter intervals along the sides of the field and down each of the two center strips. These flags were for orientation purposes before entering the stand to collect data at a given sampling site.

Field boundary coordinates were gathered and stored as INFO format files using an OmniStar GPS linked to a laptop computer running MapInfo® direct GPS software. The manufacturer of this system claims a nominal accuracy of 1- 3 meters. The results of the boundary survey were converted to a shape file (*.shp) format loaded into a desktop

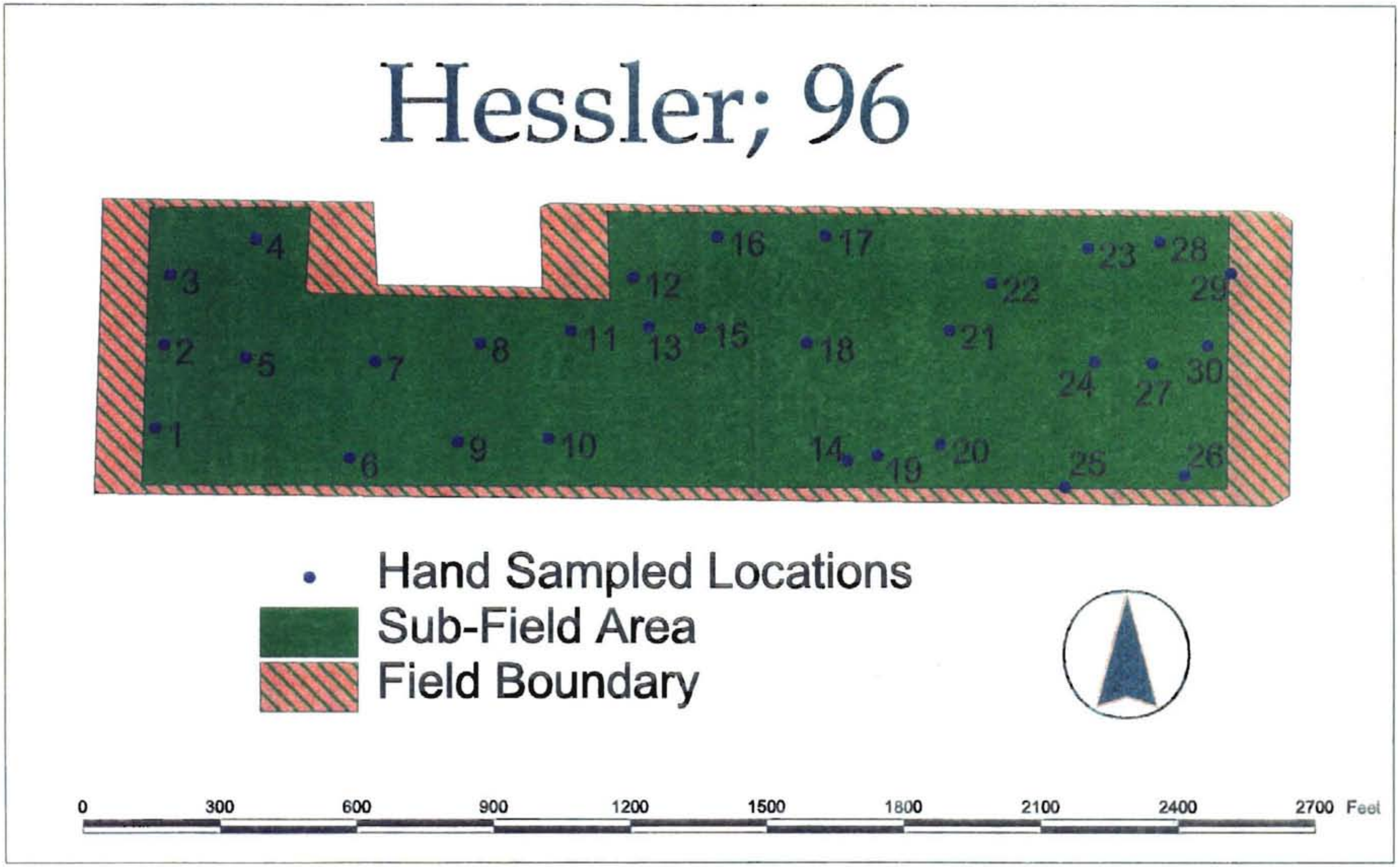

Figure 3. Hand sampled locations. Cross-hatched region harvested prior to hand sampling.

PC running SSToolbox® precision farming software.

A systematically aligned grid of 30 points was generated using the way-point generator module of SSToolbox. Each point was offset using a random point generator. The offset for each point was constrained to no more than four meters in the X direction (longitude) and four meters in the Y direction (latitude) from its original location. A stratified systematic unaligned sampling pattern imparts the advantages of both a systematic grid and randomization. This combination maximizes the probability that the sampling scheme covers the entire field and the entire range of yield values (Webster and Oliver 1990). Following the offset procedure, longitude and latitude coordinates were calculated for each sample point. Using SSToolbox, the author created a sampling scheme and generated a map of the field boundary and sample locations with the coordinates for each sample location displayed on the map.

Due to potential crop damage from the vehicle mounted GPS, the map and the previously discussed pin flags were used to find the approximate location of each sample. The actual coordinates for each sample point were gathered post-harvest. The actual pre-harvest sample locations were estimated and marked with a bundle of 8-12 marked pin flags. These flags remained in position through harvest because they did not reach the height of the cutter bar.

The stand of corn was sampled at 30 locations twenty-four hours before harvest (Fig. 3). Using the pin flag grid for reference, each sample point was located by dead-reckoning and sampled as follows:

1. At each sample location, 8-12 pin flags marked with the sample number were placed in the furrow between rows. The number of flags per sample point makes it easier to find each location later.
2. A distance of 52.25 inches was measured down the furrow in both directions from the sample point and a pin flag placed at each end to delineate the total 104.5 inches of row sampled.
3. Two rows to either side of the sample point for, a total of four rows, were sampled. Each pair of rows, one pair on either side of the pin flags, constituted a sample (that is, sample ***A*** or sample ***B***) for a total of two sub-samples per location. Each sample covered an area equal to 1/1000 of an acre.
4. The number of harvestable ears in each sample stand was recorded.
5. Every fifth ear in each sample stand was harvested.
6. The harvested ears from each sample were placed in a bag and labeled with the location (1-30) and the sample designation (***A*** or ***B***).
7. The samples were then removed from the field for analysis.

