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To the Graduate Council:

I am submitting herewith a thesis written by Roberto Negrão Barbosa entitled "Site-specific applications of nitrogen in corn based on yield potential." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

John B. Wilkerson, Major Professor

We have read this thesis and recommend its acceptance:

William Hart, Paul Denton

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

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We have read this thesis
and recommend its acceptance:

Paul Denton

William E. Hart

Accepted for the Council:

Associate Vice Chancellor
and Dean of the Graduate School

# SITE-SPECIFIC APPLICATIONS OF NITROGEN IN CORN BASED ON YIELD POTENTIAL

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Roberto Negrão Barbosa

August 1996

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Thesis
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# DEDICATION

This thesis is dedicated to my wife

Camila Barbosa

and my son

Kurlan Barbosa

for their support, love, and affection.

I love you very much.

# ACKNOWLEDGMENTS

I would like to thank everyone that has helped me successfully complete this project, and made these two years living in the United States a very rewarding experience. My sincere gratitude to the American Chamber of Commerce in Brazil (AMCHAM) and the Fulbright Commission for this wonderful scholarship, and the International Institute of Education (IIE) for their support during my stay.

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# ABSTRACT

Burdened by high production costs and increased environmental concerns, today's farmers are looking for new technologies that can help optimize their production efficiency. Site-specific farming is a technique to describe what some are calling the next major revolution in production agriculture which has the potential to address many of these concerns.

During the 1994 season, an experiment was conducted to document site-specific yield response of corn for different application rates of nitrogen fertilizer within soils with varying yield potentials. To accomplish this task, new technologies such as Global Positioning System (GPS), Geographic Information Systems (GIS), grain yield monitoring, and variable rate control were integrated into a overall system. A 22-acre no-till production corn field located in Milan, Tennessee was selected for this study. Prior to planting, an extensive soil survey was conducted and the field was classified based on varying levels of yield potential. Five different application rates of nitrogen were applied on the field using a variable rate applicator controlled by a laptop PC with control information being received in real-time from a GPS receiver and digital application map. Soil nutrient samples, leaf nitrogen samples, and plant population samples were collected through the season.

The GIS software in conjunction with the GPS receiver proved to be an effective method for managing spatially related information. Results indicate that variable rate application of nitrogen based on site-specific soil types within a field has the potential to increase the production efficiency for producers.

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# CHAPTER 1

# INTRODUCTION

Site-specific farming (SSF) is the ability to manage variations in production factors, such as fertilization and pest or disease occurrences, that take place in an agricultural field. SSF uses high-tech tools such as the Geographic Information Systems (GIS), the Global Positioning System (GPS), variable-rate controls, and yield monitors. The objective of site-specific farming is the maximization of production efficiency, tailoring agricultural inputs to the field's capacity of production. Literature has defined SSF in many ways (Christensen and Krause, 1995; Kincheloe, 1994; Mangold, 1994; Reichenberger and Russnogle, 1989; Zhang et al., 1994) and other definitions such as precision farming, farming by the foot, or pinpoint agriculture are also used to express the same as SSF.

One of the most discussed and researched applications of SSF is in fertilizer management. Farmers and researchers know that different soils can actually form a single production field, but they may require different fertility inputs or different management levels to achieve their best production efficiency. Reichenberger and Russnogle (1989), discussing the application of SSF principles in fertilizer management, summarized some of the research conducted to document soil and yield variability: in

Mississippi, cotton yield varied nearly 50 percent in seemingly uniform fields. In South Carolina, corn yields varied from 59 to 127 bushels per acre. In Montana, wheat and barley yields have shown variations of 50 bushels per acre. Scientists and producers question applying the same level of fertilization for an entire field, if the yield potential varies according to the soils forming the field.

Mapping the variability in crop yields is an important tool for site-specific management (Searcy et al., 1989). The grain yield monitor was designed to assist farmers in documenting yield variations in their fields. Using a yield monitor, farmers can detect significant variations in yield and begin delineating the areas with different yield production capabilities. The Global Positioning System (GPS), a satellite-based system created by the US government, helps farmers identify locations of yield variations. The yield monitor and the GPS provide yield measurement and field location capabilities to farmers allowing yield mapping.

The Geographic Information Systems (GIS), a computerized system used to store information and its geographic position, is another tool being used by farmers and scientists to implement SSF. Using GIS, farmers can store information about their fields (i.e. crop yields, weed locations, and pest damages) for several years and then evaluate them based on their geographic position, thereby creating a field history that will help explain portions of the yield variation.

The concept of SSF is not a new one. According to Rudolph and Searcy (1994), ancient agronomists practiced "fish and hoe" agriculture. Planting a dead fish under a hill of corn was observed to increase yield. Poorer soils required a bigger fish to achieve the same yield. Weed pressure demanded the precise application of a hoe. The utilization of SSF in commercial agriculture was made possible after the development of machines and electronic components that are used to automate the process of distributing fertilizer and chemicals. In 1929, researchers of The University of Illinois outlined a plan to vary application of lime across the field, but the lack of equipment for the application turned the operation much more complicated (Rudolph and Searcy, 1994). Therefore, the technology developed in the last decades allowed farmers to make use of site-specific principles. The rapidly decreasing cost in computer hardware and electronic equipment has made the utilization of such technologies affordable to farmers.

The potential of SSF relies on optimizing agricultural inputs. Farmers have been burdened with high costs of production and low prices of crop products in the past years. SSF can help the farmer optimize inputs according to the field's capacity of production. This optimization leads to economy, which is a major factor of interest for farmers. Over-treatment of agricultural fields wastes chemicals (pesticides and fertilizers), increases the production cost of crops, and has the potential to create a water-quality problem. Under-treatment of fields reduces weed control or does not supply enough fertilizer to secure the best yield, ultimately reducing returns (Qiu et al., 1994).

Site-specific farming is a technology in its infancy. Many procedures and standards need to be developed for this technology be used by farmers and crop producers. The lack of options in variable-rate application equipment is one of the problems found when farmers choose to start a SSF project. Options found in the market today point to the use of commercial applicators. The management of the yield data (yield and position) and its consequent input in a GIS is another problem faced by SSF users.

## OBJECTIVES

The objective for this project was to evaluate site-specific applications of nitrogen in corn based on yield potential. Specific objectives include:

- To adapt a liquid fertilizer applicator to automatically apply different rates of nitrogen fertilizer throughout the field, according to GPS signals and a digital application map.
- Yield map a production size corn field using a commercially available yield monitor and GPS receivers.
- To evaluate yield response in corn to different rates of nitrogen fertilizer based on varying yield potential areas within the field.

- To create a GIS database for the test field to manage all geographically related information.

# CHAPTER 2

# BACKGROUND AND REVIEW OF LITERATURE

## TRENDS IN PRODUCTION AGRICULTURE

Production agriculture is an enterprise influenced by the rapid development of new technologies. Agriculture is the same activity today that it was years ago; only the tools for production have changed. The evolution of agriculture is necessary for its adaptation to the world's new realities (including the increase in food consumption and the increase in production cost).

Recent developments in areas such as electronics and computers have brought a great benefit to agriculture. Activities like yield monitoring, soil sampling, and pest and weed scouting are much easier with the utilization of new electronic products. Farmers and agronomists have more data to analyze and use to support their research. Through the understanding and development of new products and technologies, agriculture has grown to new levels of production. Corn is a good example of this growth in production. Farmers have used new products such as hybrid seeds and commercial fertilizers, to increase corn yield from 37 bushels per acre in the '50s to 120 bushels per acre in '80s (Tisdale et al., 1993).

Producers today are looking for potential technologies to help increase productivity while keeping a low cost of production. The key phrase today in the agricultural vocabulary of farmers and researchers is the optimization of agricultural inputs. Four trends are helping researchers and farmers in this quest for the optimization in agriculture:

- Utilization of electronics and smart machines in agriculture;
- Use of Best Management Practices (BMP);
- Optimum use of fertilizer and pesticide products; and
- Increase in plant resistance to insects, diseases, and to weed competition.

The utilization of electronics and smart machines in agriculture has become widespread today. Producers use satellites to locate positions in the field, allowing better weed and pest scouts. Satellites also assist producers to map soils and yields. Tractors and combines equipped with electronic monitors, have the potential to improve the safety of the machine and increase the producer's management capability. Smart machines are being researched and built to decrease labor expenses of some activities in agriculture such as harvest.

Best Management Practices (BMP) are another trend in agriculture. BMPs have been proven in research and tested through farmer implementation to give optimum production potential, input efficiency, and environmental protection (Kincheloe, 1994). Integrated Pest Management (IPM) is one BMP adopted today. The major objective of the IPM is the reduction of pesticide usage, which reduces the cost of production in agriculture and reduces the negative effects of pesticides in the environment. Crop rotation, soil testing, management of fertilizer's application timing and rate, and scheduling irrigation are some other examples of BMPs that are being adopted by producers today. The idea of BMPs is simply to maximize the efficiency of all inputs and manage steps to produce the highest yield at maximum profit, while enhancing environmental stewardship (Kincheloe, 1994).

While aiming for maximum economic yield possible, farmers and researchers discuss the possibility of decreasing levels of application of fertilizers and pesticides. The understanding of field variability in the occurrence of pests and diseases, in fertility levels, and in yields resulted in many farmers weighing the advantages of site-specific pesticide and fertilizer applications in the fields. Environmental concerns enhanced the discussion. The farm use of herbicides, for example, rose from 207.2 million pounds of active ingredients in 1971 to 451.4 millions in 1982, increasing the use by 117.8%, against a 16% increase in number of acres treated (USDA, 1984).

The increase in plants' resistance to diseases and pests is a way of responding to the growing concern about the quantity of chemicals used in agriculture. Research is being conducted to improve crops resistance to insects and determined diseases, decreasing the necessity for pesticide applications.

Site-specific farming has resulted in investigation of the rational utilization of fertilizers and pesticides in agriculture. This farming practice must now be researched from the standpoint of its implementation and use as related to economic and environmental benefits.

## ECONOMIC BENEFITS OF SITE-SPECIFIC FARMING

Site-specific farming researchers maintain that the input of products necessary for the generation of a good yield has to be done according to the field's capacity of production. Applying products to crops according to site-specific farming's concept brings at least two advantages: (1) it optimizes the utilization of products necessary for a good yield production, and (2) it is safer for the environment.

Using SSF principles, producers would apply fertilizers only in the quantity demanded by the soil to produce a good yield. Pesticides would only be applied when needed, in areas of infestation that can cause economic damage. Although conceptually right, varying the application rate of products in a field requires employment of high technology.

Several results show that SSF has a very promising future. Mulla (1993) concluded, after mapping and managing soil fertility differences and crop yield, that nitrogen fertilizer recommendations in different areas of the field were significantly lower than the uniform rate applied by the producer. Fiez et al. (1994) reported that variable application of nitrogen fertilizer increased net returns. Macy (1992) declared a $14 per acre savings in 1991 by using variable rate application of fertilizers and seeds. Holmes (1993) reported a 7% increase in net return using variable rate against single rate in a Missouri field. Reichenberger (1995) cited an Illinois farmer who applied different rates of nitrogen in the different soils forming his fields. Soils receiving 30% less nitrogen than the usual percentage produced similar yields.

A very important issue in the economics of SSF is soil sampling. To delineate areas with different fertility levels, the producer has to sample the field more intensively. Costs involved in sampling and analyzing the soil could dissipate any extra profit realized by variably applying fertilizers. A higher density of soil samples results in more efficient field fertilization, but it also eliminates the economic benefits of site-specific farming (Wibawa et al. 1993). The question then becomes what is the minimum area to be represented by a soil sample needed to accurately delineate the different fertility levels in the field.

Wollenhaupt et al. (1994) summarized the research findings about the necessity of precision in soil sampling. Wibawa et al. (1993) concluded that small grain yields were higher when fertilizer application was based on 50-foot grid sampling. Mulla and Hammond (1988) sampled soils on 100-, 200-, and 400-foot grids. They concluded that a 200-foot grid interval was adequate for developing soil test maps. Wollenhaupt et al. (1994) tested a point soil sampling versus a 318-foot grid basis. They concluded that soil sampling in a grid basis was more accurate in mapping soil test spatial variability than point soil sampling. It seems that researchers have not yet reached a conclusion about the best sampling method nor the minimum area to sample for SSF to secure profit and precision for fertility mapping.

However, the environmental benefits brought by SSF are not questioned by anyone. Optimizing the use of fertilizer and pesticide in agriculture has the potential to decrease the concentration of these products in water supplies.

# ENVIRONMENTAL BENEFITS OF SITE-SPECIFIC FARMING

Groundwater pollution is an issue of great concern in the US today. The increase in fertilizer and chemical use in agriculture has the potential to increase concentration of pollutant products in drinking water.

Marks and Ward (1992) reported that nitrogen fertilizer utilization in the US increased nearly fourfold from 1960 to 1990. In 1990, farmers applied 11 million tons of nitrogen fertilizer to boost crop production. Fertilizers leach to groundwater supplies and runoff to surface water supplies, mainly due to their excessive use in agriculture (Marks and Ward, 1992). Producers often overestimate yield goals and use more fertilizers than necessary to produce the actual yield. Randall (1992) indicated that farmers tend to set unrealistic goals for production, commonly missing them by 10 to 30% (Randall, 1992).

Fertilizer pollution in surface water causes eutrophication, which occurs because of the excessive amount of nutrients in the water. The rich environment causes an accelerated growth in the population of algae, which ends up using the oxygen supply of the water in their decomposition process, leading to the killing of other aquatic lives such as fish. In groundwater supplies, the increased concentration of nitrogen fertilizers in the form of nitrates can cause methemoglobinemia, which is also known as "baby blue syndrome." Marks and Ward (1992) also related that nitrate contamination can lead to cancers, birth defects, and high blood pressure.

Water pollution by agricultural pesticides is another concern for society. Agriculture accounts for 67% of all pesticides used in the US (Miller and Donahue, 1990). Pesticides pollute drinking water and can cause toxicity in humans and animals. Marks and Ward (1992) stated that recent US Geological Survey (USGS) findings reveal widespread herbicide contamination of rivers and streams throughout the Mississippi River Basin, and that one-fourth of the samples collected by the USGS exceeded federal health levels for atrazine, a leading herbicide used in agriculture.

Using SSF technologies to tailor the input of fertilizers and pesticides to the actual need for production is the best way to optimize the use of these products in agriculture and decrease water pollution levels. Controlling agricultural water pollution from nutrients and pesticides is an urgent environmental priority. Site-specific farming represents an encouraging element in a strategy to stop pollution at the source (Marks and Ward, 1992). Site-specific farming can enhance the farmer's profitability while decreasing the negative effects of agriculture in water quality (Randall, 1992).

# SOIL AND YIELD VARIABILITY

The Soil Science Society of America defines soil as the "unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for growth of land plants." Five factors are involved in the soil-forming process (Miller, 1990):

- Parent materials: all soils are developed from weathered rocks, volcanic ash deposits, or accumulated plant residues. Those materials are called parent materials. They influence soil formation by their different rates of weathering, their nutrient content for plant use, and their particle size.

- Climate: the climate is a dominant factor in soil formation because of the effects of precipitation and temperature.

- Living organisms: the biota helps soil development by decomposing organic matter and forming weak acids that dissolve minerals better than does pure water.

- Topography: topography influences soil formation, primarily due to its association with temperature and water.

- Time: time interrelates the above factors in soil formation. Under ideal conditions for development, a soil profile can develop within 200 years. In less favorable conditions, it might take several thousand years for this development.

Soils are often defined in terms of these factors as "dynamic bodies having properties derived from the combined effect of climate and biotic (organisms) activities, as modified by topography, acting on parent material over periods of time" (Brady, 1990). Due to the variation of components forming the soils (different rocks, topography and weather influence), soils have variable fertility level, physical aspects and aptitude for agricultural production.

Soil varies from place to place in such a way that any one of its properties is best considered mathematically as a random function (Webster and Burgess, 1983). "There is a great variability in the soil profile characteristics from one location to another. Differences are found in soil properties like soil depth, organic matter content. Notable differences in soil composition are sometimes found within a matter of meters" (Brady, 1990).

Nutrient management for crop production begins with an inventory of the soil test nutrient levels in a field. Fertilizer recommendations are based on expected response to fertilizer application as a function of soil test levels. Therefore, fertilizer applications can be no better than the accuracy of the soil test map upon which the fertilizer recommendations are based. The larger the area represented by a soil sample, the greater the possibility of losing information about soil variability (Wollenhaupt and Wolkowski, 1994). Soil sampling in a 15-meter grid can effectively evaluate soil fertility variability within a field. A 15-meter grid soil sampling and fertilization resulted in a greater yield than a 80-meter grid (Wollenhaupt et al. 1994).

As a result of the soil's inherent variability, yields are also spatially variable. Ancient agronomists placed dead fish in corn plants to help get better yields. They soon recognized that not all soils needed the same size of fish to produce equal yields (Rudolph and Searcy, 1994). Reports of several experiments show that the difference in fertility levels between soils in some fields was a major cause of crop yield variability. Other studies proved that differences in available water largely explained yield variation between soils (Carr et al., 1991).

Weather plays an important role in yield variability. Water availability to plants and air and soil temperatures are major factors influencing yields. In corn yield tests in Nebraska from 1945 to 1965, irrigation reduced year-to-year yield variability to half of those found in dryland areas (Colville, 1967). The weather factor has to be controlled somehow. Irrigation is a form of control. The development of more accurate long-term weather forecasts is also a form. Unless control of the weather is exercised, farmers take a great risk planning for maximum yields through increasing input product levels (Polito and Voss, 1991). Nitrogen fertilizer and irrigation are important factors in corn production. In tests with corn conducted in Wisconsin, fertilizer rates explained up to 38% of the yield variation on a non-irrigated soil, but explained 65% of the variation on an irrigated soil (Oberle and Keeney, 1990). When the influence of the weather is minimum, the variability concentrates on other points.

In the past, farmers and agronomists, even though acknowledging spatial variation in yields, had few options in managing the variability present in a large area of grain production. The machines used to perform operations such as planting, fertilizing, and spraying were designed to uniformly apply products in the entire field. Computer and electronic technologies helped develop the possibility of applying different rates of fertilizer and pesticides in the field. The Geographic Information System (GIS) and Global Positioning System (GPS) will allow farmers to manage fields in accordance with the variability in the yield potential of the soils (Qiu et al., 1994).

### *Yield Potential*

Yield potential can be described as the ability of a particular soil unit for agricultural production. Yield potential depends on a series of factors. Physical and chemical characteristics of the soil influence the yield potential. Weather and management practices also have their influence. To determine the yield potential of the soil, the producer has to recognize the soil as a complex unit. The producer's experience and current research in the production area help to determine the yield potential. All this research and determination is done trying to achieve the maximum economic yield, the point as which the last increment of an input just pays for itself (Tisdale et al., 1993). To achieve the maximum economic yield, inputs have to be tailored following the yield potential of the soil and its capacity of production.

## TECHNOLOGIES ASSOCIATED WITH SITE-SPECIFIC FARMING

Site-specific farming (SSF) relies on several new technologies available for its implementation. Technologies like the Global Positioning System (GPS) and the Geographic Information Systems (GIS) are possible today due to developments in the electronic and computer industry. The advancement of computers and electronics made operations like yield monitoring and variable rate control of fertilizers and pesticides possible for the farmer. The producer today can see a new perspective of management in farm operations: the information management era.

Most of the technologies used in precision farming are being applied in different areas with a great deal of success. The Global Positioning System (GPS), a satellite-based navigational system developed by the US Department of Defense (DoD), is being used in several operations such as fleet management, air traffic control, and wildlife monitoring. The

Geographic Information Systems (GIS), a computer based data information system, is widely used in urban planning and environmental modeling, and is a key component to managing spatially variable data. The implementation of these technologies in agriculture was a consequence of their recognized success in other industries. New technologies used in SSF are described in the following sections.

### *Global Positioning System*

The NAVSTAR (NAVigation Satellite Timing And Ranging) Global Positioning System (GPS) is a satellite-based system used for navigation and positioning purposes, created and operated by the US Department of Defense (DoD). The GPS provides users with precise position information anywhere on earth.

The DoD invested over $12 billion in the system to be used primarily by the US military, but GPS is considered such a good invention that it has begun to be called the next utility (Hurn, 1989). The potential for GPS is so big that by the year 2000 more than 1 million users will benefit from the GPS system in a variety of applications such as marine, air traffic, agriculture, and fleet management applications (Kruger et al., 1994).

Navigation and position determination technologies are problems that people have tried to solve for a long time. Systems other than GPS are available, like LORAN and DECCA. These systems consist of a ground-based network of low frequency transmitters, but they have limited coverage and are unable to determine precise positions (Stafford and Ambler, 1994).

