AN EVALUATION OF SOIL SAMPLING METHODS IN SUPPORT OF PRECISION AGRICULTURE IN NORTHEASTERN NORTH CAROLINA

by

Joshua Britton Harrell

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TABLE OF CONTENTS

Acknowledgements ii

List of Figures v

List of Tables vii

List of Abbreviations viii

Abstract ix

Chapter 1: Introduction 1

Chapter 2: Related Work 10

- 2.1 Random Composite Sampling vs. Point Sampling 11
- 2.2 Grid Soil Sampling Methods 11
  - 2.2.1 Point Methods 12
  - 2.2.2 Random Composite Cell Sampling Method 15
- 2.3 Management Zone Sampling Methods 15
- 2.4 Grid/Management Zone Hybrid Soil Sampling Method 18
- 2.5 Traditional Soil Sampling Methods 19
- 2.6 Precision Soil Sampling Guidelines 20

Chapter 3: Methods and Data Sources 22

- 3.1 Climate 23
- 3.2 Soil Characteristics 24
- 3.3 Agricultural Practices 25
- 3.4 Research Location 25
- 3.5 Sampling Scheme Creation 25
  - 3.5.1 Traditional Sampling Scheme 26
  - 3.5.2 Grid Sampling Schemes 27
  - 3.5.3 Management Zone Sampling Schemes 27
  - 3.5.4 Hybrid Sampling Schemes 29

3.6 Physical Sample Collection..30
3.7 Method Used to Compare Sampling Procedures 34

Chapter 4: Results and Discussion..36
4.1 Measurements..36
4.2 Interpolation Results 46
4.3 Real World Application 54

Chapter 5: Conclusions..56
5.1 Final Thoughts..56
5.2 Considerations for Future Research 57

LIST OF FIGURES

Figure 1: Regular systematic sampling grid scheme 13

Figure 2: Staggered start grid sampling scheme 14

Figure 3: Systematic unaligned grid sampling method 15

Figure 4: Random composite cell sampling 16

Figure 5: Point sampling for management zones 17

Figure 6: Random composite sampling for management zones 18

Figure 7: Process for creating hybrid grid/management zone scheme 19

Figure 8: Physiographic regions of North Carolina 22

Figure 9: Sub-regions of North Carolina 23

Figure 10: Research location map showing soil survey map units 26

Figure 11: Final grid structure for study site 28

Figure 12: Creation of final management zones 29

Figure 13: Hybrid sampling scheme creation 30

Figure 14: Field condition 31

Figure 15: Automatic soil sampler mounted on ATV 32

Figure 16: Automatic sampler obtaining a soil probe 32

Figure 17: Assuring a 6" sample core. 33

Figure 18: Processing the samples 33

Figure 19: Processing the samples 34

Figure 20: One acre systematic aligned sampling procedure used as “gold” standard ... 35

Figure 21: Traditional sampling pH results 38

Figure 22: Center point sampling pH results 38

Figure 23: Staggered start sampling pH results 39

Figure 24: Random point sampling pH results 39

Figure 25: Composite cell sampling pH results 40

Figure 26: Management zone point sampling pH results 40

Figure 27: Management zone composite sampling pH results 41

Figure 28: Hybrid point sampling pH results 41

Figure 29: Hybrid composite sampling pH results 42

Figure 30: 1 acre grid point sampling pH results ("gold" standard) 42

Figure 31: Center point pH interpolation results 48

Figure 32: Staggered start pH interpolation results 48

Figure 33: Random point pH interpolation results 49

Figure 34: Management zone pH interpolation results 49

Figure 35: Hybrid point pH interpolation restults.. 50

Figure 36: 1 acre grid pH interpolation results ("gold" standard).................................. 50

LIST OF TABLES

Table 1: Current Precision Agriculture Technologies 2

Table 2: Differential Correction Services for Precision Agriculture 4

Table 3: Partial NCDA&CS Soil Test Report Attributes and Their Importance............... 7

Table 4: Advantages and Disadvantages to Point and Composite Sampling 12

Table 5: Summary of Sample Results.. 37

Table 6: Difference of pH units estimated with the “gold” standard and each of the other sampling methods expressed as percentage of the field 44

Table 7: Absolute differences of pH units estimated with the “gold” standard and each of the other sampling methods expressed as percentage of the field................. 46