After all samples were removed from the field, each sample of corn was shelled using a hand powered sheller. The shelled grain was collected for each sample and weighed using an O'Haus GT4000L® gram scale. Immediately after weighing each sample, a moisture reading for that sample was taken using a Steinlite Moisture Meter®, model SS250 set for high moisture corn (25-35%). The total time elapsed during the sampling process, from the bagging of the first sample in the field to the last moisture reading, was approximately 36 hours. The combine operator completed the harvest of the study site approximately two hours before the last moisture reading was taken.

An AgLeader Yield Monitor 2000 mounted on a John Deere 9600 combine gathered harvest data from the study site. A factory installed magnetic pick-up mounted inside the transmission monitored combine speed and distance traveled. The AgLeader 2000 monitor is an impact based system that measures the force of clean grain striking a curved plate mounted at the top of the clean grain elevator. The monitor calculates flow based upon the impact measurement, elevator speed and other measurements taken by the monitor. The combine operator calibrated the yield monitor according to the manufacturer's instructions in a second cornfield six times before harvesting the study site. The yield monitor was then re-calibrated two more times at the study site to insure that it was measuring accurately. At each point, the monitor recorded yield points on a one second interval as it harvested and saved the data to a PCMCIA card located in the cab unit of the grain monitor. The monitor recorded grain flow in pounds, grain moisture, vehicle speed, distance traveled, latitude and longitude coordinates, GPS status, swath width (fixed), load number. After harvest, data were downloaded to a desktop PC using the AgLeader 2000 companion software. All data were then imported into SSToolbox for display, initial correction, and analysis.

ANALYSIS

The analyses of the hand sampled and yield monitor data focused on the variability in each data set and the correlation between data sets. To utilize yield monitor data for the creation of yield maps and to use those maps to improve decision making, the yield monitor data must accurately and precisely estimate yield at any given point in a field

(Schnug et al. 1993). If the yield monitor data cannot do this, the grower should not use these data to measure yield variability in that field. The analysis described in the remainder of this section was designed to determine if yield monitor data from this study site was an accurate measure of crop variability in the field for the 1996 growing season.

Raw yield monitor data are analyzed for outliers and cleaned of otherwise questionable data values. This post processing removed data points with extreme spatial coordinates or yield values. Data were considered questionable if spatial integrity was compromised because GPS coordinates drifted across rows or fell outside the field boundary due to loss of satellite differential lock. Points were also removed if grain flow values resulted in improbable bushels/acre estimates for the study site (estimates > 200bu/ac). Those data values that estimated extremely low yield were retained since actual localized variations in soil and crop parameters could account for these values. In a production situation, the grower could eliminate zero values if he/she had sufficient knowledge of field conditions and actual harvest events.

Once the questionable data values were removed from the data set, the information was smoothed using a linear running average of 12 seconds (Appendix A, Fig.1). End row points were smoothed using neighboring points from the same pass. This smoothing was necessary to offset grain lag through the machine and to match the grain impacting the yield monitor with the position of the combine when this grain first came in contact with the equipment header. The smoothed data were then adjusted for moisture and recalculated to reflect yield in pounds per acre using the following formula:

$$([\text{Flow}] * ((100 - [\text{Moisture}])/(100 - 15.5))) * ((6272640\ \text{in}^2/\text{ac})/ ([\text{Swath}] * [\text{Distance}]))$$

Where: **[Flow]** = the flow in pounds per yield point

[Moisture] = grain moisture per yield point

[Swath] = width of the combine header (240 in)

[Distance] = the distance the combine traveled per yield point

A block-average yield map was created using the corrected and smoothed yield data (Appendix A, Fig. 2). The cell width and length used for a given cell length corresponds to a single swath width of 240 inches. The block average values for those cells that contain the coordinates for the hand sampled data set were then compared to the hand sampled data using a matched-pairs t test ($\alpha = 0.05$).

$$t_{mp} = \bar{d} / \sigma_d$$

Where: t_{mp} = matched pairs t

$\bar{d}$ = mean difference between paired values

σ = standard error of the pair differences

Kriging and inverse distance weighted interpolation algorithms were employed to create continuous surfaces of the raw and smoothed data for a total of four surface files (Appendix A, Figs. 3 and 4). Each surface was created using the Surfer® software package. A 240 inch grid cell size was chosen to match the combine's header width as an approximation of the combines sampling area per yield point.

The two methods of interpolation (ordinary kriging and inverse distance weighted interpolation) and block averaging were applied to the post-processed yield data to create three of the most common types of yield maps (Webster and Oliver 1990). Analysts can compare yield maps of equal resolution on a cell-by-cell basis to determine the amount of agreement (correlation) among the three types of estimation. Comparisons were made between the interpolated maps and the block average map, and between the hand-sampled point data and the three types of yield maps (Birrell et al. 1996a). To make the comparisons between yield maps or the block averaged map and the hand sampled data, the nearest grid centroids to the hand sampled locations were used.

The hand sampled data were used to calculate two estimates of yield in pounds/0.001ac at each sample location. This resulted in 30 estimates from the ***A*** sample set and 30 from the ***B*** sample set for a total of sixty 0.001 acre samples. A combined value for ***AB*** was also calculated for each location for a total of 30 combined estimates of two thousandths of an acre each. Each set of 30 hand sampled yield estimates (***A***, ***B***, or ***AB***) was compared to the other two sets of 30 hand sampled yield estimates for correlation using Pearson's product-moment correlation coefficient, ***R*** (McGrew and Monroe, 1993). The equation used to calculate ***R*** is as follows:

$$\mathbf{R} = \frac{\Sigma[(X - \bar{X})(Y - \bar{Y})]/N}{S_X S_Y}$$

Where: ***R*** = Pearson's correlation coefficient

N = the number of paired data values

S_X = the standard deviation of X

S_Y = the standard deviation of Y

The hand sampled yield estimate distributions and the corrected yield monitor estimate distributions were also analyzed for skewness and kurtosis (McGrew and Monroe 1993).

CHAPTER 4

RESULTS AND CONCLUSIONS

RESULTS

On average there were 18 harvestable ears per sample site and an average of three ears were removed from each location (Appendix B). Moisture readings ranged from 23-36% for the entire data set. Both ***A*** and ***B*** sample sets, showed moderate standard deviations for mass with values of 0.283 where $\overline{X}$ = 1.492 lb. for set ***A*** and SD = 0.262 where $\overline{X}$ = 1.424 lb. for set ***B***(Appendix B). Similar results carried through when an estimation of mass for the total area sampled was made. Standard deviations of 2.996 and 2.522 were found for sets ***A*** and ***B*** respectively. The standard deviations for the ***A-B*** combined values of mass were slightly higher (Table I).