The GPS relies on satellites orbiting the earth for position determinations. The system is composed of three segments:

- The *Space* segment includes 24 satellites orbiting the earth at an altitude of 20,000 kilometers on six different orbits. Each orbit has four satellites and it is inclined 55° to the equatorial plane (Wolf and Brinker, 1994). All six orbits are spaced 60° apart and each takes 11 hours and 58 minutes to be completed. This means that each satellite circles the earth twice a day (Kruger et al., 1994). The satellites were manufactured by Rockwell International; each satellite weighs 860 kilograms in orbit and is 5.1 meters in length with the solar panels extended (Hurn, 1989).

- The *Control* segment consists of a master control station, worldwide monitor stations, and ground control stations. Functions of the control segment are to accurately track GPS satellites; to provide periodic updates of ephemeris data, which are positional satellite data transmitted to the user; to correct satellite clocks errors; and to monitor the general health and status of the satellites (Rupert and Clark, 1994).

- The *User* segment is composed of an unlimited number of GPS users and their receivers tracking satellites to receive information required for position determination.

*How GPS Works*

To determine positions on earth using GPS, users connect their receivers to a GPS satellite via a radio link. A radio transmitter in each satellite produces radio waves that connect the satellite and the receiver forming a sphere, centered on the satellite. A connection with another satellite produces a second sphere. The receiver's location could be anywhere in the circle formed by the intersection of the two spheres. A third connection narrows down the receiver's position to one of two points in the intersection of the three spheres.

GPS receivers exclude one of the points because it is an absurd answer (a point very far away from the surface of the earth, or moving at a very high speed). A fourth satellite connection is still needed to promote synchronization between the satellites and the receiver.

To calculate its position, the receiver needs to know the exact location of the satellites being used in the measurement. GPS satellites are put in a nongeo-synchronism orbit around the earth. This means that, relative to earth, the satellites are not stationary in space but circling the globe. This gives the DoD a chance to monitor their altitude, speed, and position, to make small adjustments if necessary (using the control stations), and to transmit these data back to the satellite. The data is re-transmitted from the satellites to the GPS receiver, which uses this information to precisely locate satellites in space.

After locating all four satellites in space, the receiver calculates the distance between itself and the satellites, using the time of travel spent by the signal to reach the receiver. The receivers use the speed that the radio waves travel in space (299,792,458 meters per second) to determine this distance (Hurn, 1989).

Having a common point with all four satellites and knowing the distances between itself and the satellites, the receiver calculates its position, solving four equations with four unknowns (X, Y, Z and time). After the position is found, it is converted into a geo-reference system such as longitude, latitude, and altitude according to the World Geodetic System of 1984 (WGS 84). This system is the most precise worldwide description of the earth ellipsoid in space (Kruger et al., 1994).

GPS satellites broadcast a radio signal called pseudo-random code used by the receiver to calculate positions. There are two groups of codes transmitted: the C/A code (Coarse Acquisition) available for civilian use and the P code (PPS or Precise Positioning Service) with use restricted to the military. Each satellite transmits codes in two frequencies: 1575.42 MHz and 1227.60 MHz. Since each satellite produces its own pseudo-random code, they all share the same frequencies without disturbing each others' signals.

*Precision and Sources of Errors*

Although GPS is a very precise location and navigation system, its precision depends on several factors. The native or inherent accuracy of the GPS system is 20 meters, based on a 95% probability that the position given will be within 20 meters of the true position (Shrosphire et al., 1993). Some factors contributing for this low precision are:

- Ionospheric and Atmospheric Delays - The ionosphere, a blanket of negatively charged particles 130 to 200 kilometers above the earth, can make the pseudo random code slow down and not maintain the speed-of-light rate. The earth's atmosphere can also delay the code. These delays introduce error in the estimate of position. They can add up to 3.5 meters of error in estimating positions (Hurn, 1989).

- Satellite Clock Errors and Receiver Errors - Even though satellites have very precise atomic clocks, they are subject to small variations. The receiver can also round off some mathematical operation or suffer some electrical interference that leads to an erroneous determination. These two factors may add up to as much as two meters of error in estimating a position. (Hurn, 1989).

- Multipath Error - Multipath error occurs when the incoming satellite signals bounce off some other structure (walls of buildings, tops of cars) before reaching the GPS antenna. The receiver calculates the distance from the satellite using the reflected path, inducing an error. A typical multipath error can produce up to a 20-meter error in estimating a position (Hurn, 1989).

- Ephemeris Error - Ephemeris errors are those resultant from lack of knowledge about the exact location of the GPS satellites (Wells et al., 1987). An ephemeris error can add up to 0.5 meter of uncertainty in estimating a position (Hurn, 1989).

- Selective Availability (S/A) - The DoD, concerned about the use of the system by hostile forces, added selective availability to the system. This means that when activated, S/A causes the system's accuracy to be intentionally degraded due to insertion of errors in the satellite orbit information. Because of the large amount of civilian use of GPS signals, S/A is being restricted to reduce the system accuracy to no more than 100 meters (Shropshire et al., 1993). Special military GPS receivers are able to decode information on both of the satellite signals to determine accurate positions even with S/A turned on.

- Geometric Dilution of Precision (GDOP) - GDOP is the error introduced in the system based on the geometric order of the satellites used to calculate the receiver's position (Kruger et al., 1994). Position Dilution of Precision (PDOP) is a factor based on the GDOP and used to calculate the instantaneous accuracy of the system. A PDOP of four or less yields excellent precision. A PDOP between five and seven is acceptable, but a PDOP higher than seven is poor (Hurn, 1989). Error due to GDOP can be minimized by using the system at times of day when the PDOP is low.

*Differential GPS*

The lack of precision resulting from S/A has forced part of the user segment, such as precision farming, to search for another way to achieve accurate positions. The result was the introduction of the Differential Global Positioning System (DGPS). DGPS is the technique of using two GPS receivers to collect data, instead of only one. One of the receivers (the base station) is set up in some fixed, known point and it logs data continuously. The other receiver (the rover) is used to make the desired measurements. Comparing the measurements made by the base station with its known location, the error is estimated and eliminated. This error rate is transmitted to the rover, which uses it to correct its own measurements. The requirements for use of DGPS are (1) to use at least two receivers, and (2) to configure the base station to calculate an error code for each of the satellites being used by the rover in its calculations.

There are two ways of using DGPS:

- Real Time DGPS - Real Time DGPS means the transmission of the error code to the rover at the same time that data is being collected. The user has to connect both receivers using a modem and a radio link, and the rover has to have the ability to receive real time correction signals and process them. Some of the options to receive real time correction signals include:

1. Having your own base station and the radio transmission equipment to send the correction signal.

2. Subscribing to a commercially available DGPS service in the area. A common practice today for some companies is to offer a subscription of DGPS correction signals valid for a determined area, and to charge a fee for this service.

3. Using the signal provided by the US Coast Guard. The coast guard transmits DGPS signals without any cost involved. The only requirement to use their signals is to have a beacon receiver. However, the area where the signal is available is restricted to coastal areas.

- Post-Processed DGPS - To post-process means to correct positions, eliminating the S/A and atmospheric errors after they were collected. This is a common procedure for users that have no need of correcting the signals in real time. Many companies selling GPS receivers also sell computer software capable of correcting a rover file based on a remote base station file. Base files can be obtained in different ways. Some companies post them on the Internet or on Computer Bulletin Boards (BBS); others charge a fee for using theirs. Base and rover files have to be collected at the same time.

One of the potential problems with DGPS is the distance between the base station and the rover. The accuracy of the corrected rover file is a function of the distance that separates both receivers. The closer the rover is to the base station, the more effective differential corrections will be in removing errors of the rover file (Rupert and Clark, 1994). Rupert and Clark (1994) demonstrated that for a distance of 103 meters to 398 kilometers between rover and base station, the relationship between circular error of position and distance between receivers is linear. The error in the rover file increased about 0.6 meters for every 100 kilometers increase in the distance between receivers.

### *DGPS in Site-specific Farming*

In agriculture, the utilization of DGPS is almost a requirement. Researchers, farmers and fertilizer dealers are using GPS as a tool to precisely describe where the variability is occurring in the field (yield, nutrients variations and pest occurrences). For this reason, the more accurate the system is in describing the variations in the field, the better use it has.

Several works describe GPS as the most precise and useful navigation system for agricultural operations. Auernhammer et al. (1994) used GPS for yield mapping on combines and concluded, after a series of trials, that DGPS allows yield mapping with a sufficient precision for current farming practices. Among several positioning techniques, GPS is shown to have the best overall potential (Stafford and Ambler, 1994). Non-differential GPS lacks accuracy for spatially variable agriculture, but both post-processed and real-time GPS can be used for spatially variable farming (Shropshire et al., 1993).

### *Geographic Information Systems*

Geographic Information Systems (GIS) are computerized systems that have the ability to store spatially varying information (as a database) using geographic references. A GIS can store any data that has a location reference, such as addresses in a city or crops cultivated in different parts of a field. Information is stored, manipulated, and retrieved according to its geographic location; or it is used to generate new information.

The Environmental Systems Research Institute[1] (ESRI), one of the leading institutes in GIS technology and producer of the GIS software ARC/INFO, PC ARC/INFO, ArcView and others, defines GIS as the only system that permits spatial operations on the data. Spatial operations are queries that can only be answered using the geographic information and the attributes of the data (ESRI, 1995). A GIS can define five aspects of the data:

- Location: A location can be described in many ways using a geographic reference (an address, ZIP Code, latitude and longitude).

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[1] Company and trade names are given for the benefit of the reader and do not imply endorsement of the product or company by the author or The University of Tennessee.

- Condition: Generally a GIS is used to find locations that satisfy determined conditions (for example, corn planted in soil with slope lower than five percent and soil depth greater than 10 inches).

- Trends: A GIS can determine trends in areas looking at the differences over time (how the yield of corn in the same area behaves from year-to-year).

- Patterns: A GIS can be used to reveal patterns in the data.

- Modeling: GIS can be used to answer "What if . . ." questions (what happens if a toxic substance seeps into a local groundwater supply?).

### *Development of GIS*

The development of the GIS has its roots in at least two overlapping areas: an interest in managing the urban environment and a concern for utilizing environmental resources (Star and Estes, 1990). The first system in the modern era to be generally acknowledged as a GIS was the *Canadian Geographic Information System* (CGIS). The main purpose of the CGIS was to analyze Canadian land inventory data. Following the implementation of the CGIS, the *New York Landuse and Natural Resources Information Systems* was implemented in 1967, and the *Minnesota Land Management Information System* in 1969.

In the past decades, GIS technology has become widely used in many different areas. Two of the reasons for this spread in utilization of GIS technology are the rapidly decreasing costs in computer hardware and the realization that geography (and the data describing it) is part of the everyday world; almost every decision made is constrained, influenced, or dictated by some factor of geography (ESRI, 1995).

A technology being used in such different areas has to have flexibility in data storage. A GIS supports two types of data: Raster and Vector. Raster Data Models store data in a cell structure. The accuracy of the data is dependent on the cell's size. Raster models use less storage space and are computationally easier when compared to Vector models. Vector Data Models use a single coordinate position (X, Y) to represent each location. The great advantage of a Vector-based system is the topology concept (Hoskinson, 1995). Topology is the procedure used by a GIS of spatially relating all components of a database. These relations provide two of the five aspects outlined earlier in this report (pattern and modeling).

## *Elements of a GIS*

Generally a GIS is implemented in the form of a project. Every GIS project should consist of five essential elements (Star and Estes, 1990):

1. Data acquisition is the process of identifying and gathering the data required for the application.

2. Pre-processing involves manipulation of the data in several ways in order to prepare it to input in the GIS.

3. Data management functions provide consistent methods for data entry, update, deletion and retrieval.

4. Manipulation and analysis allow analytic operators to work with the database and derive new information.

5. Product generation is the phase where final outputs from the GIS are created. These output products might include statistical reports, maps and graphics.

Data to be entered into a GIS project may come from different sources and forms. Some data come in graphic and tabular forms (maps and photographs); others may come in digital form (computer records). Data can also be captured using the GPS or some other source to geographically reference it. To digitize maps is a common way of input cartographic data into a GIS. Also, private companies or public agencies such as the US Geological Survey National Mapping Division or the US Department of Agriculture can be sources of digital data (Star and Estes, 1990).

The costs involved in collecting initial data can never be underestimated. The accuracy of the decisions reached through spatial analysis of the data is limited by the precision of the original data. After collecting the original data, the user starts the pre-processing phase of the GIS project that includes procedures to convert a database into a form suitable for permanent storage. Often, a large proportion of the data entered in a GIS requires some kind of processing and manipulation to make it conform to the system.

### *Geographic Reference Systems*

Latitude and longitude are probably the most common way of specifying locations on earth. Latitude and longitude are angles measured from the earth's center to a point on the earth's surface. Longitude is measured east and west, and its lines are called meridians. Latitude is measured north and south, and its lines are called parallels. Because they are based on angles rather than distances, latitude and longitude are a geographic reference system.

Another geo-reference system is the Universal Transverse Mercator (UTM), a coordinate system based on the transverse mercator projection. This system is used just for small areas because of the distortion involved in representing area. UTM divides the earth's surface into zones that are six degrees wide of longitude. Precise locations on the earth are described in terms of north-south and east-west distances, measured in meters from the origin of the appropriate UTM zone.

### *Data Management*

The phase of data management comes after collecting and deciding what is the best way to store the data. This part of the GIS project makes the information collected and pre-processed available to the users. Through manipulation and query, the users can obtain information that is stored in the database. Ultimately, the user is able to retrieve from the GIS data relational to some geographic point on Earth. Besides answering questions about spatial data, a modern GIS should possess a number of qualities that are common to all database management systems (Star and Estes, 1990):

- efficiency;
- capability of handling multiple users and databases;
- lack of redundancy of data;
- data independence, security and integrity.

By manipulating and analyzing the data, users have answers to some of their questions. Generally a GIS will store data in layers of information. One layer, for example, can store data about all the soil types in a region, and another layer can store data about crops planted. The overlay of layers answer questions such as the total area of a soil type planted with a specific crop.

Geometric and spatial operations, measurements, statistical analysis and modeling are some of the operations performed in the manipulation and analysis part of the project to achieve the product generation phase. The last phase of a GIS project summarizes the different types of products derived from the analysis and manipulation of the data. The most common product of a GIS project is a thematic map.

*Thematic Maps*

A thematic map is used to illustrate features of a determined region according to the message the user wants to convey to the audience. A thematic map illustrating differences in fertility of an agricultural area may lead the farmer to vary the distribution of fertilizers according to the fertility levels. Other graphics can also be used as product generation of a GIS project. Charts (pie and bar charts), scatter plots, and histograms are powerful tools to convey information.

*GIS in Agriculture*

Information is what producers and researchers expect to get with the utilization of GIS technology in agriculture. Utilization of GIS in agriculture is growing with the rapidly decreasing price of computer hardware and software. The important link that GIS offers between geographic locations and attribute information is the key to the successful use of this technology in agriculture, since the majority of information in this area is geographically referenced.

Evans et al. (1995), relating GIS capabilities and limitations for precision farming, indicates that GIS is an effective tool for handling a large amount of spatial data in site-specific crop management and that a Raster-based GIS is preferred to a Vector-based system. The lack of geostatistical tools for database creation and the difficulty of being linked with external simulation models are the two major limitations of the current GIS.

One of the most straightforward and widely publicized applications of GIS in site-specific farming is the production of the yield map (Hoskinson, 1995). In precision farming, GIS can be used for much more than just yield map production. The ability to query the data and manipulate it according to geographic locations can contribute to a better understanding of variations in yields, in pest location, and in nutrients availability, that ultimately will translate into an optimization of application and use of input products in agriculture.

### *Yield Monitors*

Site-specific farming (SSF) brings a better management of the spatial variations occurring in the field. Spatial variations of weed infestation, of pests and disease occurrences, of water distribution and of nutrients occur in every field. Grain yields can also vary drastically within a field.

Examples of yield variations are found extensively in agricultural magazines and scientific reports about SSF. Pierre Robert, extension soil specialist of the University of Minnesota, found yield variability of 100 bushels per acre in some of the fields where he conducts SSF research (*Farm Industry News*, 1994). Tom Colvin, from the National Soil Tilth Laboratory, found variations of more than 50 bushels per acre in a 160-acre corn farm (*Farm Industry News*, 1994). An agronomist at Mississippi's Delta Branch Experiment Station, Dean Pennington, found yield variations of nearly 50% in fields of cotton (*Farm Industry News*, 1994).

To better understand the agricultural production process, farmers need to recognize the variability present in the soil and start treating fields that are composed of different soils, differently. To put the concept of site-specific farming (and the treatment of the different parts of the field differently) in practice among producers and scientists, measuring the variability of grain yield in a field is one of the first tasks to be done. The entire concept of SSF is based on detecting significant variations in yield within fields, knowing where those areas and variations are, and beginning the quest for solutions (*Farm Industry News*, 1994). Mapping the resulting variability in crop yields could be an important input for site-specific decision making, either by itself or in combination with other spatial data (Searcy et al., 1989).

The development of electronic sensors and computer products in the past decade was fundamental for the success of electronic-based measurements in agriculture. The utilization of electronics in agriculture did not occur until the development of dust-proof, vibration-resistant sensors and monitors. After the development of these components, agriculture could benefit from all measurement capabilities that electronics have to offer.

Measurements of on-the-go yield can be made either directly or indirectly. In a direct measurement, the actual weight of the grains being harvested is recorded and related to the area harvested. This measurement is referred to as *mass flow meter* measurement. In an indirect measurement, other determination is made and used to correlate to the amount of grain harvested. There are different types of indirect measurement such as a *flow meter* and a *force estimate*.

Several works describe different approaches used by engineers and scientists to measure on-the-go yield. Searcy et al. (1989) reported using a six-bladed paddle wheel mounted on an Allis-Chalmers combine to predict yield of sorghum. The paddle wheel used was a grain flow meter sensor and was mounted on the discharge side of the grain tank filling auger. Stafford et al. (1991) used a gamma-ray absorption mass flow meter and a capacitive sensor on a combine in order to measure yields (Auernhammer et al., 1994).

There are two options to choose from when shopping for a yield monitor in the US (Walter, 1994). Although they come from different manufacturers, the principle of operation for both monitors is the same: to measure the force of the grain flow entering the grain elevator. Both monitors use the same type of sensor to measure the force resulting from the grain entering the combine's bin and impacting onto a sensor plate. The force measured is then related to the area harvested using the combine's forward speed and the width of the combine's header.

Little independent research is available on the accuracy of the monitors currently available in the market. The companies claim that, with proper calibration, both monitors can deliver 2-4% accuracy (Walter, 1994).

Regardless of the method used for measuring the yield during harvest, an important sensor that is part of the yield monitor is the grain moisture sensor. The moisture present in grains is very dependent on several factors, such as time of harvest and general conditions of the harvest season (wet or dry). It is important for the producer to use a standard measurement of yield for comparison purposes. For example, the corn producer has to know the weight of grain harvested based on a standard moisture content of 15.5% (Loewer et al., 1994). Grain harvested with a higher or lower moisture content should be adjusted to a standard value. Therefore, it is vital for a yield monitor to have a moisture sensor to measure the moisture of the incoming grain.

*Yield Mapping*

After measuring the grain flow in the combine and correcting the weight according to the moisture content, the yield must be geo-referenced to a location in the field. Auernhammer et al. (1994) summarized several works that have tried different ways of linking the yield produced with its geographic position. Schueller et al. (1987) tried positioning a combine in the field using an ultrasonic transmitter/receiver assembled on the combine with two or three reflectors at the field borders. The system had a good precision at great distances, but it performed poorly when the machine approached the reflectors. Stafford et al. (1991) tried detecting the position of the combine using a dead reckoning system. No information is given regarding the precision of the system.

Searcy et al. (1990) related that a microwave frequency triangulation is a reasonably accurate way of detecting positions of agricultural machines in the field, but what brought a decisive answer for the positioning question was the GPS. The GPS integrates the yield monitor, producing a system capable of recording yield and its place of occurrence. The GPS produces geographic data readily usable for different software to map yields. Several researchers have used GPS as the source for geographic reference to create yield maps (Reitz and Kutzbach, 1992; Schnug and Murphy, 1992; and Pringle et al., 1993). Auernhammer (1994) concluded that GPS allows yield mapping with sufficient precision for current farming practices.

Better management practices allow the producer to make wiser decisions about fertilizing fields and applying expensive pesticides. The first steps for a better practice are to recognize and map what the field has given back to the producer at harvest time. Acknowledging yield variations allowed Carr et al. (1991) to conclude that in the same production area, high yielding soil units produced twice as much grain (wheat) as low yielding soil units. He suggested that it would have increased the profitability if low yielding soil units were taken out of production in 1987. This conclusion could be the same for many other farmers who are producing grains in the world today. The only way for them to make those decisions is to start recording and mapping the yield produced.

### *Variable Rate Control*

Fertilization, pesticide applications, and irrigation are agricultural operations often performed to supply soil nutrients, to control pests, or to provide water for the development of crops, and to achieve a higher yield. All these operations require control for site-specific applications. The producer has to control the quantity and quality of the input product used to obtain the desired yield results. Controls are among the primary mechanisms used in engineered systems to maximize productivity, efficiency, and product quality (Stone, 1991).