Table 8: Summary of Interpolation Results 47

Table 9: Difference of pH units estimated with the “gold” standard and each of the other sampling methods expressed as percent of the field.. 51

Table 10: Absolute differences of pH units estimated with the “gold” standard and each of the other sampling methods expressed as percentage of the field................. 52

Table 11: Absolute differences of pH units estimated with the “gold” standard and each of the other sampling methods with and without interpolation expressed as percentage of the field 54

Table 12: Combined composite and interpolated point comparison results 54

LIST OF ABBREVIATIONS

DGPS	Differential Global Positioning System
GIS	Geographic Information System
GPS	Global Positioning System
NCDA&CS	North Carolina Department of Agriculture and Consumer Services
NRCS	Natural Resources Conservation Services
USDA	United States Department of Agriculture
VRT	Variable-rate Technology

ABSTRACT

Precision agriculture is a rapidly developing set of technologies that aids management decisions in agricultural entities. Fertility and lime management is directly impacted by precision agriculture through the application of variable-rate technology (VRT). This allows for the rate of application of one or more materials to be adjusted based on positioning information and predetermined application rates. The basis for VRT is soil sampling. In this study, multiple precision agriculture grid and zone-based soil sampling methods and procedures are utilized on a farm in northeastern North Carolina. The results from these soil sampling methods are evaluated against the results of a "gold" standard sampling method. The findings will potentially begin to determine one or more best suited soil sampling methods for northeastern North Carolina, while also potentially eliminating ineffective ones.

CHAPTER 1: INTRODUCTION

Agriculture is one of the world's oldest economic practices. Before the advent of mechanical equipment, many farming practices were performed by hand, keeping early farmers closely connected to the land. Early farmers retained key information about the land in their memory or on paper. This information was used to make land management decisions from year to year. These decisions were crucial to early farmers because the livelihood of their families was directly impacted by their quality.

Agriculture has developed into a technologically advanced industry and it currently plays a substantial role in global sustainability. The world population is projected to reach 8.5 billion in 2025, which will be more than double the population in 1992 (Roy 2011). This increase in population creates increased demand for agricultural outputs. Precision agriculture refers to an emerging set of technologies to simultaneously help meet this demand and also promote sustainability.

Precision agriculture aids in making more informed management decisions that may lead to greater profitability (Agricultural Research and Extension Council of Alberta 2010). It involves multiple technologies and disciplines. Traditional practices manage whole fields as a single unit, whereas in modern precision agriculture, the farm management unit is shifted from whole fields to small areas within fields. Precision agriculture creates a systematic approach to managing variability by focusing on small areas within fields (Davis, Casady and Massey 2010). Table 1 shows examples of current precision agriculture technologies and their functions.

Table 1: Current precision agriculture technologies

Precision Ag Technology	Function
Field boundary mapping	Create georeferenced field borders.
Automated steering	Equipment follows predefined paths through field.
Lightbar/On-screen guidance	Navigation guided by GPS.
Yield monitoring	Collects georeferenced yield data at harvest.
Drain mapping	Determines best location for drainage systems from aerial photography.
Asset tracking	Accounts for various components of an operation.
Crop scouting	Georeference areas of interest in fields.
Variable-rate chemical application	Automatically adjusts chemical rates to predefined amounts (based on crop scouting results).
Variable-rate seeding	Automatically adjusts seeding rates to predefined amounts (usually based on soil zones and other data).
Variable-rate fertility and lime management	Automatically adjusts material application to predefined amounts (based on results from georeferenced soil samples and other data).
Remote Sensing	Data collected from a distance, usually with handheld devices, mounted on aircraft, or satellite-based.
GIS/GPS guided soil sampling	Assists in creating and locating sampling points/zones.

Sources: Data adapted from Agricultural Research and Extension Council of Alberta (2010) and Davis, Casady and Massey (2010)

Oliver (2010) provides a brief history of precision agriculture. She discusses that until the 1980s, farm management primarily dealt with fields as the management unit, meaning fields were evaluated as a whole and treated uniformly. The term “precision agriculture” was not commonly used until the mid-1990s. Before then, it was described using the phrases “site-specific crop management” or “site-specific agriculture”.