The average mass per ear per sample site was calculated and the results used to estimate the total yield in pounds from each sample location (Table I). The estimated total pounds per sample site was then adjusted for moisture to produce an estimate of dry yield (Table II).The moisture adjusted pounds per sample site was then adjusted for area sampled to produce a bushels per acre estimate (Table III).

TABLE I

DESCRIPTIVE STATISTICS FOR HAND SAMPLED YIELD DATA
SETS A, B, AND AB COMBINED.

	N	MEAN (lbs)	MIN (lbs)	MAX (lbs)	RANGE (lbs)	VAR	STD DEV	SE MEAN	SKEW.	KURT.
A	30	8.5	5.	10.8	4.8	1.8	1.34	0.24	-0.11	-0.87
B	30	8.2	5.9	12.8	6.9	2.4	1.56	0.28	0.82	1.06
AB	30	16.8	13.0	23.3	10.3	4.6	2.15	.39	0.77	1.41

TABLE II

DESCRIPTIVE STATISTICS FOR HAND SAMPLED YIELD DATA
ADJUSTED FOR MOISTURE.

	N	MEAN (lbs)	MIN (lb/ac)	MAX (lb/ac)	RANGE (lb/ac)	VAR	STD DEV	SE MEAN	SKEW.	KURT.
A	30	6.0	3.8	7.9	4.1	1.1	1.07	0.19	-0.17	-0.65
B	30	5.9	4.1	9.4	5.3	1.3	1.15	0.21	.098	1.51
AB	30	11.9	9.2	17.3	8.1	2.9	1.71	0.31	0.90	1.94

TABLE III

DESCRIPTIVE STATISTICS FOR HAND SAMPLED YIELD DATA
ADJUSTED FOR MOISTURE AND AREA-SAMPLED.

	N	MEAN (lb/ac)	MIN (lb/ac)	MAX (lb/ac)	RANGE (lb/ac)	VAR	STD DEV	SE MEAN	SKEW.	KURT.
A	30	8546.2	5911.6	10761.3	4849.71	1785962.5	1336.4	243.99	-0.11	-0.87
B	30	8225.0	5922.6	12852.2	6929.55	2426956.3	1557.9	284.42	0.82	1.06
AB	30	8149.6	6497.7	11650.0	5152.3	2844131.0	1686.5	302.90	-2.26	10.21

Yield monitor estimates per load closely matched individual load weights (Table IV). The total yield for the field was estimated by the grain yield monitor to within 1.3% of the total weight for all loads. The yield estimate for the entire field falls within the monitor manufacturers specification of 1-3%.

TABLE IV

ESTIMATED AND ACTUAL LOAD WEIGHT WITH DISCREPANCY
IN POUNDS AND PERCENTAGES

LOAD NUMBER	EST. WEIGHT (lbs)	WEIGHT@ SCALE (lbs)	DISCR. (lbs)	% DISCR.
L1	362.42	342.2	20.22	5.9
L2	343.04	339.45	3.59	1.1
L3	241.74	226.48	15.26	6.7
L4	353.44	346.07	7.37	2.1
L5	351.34	339.3	12.04	3.5
L6	329.54	339.86	-10.32	-3
L7	358.06	349.3	8.76	2.5
L8	142.87	145.7	-2.83	-1.9
L9	346.26	355.09	-8.83	-2.5
L10	340.29	346.2	-5.91	1.7
L11	171.58	171.84	-0.26	-0.2
TOTAL	3340.58	3301.49	39.09	
Total % Diff.	-1.2			

For the sample ***A-B*** comparison, a test statistic of $t_{mp} = 0.8306$ with 29 degrees of freedom and a p-value of 0.2119 were generated. Therefore, the null hypothesis, H_o was not rejected. The two hand-sampled sets may be treated as being from the same population. After this conclusion was made, the combined ***A-B*** data set was used exclusively for all comparisons to yield monitor data.

Matched pairs comparisons between the combined ***A-B*** hand sampled data and the raw yield monitor data resulted in a rejection of the null hypothesis at $t_{mp} = -40$, d.f.=29, and $p < 0.005$. Similar results were found after the raw data and the combined hand sampled data were adjusted for moisture and area; the null hypothesis was rejected at $t_{mp} =$

8.7, for d.f. = 29, and p<0.005. Given these results, the two sets of post-processed yield data (hand and mechanically sampled) cannot be assumed to represent the same population of yield values

Pearson's product-moment correlation coefficient (R) was calculated for hand sampled and yield monitor data to detect trends in yield as estimated by the two methods. One outlier (Sample site #1) and three sites within 20 meters of field ends (#2, #3, and #29) were removed from the hand sampled data sets before the correlations were calculated. Removal of these end locations was necessary because insufficient crop moved through the combine at the ends of each pass to provide accurate yield estimates. As predicted from the results of the matched pairs t-test, correlation coefficients for all combinations of hand sampled and yield monitor derived data were non-significant at $p<0.05$ (Table V). A general increase in correlation between hand sampled and yield monitor data was noted when flow values were smoothed for lag time in the combine and the resulting values adjusted for the area sampled and moisture content (Table V-VII).

TABLE V

PEARSON'S CORRELATION VALUES (R) FOR HAND SAMPLED (AB) AND YIELD MONITOR DATA.

N = 26	Raw Flow	Raw Flow*	Raw Flow**	Smoothed Flow	Smoothed Flow*	Smoothed Flow**
AB	.18	.21	-0.11	.28	.19	.32
AB*	.21	.26	-.05	.29	.24	.23
AB**	.21	.26	-.05	.29	.24	.23

*Yield adjusted for moisture.
**Yield adjusted for moisture and area sampled.

TABLE VI

PEARSON'S CORRELATION VALUES (*R*) FOR HAND SAMPLED (AB)* AND YIELD ESTIMATES DERIVED USING A KRIGING ALGORITHM.

N = 26	Raw Flow**	Smoothed Flow**
AB	.12	.05
AB*	.19	.11
AB**	.20	.29

*Yield adjusted for moisture.
**Yield adjusted for moisture and area sampled.

TABLE VII

PEARSON'S CORRELATION VALUES (*R*) FOR HAND SAMPLED (AB) AND YIELD ESTIMATES DERIVED USING AN INVERSE DISTANCE WEIGHTED ALGORITHM.