Controls are found in many aspects of agricultural machines today. Among the control features on planters are the mechanisms to adjust seeding rates. An irrigation system controls the amount of water supplied in an area. A sprayer uses nozzles and pressure regulators to limit the amount and the size of the droplets that are sprayed over the crop. Unfortunately, most of the machines found on the market today are equipped with a type of control that enables them to deliver a fixed amount of product during the operation. Some electronic controls are available to apply variable rates of fertilizer and herbicides, but they lack the ability to geo-reference the application rate.

Research has proved that most of the factors influencing agricultural production, such as nutrient and water availability or weed infestation occurrence, do not take place at the same intensity level within the entire field (Reichenberger and Russnogle, 1989). Any application of products with the objective of controlling the factors affecting crop production should be made according to the variable pattern of their occurrence in the field.

Over-treatment wastes agricultural chemicals, increases the cost of production, may cause crop injury, and has the potential to create a water quality problem. Under-treatment reduces weed control, which results in increased competition for nutrients, reduction in yields, and ultimately reduced returns (Qiu et al., 1994). Although it may appear logical to apply different rates of products throughout the field, this is not an easy task.

*Features of VRC*

Variable Rate Control (VRC) is a system that uses today's advanced electronic and computerized technology to enable delivery of variable rates of agricultural input products (fertilizer, seeds, herbicides, and water) to the field. VRC is costly to implement due to the technology involved, and at today's crop values such costs are not easily absorbed by the producer. Sawyer (1994) lists some of the complicating factors of adopting VRC:

- Cost of implementation (sampling, mapping, equipment, trained personnel).
- Lack of expected increase in yield.
- Lack of input savings.

Recent technological improvements have brought hope to those awaiting VRC. Technologies like the GPS and the GIS have made it possible to apply variable inputs to agricultural operations. Aucrehammer and Muhr (1991) have foreseen a great use of GPS and GIS technologies in agriculture. In fact, when compared with traditional broadcast application technique, they show that approximately 60 to 70% of the present expense and quantities of agricultural chemicals could be saved by using VRC. Advantages that producers can obtain using VRC over the one-rate-entire-field approach are numerous such as (1) adjusting yields according to the field's capacity of production and (2) potential to reduce water pollution by optimizing the amount of chemicals applied.

The VRC system is a computer-based control system that is mounted on a agricultural applicator (fertilizer or sprayer). The unit receives information based on the desired rate of application from a digital map. The VRC unit checks its position in the field using the GPS, looks for the application rate in the digital map, and applies it. Output signals from an electronic controller are used to open or close valves, or to control the speed of a hydraulic motor to vary the application rate. There are two types of controls:

- Continuous, where the application rate can be adjusted from 0 to 100% of the range of application.

- Discrete, where pre-determined values are set and the control unit varies the application rate according to them.

There is no complete equipment solution in variable-rate applicators in the market today. Farmers and researchers are building their own equipment due to (1) none availability of small applicators and (2) different requirements for the application.

Reichenberger (1994) relates that the applicator used in a Minnesota farm to variably apply nitrogen fertilizer is an adaptation of several pieces of equipment. Computer and software components are supplied by Soil-Tech Inc., and nitrogen fertilizer is applied and adjusted by a DICKEY-john flow-control monitor. Rudolph and Searcy (1994) developed a chemical applicator that could vary the chemical rates on-the-go, using for this a laptop computer, a GPS unit, and a direct injection unit. The system performed well regarding the automatic change of rates; the problem found was the time lag between the command to change the rate and the actual occurrence in the nozzles.

Some potential problems exist with VRC such as response time, cost, and dynamic operating range. The response time can be defined as the time needed for the electrical signal to produce the desired variation in the application rate. If the equipment travels in the field at 8 km/h, a two-second delay produces an offset of 4.5 meters. This delay means that the desired rate will always be off by some distance (Rudolph and Searcy, 1994). Also, drastic variations in the application rate results in response time problems. Rate variations mean to physically open or close valves to achieve the desired rate. If the variation is too broad, there will be a time lag until the next desired rate is obtained.

Cost is another potential problem with VRC. Even though technology is available, components to produce variable rate equipment are expensive. One of the approaches being used to avoid the prohibitive cost is leave the implementation of VRC to the chemical dealers.

Dynamic operating range is the third problem found in VRC. The application range of liquid fertilizers or herbicides can be very broad. Application rates can vary from 0 to 150 liters per hectare, for example. Components of an agricultural applicator, such as nozzles, generally are not recommended to work outside a specified range. There is not an automatic way of changing nozzles in a VRC equipped machine, and there are not components certified to work in a very broad range.

VRC technology is available today. Studies are under way to determine whether large economical, environmental, or agronomic differences are found between variable and uniform rate application of agricultural inputs. The lack of VRC equipment for farmers is one of the barriers to the full adoption of this technology.

# CHAPTER 3

# METHODS AND MATERIALS

## OVERVIEW OF THE TEST

The experiment was conducted in a field labeled A6/A7 at The University of Tennessee Milan Experiment Station. The experiment station is located in the west side of the state, 310 miles (500 kilometers) from Knoxville and 180 miles (290 kilometers) from Nashville. The station has a tradition of leadership in researching new technologies in agriculture. No-till planting has been researched there for the past 20 years.

The test field has a total area of 22.5 acres (9.0 hectares), and it is continuously used for agricultural research. In the past 10 years it has been in a corn/wheat/soybean no-till rotation. Figure 1 is an aerial photograph of the field.

In February of 1993, 2,204 lbs/ac (2,470 kg/ha) of lime were applied to the test field. On March 15, 1995, 80 lbs/acre (89.6 kg/ha) of $P_2O_5$ and $K_2O$ were applied in the field. Corn was planted on April 5 and 6, 1995. The cultivar used was FFR-943 with a population of 25,000 plants per acre.

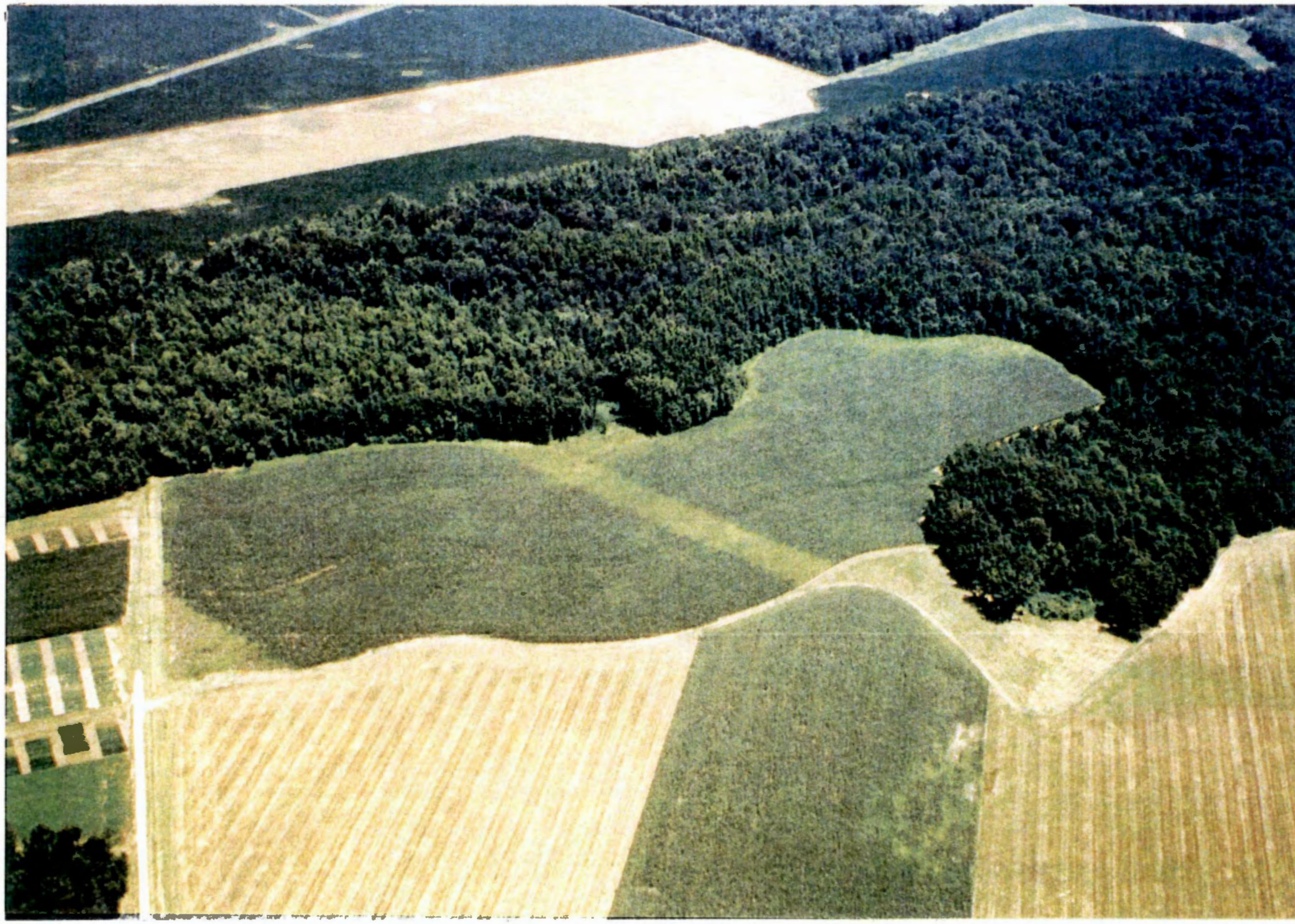

Figure 1. Aerial photograph of field A6/A7 located on the Milan Experiment Station.

Variable rates of liquid nitrogen fertilizer were the only treatments applied to the field. Five discrete rates were randomly applied, using GPS and variable rate technology. Corn yield was recorded using a yield monitor and GPS equipment. All field data were later input into a GIS package for analysis of the effect of the various nitrogen rates on corn yield by soil groups.

### *GPS Equipment*

In this research, three different GPS receivers were used, all manufactured by Trimble Navigation. All data collection was performed using real-time DGPS. A Trimble 4000 RS was used as the reference station, while a Trimble 4000 DS was used as a rover to collect data when applying the fertilizer and harvesting the corn. A Trimble Pathfinder Basic+ was used to record positions of soil and nitrogen leaf samples. Features of the GPS receivers are described in Table 1.

A well-head located near the western boundary of the field was chosen as the fixed point to locate the reference station. The GPS reference station antenna was mounted over the well-head and GPS data was collected for a period of two hours. An average of the coordinates (latitude, 35°33'56.93" and longitude, 88°25'40.68") was used to calculate the errors associated with S/A. The errors were transmitted every two seconds to the

Table 1. Features of the GPS receivers used in the experiment.

| | Pathfinder Basic+ | 4000 (DS, RS) |
|---|---|---|
| GPS Channels | 6 | 9 |
| Update Rate (max.) | 1 second | 0.5 second |
| Max. Satellites Tracked | 8 | 9 |
| Resolution | 1 - 5 meters | less than 1m RMS |

rover unit, mounted in the combine or tractor. This error code transmission was done using Trimtalk radio-modems manufactured by Trimble Navigation. The radio-modems require no FCC license and provide a wireless data connection up to a 10 mile line-of-sight. The radio links use a carrier frequency of 902-928 MHz.

## SOIL SURVEY AND CLASSIFICATION

An extensive soil survey of the field was conducted during the fall of 1994. The objective was to classify the soils based on series, slope, and depth to fragipan. A total of 119 soil samples were extracted, examined, and geo-referenced using a GPS receiver.

### *Soil Series of the Test Area*

Six different soils series formed the test field. A summary of the series, families, and characteristics are presented below.

- Collins (Co) - Coarse silty, mixed, acid thermic aquic udifluvents. This is a moderately well drained soil with slow runoff, and moderate permeability. This soil is subject to overflow.

- Grenada (Gr) - Fine silty, mixed, thermic glossic fragiudalfs. A moderately well drained soil, that has a runoff rate slow to medium, and moderate permeability. Grenada soils have a fragipan, where the water is usually perched during high rainfall periods. The fragipan occurs at a depth of 2.5 to 4 feet in uneroded profiles, but may be nearer the surface on severely eroded sites.

- Henry (He) - Coarse silty, mixed, thermic typic fragiaqualfs. This is a gray silty soil that has a fragipan. Henry soils are poorly drained and runoff is slow to very slow. Permeability is also very slow in the fragipan.

- Lexington (Lx) - Fine-silty, mixed, thermic typic paleudalfs. This soil is deep and well drained. It has moderate permeability in the upper part and moderate to rapid permeability in the lower part. Runoff is medium.

- Loring (Lo) - Fine silty, mixed, thermic typic fragiudalfs. This soil generally has a fragipan beginning at about 30 inches below the surface. As with Grenada soils, the fragipan may be near the surface in eroded soils. It is moderately well drained and has moderate permeability above the fragipan, with very slow permeability in the fragipan.

- Providence (Pr) - Fine silty, mixed, thermic typic fragiudalfs. This soil has a depth to the fragipan variable from 18 to 38 inches. The soil ranges from medium to very acid. Providence soils are moderately well drained, have slow to medium runoff, and moderate permeability above the fragipan with slow permeability in the fragipan.

The Loring, Grenada, Henry, Lexington, and Providence series belong to the same order of soils, the *Alfisols*. This order is characterized by being moist mineral soils, with gray to brown surface horizons. Some of the best agricultural soils in the US are in the *Alfisol* order (Brady, 1990).

The Collins series belong to the *Entisols* order, which is characterized by mineral soils without natural genetic horizons or with only the beginning of such horizons. All soil series belonging to the *Entisols* order lack significant profile development. The agricultural productivity of soils of such order is variable depending on their locations and properties (Brady, 1990). Figure 2 shows the makeup of soil series in the test area.

### *Soil Depth in the Test Area*

Soils were classified into five different groups based on depth to a fragipan. The fragipan is a dense and brittle pan or subsurface layer in soils. The material in place is so dense that roots and water move through it

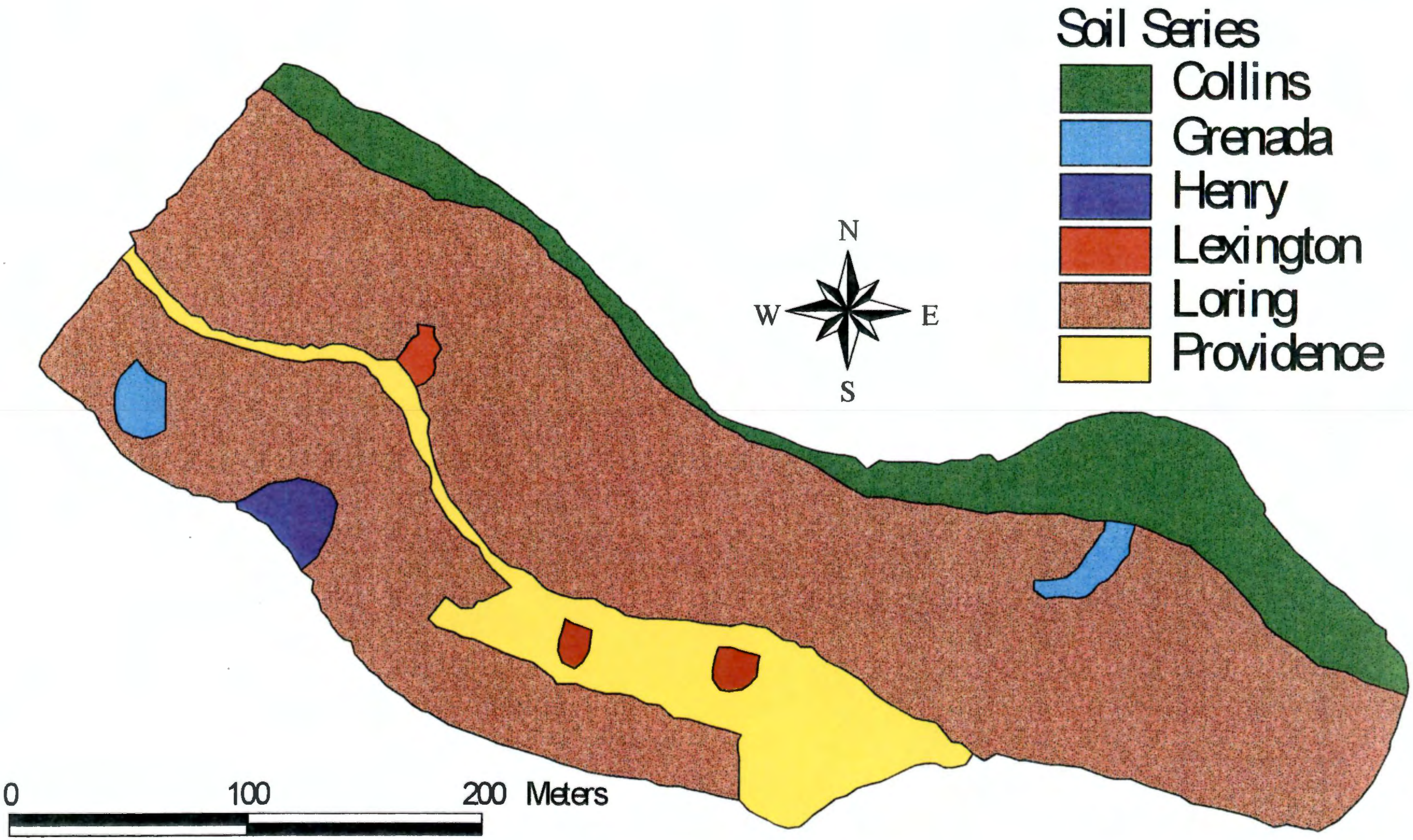


Figure 2. Soil series of the test field.

very slowly (Brady, 1990). The occurrence of fragipan is very common in the West Tennessee area. Depth to the fragipan was used as a criteria because it limits rooting depth and the yield potential; therefore limiting the potential response to nitrogen fertilization. Table 2 lists all depth groups and the associated code used to classify each unit. Figure 3 shows the depth to the fragipan areas of the test field.

Table 2. Soil classes based on depth to the fragipan with their associated codes.

| **Depth to the fragipan (inches)** | **Code** |
|---|---|
| No pan found < 36 | 0 |
| 30 - 36 | 1 |
| 20 - 30 | 2 |
| 12 - 20 | 3 |
| 0 - 12 | 4 |

### *Slopes of the Test Area*

A topographic survey detailed the slopes of the test area. Random points totaling 316 samples were collected using a PENTAX PTS-III 10 electronic total station. Points were collected and stored into an automatic data collector. slope was used as a criteria in grouping soils because of its effect on runoff and therefore on water supply. Figure 4 shows the slopes present in the test field.

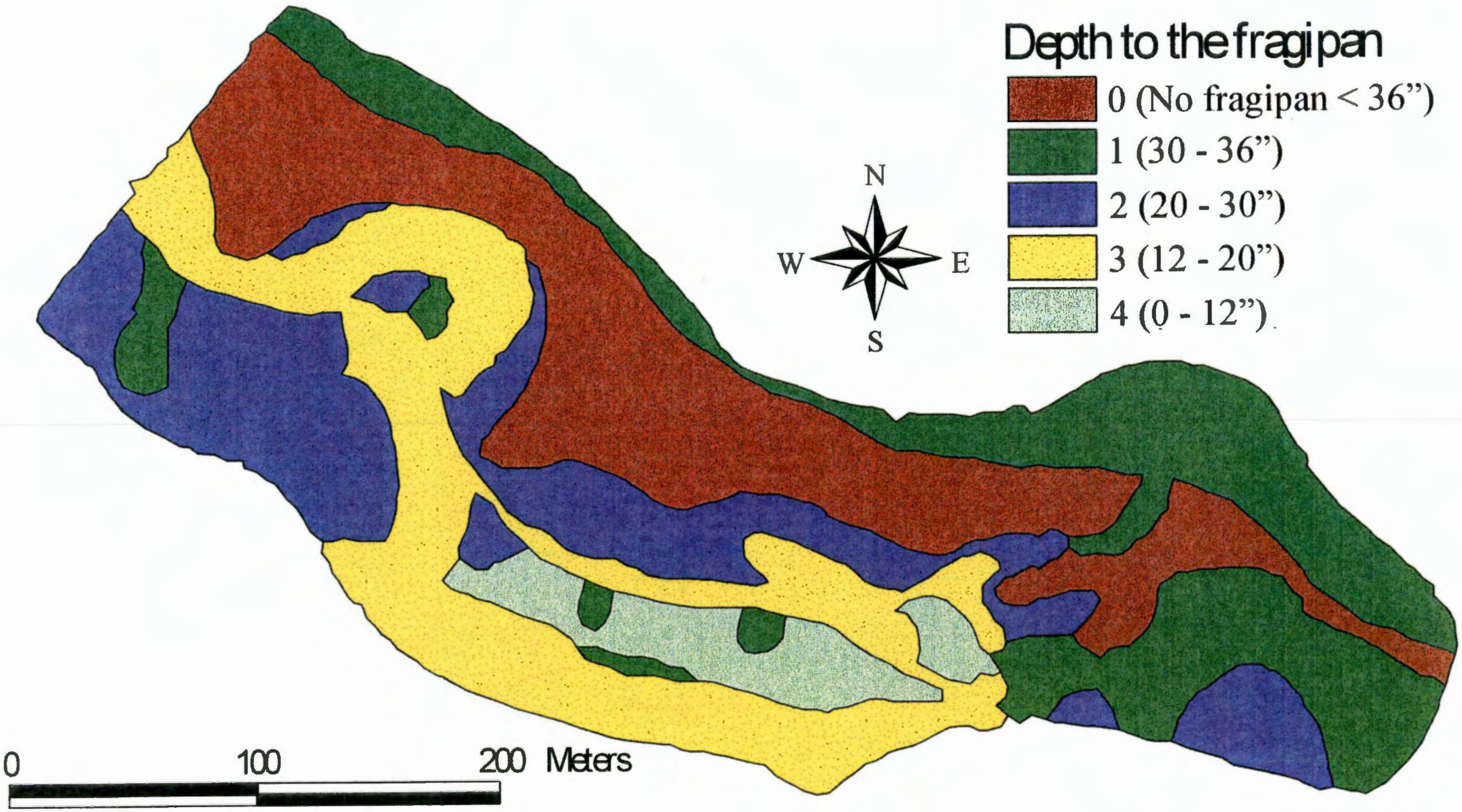


Figure 3. Depths to the fragipan of the test field.