Early endeavors at precision agriculture usually consisted of an equipment operator with extensive knowledge of a field, adjusting inputs manually. The advent of the Global Positioning System (GPS) launched modern precision agriculture technologies (Cengage Learning 2013). GPS is a group of Earth orbiting satellites that was initially launched by the U.S. government for military applications. The introduction of GPS guidance in agriculture allowed for reliable positional information to be incorporated into farm management decisions (Agricultural Research and Extension Council of Alberta 2010).

Roving GPS signals offer 15 m accuracy and are typically not accurate enough for precision agriculture applications (Agricultural Research and Extension Council of Alberta 2010). A correction process known as Differential Global Positioning System (DGPS) is available to improve positional accuracy, reliability, and repeatability (Mullenix et al. 2009). In a DGPS, a fixed receiver calculates error associated with the GPS signal and then broadcasts the correction information to mobile receivers. Several free and subscription-based differential correction services are available for civilian use (Table 2).

The decisions made within precision agriculture are based on information, and this information is directly derived from data. Geographic information systems (GIS) play a vital role in creating, collecting, managing, and visualizing georeferenced data. The data within a GIS are stored and displayed in layers, adding a visual perspective for interpretation. A GIS also allows the computer to do the "visualization" by comparing layers and reporting the correlations and differences between them (Agricultural

Research and Extension Council of Alberta 2010). This allows for farming operations to evaluate present management decisions versus alternative management decisions. Common layers within an agricultural GIS include: field boundaries, soil survey maps, yield maps, elevation, soil nutrient/fertility levels, topography, remotely sensed data, crop scouting reports, handheld sensor data, and management zones (Agricultural Research and Extension Council of Alberta 2010; Davis, Casady and Massey 2010; Grisso et al. 2011).

Table 2: Differential correction services for precision agriculture

Correction Service	Provider	Operating Fee	Pass-to-Pass Accuracy	Static Accuracy
WAAS	Federal Aviation Administration (FAA)	No	8-12 in	> 2 ft
Beacon	U.S. Coast Guard	No	3-6 ft	3-6 ft
VBS	OmniSTAR	$800/year	< 40 in	< 40 in
XP		$800/year	+/- 6 in	+/- 8 in
HP		$1500/year	< 4 in	+/- 4 in
StarFire 1	John Deere	No	+/- 12 in	+/- 30 in
StarFire 2		$800/year	+/- 4 in	+/- 10 in
RTK	*Multiple Providers*	No	< 1 in	+/- 1 in
CORS	National Geodetic Survey (NGS)	No	< 1 in	+/- 1 in
Real-Time Networks	*Multiple Providers*	*To be determined*	< 1 in	+/- 1 in

Source: Mullenix et al. (2009)

One of the precision agriculture technologies attracting attention is variable-rate technology (VRT). VRT uses on-board computers paired with rate controllers or sensors to adjust input (seed, fertilizer, lime, pesticides, herbicides, etc.) rates as the applicator travels across the field. These systems are usually loaded with maps containing georeferenced input application rates and the amount applied depends on the acquired position from a GPS receiver. It is possible with certain controllers to adjust the rate of multiple inputs simultaneously. If georeferenced applied rate data is collected, this can be compared to intended application data to ensure that proper rates were distributed (Reetz 1999a).

VRT can be used to optimize farm management decisions related to input applications. The first VRT machines were produced by SoilTeq in the mid-1980s. They attempted to create a spreader that could change the blend and rate of fertilizer “on-the-go” (Oliver 2010).

VRT can help tackle the economic challenges facing agriculture today. Costs are rising for agricultural business inputs (e.g., seed, fuel, chemicals, lime, and fertilizers) and growers are looking for ways to save money. Utilizing variable-rate technology may reduce expenses by avoiding the unnecessary cost of applying excess material.

Using VRT, farming operations can not only lower application costs but also reduce the environmental impacts of over-fertilization (Davis, Casady and Massey 2010). There is growing concern about agricultural pollution of sensitive areas. Regulations in North Carolina and the Chesapeake Bay area (two contiguous areas), for example, call for stringent nutrient management programs to maximize environmental protection (National Association of State Departments of Agriculture Research Foundation 2001; Scientific and Technical Advisory Commitee 2004).