N = 26	Raw Flow**	Smoothed Flow**
AB	.17	.09
AB*	.23	.15
AB**	.30	.22

*Yield adjusted for moisture.
**Yield adjusted for moisture and area sampled.

TABLE VIII

PEARSON'S CORRELATION VALUES (*R*) FOR HAND SAMPLED (AB) AND YIELD ESTIMATES DERIVED USING A BLOCK-AVERAGING ALGORITHM.

N = 26	Block-Averaged Cells**
AB	.05
*AB**	.07
*AB***	.11

*Yield adjusted for moisture.
**Yield adjusted for moisture and area sampled.

CONCLUSIONS

Three main points regarding this study require discussion before conclusions concerning the capability of yield monitors as estimators of grain yield variability are made. The first point concerns discrepancies between hand sampled mean flow values and those obtained by the yield monitor. The second concerns the influence that smoothing the raw yield data had upon correlation values. The third point, which partially embodies the first two points, is the matter of scale; or, the compatibility between the grain size of the measurements and extent of the two sampling methods (manual v. mechanical).

The mass and moisture discrepancies between hand sampled and combine sampled yield data fall into two categories, possible measurement errors and sampling scale differences. Artifacts of the sampling method partially explain the consistently higher flow values for hand sampled data (14-19% higher on average). By removing the entire ear from the field and retaining all the kernels from each ear, no grain from the sample ears was left in the field. It is common knowledge that a combine leaves a some grain on the ground. In the case of the combine used in this study, the grower estimated that approximately 2-3% of the total yield was lost (personal communication 1996). Skotnikov and McGrath (1996) reported higher levels of grain loss and it is possible that grain loss at the study site was higher than 2-3%. The composition of the material expelled by the hand sheller explains the remainder of the mass discrepancy. Whereas, the combine screened the grain to remove any debris or undersized kernels the hand sheller did not. During the hand shelling operation performed on the hand sampled ears, all material was retained except for the cob, silk, and husks. Undersized kernels and miscellaneous debris were included in the mass and moisture measurements. After measurements for each sample were taken, the grain was emptied into a common grain bin and sent to the elevator thus making it impossible to clean and re-weigh it. Because there is no post-hoc method of accurately estimating the extraneous material each sample contained, the comparison of mean differences between the hand and mechanical samples cannot be made with certainty. However, since all samples were taken from the same population of plants, a correlation between the hand and mechanical sample can be reasonably expected. From the correlation indices returned for the actual hand sampled data and the raw yield data, this assumption was unsupported. Smoothing and normalizing did increase correlations overall, but none were significant.

Correlations were non-significant except for a negative correlation found when raw flow adjusted for area and moisture was paired with the ***B*** hand sampled data adjusted for area and moisture. There was, however, a general trend towards increased positive correlation when either yield monitor data were adjusted for area and/or moisture or hand sampled data were aggregated. These manipulations are necessary to remove variability in yield values attributable to moisture and actual area sampled per yield point. Correlations increased as yield monitor data more closely matched the real distribution of yield as reflected in the hand samples taken at documented locations. Further adjustments made to yield values removed the effects of moisture on the actual mass of the grain. The effect of smoothing on correlations is not surprising, when one understands that these post-processing procedures are increasing the spatial accuracy and precision of the yield data. The smoothed yield values, when properly produced, more closely reflect yield at a given location than the yield monitor data uncorrected for grain lag.

Transport delay is the most difficult error to take into account since lag time may vary considerably during harvest depending on field conditions and topography. Consider the misleading comparison of two yield points, each with the same value, suggesting equal yield at two locations. It is likely that the area represented at the two points differs significantly. With combine velocities changing due to turning at field ends, obstacles, uncultivated patches, or steep slopes, the amount of area covered in a given second may vary greatly from yield point to yield point. Therefore, the practice of simply displaying raw yield data as a true and spatially accurate representation of yield variability is questionable. Also questionable, is the use of raw yield data as a dependent variable when calculating the coefficient of determination (R^2) for manageable variables such as crop nutrients. Low R^2 values resulting from the use of unprocessed yield data may divert a farm manager's attention from a manageable or important fertility issue on his/her farm to one that is actually unimportant or unmanageable.

A final point concerns the issue of sampling scale. The observed correlations may be a result of a difference in sampling scale between the hand samples and the yield monitor. On average, each yield monitor point estimated yield from an area slightly less than twice the area represented by a combined ***A-B*** sample pair or roughly four times the area sampled by a single *A* or *B* sample. It is the author's belief that, a hand sampling unit area equivalent to the average area sampled per yield monitor sample is more desirable in this type of matched pairs study. A larger area sampled per hand sampled value could conceivably have smoothed the extreme variability found for the 1/1000 of an acre plots sampled in this study. When studying processes in a complex natural setting, it is desirable to set the measurement scale of the study to a dimension suitable for picking up the determinants of yield at work at a finer scale than the one that is to be modeled. Simultaneously, the sampling must consider the constraints imposed on the dynamics of interest by the next hierarchical level up (Urban et al. 1987). In the case of grain yield, the determinants of yield variability are all the actions of the fine scale variables acting upon the individual plant at the level of its local environment (the root zone). The farm manager generally does not manage a field at the fine scale of the root zone of the individual plants (planting hybrids is one method of directly managing at this fine scale). Management practices generally happen at a much coarser scale, such as the scale at which fertilizer is applied. Therefore, since yield monitors operate at a scale coarser than the root zone, the data they produce is better suited for comparison with variables sampled at a scale greater than that sampled by the yield monitor. By the theories of hierarchy and scale, those variables that constrain the yield monitor sampling scale will occur at a scale greater than the sampling scale of the yield monitor. It is these relatively coarser scale variables that define or constrain the general trends within the finer scaled yield data.

The constraints applied to crop yield by the next higher level may come from manageable variables such as soil fertility and tillage practices. Constraints at this level also include unmanageable factors. For example, topography, soil type, soil depth, climate, and local weather patterns are not readily manageable yet often prove to be the greatest determinants of corn yield (Khakural et al., 1996a).