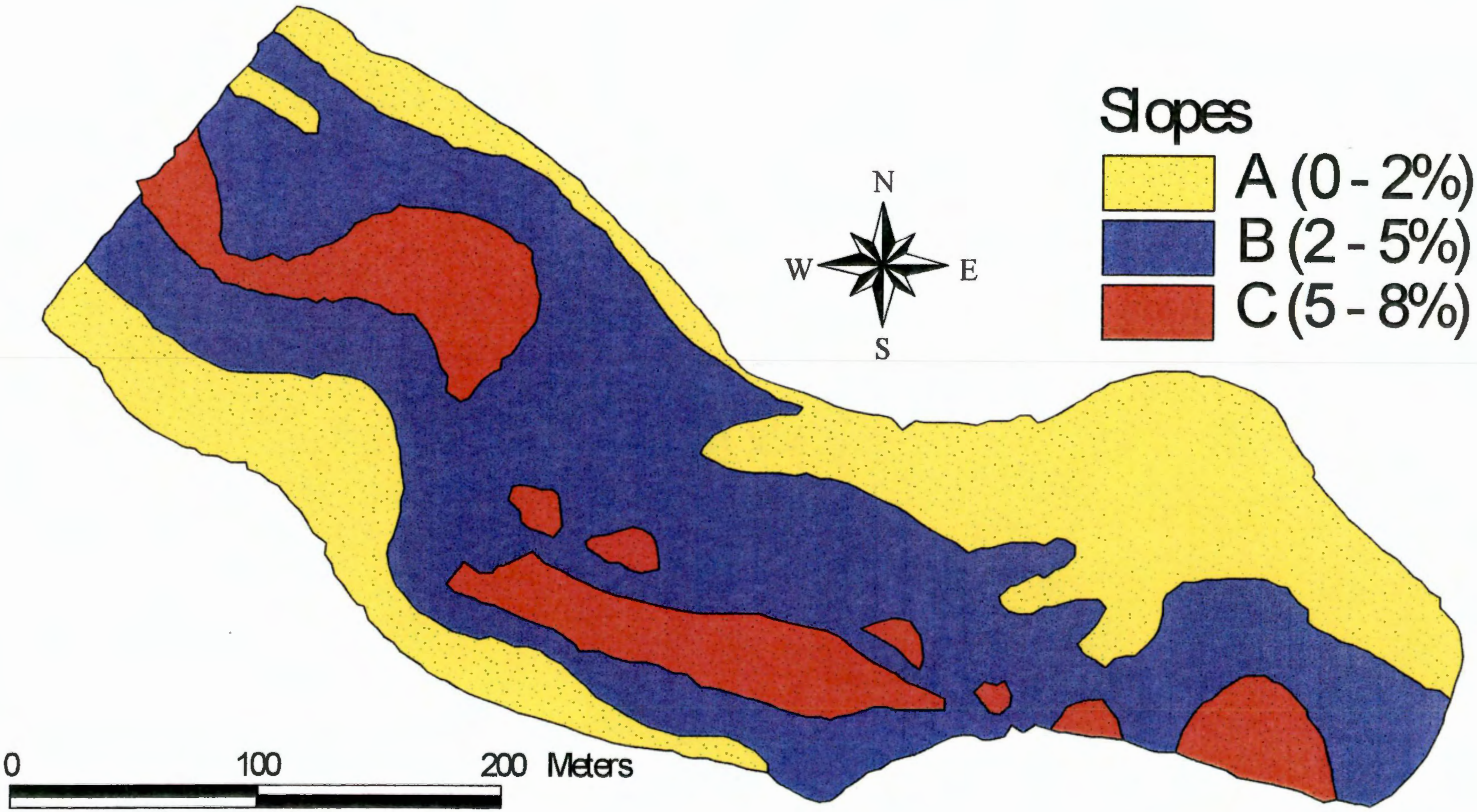


Figure 4. Slopes of the test field.

### *Soil Classification in the Test Area*

Soils within the test area were classified based on soil series, depth to a fragipan, and slope. Table 3 lists the soil descriptions and labels used. Figure 5 shows their distribution in the test area.

### *Grouping of Similar Soils by Yield Potential*

After the classification of the soils in the test area, similar soils were grouped with the objective of creating larger areas of common yield potential. Figure 6 shows the soil groups formed. Five groups were proposed according to the definitions in Table 4.

Table 3. Soil types identified in the test area.

| Soil Unit | Description |
|---|---|
| LoA0 | Loring series, 0-2% slope, fragipan at or greater than 36”. |
| LoA2 | Loring series, 0-2% slope, fragipan between 20 - 30”. |
| LoA3 | Loring series, 0-2% slope, fragipan between 12 - 20”. |
| LoB0 | Loring series, 2-5% slope, fragipan at or greater than 36”. |
| LoB | Loring series, 2-5% slope, fragipan between 30 - 36”. |
| LoB2 | Loring series, 2-5% slope, fragipan between 20 - 30”. |
| LoB3 | Loring series, 2-5% slope, fragipan between 12 - 20”. |
| LoB4 | Loring series, 2-5% slope, fragipan between 0 - 12”. |
| LxC | Lexington series, 5-8% slope. |
| LoC2 | Loring series, 5-8% slope, fragipan between 20 - 30”. |
| LoC3 | Loring series, 5-8% slope, fragipan between 12 - 20”. |
| GrA | Grenada series, 0-2% slope, fragipan between 30 - 36”. |
| HeA2 | Henry series, 0-2% slope, fragipan between 20 - 30”. |
| PrB3 | Providence series, 2-5% slope, fragipan between 12 - 20”. |
| PrC4 | Providence series, 5-8% slope, fragipan between 0 -12”. |
| CoA | Collins series, 0-2% slope. |

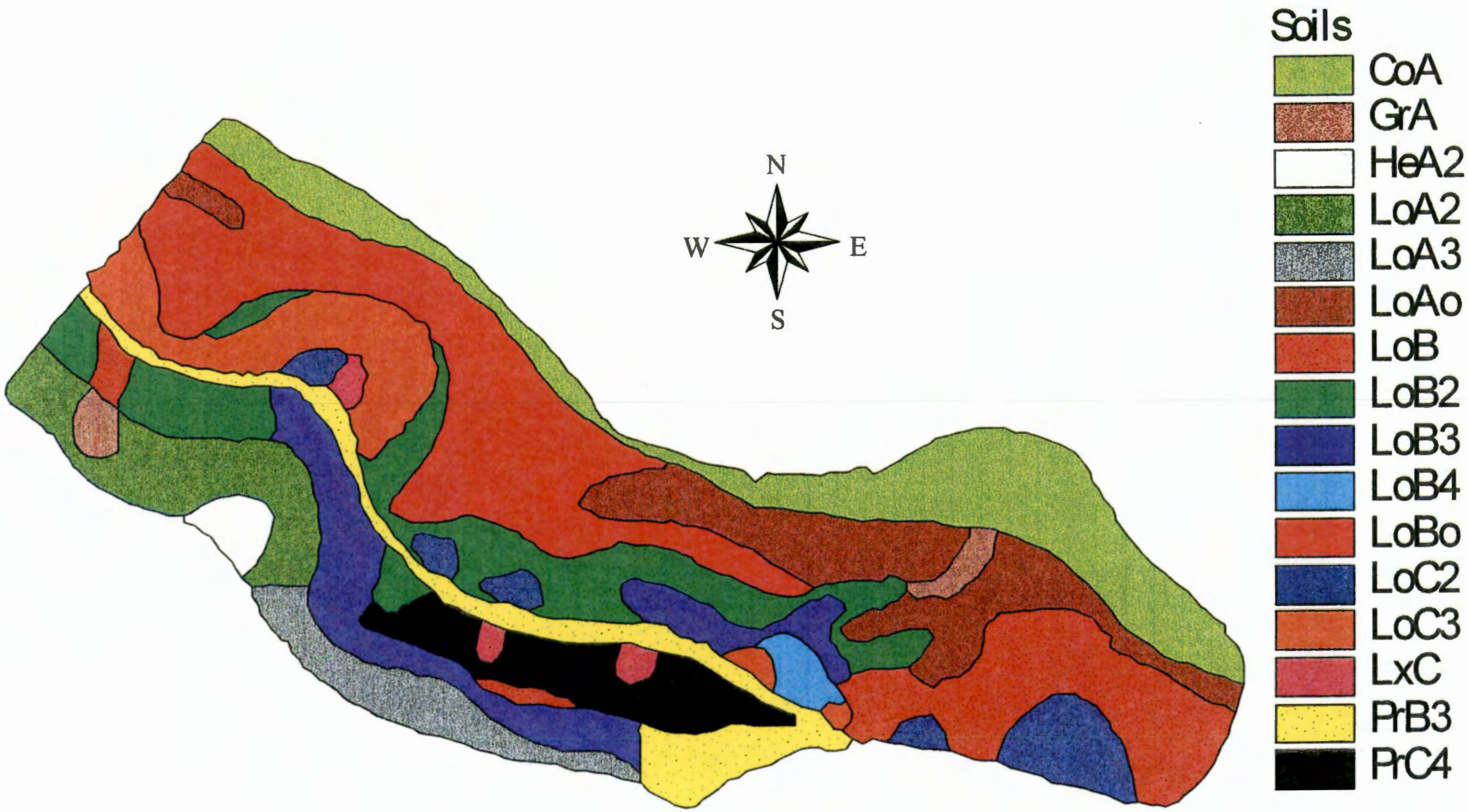


Figure 5. Soil types of the test field.

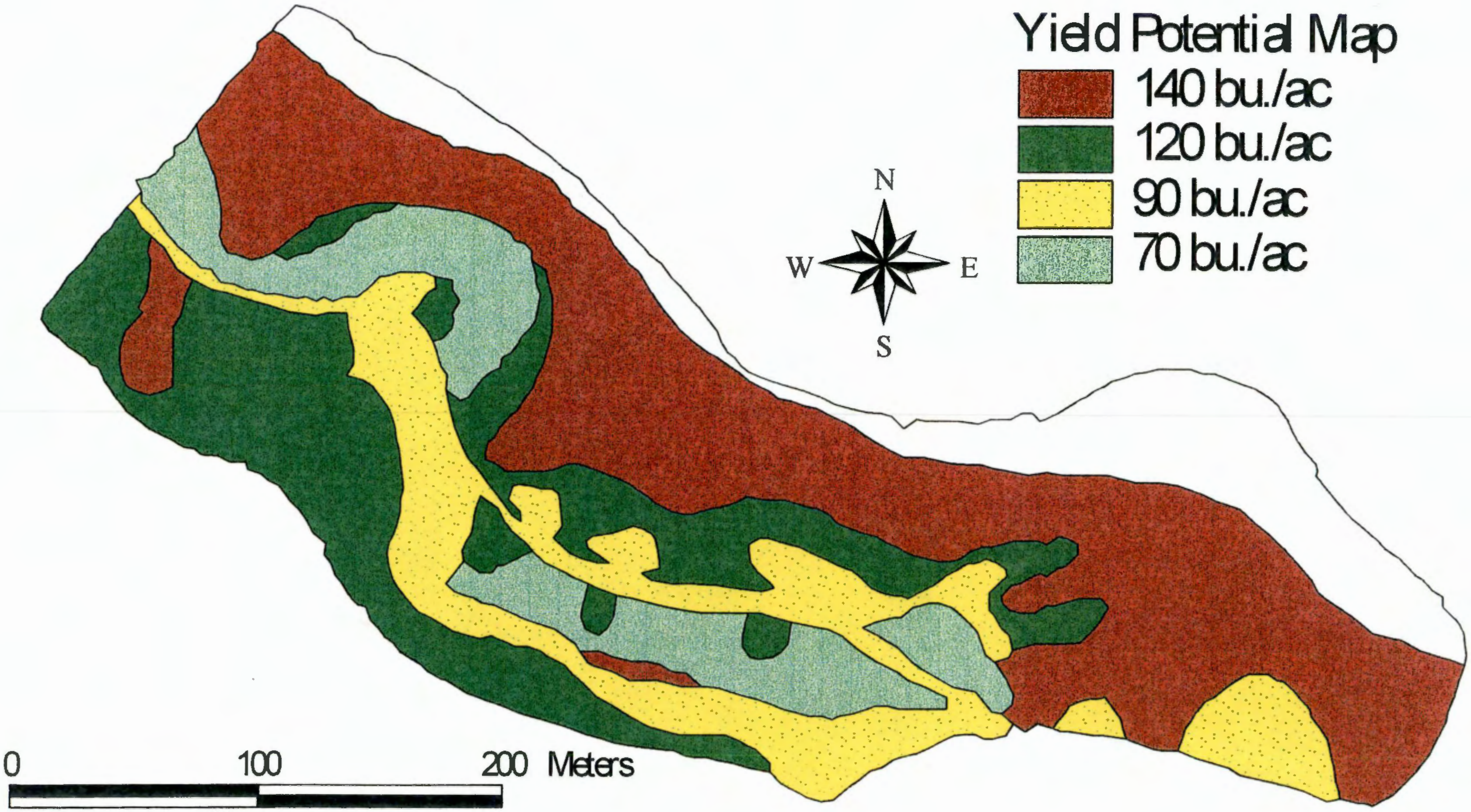


Figure 6. Yield potential map of the test field.

Table 4. Soil Groups created based on projected yield potential.

| GROUP | YIELD POTENTIAL | DEFINITION |
|---|---|---|
| HIGH | 140 | Moderately well-drained soils with at least 36 inches of depth to the fragipan and less than 5% slope. Units in this group: LoA0, GrA, LoB0, LoB. |
| GOOD | 120 | Soils with 2 to 5% slope and depth to the fragipan between 20 and 30 inches. Soils with 0 to 2% slope and depth to the fragipan of 12 to 20 inches. Deep soils (no fragipan) on 5 to 8% slope. Units in this group: LoA2, HeA2, LoA3, LoB2, LxC. |
| FAIR | 90 | Soils with a combination of slope between 2 to 5% and 12 to 20 inches of depth to the fragipan. Soils on 5 to 8% slope and depth to a fragipan between 20 and 30 inches. units in this group: LoB3, PrB3, LoC2. |
| POOR | 70 | Soils with a depth to the fragipan less than 12 inches. Soils with depth to the fragipan between 12 to 20 inches and slope between 5 to 8%. Units in this group: LoB4, LoC3, PrC4. |
| WET | * | Soils poorly drained in the test area. Unit in this group: CoA. |

* This part of the field was used to calibrate the yield monitor and not used to compute yields.

# FERTILIZER APPLICATION

A mixture of urea and ammonia nitrate, containing 32% nitrogen, was used as the nitrogen fertilizer source (N) in the application. Based on an estimate that takes 1.2 to 1.3 pounds (0.54 to 0.58 kg) of nitrogen to produce one bushel of grain corn and on the yield goal for each class of soils, five different rates were chosen: 0 lb N/ac (0 kg N/ha), 90 lbs N/ac (100 kg N/ha), 120 lbs N/ac (177 kg N/ha), 150 lbs N/ac (168 kg N/ha), and 180 lbs N/ac (201 kg N/ha). After calibrating the applicator based on a speed of 5.8 mph (9.3 km/hr), row spacing of 30 inches (0.76 m), and pressure of 40 PSI (275.8 KPa), the actual rates applied were: 0 lbs N/ac (0 kg N/ha), 84 lbs N/ac (94 kg N/ha), 127 lbs N/ac (142 kg N/ha), 143 lbs N/ac (160 kg N/ha), and 181 lbs N/ac (203 kg N/ha).

## *Distribution of Fertilizer Rates in the Test Area*

To expose all groups of soils to every N rate, the fertilizer was applied according to the following pattern: the field was divided into 22 strips parallel from North to South. Each strip had a width of 0°00'01" latitude (approximately 30 meters). The applicator, equipped with a laptop, a single-board computer, and a GPS system, changed the rates every time it crossed the lines separating each sub-area. Figure 7 shows the different rates applied throughout the field.

### *Liquid Applicator Design*

A fertilizer applicator was adapted, capable of delivering five discrete rates through the combination of three different orifices. The applicator consisted of a centrifugal pump manufactured by Hydro Corporation, with a maximum pressure output of 100 PSI (689.5 KPa) and maximum flow of 90 GPM (340 l/min); a 200-gallon (757 l) tank manufactured by Raven; three pressure compensating solenoid valves manufactured by Spraying Systems, that controlled each of the three orifices; line strainers; pressure regulators; and five 20-inch (0.5 m) bubble coulters. The orifices were mounted in each row directly behind the coulter. The applicator was equipped with 5 coulter units. Figure 8 is a diagram of the applicator.

To use a five-row fertilizer applicator on four rows, it was necessary that the two outside orifices deliver half the rate delivered by the inside ones. The rates are completed when the applicator turns and positions its first coulter on the last row applied. Spraying Systems Teejet orifice numbers 32, 46, and 67 were used on the outside rows, and orifices 46, 67, and 93 were used on the three inside rows.

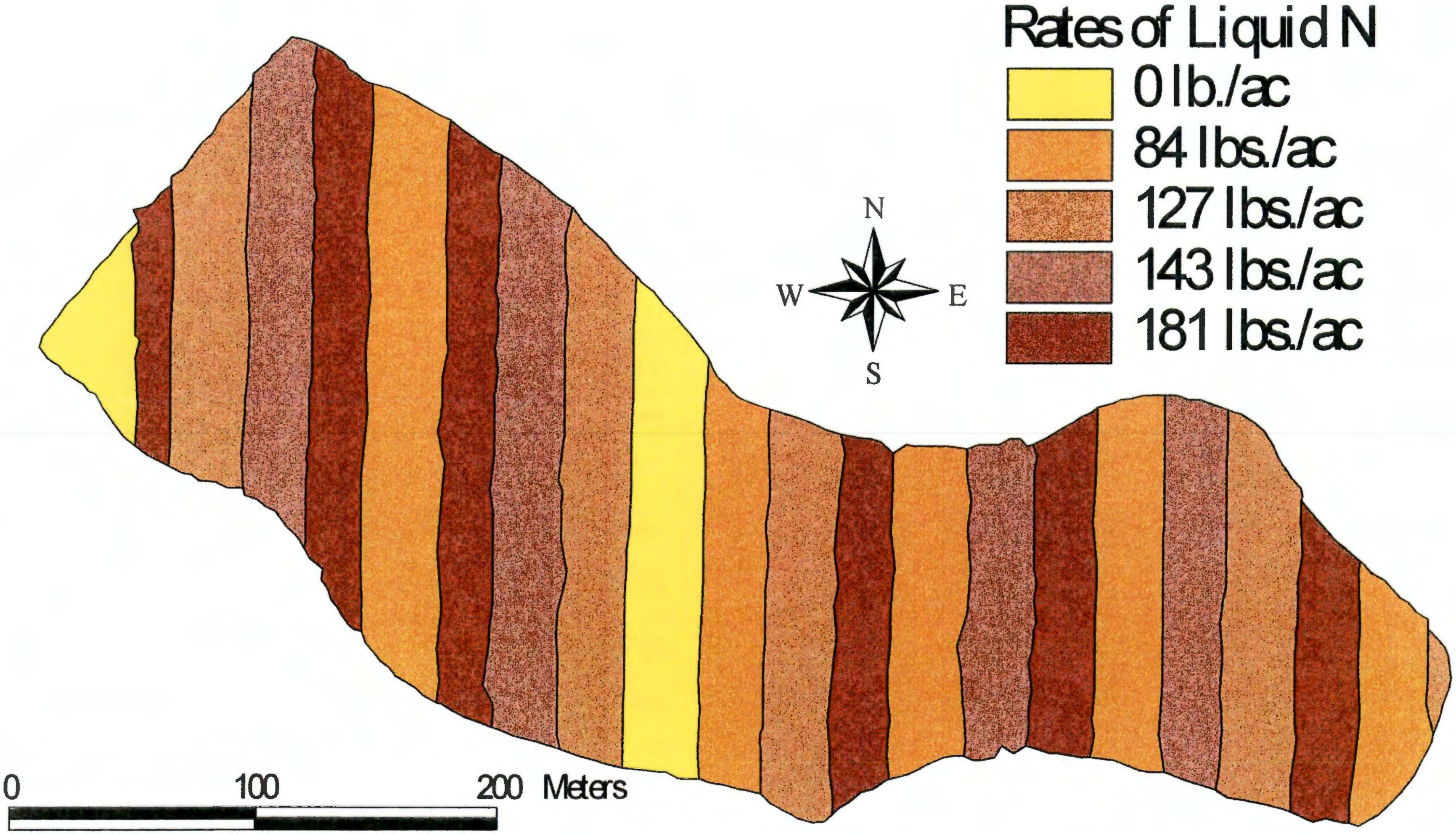


Figure 7. Layout of rates applied in the test field.