Ravensdown, New Zealand's largest manufacturer and distributor of fertilizers, helps farmers manage their fertilizer inputs using GIS and GPS guidance. These approaches have helped clients (farmers) reduce the impact of environmentally harmful resources whilst reducing their total fertilizer expenditures by up to 10 percent (Esri 2007). There are two methods of variable-rate application: sensor- and map-based (Grisso et al. 2011).

Sensor-based variable-rate application employs equipment mounted sensors to measure and record soil information or crop characteristics. As the equipment moves across the field, sensor data is continuously sent to the rate controller. Instantaneously, input needs are calculated and the controller adjusts the rate of the product "on-the-fly". This system is most commonly used for nitrogen applications. The sensor measures crop vigor and adjusts the nitrogen application rate accordingly; putting less nitrogen on healthy plants and more nitrogen on weaker plants.

Map-based variable-rate application pairs an onboard computer with an electronic product-delivery controller, each of which is usually mounted inside the cab. A prescription map, containing georeferenced application rates, is created beforehand using GIS software. The system is loaded with the prescription map and, using GPS readings, the controller changes the amount and/or kind of input according to the prescription map (Davis, Casady and Massey 2010). This system is most common when variable-rate is desired for fertilizer, lime, seed, herbicide, insecticide, fungicide, irrigation, or desiccation (Agricultural Research and Extension Council of Alberta 2010).

Variable-rate lime and fertilizer application are directly guided by soil pH and fertility datasets. This information is acquired by collecting soil samples and having them tested at an agronomic lab. The results of testing (soil test reports) supply information on the physical and chemical (fertility) properties of the samples. Table 3 shows a portion of the information reported by the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) lab. The accuracy of field representation can be maximized in the soil test report by using the most effective soil sampling method.

Table 3: Partial NCDA&CS soil test report attributes and their importance

Soil Test Report Attribute	Importance to Agriculture
pH	Optimum soil pH level improves crop performance and makes certain nutrients more available for plant use.
Lime Recommendation	Recommended rate of lime to optimize pH level.
Phosphorus, Potassium, & Nitrogen (Primary Nutrients)	Nutrients utilized in the largest amounts by crops.
Calcium, Magnesium, & Sulfur (Secondary Nutrients)	Essential for plant growth but required in smaller amounts than primary nutrients.
Copper, Manganese, Zinc, etc… (Micronutrients)	Essential for plant growth but required in smaller amounts than secondary nutrients.
Soil Class	Classification of soil as organic, mineral-organic, or mineral.

Sources: Data adapted from Snyder (2001) and Tucker (1999)

Thus, it is imperative for farming operations in these and other geographic regions to be as efficient as possible with fertilizer and lime management. Compared to traditional techniques, proper soil sampling methods paired with variable-rate fertilizer and lime management can reduce the risks associated with over-fertilization, and the resulting environmental harm (Davis, Casady and Massey 2010). The key to a successful variable-rate fertilizer and lime management plan is establishing effective soil sampling methods (Mylavarapu and Lee 2011).

There are various opinions throughout the country on which sampling method or methods are best at representing field fertility needs. Little research has been conducted in northeastern North Carolina on this topic. Based on personal observations of farming operations and numerous informal conversations with agricultural consultants in northeastern North Carolina, traditional composite and zone-based composite are the most popular sampling methods. It is important to evaluate multiple soil sampling techniques in northeastern North Carolina to help identify the best soil sampling method(s) for this area. In this study, multiple precision agriculture soil sampling methods and procedures are implemented and then evaluated on a farm in northeastern North Carolina. The working hypothesis for this study is that the fertility and lime needs of this farm will be best represented by a hybrid soil sampling method.

The remainder of this thesis consists of four chapters. Chapter 2 summarizes the common precision soil sampling methods and procedures, as well as, precision soil sampling guidelines for North Carolina. Chapter 3 provides an overview of the physical attributes of the study area, the sampling schemes used, and the method used to compare and contrast the sampling schemes. The results are presented in Chapter 4 and some broader discussion of their significance and some ideas for future research are offered in Chapter 5.

CHAPTER 2: RELATED WORK

The ultimate goal of soil sampling is to characterize the nutrient status of a field as accurately as possible, while also considering the associated costs (Dinkins and Jones 2008). In precision soil sampling, sample locations (point and/or zone) are georeferenced, allowing the soil test results to be correlated with spatial details of the sample. It is possible to establish georeferenced soil sampling locations using one of two processes.