CHAPTER 5

DISCUSSION AND SUMMARY

DISCUSSION

Yield monitors are promoted as giving the producer accurate and precise yield data with which he/she can evaluate past management practices and plan future actions to achieve maximum efficiency and monetary return. Considering the results of this study, whether yield monitor data can actually provide a true and accurate representation of yield variability becomes a function of scale. Scale, in this context, is defined as the minimum resolution of a particular data type. While this study was limited by the untested sampling methodology it relied upon, a trend toward increased positive correlation as hand sampled yield data were aggregated suggests that the yield monitor used does not measure yield at the scale that the yield variability in the field was actually determined (i.e., the individual plant). Therefore, the utility of yield monitor data lies in its application to the analysis of yield as compared to those variables present at a scale equivalent to or greater than that of the yield monitor data (e.g., soil type, soil depth, moisture holding capacity, climate, topography, and local weather patterns). Comparing corrected yield data to these types of variables may explain the general yield trends that a yield map reveals. Studies cited in this paper concerning the prediction of grain yield data based upon soil type and structure suggest that this type of comparison is valid. First, there appears to be a lack of truly significant correlation between grain yield and soil fertility parameters. Second, there is an apparent lack of yield stability at given locations from year to year. Third, soil nutrients may vary widely, both spatially and temporally, resulting in soil nutrient maps with widely varying accuracy. Therefore, meaningful comparisons between grain yield and soil fertility are difficult to achieve. There is also the possibility that the effects of soil fertility on grain yield are being masked by fluctuations in a more important limiting factor such as the frequency and intensity of rainfall events. Managers and researchers must account for these unmanageable variables before they compare grain yield and soil fertility data.

SUMMARY

In summary, the combine mounted yield monitor and GPS did not produce data that conclusively reflected the yield variability as estimated from pre-harvest samples. A trend towards greater positive correlation, as hand sampled yield data were aggregated to represent a larger sampling area, was noted. This trend suggests that yield monitor data for this field reflected the fine scale, plant-to-plant variability in yield that actually existed on the study site during the 1996 growing season as an average for the area sampled. Therefore, yield monitor data measures yield variability at a coarse scale and comparing this data to a highly variable, fine scale soil fertility data is of limited value. Instead, corrected yield variability must be quantified for the entire field at a scale that approximates the scale of the individual root zone thereby approaching the fine grain of fertility data. As yield monitor data is currently collected, successful analysis using this scale of data will be limited unless the investigator uses variables that occur at a scale coarser than the yield monitor samples (e.g., topography, soil types, etc.). Conclusions concerning the continuous surface estimates created in this study are similar to those just presented. The lack of correlation between the hand-sampled data and the interpolated surfaces reflects the difference between the sampling scales of the two types of data. The same suggestion of reserving analysis of yield surfaces to comparisons with coarse scale variables is offered for this type of data.

The problem of comparing yield data to fine scaled soil fertility data is moot, however, if the yield data is not adequately corrected for outliers, under estimating row ends, lag-time errors, and grain mixing before analysis occurs. Unfortunately, these errors are unique from field to field and cultivar to cultivar. While correcting for these errors is paramount, the actual data processing requires not only a knowledge of yield potentials, equipment responses, and field conditions but of the actual rate at which grain lag was occurring at a given location. Currently, there is little mention of grain lag monitoring in the literature. Although the rate of lag may vary greatly depending upon topography, weeds, and crop moisture this variability can significantly effect the spatial integrity of the yield data, this variation in the data is generally unaccounted for when producing a yield map. The practice of smoothing yield data by a single average lag value offers some improvement to data if the data comes from a relatively level terrain with a relatively homogenous standing crop that is free of weed patches. These ideal conditions cannot be expected in the majority of situations.

It is the lack of a simple strategy for correcting yield monitor data that ultimately limits this data's usefulness to broad generalizations. Improvements are needed in yield monitors to account for combine generated errors from variations in grain lag time, the mixing of grain within the combine, and the underestimation of yield at row ends. Some models allow the combine operator to record weed patches in a separate file that can be used to explain yield patterns or possible reasons for data error. It is my opinion that without the ability to easily account for sources of data error, the average user of yield monitor data will not perform sufficient corrections to the data. Without sufficient correction of the data, the full potential of the yield monitor to provide quality data for precision agriculture decision making will not be realized.

One potential alternative source of precision yield data exists, remotely sensed imagery. Strategies and software exist for correcting any spatial errors in this type of data. Once corrected, this data returns highly accurate information concerning the position and reflectivity of a given feature or unit of area within the image. This information can be used to calculate the approximate biomass occurring at a given location. Once biomass is calculated, the potential for estimating yield exists.

There are several potential advantages to using imagery of equipment mounted yield monitors. Imagery requires very little special equipment to utilize beyond a desktop PC. No equipment modifications need to be made to combines. No ground speed or positioning equipment is necessary. And, no special knowledge of the area is needed to perform the required image corrections. If a fine resolution yield map with little spatial error can be produced from remotely sensed imagery, a farm manager would have the yield data necessary to compare to fine scale soil fertility data as well as larger scale topographic and soil type data. If research supports the use of remotely sensed imagery to accurately model yield, and, relatively inexpensive image products can be marketed, combine-mounted yield monitors may lose their appeal.

The lack of correlation between the hand-sampled data and the yield monitor gathered data was exacerbated by the difference in areas sampled per yield value, the lack of accounting for grain loss, and smoothing the data according to a fixed lag rate. Future studies should address these issues by hand sampling an area equivalent to or larger than the average area sampled by the combine per yield value. Based upon the data used in this study, an area of approximately twenty feet across rows and ten to fifteen feet down rows would effectively duplicate the area swathed per second by a grain combine.

Grain loss could be addressed by one of two approaches. The first would be to screen the hand samples to remove any fines or undersized kernels. In this way, the action of the combine as it screens the grain would be approximated. The second approach would be to mount a grain loss monitor to the combine and adjust the yield map accordingly. Hand samples need not be screened with this scenario. Of the two alternatives, the former would be the simplest as it is straightforward. The latter approach would require greater equipment costs, add to calibration time, and introduce a second set of spatial data that would need correcting.

Two other changes could also be made to improve future studies. Install a ground sensing radar on the combine instead of a less reliable transmission mounted sensor. This would eliminate potential spatial error resulting from wheel slippage. Flags should be placed at the ends of rows to mark each pass of the combine. This will insure that the combine lines up with the hand-sampled sites without overlapping unsampled rows.