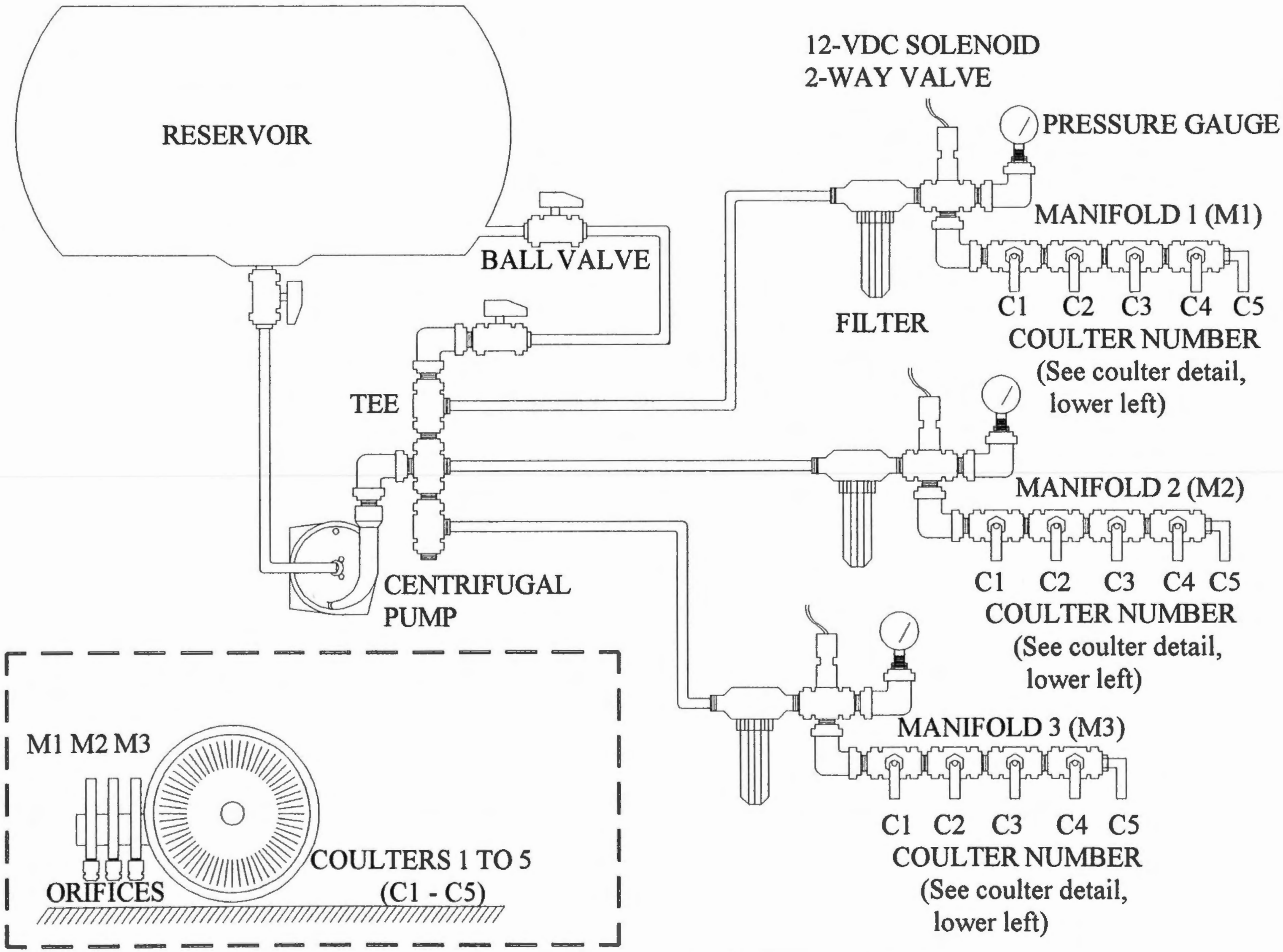

Figure 8. Diagram of the liquid nitrogen applicator.

The desired rates were achieved through orifice combinations. In the outside rows, the combination of orifices 32 and 46, with an operating pressure of 40 PSI (275.8 KPa), produced a rate of 42 lbs N/ac (47 kg N/ha). Orifice 67 delivered 65 lbs N/ac (73 kg N/ha), and orifices numbers 32 and 67 together produced a rate of 77 lbs N/ac (86 kg N/ha). Finally, combining 46 and 67 produced 92 lbs N/ac (103 kg N/ha).

For the three inside rows, combining orifices 46 and 67 produced 84 lbs N/ac (94 kg N/ha); orifice 93 produced 127 lbs N/ac (142 kg/ha). The combination of orifices 46 and 93 produced 143 lbs N/ac (160 kg N/ha), and orifices 67 and 93 produced 181 lbs N/ac (203 kg N/ha).

*Electronic Control of the Applicator*

The applicator was controlled by a laptop computer interfaced with a single-board computer (SBC). Figure 9 illustrates the flow of information from the GPS receiver to the laptop, the SBC, and the fertilizer applicator. The laptop computer and the GPS receiver were located inside the tractor's cab. The laptop received information about the geographic position of the sprayer, looked up the desired application rate at that location, and sent the rate information to the SBC. The SBC calculated what orifice combination produced the desired rate and sent an electrical signal to the solenoid valves to open or close the required orifices. The laptop computer recorded each field position during the application, along with the rate applied. The files were later used to create maps of application in the area using GIS.

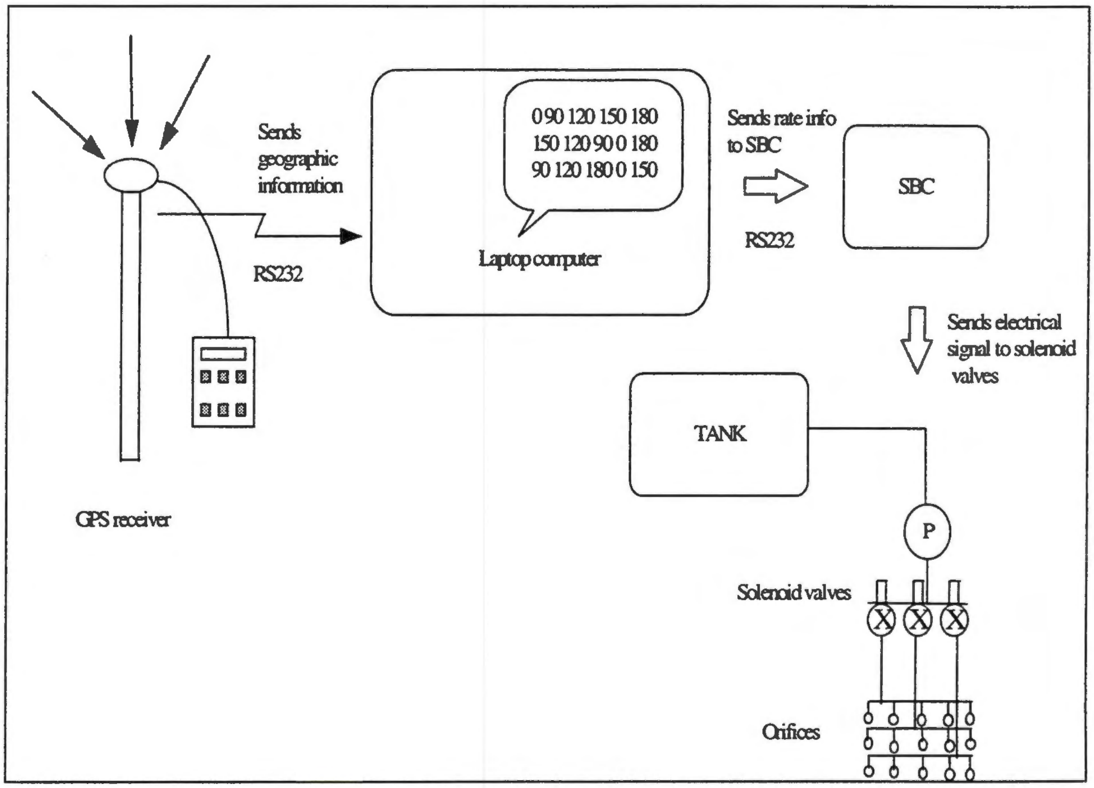


Figure 9. Information flow for the liquid nitrogen application.

Figure 10 is a photograph of the variable-rate applicator during the liquid nitrogen application.

Figure 10. Photograph of the liquid nitrogen applicator.

# SAMPLES EXTRACTED IN THE TEST AREA

## *Leaf Nitrogen and Population Sampling*

Corn ear-leaf samples were taken on June 29, 1995 from 75 different locations throughout the field. Samples were analyzed for total microkjeldhl nitrogen (TKN). Random plant population counts were also performed on June 29, 1995. A 30-foot chain was extended along the corn rows and the population computed by counting the plants in two adjacent rows. The average number of plants from both rows was used to calculate the number of plants per acre at that field. The sample locations were recorded using the GPS Pro-Basic+ receiver.

## *Soil Sampling*

After the corn was harvested, soil samples were collected and analyzed for pH, phosphorus (P), and potassium (K) content. A total of 83 samples were taken and their locations recorded using the Pro-Basic+ GPS receiver. Figure 11 shows the location of the soil samples and of the leaf nitrogen and population samples taken in the test field.

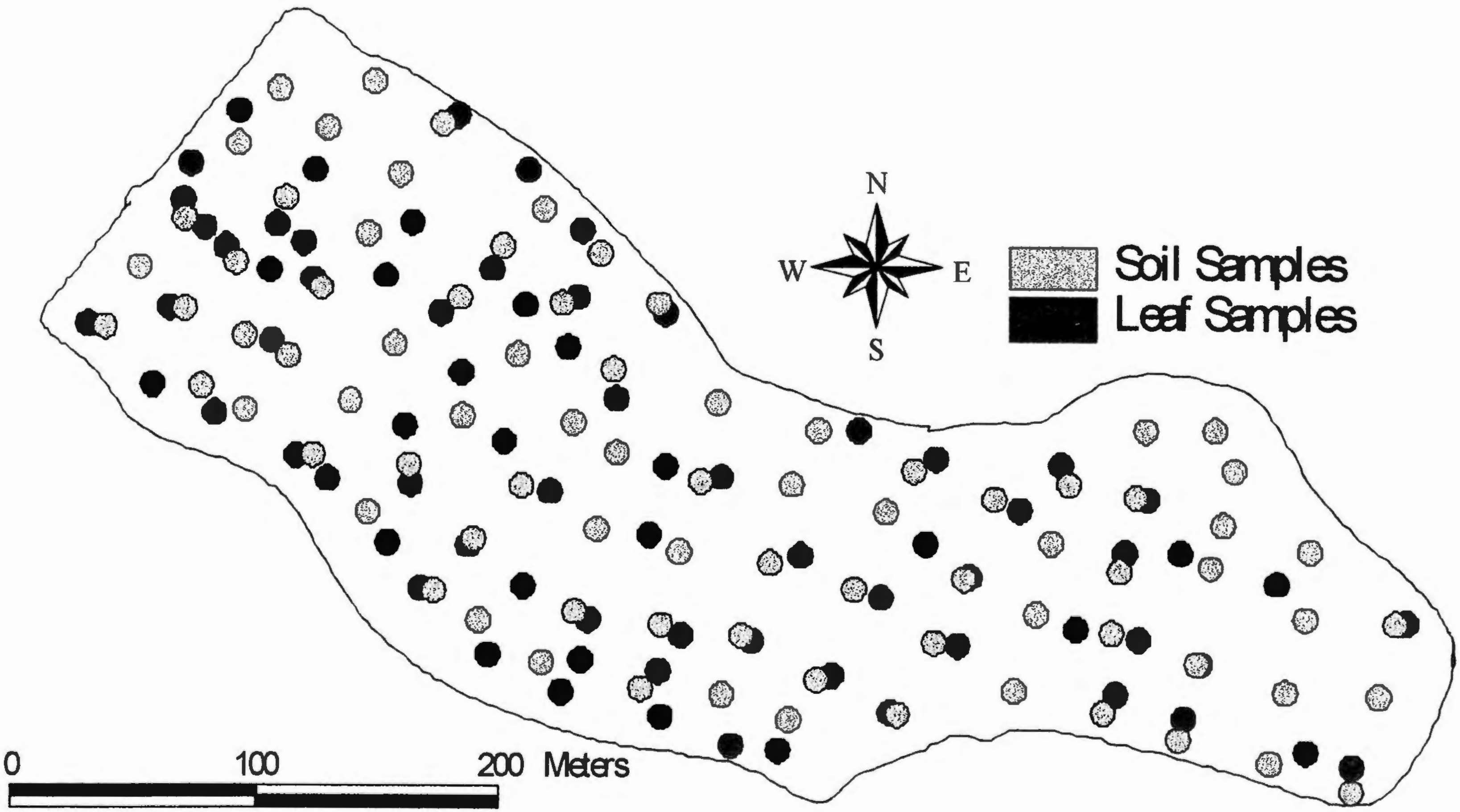


Figure 11. Location of soil and leaf nitrogen samples in the test field.

# YIELD DATA COLLECTION

The corn was harvested on September 12, 1995. A John Deere combine model 4425 with a four-row corn header was used in the harvest. A yield monitor and GPS receiver were used to record the corn yield and its geographic position. Data from the GPS receiver and yield monitor were recorded every second by the laptop PC.

The yield monitor used was the AgLeader 2000, manufactured by AgLeader Technology Inc. of Ames, IA. The yield sensing device determined the mass flow rate of grain through the combine by measuring the force resulting from grain impacting a load sensor just past the top of the clean-grain elevator. This force measurement, in conjunction with elevator speed was used to quantify grain flow. In addition, grain moisture was electrically measured during the harvest with an on-board moisture sensor.

A program written in C-language captured the incoming data from both devices and stored it into two separate files. For each pass of the combine in the field, a file with the *.pos* extension stored the geographic data, while another file with the *.yld* extension stored yield data. Both files were recorded in ASCII format. The program used is listed in Appendix B.

### *GPS Data Format*

The GPS receiver was programmed to output positional data which conforms to the NMEA-0183 format. This format is a standard established by the National Marine Electronics Association. An example data string:

"$GPGLL,3556.561084,N,08842.798226,W,161347,A*33"

where;

- $GPGLL - is the message ID consisting of $GP plus the message type, which in this case was the GLL (position fix, time of position fix, and status),
- 3556.561084 - latitudinal data, expressed in degrees, minutes and decimals of minutes,
- N - direction of latitude (N or S),
- 08842.798226 - longitudinal data,
- W - direction of longitude (E or W),
- 161347 - Universal Time Coordinate (UTC), hhmmss,

- A*33 - status of the data. The letter A indicates that the data is valid.

### *Yield Monitor Data Format*

Data coming from the yield monitor detailed the harvest operation, as well as some features of the combine during the operation. The format of data recorded from the yield monitor is illustrated by:

"12:22:07 01+4.940 02+3.352 03+1 04+500.0 05+120 06+12.644 07+173.7 08+17.9."

where;

- 12:22:07 - time of the day (ET), based on the laptop's clock,
- 01+4.940 - instantaneous velocity of the combine measured by the radar velocity sensor (ft/s),
- 02+3.352 - computed combine speed (mph),
- 03+1 - header position (0 - up or 1 -down, harvesting),
- 04+500.00 - combine's elevator velocity (rpm),

- 05+120 - effective harvest width (in),
- 06+12.644 - mass flow rate (lbs/s),
- 07+173.7 - grain yield (Bu/ac),
- 08+17.9 - moisture content (%) of the incoming grains.

## GIS DATABASE

### *GIS Software Selected*

The GIS software used for this project were PC ARC/INFO and ArcView. Both software are manufactured by the Environmental Research Institute (ESRI) from Redlands, CA.

PC ARC/INFO and ArcView are vector-based GIS products; PC ARC/INFO is DOS-based software with topological concepts like: from, to, left, and right. ARCVIEW is Windows-based software that uses the whole polygon model. The reason to use both packages is that PC ARC/INFO is generally used to generate coverages, digitize maps, and perform geographic analysis, while ArcView is used to display the data and create thematic maps.

### *Formatting The Data*

A map consists of two types of information: spatial and descriptive. The spatial information is the relation between the data and the original location. The descriptive information links the features of the data to the positions on earth (ESRI, 1995). PC ARC/INFO uses a hybrid data model, which means that this system stores geographic and descriptive data in two different files. Both files should contain a common ID to relate position to its attribute. The positional data is stored in the format longitude/latitude in degrees and decimals of degrees, for example. The descriptive data is stored describing the position. In both files, all data should be separated by commas, and the word "end" should indicate the end of the data. Table 5 exemplifies the formatting of the data to generate coverages using PC ARC/INFO.

The format used to generate the coverages is valid for the creation of a point coverage. Line coverages such as roads or rivers, or polygon coverages such as lakes or enclosed areas, have their own format.

#### Nitrogen Application Data Format

Data from the nitrogen fertilizer application was stored in the laptop computer. It contained the geographic position of the applicator and the rate applied in the location. The GPS data was stored in the NMEA-0183 format. The rate applied was indicated by the numbers:

Table 5. Example of data format used by PC ARC/INFO.

| Spatial | Descriptive |
|---|---|
| id, longitude, latitude | id, speed, indicator, yield |
| 1, 88.70723958, 35.94116743 | 1, 3.78, 1, 150.7 |
| 2, 88.70724055, 35.94116799 | 2, 3.78, 1, 149.8 |
| 3, 88.70724121, 35.94116824 | 3, 3.81, 1, 150.3 |
| end,, | end,, |

0 - 0 lb N/ac,

1 - 84 lb N/ac,

2 - 127 lb N/ac,

3 - 143 lb N/ac, and

4 - 181 lb N/ac.

A BASIC program was used to read the original data files stored on the laptop and create a new file with the necessary format illustrated in table 5. The program code is listed in Appendix B.

*Yield Data Format*

Spatial data from the corn harvest was stored in a file with a *.pos* extension, while descriptive data was stored in a *.yld* extension file. Both files are in ASCII format. Since the files started being recorded at the same time, the time stamp was used to pair each position with its descriptive data.

Another BASIC program extracted the necessary information from the files. The program code is listed in Appendix B. Since the yield monitor recorded extra information during harvest such as elevator's velocity and width of the combine's header, the computer program filtered the data and extracted only the necessary information to compute yield (speed, mass flow rate, header position, yield, and moisture).

Two adjustments had to be made on the yield data. The first one was in respect to the time lag between the time corn entered the picker and the time the grain was measured. Since the sensor responsible for the yield measurement is located in the combine's grain bin, it took approximately 15 seconds between harvesting and recording it. This delay could induce the wrong pairing of descriptive and positional data. The solution was to input each pair of files into a spreadsheet and shift the yield data up, in respect to the positional data, 15 seconds (time could be slightly different for each file). Since the indicator of header position (0 or 1) was also recorded, it was easy to see in the files the beginning of harvest (when the indicator changed to 1), and the yield measurements coming up several seconds later.

The second adjustment made was the yield calculation performed by the yield monitor. Since the monitor based its calculation on more than one second of data, the integration of points tend to smooth the data, hiding lower or higher yield spots. The solution was the calculation of an instantaneous yield, based on the data from the mass flow sensor, according to the formula:

$$Yield = \frac{m}{sw}c \quad \text{where;}$$

Yield = corn yield (Bu/ac),

m = mass flow rate of grains (lbs/sec),

s = speed of the combine (mph),

w = effective harvest width (inches),

c = 356,400 (assumptions: 4-row corn header, 30-inch-row corn, 1 bushel of corn weighs 56 pounds, 15.5% dry-basis moisture).