The first process is to save soil sampling locations as the actual physical samples are being collected. This is accomplished using GPS equipment and mobile software. The advantage to this process is that no time is needed to plan, but it has the disadvantage that no other data is used to direct the creation of soil sampling locations, which limits its effectiveness.

The second process is to choose sample locations beforehand using GIS software. This software allows multiple datasets or layers to be visualized, which aids in establishing sampling locations. GPS equipment and mobile software are loaded with these locations and are used for guidance to these locations. This ensures that the physical samples are obtained from the pre-determined positions in the field. For precision soil sampling, this procedure is the most effective in the selection of sampling locations.

2.1 Random Composite Sampling vs. Point Sampling

Composite soil sampling consists of physical probes being taken at randomly chosen sites throughout an entire sampling area and combined into a single sample. It is suggested to travel a zigzag pattern within the sampling area when collecting probes for composite samples (Reetz 1999b; Hardy, Myers and Stokes 2008; Crozier et al. 2010). The soil test results from the sample are used to represent the entire sampling area. A disadvantage to composite sampling is that it poorly characterizes field variability, creating coarse maps with distinct, sharp divisions between sampled areas (Crozier and Heiniger 2001).

In point sampling, a sample location (point) is established and the physical sample is obtained within a specified radius from this point. Soil test results are linked to each sample point and interpolation methods are used to obtain values for the remaining unsampled areas of the field (Wollenhaupt, Mulla and Crawford 1997). Technically, point sampling can be considered a variation of composite sampling, but differs because it represents a single point, not an entire area.

Table 4 shows proposed advantages and disadvantages of point and composite sampling. The soil sampling methods discussed in the following sections (grid, management zone, and hybrid) can utilize both point and composite sampling to gather data.

2.2 Grid Soil Sampling Methods

Grid soil sampling subdivides a field into an arrangement of cells (usually squares) and a sample is taken from each of these cells (Mallarino and Wittry 2001). There are several sampling pattern schemes that might be considered in grid sampling. These include regular systematic point, staggered start point, systematic unaligned point, and random composite cell (Franzen 2011).

Table 4: Advantages and Disadvantages to Point and Composite Sampling

Type of Sampling	Advantages	Disadvantages
Point	Better for detecting patterns of field variability Surface maps can be created from soil test results	Close spacing required for estimates to be accurate Tends to be more expensive
Composite	Relatively inexpensive Results can be easily tracked from year to year Mostly reproducible	Large portions of the field may be over- or under-fertilized Creates coarse maps with distinct sharp divisions Generally better for determining needs for uniform application

Sources: Data adapted from Reetz (1999b), Franzen and Cihacek (1998), and Crozier and Heiniger (2001)

2.2.1 Point Methods

Regular systematic sampling (sometimes called cell center sampling) takes one sample from the center of each grid cell. This method was one of the most common approaches even before the rise of precision agriculture technology, because it allowed the person collecting the samples to use a tachometer or “step off” distances between sample points (Franzen 2011). Figure 1 shows an example of a regular systematic sampling schema. One soil sample would be taken from each of the center-aligned circles.

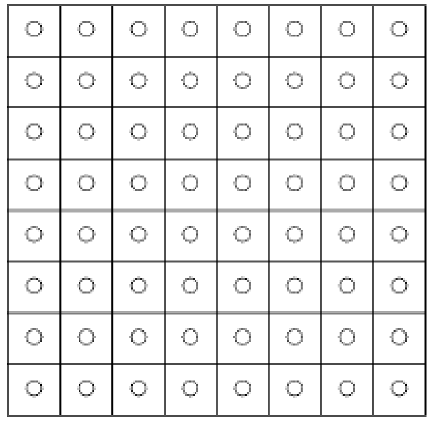

Figure 1: Regular systematic sampling grid scheme (Mylavarapu and Lee 2011)

In staggered start sampling (sometimes called triangular or diamond sampling), the start and end of each sampling rank are offset to compensate for systematic errors in one direction (Franzen 2011). These errors or biases are a direct result of past management practices. Past application of banded fertilizer may create "streaks" of higher nutrients from one end of the field to the other (Gelderman, Gerwing and Reitsma 2006). Errors can also occur from differentially applying manure, planting in the same direction year after year, inconsistencies in broadcast fertilizer spreading patterns, and variability of dry fertilizer pellet size (Franzen 2011).