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APPENDIX A:

YIELD MAPS

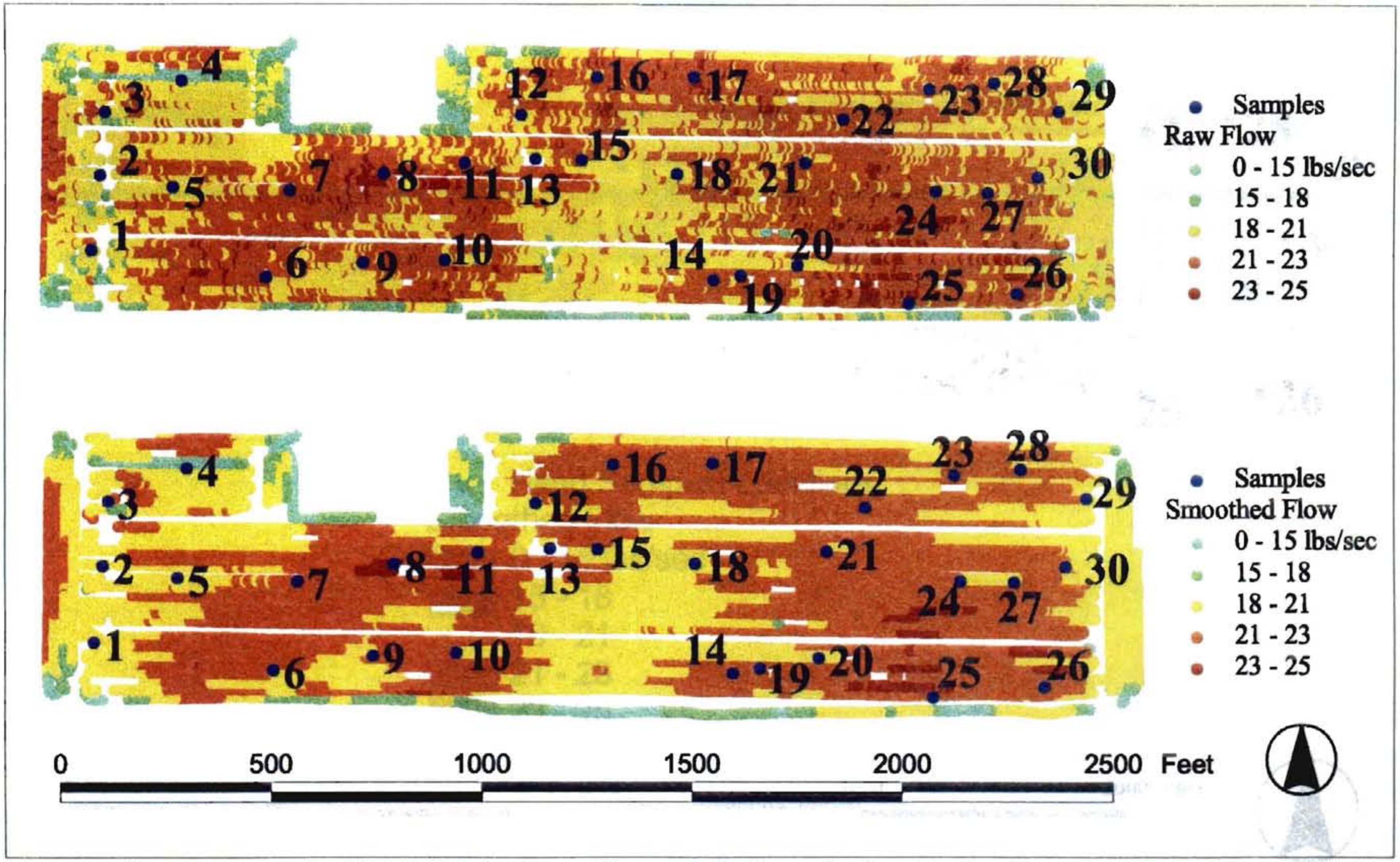

Figure 1. Raw and Smoothed Yield Points. Smoothing was Performed with a Twelve Second, Moving Average Window.