A three-second running velocity average was used to dampen the dynamic effects of velocity on yield determination. This was very important in situations where the combine decreased the velocity abruptly, in a ditch for example.

*Leaf and Soil Samples Data Format*

The coordinates for both soil and leaf samples were stored in the Pro-Basic+ GPS receiver. PFINDER, a software provided by Trimble Navigation, was used to extract the coordinates of each sample and write them to an ASCII file. Each sample received a unique ID, and the coordinates of each sample were transformed into degrees and decimals of degrees. Another file relating all descriptive data for each sample was created. Laboratory results were linked to the ID for each field location.

## *Coverage Creation*

Five coverages were created using PC ARC/INFO. Four of the coverages are point coverages representing the corn yield, the nitrogen application areas, the soil samples locations, and the leaf samples locations. The fifth coverage is a polygon coverage representing the different soil units of the test area.

### *Point Coverage*

The yield map generated based on the yield monitor and GPS coordinates is an example of a point coverage. The command GENERATE was used in PC ARC/INFO to create the point coverage from a file containing coordinate positions. After creating the coverage, the command BUILD was used to create the topology necessary to store the descriptive data of the positions. It is necessary to create topology in order to create spatial relationships between features in a coverage. Figure 12 shows the corn yield coverage created using data extracted from the yield monitor.

### *Transforming the Nitrogen Point Coverage into a Polygon Coverage*

The nitrogen application coverage was generated as a point coverage. Since points with the same application rate defined an enclosed area, the coverage was transformed to a polygon coverage by simply drawing lines to indicate the areas with different rates of nitrogen fertilizer. The process of

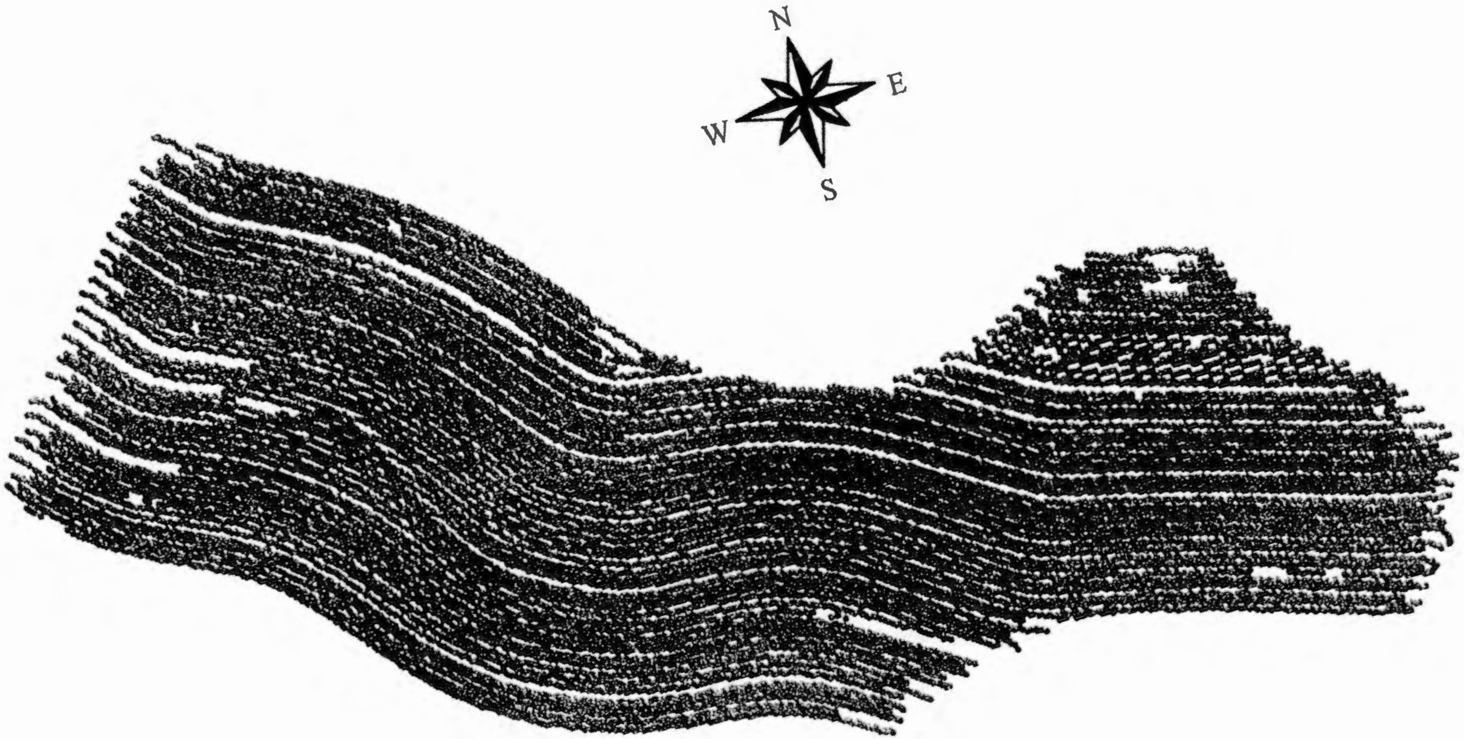


Figure 12. Point coverage of the 1995 corn yield.

drawing the lines was accomplished using ARCEDIT, a module of PC ARC/INFO.

*Digitizing the Soil Map*

The soil survey outlined the several soil units present in the test area. A digitizer was used to input this data into PC ARC/INFO. Digitizing converts spatial features on a map into a digital format. Point, line and area features that compose a map are converted into x,y coordinates.

A CALCOMP digitizer model 9100 was used to input the necessary soil data into digital format. Prior to the digitizing process, a minimum of four control points are required on the map. Four control points were used to relate the measurements on the map (usually in inches) performed by the digitizer, to real-world coordinates.

Digitizing involves manually tracing all features on the map with the keypad. The digitizer has an electronic wire grid capable of recording the position of the keypad while it traces the map's features, with an accuracy of 0.001 inch.

*Transformation of a Geographic Reference System to a Coordinate System*

To measure distances, all coverages should have their coordinate points expressed in some measurement system, meters for example. Latitude and longitude are angles measured from the center of the earth, and they are not used to express distances on a map. For this reason, all coverage coordinates were transformed from degrees latitude/longitude to units of length (meters North and South) using the Universal Transverse Mercator (UTM).

### *Geographic Relations of the Data*

PC ARC/INFO performs geographic analysis on the data, which is the main objective of any GIS software. Among the abilities found in PC ARC/INFO, the overlay of point-in-polygon, line-in-polygon, and polygon-in-polygon creates a new coverage with descriptive data from both coverages used. An example of this is the overlay of a point coverage representing corn yield harvested, into a polygon coverage representing the soil types found in the area. This overlay permits the relation of yield with soil type, otherwise unavailable because these data belong to different databases. This overlay process is solely based on geographic positions.

Further abilities, like buffer creation, can relate specific parts of a coverage to another one. Soil sample points can be used to create buffer regions and relate it with grain yield or soil type. A description of each PC ARC/INFO command used in the project to perform geographic relations is listed below.

*Spatial Join*

The INTERSECT command computes the geometric intersection of two coverages. Only feature attributes of the input coverage common to the intersect coverage are joined in the output coverage. In this project, the corn point coverage was intersected with the soils coverage to create an output coverage containing features of both coverages.

*Buffer Generation*

The BUFFER command creates buffer polygons around selected coverage features (points, lines, or polygons). This command was used to generate 5 meter radius buffers around the soils and leaf nitrogen samples.

*Feature Extraction*

The CLIP command extracts features from a coverage that overlaps another coverage using the first one as a "cookie cutter." In this project, for example, the buffer coverage created with the samples was overlapped with the corn yield coverage. The resulted coverage contained data from both input coverages, permitting to average the corn yield in each sample location for posterior statistical analysis.

The RESELECT command extracts map features of a coverage based on attribute values. Using the output coverage from the yield and soil intersect, the selection of all points that had the LoB0 soil type created a smaller coverage with only points with this common feature.

In ARCVIEW spatial join has a limited availability. The user can quickly join two coverages using their geographic locations as the common point, but it is impossible to perform operations like the ones described above.

Another useful characteristic of both GIS packages is the capability to relate new information based on a common item. Any type of information can be brought into the project if it has at least one common column of information to the data stored.

# CHAPTER 4

# RESULTS

## YIELD VARIABILITY

The overall yield result of the no-till corn field is shown in Figure 13. The average corn yield of the field was 161.2 bushels per acre.

### *Yield Results by Nitrogen Rate*

Figure 14 illustrates the yield results according to the nitrogen rate applied. Each rate occupied the following areas, in acres: 0 lb N/ac - 1.78, 84 lbs N/ac - 4.70, 127 lbs N/ac - 4.32, 143 lbs N/ac - 4.06, and 181 lbs N/ac - 4.54. Rates 181 and 143 were found not to be statistically different ($P>0.05$), while rates 0, 84, and 127 differ from each other ($P<0.05$). Nitrogen rates were found to be the most significant factor affecting yield, when compared to physical and chemical components of the soil.

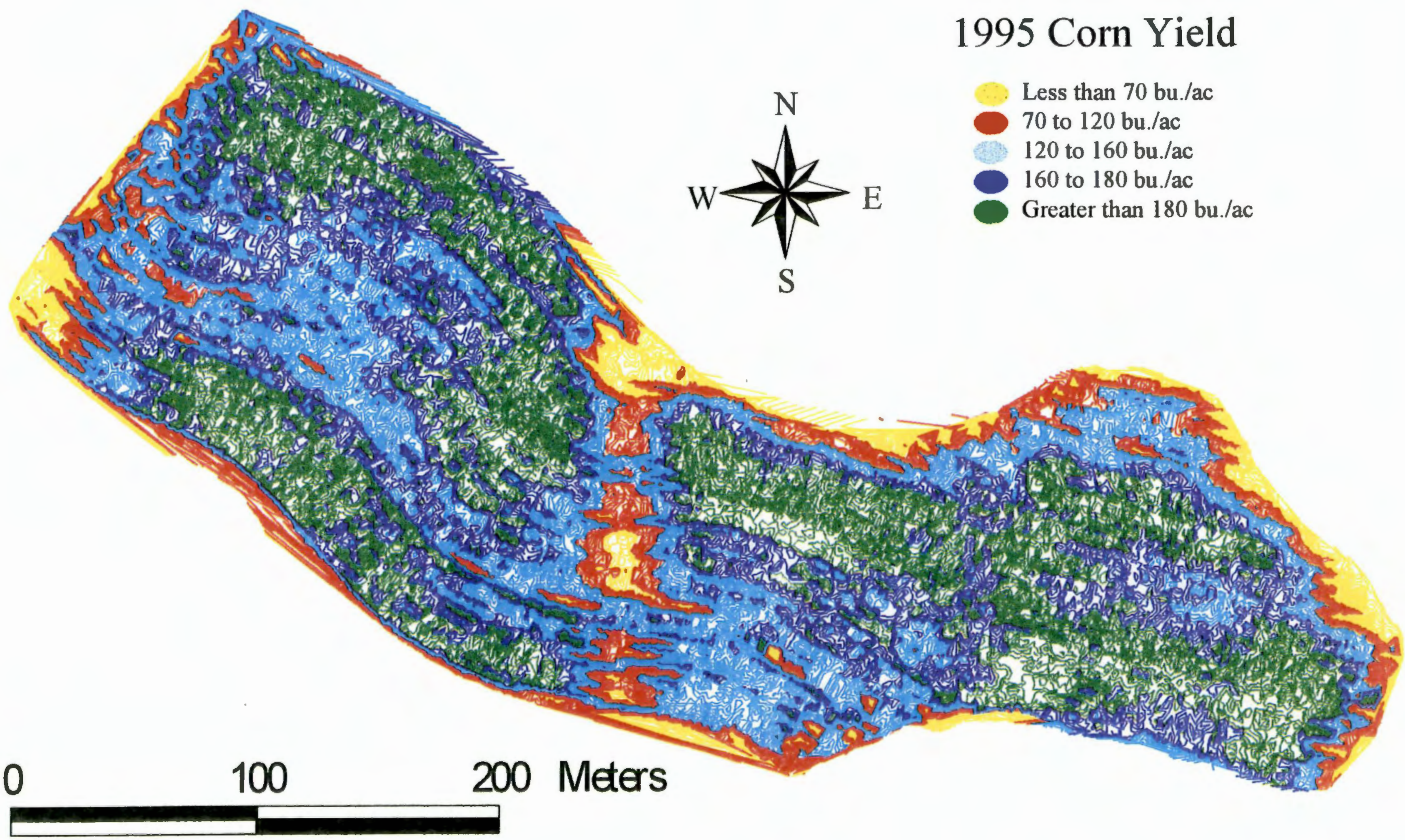


Figure 13. Yield map of the 1995 corn harvest based on equal contour lines.

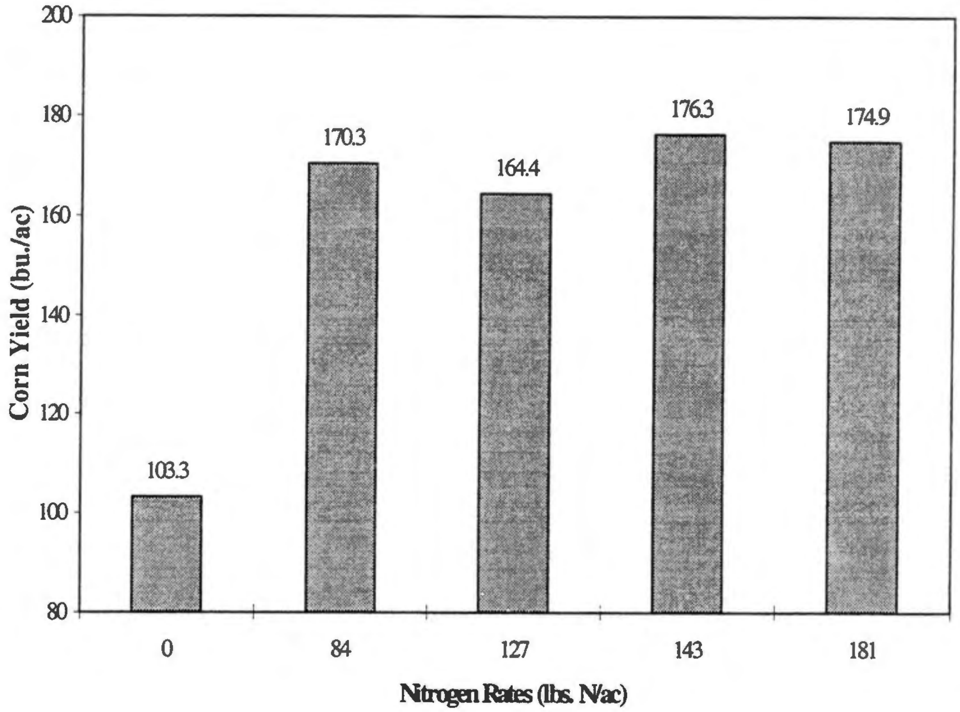


Figure 14. Yield results of the 1995 corn harvest within each N rate.

Interactions between rates and series, rates and slope, rates and depth to the fragipan, series and slope, series and depth, and slope and depth were found to be significant ($P<0.05$). These interactions may have contributed to higher yields in the 84 lbs N/ac rate than yields of the 127 lbs N/ac rate.

### *Yield Results by Group*

Figure 15 shows the arithmetic means of yield for each group of soils present in the field according to the nitrogen rate applied. Results of the group labeled *Wet* are not included because this area was used for the calibration of the yield monitor. Groups *High*, *Good*, *Fair*, and *Poor* were found to be statistically different (P<0.05). Table 6 shows the arithmetic means of yield and the area of each soil group within each nitrogen rate.

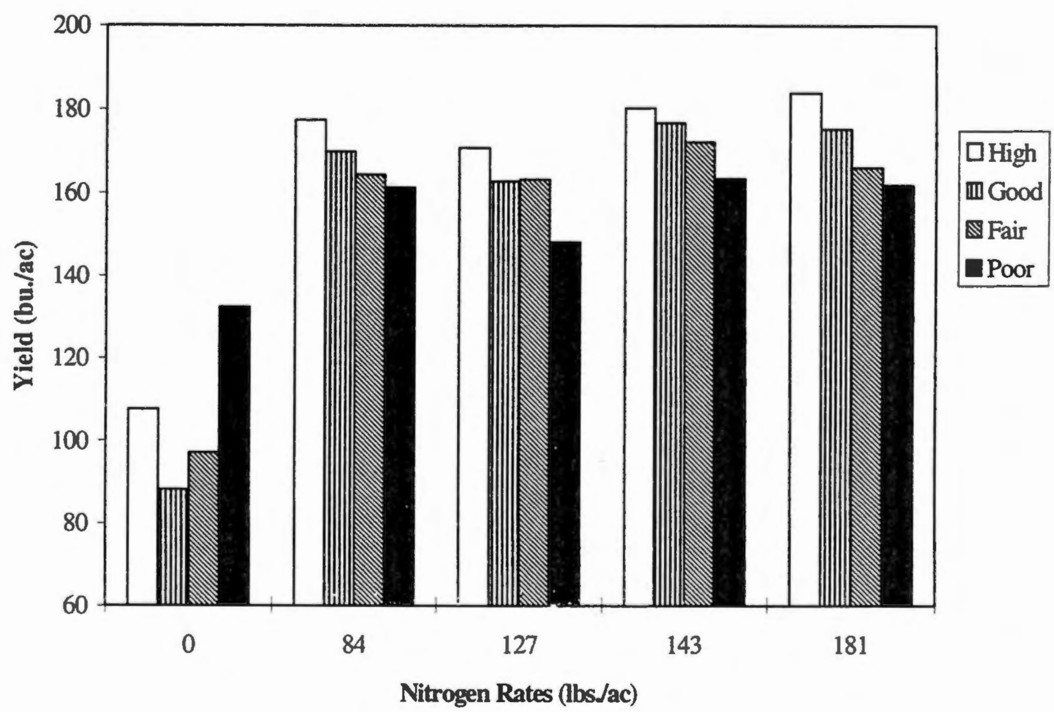


Figure 15. Yield results by soil group within nitrogen rates.

Table 6. Yield results by group of soils within nitrogen rates.

| | Rates (lbs N/ac) | 0 | 84 | 127 | 143 | 181 |
|---|---|---|---|---|---|---|
| HIGH | Yield (bu/ac) | 107.6 | 177.3 | 170.7 | 180.3 | 183.8 |
| | Area(ac) | 0.6 | 1.9 | 1.7 | 1.9 | 1.7 |
| GOOD | Yield (bu/ac) | 88.2 | 169.7 | 162.7 | 176.8 | 175.1 |
| | Area(ac) | 0.6 | 0.8 | 0.9 | 1.1 | 1.2 |
| FAIR | Yield (bu/ac) | 97.1 | 164.3 | 163.2 | 172.1 | 166.0 |
| | Area(ac) | 0.2 | 1.2 | 0.9 | 0.5 | 0.8 |
| POOR | Yield (bu/ac) | 132.4 | 161.1 | 148.1 | 163.4 | 161.8 |
| | Area(ac) | 0.2 | 0.6 | 0.5 | 0.4 | 0.8 |

### *Yield Results by Soil Series*

Yield results of the different soil series of the field are presented in Table 7, according to the nitrogen rate applied. The Henry and Loring series were found not to be statistically different ($P>0.05$). The Lexington and Providence series were also not statistically different from each other ($P>0.05$). Grenada was found statistically different from every other soil series in the area $P<0.05$).

Table 7. Yield results and standard deviation of soil series for the test field within nitrogen rates.

| SERIES | RATES | 0 | 84 | 127 | 143 | 181 |
|---|---|---|---|---|---|---|
| COLLINS | Yield (bu./ac) | 82.9 | 122.5 | 117.8 | 137.8 | 140.9 |
| | σ | 52.6 | 56.1 | 52.5 | 40.6 | 47.3 |
| GRENADA | Yield (bu./ac) | 118.8 | 187.8 | -* | -* | 160.0 |
| | σ | 42.5 | 11.0 | - | - | 31.5 |
| HENRY | Yield (bu./ac) | -* | -* | -* | 162.6 | 178.9 |
| | σ | - | - | - | 48.6 | 32.8 |
| LEXINGTON | Yield (bu./ac) | -* | 154.6 | 148.4 | -* | 168.6 |
| | σ | - | 19.6 | 37.1 | - | 17.6 |
| LORING | Yield (bu./ac) | 98.8 | 172.8 | 167.5 | 178.5 | 177.1 |
| | σ | 43.8 | 29.0 | 33.8 | 23.1 | 26.9 |
| PROVIDENCE | Yield (bu./ac) | 120.0 | 151.7 | 150.4 | 153.7 | 159.2 |
| | σ | 38.6 | 27.2 | 26.3 | 28.6 | 23.4 |

* Nitrogen rate not present in the soil series.