The offset of the sample locations can be achieved by shifting the sample points one-half the distance from the cell center to the edge of the cell (Midwest Laboratories 2009). This shift should occur in the opposite direction of past management practices that have the potential to create biased results.

Figure 2 shows an example of a staggered start sampling scheme, where the black dots represent sample locations. In this example, past fertilizer applications would have been in a "top to bottom" direction. If sampling locations are aligned in this direction, error could be introduced into the sampling results. Therefore, the offset of sampling locations are "left" and "right" of the grid center.

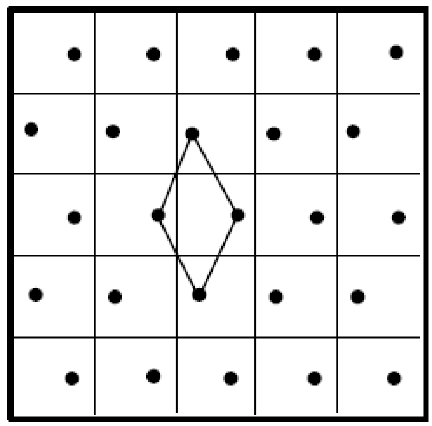

Figure 2: Staggered start grid sampling scheme (Midwest Laboratories 2009)

In systematic unaligned sampling (or sometimes called systematic random sampling), GIS software is used to create a random sample location in each grid cell (Interstate Technology & Regulatory Council 2012). This approach compensates for the same systematic errors as the staggered start approach, but is slightly different because it compensates in two directions (Franzen 2011). Figure 3 shows a potential scheme for implementing this particular method. Franzen (2011) has noted that the systematic unaligned sampling approach is the most common method used by commercial grid samplers.

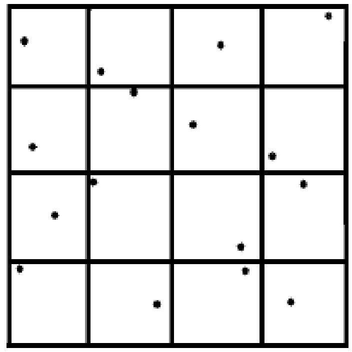

Figure 3: Systematic unaligned grid sampling method (Interstate Technology & Regulatory Council 2012)

2.2.2 Random Composite Cell Sampling Method

Random composite cell sampling (or grid-cell sampling as it is sometimes called) is accomplished when soil probes are taken from random locations within a grid cell, and one composite sample is created from these probes (Dinkins and Jones 2008). Figure 4 shows one cell of a grid with the random composite cell sampling method. A physical probe is taken at each black dot and then combined into a single, composite sample. Note the zigzag pattern traveled to obtain the sample.

2.3 Management Zone Sampling Methods

An alternative to grid soil sampling is management zone sampling (also called directed or smart sampling). Actual management zones are established using a variety of resources and/or datasets. These include soil surveys, past yield data, remote sensing imagery, landscape/topography, elevation, electrical conductivity, and/or past knowledge of field characteristics (Thompson et al. 2004; Gelderman, Gerwing and Reitsma 2006;

Agricultural Research and Extension Council of Alberta 2010). Correlations within these datasets can be discovered using GIS software, leading to the formation of areas of interest or management zones. As in all applications of GIS, the dataset integrity needs to be analyzed before using these data to guide important management decisions.

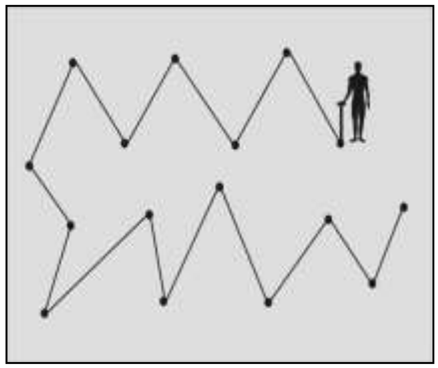

Figure 4: Random composite cell sampling (Hardy, Myers and Stokes 2008)

Unlike grid sampling, the shape, size, and number of management zones will vary depending on field variability and the information derived from datasets (Dinkins and Jones 2008). When compared to grid sampling, management zone sampling tends to reduce the sample size and cost of sampling, while still supplying accurate information on field fertility needs (Mallarino and Wittry 2001).