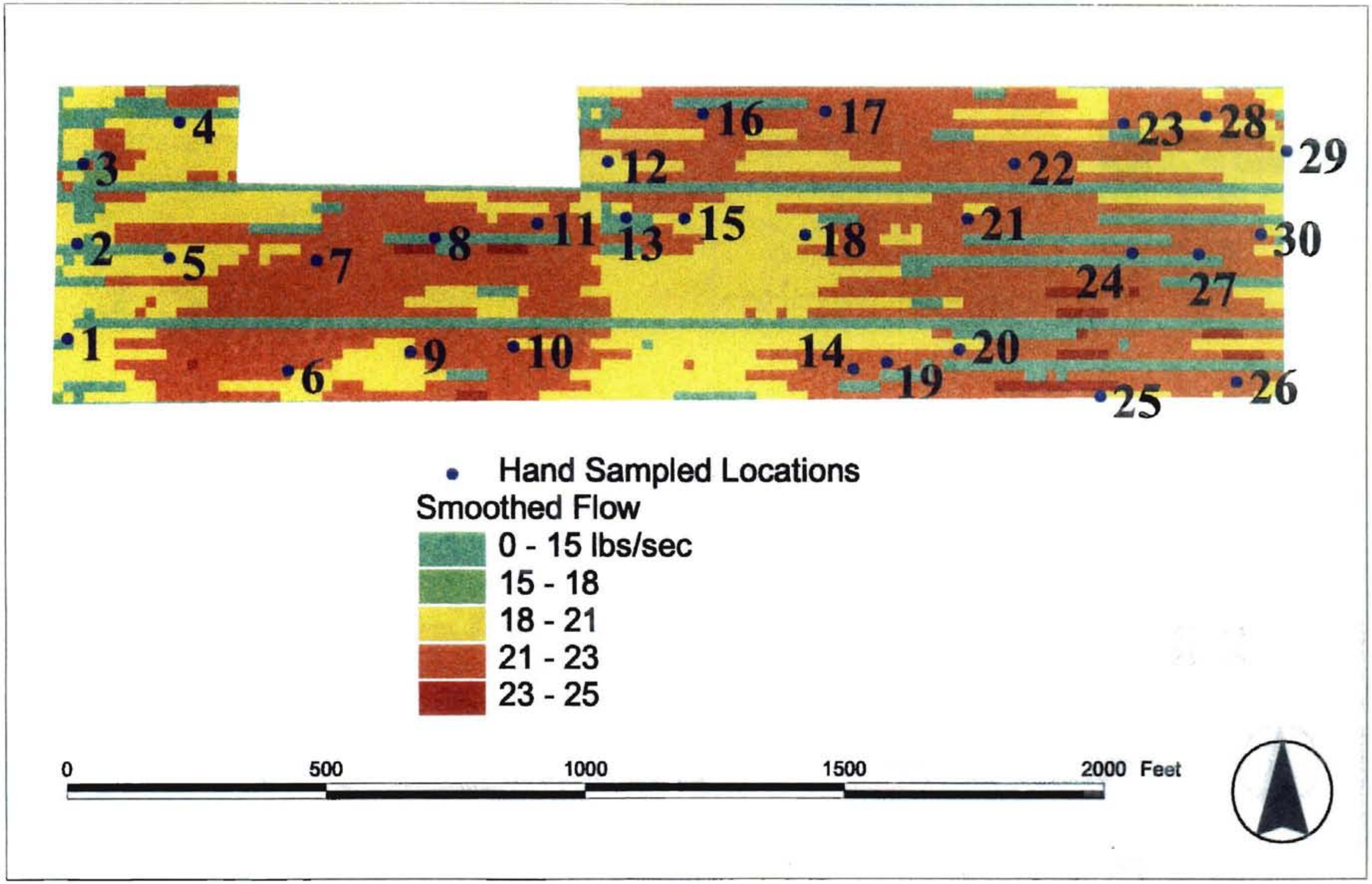

Figure 2. Smoothed Flow Averaged Over Twenty Foot Grid Cells.

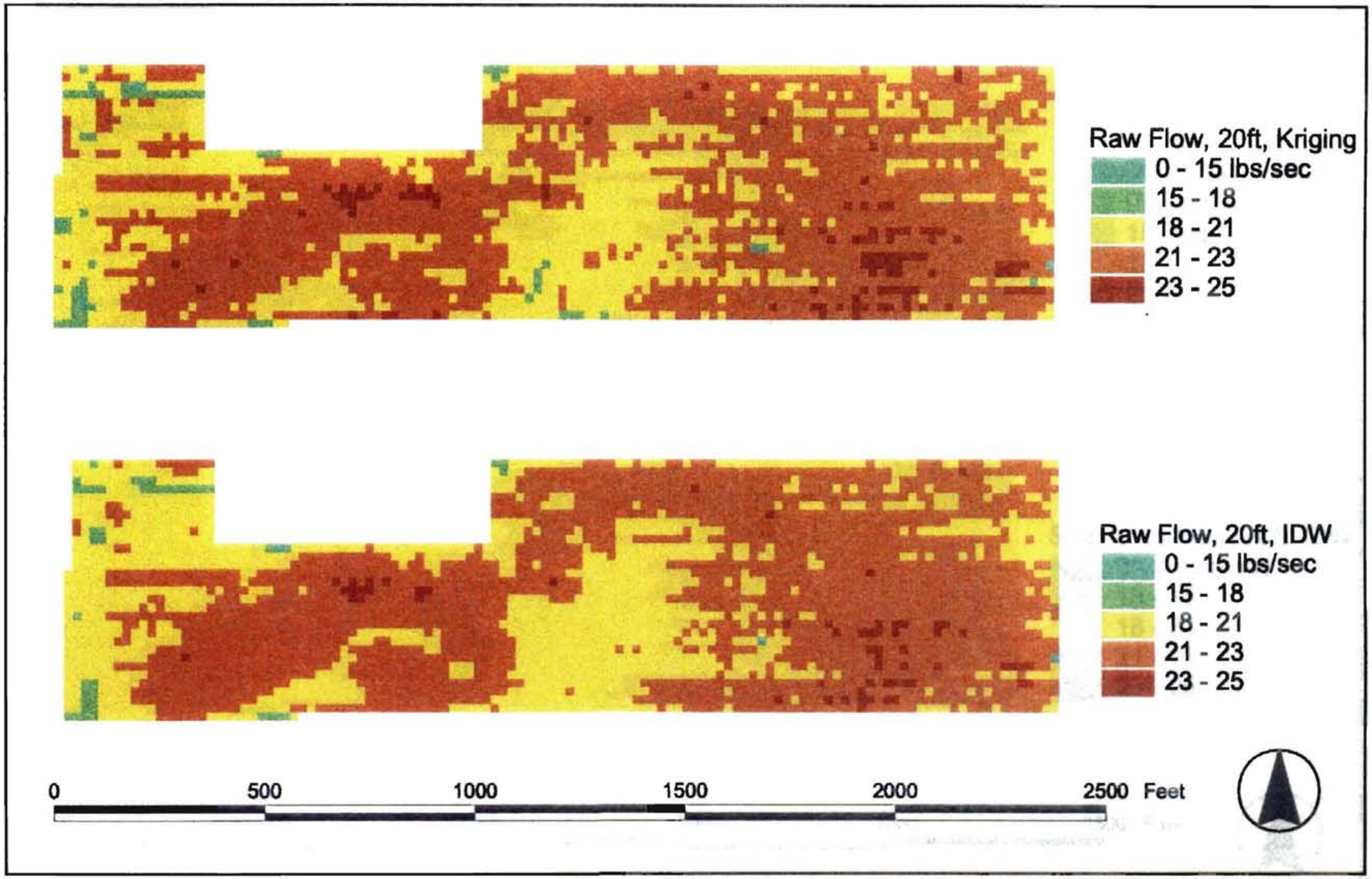

Figure 3. Raw Flow Surfaces Created Using Kriging and Inverse Distance Weighted (IDW) Algorithms.