### *Yield Results by Soil Types*

Table 8 present the yield performance for each soil type, the standard deviation of yield, and the number of observations used to calculate the average yield, according to the nitrogen rate applied.

Table 8. Yield results of soil types in the test area.

| SOIL TYPES | | RATES (lbs. N/ac) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 84 | 127 | 143 | 181 |
| LoA0 | Yield (bu/ac) | 150.1 | 187.8 | 159.1 | 179.7 | 179.9 |
| | σ | 7.1 | 27.0 | 41.4 | 18.4 | 22.4 |
| | n# | 7.0 | 656.0 | 309.0 | 451.0 | 408.0 |
| LoB0 | Yield (bu/ac) | 105.4 | 173.7 | 175.3 | 180.0 | 191.6 |
| | σ | 44.1 | 40.3 | 34.8 | 25.9 | 15.0 |
| | n# | 441.0 | 474.0 | 840.0 | 819.0 | 469.0 |
| LoB | Yield (bu/ac) | 113.7 | 182.7 | 170.0 | 181.5 | 185.0 |
| | σ | 36.9 | 31.8 | 19.1 | 17.8 | 28.7 |
| | n# | 41.0 | 311.0 | 304.0 | 335.0 | 398.0 |
| GrA | Yield (bu/ac) | 118.8 | 187.8 | -* | -* | 160.0 |
| | σ | 42.5 | 11.0 | - | - | 31.5 |
| | n# | 40.0 | 94.0 | - | - | 105.0 |
| LoA2 | Yield (bu/ac) | 77.6 | 185.8 | 170.5 | 195.1 | 179.6 |
| | σ | 43.3 | 14.1 | 37.6 | 19.8 | 31.0 |
| | n# | 160.0 | 165.0 | 183.0 | 166.0 | 235.0 |
| LoA3 | Yield (bu/ac) | -* | 134.2 | 126.7 | 166.2 | 149.0 |
| | σ | - | 46.5 | 49.9 | 42.0 | 43.9 |
| | n# | - | 60.0 | 51.0 | 109.0 | 51.0 |
| LoB2 | Yield (bu/ac) | 96.0 | 173.9 | 166.1 | 174.9 | 175.0 |
| | σ | 42.9 | 20.9 | 26.9 | 19.1 | 22.7 |
| | n# | 218.0 | 203.0 | 400.0 | 515.0 | 506.0 |
| HeA2 | Yield (bu/ac) | -* | -* | -* | 162.6 | 178.9 |
| | σ | - | - | - | 48.6 | 32.8 |
| | n# | - | - | - | 63.0 | 80.0 |
| LxC | Yield (bu/ac) | -* | 154.6 | 148.4 | -* | 168.6 |
| | σ | - | 19.6 | 37.1 | - | 17.6 |
| | n# | - | 93.0 | 66.0 | - | 4.0 |
| LoC2 | Yield (bu/ac) | 100.1 | 160.1 | 177.0 | 181.5 | 164.7 |
| | σ | 20.5 | 14.5 | 19.3 | 12.5 | 50.4 |
| | n# | 30.0 | 75.0 | 146.0 | 101.0 | 51.0 |
| LoB3 | Yield (bu/ac) | 99.5 | 168.4 | 171.7 | 181.0 | 170.9 |
| | σ | 42.2 | 24.4 | 22.4 | 16.7 | 20.5 |
| | n# | 104.0 | 628.0 | 173.0 | 134.0 | 269.0 |
| PrB3 | Yield (bu/ac) | 92.4 | 154.1 | 144.7 | 150.5 | 158.7 |
| | σ | 28.2 | 22.7 | 19.5 | 29.4 | 23.1 |
| | n# | 74.0 | 225.0 | 188.0 | 98.0 | 172.0 |
| LoC3 | Yield (bu/ac) | -* | 166.8 | 136.8 | 168.3 | 162.4 |
| | σ | - | 12.7 | 30.3 | 22.6 | 26.2 |
| | n# | - | 224.0 | 453.0 | 230.0 | 471.0 |
| LoB4 | Yield (bu/ac) | -* | 168.1 | -* | 160.8 | -* |
| | σ | - | 17.4 | - | 14.3 | - |
| | n# | - | 127.0 | - | 29.0 | - |
| PrC4 | Yield (bu/ac) | 132.4 | 148.5 | 154.1 | 156.0 | 159.7 |
| | σ | 36.2 | 32.1 | 29.4 | 27.9 | 23.7 |
| | n# | 165.0 | 173.0 | 286.0 | 141.0 | 138.0 |

* Nitrogen rate not present in soil type.

# YIELD RESULTS BASED ON PLANT POPULATION, pH, P, K, and LEAF N

A five-meter radius buffer was created using PC ARC/INFO in each location of the field where the 83 soil samples and the 75 leaf nitrogen and plant population samples were collected. The average yield in each buffer was computed and used for comparison of soil tests, plant populations, and leaf nitrogen contents. The nitrogen rate was found to be the most important factor influencing yield ($P=0.0001$), followed by Phosphorus (P) ($P=0.0123$). Potassium (K), pH, plant population, and nitrogen leaf content were found not to be statistically significant to affect yield ($P>0.05$).

Test results indicated a high degree of soil nutrients variability in the test field, even though the area was uniformly treated with lime, P, and K applications. Plant population also varied among locations throughout the field, despite the fact that the planter was set to deliver 25,000 plants per acre in the entire field. Table 9 is a summary of test results in the test field. Complete test results are listed in Appendix A.

Table 9. Summary of leaf N, plant population, pH, P, and K results.

| ITEM | LOWEST | HIGHEST | AVERAGE |
|---|---|---|---|
| Leaf N (%) | 0.6 | 3.4 | 2.2 |
| Plant Pop. (pl./ac) | 12,777.0 | 24,684.0 | 20,266.0 |
| pH | 4.8 | 6.7 | 5.7 |
| P (lbs/ac) | 12.0 | 64.0 | 32.1 |
| K (lbs/ac) | 60.0 | 250.0 | 139.6 |

## GPS AND YIELD MONITOR PERFORMANCE

The Global Positioning System (GPS) performance was very good during all field usage and data collection. Among more than 16,000 positional data recorded, less than 80 (0.5%) had to be discarded due to lack of precision.

Comparisons of yield monitor's weight readings were made against readings of a portable weight wagon. The average difference in readings was 1.8%. The highest difference was 6.2% and the lowest, 0.04%. Weight results from the yield monitor were compared against readings obtained from the grain elevator (truck weights). The yield monitor had an average error of 1.5% when compared to the grain elevator; the weigh wagon averaged 1.3%. The total weight data and readings of the yield monitor and the weight wagon are listed in Appendix D.

Comparisons of the yield monitor's moisture readings were made against a DICKEY-john GAC II moisture tester. An average error of 4.3%

was measured between the two sensing techniques. The highest error was 10.8% and the lowest error was 0%. The moisture data is also listed in Appendix D.

## ECONOMIC ANALYSIS OF VARIABLE RATE NITROGEN BASED ON YIELD POTENTIAL

The site specific farming concept is based on the premise that applying different rates of fertilizers or pesticides throughout the field has a better economic return than applying an average of these products in the entire field. In this project, four different classes of soil were proposed, all having different yield potentials and expected to produce different yields. Relating the fertilizer price and rate applied to the yield produced and the price of corn, the rate that generated the greater return can be found and the SSF concept tested.

For this exercise, a price of $0.278 dollars per pound of nitrogen was considered. This price comes from $0.089 dollars per pound paid for the UAN solution used that contained 32% nitrogen. A corn price of $2.70 a bushel was used, according to the prices received by farmers in the US in 1995 (USDA, 1996). Table 10 lists the costs of application, yield, income, and result for each group and rate applied in the field. As shown by Table 10, the best economic results obtained for the test field included the

Table 10. Preliminary economic analysis of nitrogen rates.

| CLASS | RATE | COST ($/AC) | YIELD (BU/AC) | INCOME ($/AC) | RESULT |
|---|---|---|---|---|---|
| HIGH | 0 | $ 00.00 | 107.6 | $ 290.52 | $ 290.52 |
| | 84 | $ 23.35 | 177.3 | $ 478.71 | **$ 455.36** |
| | 127 | $ 35.30 | 170.7 | $ 460.89 | $ 425.58 |
| | 143 | $ 39.75 | 180.3 | $ 486.81 | $ 447.04 |
| | 181 | $ 50.31 | 183.8 | $ 496.26 | $ 445.94 |
| GOOD | 0 | $ 00.00 | 88.2 | $ 238.14 | $ 238.14 |
| | 84 | $ 23.35 | 169.7 | $ 458.19 | $ 434.84 |
| | 127 | $ 35.30 | 162.7 | $ 439.29 | $ 403.99 |
| | 143 | $ 39.75 | 176.8 | $ 477.36 | **$ 437.61** |
| | 181 | $ 50.31 | 175.1 | $ 472.77 | $ 422.46 |
| FAIR | 0 | $ 00.00 | 097.1 | $ 262.17 | $ 262.17 |
| | 84 | $ 23.35 | 164.3 | $ 443.61 | $ 420.26 |
| | 127 | $ 35.30 | 163.2 | $ 440.64 | $ 405.34 |
| | 143 | $ 39.75 | 172.1 | $ 464.67 | **$ 424.92** |
| | 181 | $ 50.31 | 166.0 | $ 448.20 | $ 397.89 |
| POOR | 0 | $ 00.00 | 132.4 | $ 357.48 | $ 357.48 |
| | 84 | $ 23.35 | 161.1 | $ 434.97 | **$ 411.62** |
| | 127 | $ 35.30 | 148.1 | $ 399.87 | $ 364.57 |
| | 143 | $ 39.75 | 163.4 | $ 441.18 | $ 401.43 |
| | 181 | $ 50.31 | 161.8 | $ 436.86 | $ 386.55 |

application of two different nitrogen rates.

# CHAPTER 5

# CONCLUSIONS

The objectives of this study were to adapt a liquid fertilizer applicator to variable apply rates of nitrogen, to measure and geo-reference corn yield using a commercially available yield monitor and GPS receiver, to evaluate yield response in corn according to nitrogen rates applied and the yield potential areas of the test field, and to create a GIS database to manage all spatial information. Given the limited information on just one year of data, the following conclusions were reached at the end of this work:

- Variable rate applications of nitrogen in corn based on yield potential shows promise as a method for maximizing profit potential within a field.

- The variable rate applicator used in this research, proved to be an effective system for varying liquid nitrogen at pre-determined discrete rates.

- The commercially-available yield monitor proved to be an accurate method for documenting yield variability. The yield monitor was calibrated to an accuracy of 1.8% .

- The GPS receivers provided a very reliable system for geo-referencing data acquisition within the test field. With a local base station and real-time radio links for DGPS, positional accuracy was maintained at 1 meter or better 95% of the time.

- Geographic Information Systems (GIS) proved to be an effective and essential tool for managing all geographically related information within the field.

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# APPENDICES

# APPENDIX A

**Table A1: Soil test and average yield results by sample location.**

| N# | pH | P (lbs./ac) | K (lbs./ac) | Avg. Yield (bu/ac) | N# | pH | P (lbs./ac) | K (lbs./ac) | Avg. Yield (bu./ac) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.9 | 44 | 190 | 172.09 | 42 | 6.2 | 28 | 100 | 192.01 |
| 2 | 5.8 | 32 | 150 | 181.2 | 43 | 5.8 | 44 | 120 | 186.16 |
| 3 | 5.8 | 24 | 150 | 190.51 | 44 | 6.1 | 32 | 100 | 185.61 |
| 4 | 5.1 | 28 | 150 | 187.1 | 45 | 6.1 | 32 | 80 | 169.43 |
| 5 | 5.3 | 40 | 190 | 156.76 | 46 | 5.9 | 30 | 80 | 198.47 |
| 6 | 6.1 | 24 | 130 | 193.75 | 47 | 6.2 | 44 | 60 | 190.36 |
| 7 | 5.5 | 24 | 120 | 169.52 | 48 | 6.5 | 40 | 70 | 187.34 |
| 8 | 6.1 | 24 | 190 | 188.05 | 49 | 6.6 | 40 | 70 | 157.21 |
| 9 | 6.2 | 28 | 140 | 117.26 | 50 | 6.7 | 64 | 100 | 171.43 |
| 10 | 5.6 | 24 | 160 | 167.54 | 51 | 6.0 | 36 | 90 | 189.65 |
| 11 | 5.5 | 40 | 190 | 189.38 | 52 | 5.7 | 32 | 90 | 170.83 |
| 12 | 5.3 | 32 | 220 | 177.82 | 53 | 5.3 | 20 | 60 | 73.5 |
| 13 | 6.2 | 36 | 150 | 178 | 54 | 5.3 | 28 | 90 | 169.22 |
| 14 | 5.6 | 30 | 160 | 160.12 | 55 | 6.0 | 30 | 70 | 177.26 |
| 15 | 5.9 | 52 | 180 | 167.24 | 56 | 6.2 | 28 | 80 | 185.54 |
| 16 | 6.0 | 40 | 170 | 170.12 | 57 | 6.1 | 40 | 100 | 191.83 |
| 17 | 6.3 | 52 | 120 | 192 | 58 | 6.3 | 40 | 90 | 184.23 |
| 18 | 5.7 | 40 | 170 | 77.16 | 59 | 6.6 | 48 | 70 | 187.58 |
| 19 | 6.2 | 48 | 180 | 174.31 | 60 | 5.1 | 12 | 130 | 168.16 |
| 20 | 6.1 | 52 | 140 | 64.48 | 61 | 5.4 | 30 | 110 | 178.61 |
| 21 | 5.3 | 28 | 80 | 156.71 | 62 | 5.0 | 30 | 130 | 169.1 |
| 22 | 5.5 | 40 | 140 | 151.27 | 63 | 5.0 | 24 | 200 | 182.09 |
| 23 | 6.0 | 28 | 100 | 178.82 | 64 | 5.6 | 28 | 180 | 64.21 |
| 24 | 6.0 | 36 | 160 | 170.33 | 65 | 5.7 | 24 | 150 | 155.33 |
| 25 | 6.0 | 36 | 160 | 174.3 | 66 | 6.0 | 24 | 120 | 187.8 |
| 26 | 6.2 | 28 | 150 | 173.03 | 67 | 5.4 | 24 | 250 | 149.68 |
| 27 | 6.2 | 28 | 150 | 175.68 | 68 | 5.4 | 24 | 210 | 180.86 |
| 28 | 5.3 | 24 | 160 | 124.34 | 69 | 5.1 | 18 | 210 | 194.25 |
| 29 | 5.9 | 30 | 180 | 195.15 | 70 | 5.0 | 16 | 190 | 190.81 |
| 30 | 6.2 | 36 | 170 | 167.18 | 71 | 4.8 | 16 | 110 | 147.01 |
| 31 | 6.1 | 28 | 100 | 201.11 | 72 | 5.4 | 36 | 210 | 101.25 |
| 32 | 5.7 | 24 | 110 | 122.77 | 73 | 5.5 | 20 | 130 | 176.08 |
| 33 | 5.4 | 30 | 100 | 144.83 | 74 | 5.4 | 24 | 180 | 194.14 |
| 34 | 6.4 | 40 | 120 | 114.28 | 75 | 5.9 | 44 | 220 | 143.99 |
| 35 | 6.3 | 32 | 130 | 186.31 | 76 | 6.4 | 18 | 180 | 191.62 |
| 36 | 5.8 | 36 | 130 | 181.83 | 77 | 5.7 | 40 | 130 | 189.59 |
| 37 | 5.9 | 24 | 130 | 181.49 | 78 | 5.0 | 18 | 160 | 165.55 |
| 38 | 5.3 | 24 | 140 | 141.74 | 79 | 5.4 | 24 | 140 | 136.4 |
| 39 | 5.8 | 28 | 140 | 128.66 | 80 | 5.8 | 40 | 130 | 168.04 |
| 40 | 5.9 | 30 | 150 | 140.5 | 81 | 5.6 | 28 | 140 | 180.83 |
| 41 | 6.2 | 52 | 120 | 179.07 | 82 | 5.5 | 28 | 180 | 126.37 |
| | | | | | 83 | 5.3 | 48 | 210 | 152.71 |

**Table A2: Leaf nitrogen, plant population, and average yield results by sample location.**

| N# | N (%) | Pop (pl/ac) | Avg. Yield (bu./ac) | N# | N (%) | Pop (pl/ac) | Avg. Yield (bu./ac) |
|---|---|---|---|---|---|---|---|
| 1 | 0.8496 | 16552.8 | 144.57 | 36 | 2.2671 | 19747.2 | 128.79 |
| 2 | 2.8635 | 15681.6 | 175.04 | 37 | 2.027 | 21780 | 182.28 |
| 3 | 1.9873 | 17714.4 | 125.67 | 38 | 1.4812 | 19166.4 | 188.67 |
| 4 | 2.2323 | 17133.6 | 187.68 | 39 | 2.9625 | 18295.2 | 195.6 |
| 5 | 3.4776 | 13939.2 | 179.01 | 40 | 3.0322 | 23812.8 | 188.3 |
| 6 | 1.7987 | 18004.8 | 108.74 | 41 | 1.311 | 22651.2 | 187.24 |
| 7 | 0.6504 | 15100.8 | 164.33 | 42 | 2.1283 | 21199.2 | 179.28 |
| 8 | 3.0183 | 18876 | 169.11 | 43 | 2.0932 | 19166.4 | 98.57 |
| 9 | 2.9059 | 18876 | 130.76 | 44 | 1.7719 | 13939.2 | 174.54 |
| 10 | 2.0982 | 20908.8 | 184.33 | 45 | 2.1825 | 22651.2 | 197.29 |
| 11 | 2.0138 | 22360.8 | 159.05 | 46 | 2.7397 | 23232 | 179.39 |
| 12 | 2.346 | 20037.6 | 172.83 | 47 | 2.5396 | 21199.2 | 177.95 |
| 13 | 2.8173 | 22070.4 | 150.56 | 48 | 2.1687 | 20618.4 | 180.29 |
| 14 | 1.9356 | 21199.2 | 169.1 | 49 | 2.1327 | 21489.6 | 171.92 |
| 15 | 2.2738 | 24103.2 | 153.41 | 50 | 3.2569 | 18004.8 | 195.66 |
| 16 | 1.8255 | 22070.4 | 170.93 | 51 | 2.4694 | 24103.2 | 177.69 |
| 17 | 2.5879 | 24393.6 | 175.87 | 52 | - | 18585.6 | 148.29 |
| 18 | 1.5946 | 24393.6 | 158.47 | 53 | 2.644 | 18004.8 | 183.57 |
| 19 | 2.5638 | 23522.4 | 169.53 | 54 | 2.2169 | 12777.6 | 178.51 |
| 20 | 2.3466 | 24393.6 | 156.29 | 55 | 2.2184 | 12777.6 | 167.53 |
| 21 | 2.6351 | 24684 | 91.6 | 56 | 2.0818 | 24684 | 54.06 |
| 22 | 2.4232 | 21780 | 68.43 | 57 | 2.596 | 23812.8 | 196.81 |
| 23 | 2.5204 | 21489.6 | 163.11 | 58 | 2.5517 | 24684 | 135.44 |
| 24 | 2.4123 | 22651.2 | 190.2 | 59 | 1.3925 | 20037.6 | 194.74 |
| 25 | 1.4871 | 22651.2 | 27.07 | 60 | 2.0447 | 22070.4 | 154.91 |
| 26 | 2.2742 | 22651.2 | 179.01 | 61 | 2.4913 | 22941.6 | 155.26 |
| 27 | 2.4124 | 20037.6 | 160.67 | 62 | - | 21780 | 177.4 |
| 28 | 2.3215 | 21780 | 189.3 | 63 | 2.9613 | 22070.4 | 186.63 |
| 29 | 2.5119 | 20328 | 189.89 | 64 | 2.4499 | 23522.4 | 192.68 |
| 30 | - | 21780 | 157.49 | 65 | 1.7233 | 24103.2 | 122.43 |
| 31 | 2.7658 | 19166.4 | 85.34 | 66 | 2.5999 | 23232 | 123.83 |
| 32 | 3.0018 | 16843.2 | 181.54 | 67 | 1.4674 | 21489.6 | 151.63 |
| 33 | 3.1182 | 13068 | 189.22 | 68 | 0.7528 | 22360.8 | 195.48 |
| 34 | 2.854 | 17424 | 79.7 | 69 | 1.4142 | 20328 | 154.96 |
| 35 | 2.8641 | 19747.2 | 147.67 | 70 | 2.1841 | 21199.2 | 98.9 |
| | | | | 71 | 1.9791 | 15100.8 | 179.21 |
| | | | | 72 | 2.4503 | 15100.8 | 71.29 |
| | | | | 73 | 2.1775 | 13648.8 | 60.41 |
| | | | | 74 | 2.1811 | 16843.2 | 197.09 |
| | | | | 75 | 3.0607 | 20328 | 167.9 |

# APPENDIX B

## Appendix B1: C-program used to read data from the GPS receiver and the yield monitor to the laptop computer (timestmp.c)

```
/* This program will read a line from the serial port and write it to a file
** with a timestamp. There is no error checking for the serial data. The only
** command line parameter is a filename. The communication parameters are
** compiled into the program and require recompilation to alter. The default
** parameters are COM1:9600,N,8,1. Much of the code is taken from the
**SIMPLE.C program provided with the PCL4C Communications Library.
** Exit Errorlevels are:
** 0 - Normal Exit
** 1 - Improper command syntax
** 2 - Failure to open requested filename
** 3 - Failure to initialize serial port
** 4 - Failure to close data file
*/

#include <stdio.h>
#include <stdlib.h>
#include <pcl4c.h>

#define FALSE 0
#define TRUE !FALSE
#define ESC 0x1b

/*** Global Variables ***/

int Port = 0;                 /* Alter port here */
int BaudCode = Baud9600;        /* Alter baud here */
char RxBuf[1024];             /* 1024 byte recieve buffer */
char DataString[256]=0;        /* 256 byte data string buffer */

/*** Function Prototypes ***/

int ErrorCheck(int Code);      /* Traps PCL error codes */

/*** Main ***/

void main(int argc, char *argv[])
{
   char c[2]=0;
   int i, rc;
   FILE *fp

   /* Check for proper usage */
   if(argc !=2){
      printf("Usage: TIMESTMP filename.ext\n");
      exit(1)
   }
```

```
/* Parse filename from command line and open the file. */
fp = fopen(argv[1],"a");
if (fp = NULL){
   printf("Error opening file.\n");
   exit(2)
}

/* Open serial port */
ErrorCheck( SioRxBuf(Port,RxBuf,Size1024));
ErrorCheck( SioParms(Port,NoParity,OneStopBit,WordLength8));
ErrorCheck( SioReset(Port,BaudCode));

/* If serial port opened without error begin to accept input */

while(TRUE)              /* Loop continuously */
{
   if (SioKeyPress())    /* Exit program and closing port and files */
   {                  /* if escape key is pressed. */
      i = SioKeyRead();
      if ((char) i==ESC)
      {
         SioDone(Port);
         if (fclose(fp) != 0)
         {
            printf("Error closing datafile.\n");
            exit(4);
         }
         exit(0);   /* Escape was pressed so terminate normally */
      }
   }
   i = SioGetc(Port,0);   /* Read character from serial port */
   if (i>-1)             /* If the character is valid */
   {
      if (i != 0x0A)     /* and not a LF (of the CRLF pair) */
      {
         c[0]=(char) i;  /* convert c to string and cat to existing */
         strcat(DataString, c);  /* data string. */
      }
      else   /* now we deal with adding time and writing to disk */
      {

int ErrorCheck(int Code)
{
   if (Code<0)
   {
      SioError(Code);
      SioDone(Port);
      exit(3);
   }
   return(0);
}
```

## Appendix B2: Computer program used to control the nitrogen fertilizer application (Nitro5.bas)

```
DIM z%(100, 100): SCREEN 9: WINDOW (-639, 0)-(0, 349): CLS: GOSUB
1000
OPEN "com1:9600,n,8,1,cs,ds" FOR INPUT AS #1
OPEN "com2:9600,n,8,1,cs,ds" FOR OUTPUT AS #2
30 LINE INPUT #1, x$: IF LEN(x$) < 47 THEN BEEP: GOTO 30
40 LOCATE 1, 10: PRINT x$: lat = (VAL(MID$(x$, 11, 9))) / 60
lon = (VAL(MID$(x$, 26, 9))) / 60
LOCATE 3, 22: PRINT lat: LOCATE 3, 37: PRINT lon
ycoord$ = MID$(STR$(lat), 4, 5): xcoord$ = MID$(STR$(lon), 4, 5)
IF LEN(ycoord$) < 5 THEN ycoord$ = ycoord$ + "0"
IF LEN(xcoord$) < 5 THEN xcoord$ = xcoord$ + "0"
xcoord = CINT(VAL(xcoord$) / 10): ycoord = CINT(VAL(ycoord$) / 10)
LOCATE 4, 24: PRINT ycoord: LOCATE 4, 39: PRINT xcoord
x = (xcoord - 640): y = (ycoord - 4110)
IF x > 700 THEN x = 700: IF x < 10 THEN x = 10
IF y > 350 THEN y = 350: IF y < 10 THEN y = 10
LINE (x*-0.75-1, y*0.75-1)-(x*-0.75+1, y*0.75+1), z%(CINT(x/10),
CINT(y/10)), BF
LINE (x*-0.75-1, y*0.75-1)-(x*-0.75+1, y*0.75+1), , BF
r% = z%(CINT(x / 10), CINT(y / 10))
IF r% = 1 THEN r% = 3: IF r% = 2 THEN r% = 5:
IF r% = 3 THEN r% = 6: IF r% = 4 THEN r% = 7
PRINT #2, r%: PRINT #3, x$, r%
LOCATE 1, 1: PRINT z%(x / 10, y / 10): GOTO 30
RETURN
```

## Appendix B3: Computer program used to format position and yield data.

```
REM Program to fix latitude and longitude and yield data
REM After fixing the values, the program merge them into one file
OPEN "File containing GPS data" FOR INPUT AS #1
OPEN "Output file, comma separated" FOR OUTPUT AS #2
DO UNTIL EOF(1): INPUT #1, X$: INPUT #1, lad$: INPUT #1, X$
INPUT #1, lon$: INPUT #1, X$: INPUT #1, X$: INPUT #1, X$
LADDEG$ = LEFT$(lad$, 2): LONDEG$ = LEFT$(lon$, 3)
LADMIN$ = RIGHT$(lad$, 9): LONMIN$ = RIGHT$(lon$, 9)
lad# = VAL(LADDEG$) + (VAL(LADMIN$) / 60)
lon# = VAL(LONDEG$) + (VAL(LONMIN$) / 60)
PRINT #2, USING "##.########"; lon#: PRINT #2, ",";
PRINT #2, USING "##.########"; lad#
LOOP: DIM POSITION(10)
OPEN "File containing yield data" FOR INPUT AS #3
OPEN "Output file, comma separated" FOR OUTPUT AS #4
DO UNTIL EOF(3): INPUT #3, Y$: I = 1: COUNT = 1
10 POSITION(COUNT) = INSTR(I, Y$, "+")
I = POSITION(COUNT) + 1: COUNT = COUNT + 1
IF COUNT < 9 THEN GOTO 10
SPEED=VAL(MID$(Y$, POSITION(1), (POSITION(2)-POSITION(1)-3)))
MPH=VAL(MID$(Y$, POSITION(2), (POSITION(3)-POSITION(2)-3)))
HEADER=VAL(MID$(Y$, POSITION(3), (POSITION(4)-POSITION(3)-3)))
ELEVATOR=VAL(MID$(Y$, POSITION(4), (POSITION(5)-POSITION(4)-3)))
HEADWIDTH=VAL(MID$(Y$, POSITION(5), (POSITION(6)-POSITION(5)-3)))
LBSMIN=VAL(MID$(Y$, POSITION(6), (POSITION(7)-POSITION(6)-3)))
BUAC=VAL(MID$(Y$, POSITION(7), (POSITION(8)-POSITION(7)-3)))
MOIST=VAL(MID$(Y$, POSITION(8), 4))
PRINT #4, USING "####.###"; MPH:
PRINT #4, ",": PRINT #4, HEADER: PRINT #4, ",": PRINT #4, LBSMIN
LOOP: CLS: PRINT "We now are going to merge the fixed files into one"
OPEN "File containing the fixed GPS data" FOR INPUT AS #5
OPEN "File containing the fixed yield data" FOR INPUT AS #6
OPEN "Output file containing GPS and yield data" FOR OUTPUT AS #7
WHILE NOT EOF(5): INPUT #5, Z1$, Z2$
WHILE NOT EOF(6): INPUT #6, W1$, W2$, W3$
PRINT #7, Z1$: PRINT #7, ",": PRINT #7, Z2$: PRINT #7, ",": PRINT #7, W1$:
PRINT #7, ",": PRINT #7, W2$: PRINT #7, ",": PRINT #7, W3$
WEND: WEND
```

## Appendix B4: Computer program used to format fertilizer application data.

```
OPEN "File containing GPS and rate information" FOR INPUT AS #1
OPEN "Output file" FOR OUTPUT AS #2
WHILE NOT EOF(1): INPUT #1, x$: INPUT #1, LAD$: INPUT #1, x$
INPUT #1, LON$: INPUT #1, x$: INPUT #1, x$: INPUT #1, x$
LADDEG$ = LEFT$(LAD$, 2): LONDEG$ = LEFT$(LON$, 3)
LADMIN$ = RIGHT$(LAD$, 9): LONMIN$ = RIGHT$(LON$, 9)
LAD# = VAL(LADDEG$) + (VAL(LADMIN$) / 60)
LON# = VAL(LONDEG$) + (VAL(LONMIN$) / 60)
RATE = VAL(RIGHT$(x$, 1))
IF RATE = 1 THEN RATE = 84
IF RATE = 2 THEN RATE = 127
IF RATE = 3 THEN RATE = 143
IF RATE = 4 THEN RATE = 181
PRINT #2, USING "##.########"; LAD#;:PRINT #2, ",";
PRINT #2, USING "##.########"; LON#: PRINT #2, ",";
PRINT #2, RATE: WEND
```

# APPENDIX C

# Appendix C: Summary of statistics

General Linear Models Procedure

Dependent Variable: YIELD

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 58 | 7486620.26554943 | 129079.659 | 157.9 | 0.0001 |
| Error | 14373 | 11749498.3783392 | 817.47014390 | | |
| Total | 14431 | 19236118.64388860 | | | |

| R-Square | C.V. | Root MSE | YIELD Mean |
|---|---|---|---|
| 0.389196 | 17.27096 | 28.5914348 | 165.54631375 |

| **Source** | **DF** | **Type III SS** | **Mean Square** | **F Value** | **Pr > F** |
|---|---|---|---|---|---|
| RATE | 4 | 604958.8341 | 151239.7085 | 185.01 | 0.0001 |
| RATE* GROUP | 6 | 113653.0035 | 18942.16725 | 23.17 | 0.0001 |
| SERIES | 2 | 134529.63496 | 67264.81748 | 82.28 | 0.0001 |
| RATE* SERIES | 8 | 96326.170622 | 12040.77132 | 14.73 | 0.0001 |
| SLOPE | 1 | 8589.53415 | 8589.53415 | 10.51 | 0.0012 |
| RATE* SLOPE | 7 | 155668.967 | 22238.42388 | 27.20 | 0.0001 |
| DEPTH | 2 | 268997.6543 | 134498.8271 | 164.53 | 0.0001 |
| RATE* DEPTH | 10 | 120686.3265 | 12068.63265 | 14.76 | 0.0001 |

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: YIELD

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 14373 MSE= 817.4701
Critical Value of Studentized Range= 3.858
Minimum Significant Difference= 2.2065
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 2499.349

Means with the same letter are not significantly different.

| Tukey Grouping | Mean | N | RATE |
|---|---|---|---|
| A | 176.3751 | 3192 | 143 |
| A | | | |
| A | 174.9633 | 3353 | 180 |
| B | 170.3162 | 3508 | 84 |
| C | 164.4850 | 3099 | 127 |
| D | 103.3710 | 1280 | 0 |

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: YIELD

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 14373 MSE= 817.4701
Critical Value of Studentized Range= 3.634
Minimum Significant Difference= 1.8931
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 3011.446

Means with the same letter are not significantly different.

| Tukey Grouping | Mean | N | GROUP |
|---|---|---|---|
| A | 172.2929 | 6503 | High |
| B | 162.2014 | 3328 | Good |
| C | 159.7979 | 2468 | Fair |
| D | 156.8477 | 2133 | Poor |

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: YIELD

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 14373 MSE= 817.4701
Critical Value of Studentized Range= 3.858
Minimum Significant Difference= 6.615
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 278.0825

Means with the same letter are not significantly different.

| Tukey Grouping | | Mean | N | SERIES |
|---|---|---|---|---|
| | A | 171.716 | 143 | Henry |
| | A | | | |
| B | A | 167.994 | 12230 | Loring |
| B | | | | |
| B | | 164.148 | 240 | Grenada |
| | | | | |
| | C | 152.448 | 163 | Lexington |
| | C | | | |
| | C | 148.432 | 1656 | Providence |

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: YIELD

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 14373 MSE= 817.4701
Critical Value of Studentized Range= 3.315
Minimum Significant Difference= 1.5531
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 3723.978

Means with the same letter are not significantly different.

| Tukey Grouping | Mean | N | SLOPE |
|---|---|---|---|
| A | 168.8654 | 3394 | A |
| B | 166.5756 | 8495 | B |
| C | 157.6782 | 2543 | C |

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: YIELD

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 14373 MSE= 817.4701

Critical Value of Studentized Range= 3.858

Minimum Significant Difference= 2.3696

WARNING: Cell sizes are not equal.

Harmonic Mean of cell sizes= 2167.044

Means with the same letter are not significantly different.

| Tukey Grouping | Mean | N | DEPTH |
|---|---|---|---|
| A | 174.0290 | 1792 | 1 |
| B | 170.9909 | 4874 | 0 |
| C | 164.4840 | 3297 | 2 |
| D | 158.3335 | 3414 | 3 |
| E | 152.6448 | 1055 | 4 |

Model: MODEL1

Dependent Variable: YIELD

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 4 | 26445.03562 | 6611.25891 | 9.288 | 0.0001 |
| Error | 52 | 37012.42197 | 711.77735 | | |
| C Total | 56 | 63457.45759 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 26.67916 | R-square | 0.4167 |
| Dep Mean | 161.30702 | Adj R-sq | 0.3719 |
| C.V. | 16.53936 | | |

Parameter Estimates

| Var | DF | Parameter Estimate | Std Error | T for H0: Parameter=0 | Prob> \|T\| | Squared Partial Corr Type II |
|---|---|---|---|---|---|---|
| INTCP | 1 | 15.976385 | 61.188 | 0.261 | 0.7950 | - |
| PH | 1 | 20.990815 | 10.471 | 2.005 | 0.0502 | 0.07173 |
| P | 1 | -1.120706 | 0.4319 | -2.594 | 0.0123 | 0.11459 |
| K | 1 | 0.070290 | 0.0907 | 0.775 | 0.4420 | 0.01141 |
| RATE | 1 | 0.402950 | 0.074 | 5.437 | 0.0001 | 0.36244 |

Model: MODEL1

Dependent Variable: YIELD

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 3 | 22925.57334 | 7641.85778 | 6.088 | 0.0013 |
| Error | 49 | 61504.35813 | 1255.19098 | | |
| C Total | 52 | 84429.93147 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 35.42867 | R-square | 0.2715 |
| Dep Mean | 155.88208 | Adj R-sq | 0.2269 |
| C.V. | 22.72787 | | |

Parameter Estimates

| Var | DF | Parameter Estimate | Std Error | T for H0: Parameter=0 | Prob> \|T\| | Squared Partial Corr Type II |
|---|---|---|---|---|---|---|
| INTCP | 1 | 93.246525 | 37.560 | 2.483 | 0.0165 | - |
| N | 1 | -12.066794 | 8.7103 | -1.385 | 0.1722 | 0.03769030 |
| POP | 1 | 0.002288 | 0.0014 | 1.532 | 0.132 | 0.04568967 |
| RATE | 1 | 0.392774 | 0.0942 | 4.168 | 0.0001 | 0.26172561 |

# APPENDIX D

**Table D1: Calibration data for the yield monitor.**

| Load n# | Weight Wagon (lbs) | Yield Monitor (lbs) | % Error |
|---|---|---|---|
| 8 | 3924 | 3866 | -1.5 |
| 10 | 4018 | 3906 | -2.8 |
| 12 | 4106 | 3990 | -2.8 |
| 14 | 4330 | 4128 | -4.7 |
| 16 | 4330 | 4064 | -6.1 |
| 18 | 4332 | 4219 | -2.6 |
| 20 | 4468 | 4311 | -3.5 |
| 22 | 4280 | 4155 | -2.9 |
| 24 | 4258 | 4118 | -3.3 |
| 26 | 4194 | 4088 | -2.5 |
| 28 | 4060 | 3958 | -2.5 |
| 30 | 3608 | 3545 | -1.7 |
| 32 | 2972 | 2916 | -1.9 |
| 33 | 5059 | 5373 | 6.2 |
| 34 | 4968 | 4970 | 0.0 |
| 35 | 5235 | 5219 | -0.3 |
| 36 | 5386 | 5382 | -0.1 |
| 37 | 5342 | 5384 | 0.8 |
| 38 | 5205 | 5212 | 0.1 |
| 39 | 5346 | 5262 | -1.6 |
| 40 | 5076 | 5074 | 0.0 |
| 41 | 4996 | 4991 | -0.1 |
| 42+43 | 3714 | 3723 | 0.2 |
| 44 | 6272 | 6189 | -1.3 |
| 45 | 5272 | 5154 | -2.2 |
| 46 | 2632 | 2638 | 0.2 |
| 47 | 3762 | 3774 | 0.3 |
| 48 | 2164 | 2158 | -0.3 |
| 49 | 3314 | 3309 | -0.2 |
| 50 | 4504 | 4466 | -0.8 |
| TOTAL | 131127 | 129542 | 1.8% |

**Table D2: Calibration data for the in-time combine moisture sensor.**

| Yield Monitor's Moisture Readings | Moisture Tester readings | % Difference |
|---|---|---|
| 19.8 | 18.4 | 7.6 |
| 19.8 | 18.3 | 8.2 |
| 19.3 | 18.4 | 4.9 |
| 20.3 | 18.5 | 9.7 |
| 20.4 | 18.4 | 10.9 |
| 20 | 18.6 | 7.5 |
| 20.2 | 18.5 | 9.2 |
| 19.8 | 19 | 4.2 |
| 19.3 | 18.2 | 6.0 |
| 19.3 | 18.3 | 5.5 |
| 18.9 | 17.9 | 5.6 |
| 18.6 | 17.7 | 5.1 |
| 18.6 | 18.2 | 2.2 |
| 18.1 | 17.9 | 1.1 |
| 17.2 | 17.9 | -3.9 |
| 17.5 | 17.5 | 0.0 |
| 16.2 | 17.3 | -6.4 |
| 16.2 | 17.5 | -7.4 |
| 18.1 | 17.9 | 1.1 |
| 17.3 | 17.5 | -1.1 |
| 17.8 | 17.5 | 1.7 |
| 17.1 | 17.7 | -3.4 |
| 17.3 | 17.7 | -2.3 |
| 18.3 | 18.7 | -2.1 |
| 19.9 | 19.5 | 2.1 |
| 18.7 | 19.2 | -2.6 |
| 18.7 | 19.1 | -2.1 |
| 18.7 | 18.9 | -1.1 |
| 18.9 | 19.3 | -2.1 |
| 18.5 | 18.6 | -0.5 |
| | Average Error (%) | 4.3 |

**Table D3: Elevator corn weight data.**

| Loads | Total weight |
|---|---|
| Loads 7-11 | 19540 |
| Loads 12-16 | 21060 |
| Load 17 | 4220 |
| Loads 18-22 | 21480 |
| Loads 23-26 | 16900 |
| Loads 27-31 | 18680 |
| Loads 32-35 | 18100 |
| Loads 36-37 | 10680 |
| Load 38 | 5140 |
| Loads 39-43 | 19080 |
| Loads 44-48 | 20020 |
| Loads 49-50 | 7470 |
| **TOTAL** | **182370** |

**Table D4: Error comparison between yield monitor, grain elevator,and portable weigh wagon.**

| | Elevator | Weight Wagon | Yield Monitor | WW Error % | YM Error % |
|---|---|---|---|---|---|
| Loads 32-35 | 18100 | 18234 | 18478 | 0.740331 | 2.088398 |
| Loads 36-37 | 10680 | 10728 | 10766 | 0.449438 | 0.805243 |
| Load 38 | 5140 | 5205 | 5212 | 1.264591 | 1.400778 |
| Loads 39-43 | 19080 | 19132 | 19050 | 0.272537 | -0.15723 |
| Loads 44-48 | 20020 | 20102 | 19913 | 0.40959 | -0.53447 |
| Loads 49-50 | 7470 | 7818 | 7775 | 4.658635 | 4.082999 |
| | | | | | |
| | | | Avg. Error | 1.30 | 1.51 |

# VITA

Roberto Negrão Barbosa was born May 27, 1967 in Sao Paulo, BRAZIL. He graduated in Agronomy at the State University of Londrina in 1990. In 1994, Roberto received an American Chamber of Commerce (AMCHAM) and Fulbright scholarship, designed to promote the transfer of technology between countries, to study in the United States.

In the fall of 1994, Roberto entered The University of Tennessee and began working in his Master Degree. In the summer of 1996, Roberto completed the requirements for a Master of Science Degree with a major in Agricultural Engineering Technology. He is currently living in Sao Paulo, BRAZIL.

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