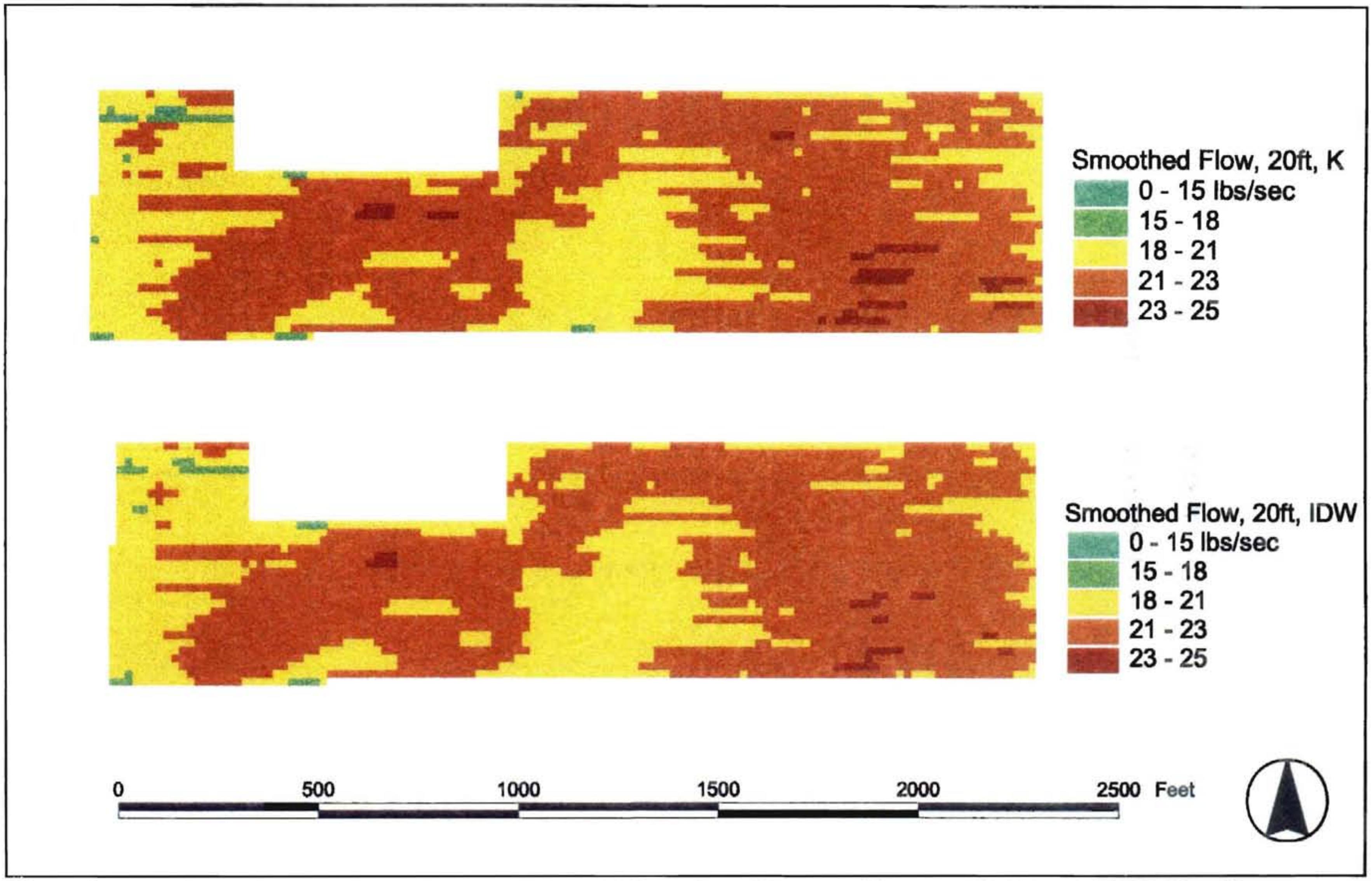

Figure 4. Smoothed Flow Surfaces Created Using Kriging (K) and Inverse Distance Weighted (IDW) Algorithms.

APPENDIX B:

ORIGINAL DATA SETS

TABLE A

HAND SAMPLED DATA SET *A*

ID	MOISTURE (%)	HARVESTABLE EARS	EARS	TOTAL KERNEL WEIGHT (LBS)
1	24.8	18	3	1.74
2	28.5	15	3	1.87
3	29.1	16	3	1.34
4	34.9	18	3	1.71
5	26.2	18	3	1.58
6	28.5	14	2	1.06
7	24.8	19	3	1.20
8	30.1	15	3	2.02
9	32.0	17	3	1.29
10	29.0	18	3	1.52
11	26.2	20	4	2.13
12	27.1	15	3	1.81
13	34.5	18	3	1.51
14	28.6	20	4	1.98
15	35.0	14	2	1.06
16	30.0	18	3	1.71
17	30.0	19	3	1.40
18	30.7	16	3	1.75
19	28.6	19	3	1.17
20	36.0	17	3	1.04
21	27.9	22	4	1.55
22	29.2	17	3	1.19
23	34.7	18	3	1.12
24	28.5	18	3	1.32
25	29.7	17	3	1.10
26	27.4	21	4	1.76
27	27.6	15	3	1.43
28	27.5	19	3	1.39
29	28.0	23	4	1.64
30	31.6	19	3	1.25

TABLE B

HAND SAMPLED DATA SET *B*

ID	MOISTURE (%)	HARVESTABLE EARS	EARS	TOTAL KERNEL WEIGHT (LBS)
1	26.6	18	3	2.14
2	27.8	16	3	1.11
3	28.6	18	3	1.73
4	25.3	20	4	1.23
5	29.3	18	3	1.54
6	26.4	18	3	1.06
7	27.1	17	3	1.18
8	28.0	20	4	2.02
9	31.4	19	3	1.28
10	27.0	17	3	1.41
11	25.3	17	3	1.29
12	26.7	17	3	1.58
13	29.1	19	3	1.51
14	27.5	19	3	1.60
15	27.9	15	3	1.46
16	30.9	20	4	1.73
17	30.4	19	3	1.51
18	31.8	19	3	1.26
19	30.1	13	2	1.17
20	34.2	22	4	1.51
21	33.5	16	3	1.17
22	27.8	17	3	1.19
23	30.7	16	3	1.36
24	29.4	18	3	1.23
25	23.1	19	3	1.07
26	27.8	18	3	1.25
27	24.5	17	3	1.64
28	27.1	19	3	1.51
29	26.9	18	3	1.51
30	27.3	21	4	1.48

TABLE C

HAND SAMPLED DATA SET *A* AND *B* COMBINED

ID	MOISTURE (%)	HARVESTABLE EARS	EARS	TOTAL KERNEL WEIGHT (LBS)
1	25.7	36	6	3.88
2	28.1	31	6	2.98
3	28.9	34	6	3.07
4	30.1	38	7	2.94
5	27.8	36	6	3.12
6	27.4	32	5	2.28
7	26.0	36	6	2.38
8	29.1	35	7	3.44
9	31.7	36	6	2.57
10	28.0	35	6	2.93
11	25.8	37	7	3.42
12	26.9	32	6	3.39
13	31.8	37	6	2.80
14	28.1	39	7	3.58
15	31.4	29	5	2.53
16	30.4	38	7	3.44
17	30.2	38	6	2.91
18	31.3	35	6	3.01
19	29.4	32	5	2.87
20	35.1	39	7	2.55
21	30.7	38	7	2.72
22	28.5	34	6	2.62
23	32.7	34	6	2.48
24	28.9	36	6	2.55
25	26.4	36	6	2.17
26	27.6	39	7	3.00
27	26.1	32	6	3.07
28	27.3	38	6	2.90
29	27.4	41	7	3.14
30	29.5	40	7	2.73

VITA

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A COMPARISON OF YIELD MONITOR AND FIELD VERIFICATION

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