Once management zones are created, they can be sampled using point or composite sampling. The procedures for each of these are the same as described for grid sampling. Each point sample should represent a certain amount of area. Therefore, the number of point samples per zone will vary depending on the size of the zone. The number of composite samples should be equal to the number of management zones.

Figure 5 shows an example of management zone point sampling. The user in this example used soil survey and yield data to define the management zones and then selected sample point locations within each zone. A radius of 20 feet around each sample point is used for probe collection.

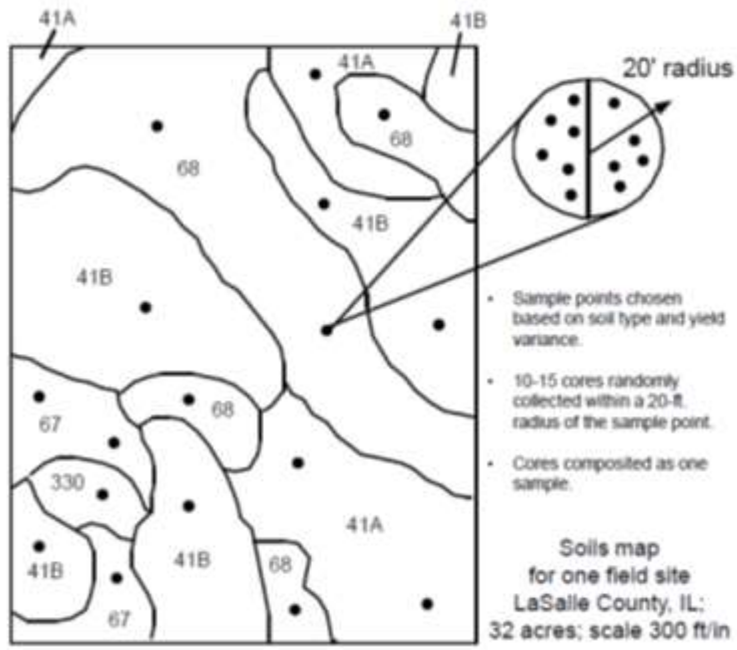

Figure 5: Point sampling for management zones (Midwest Laboratories 2009)

Figure 6 shows an example of management zone composite sampling. Management zones are displayed as various shades of gray. For each management zone, a composite sample is obtained by traveling in a zigzag pattern to collect a probe at each black dot. These probes are then combined into single samples.

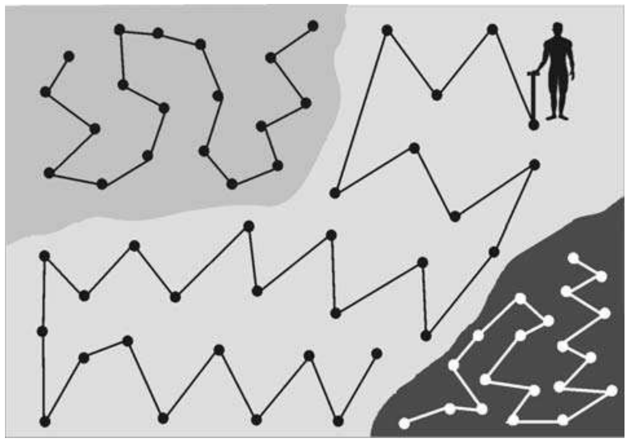

Figure 6: Random composite sampling for management zones (Hardy, Myers and Stokes 2008)

2.4 Grid/Management Zone Hybrid Soil Sampling Method

A third option for soil sampling is the grid/management zone hybrid method. For this method, management zones are created using various data sources as described previously (Section 2.3). These management zones are used as a basemap and a grid is overlaid onto this basemap. Final sampling areas are defined according to basemap properties (Crozier and Heiniger 2001). Figure 7 shows an example of the hybrid method. Figure 7a shows the soil survey being used as a basemap. Next, a grid is overlaid (Figure 7b) and split along the soil division of the basemap (Figure 7c).

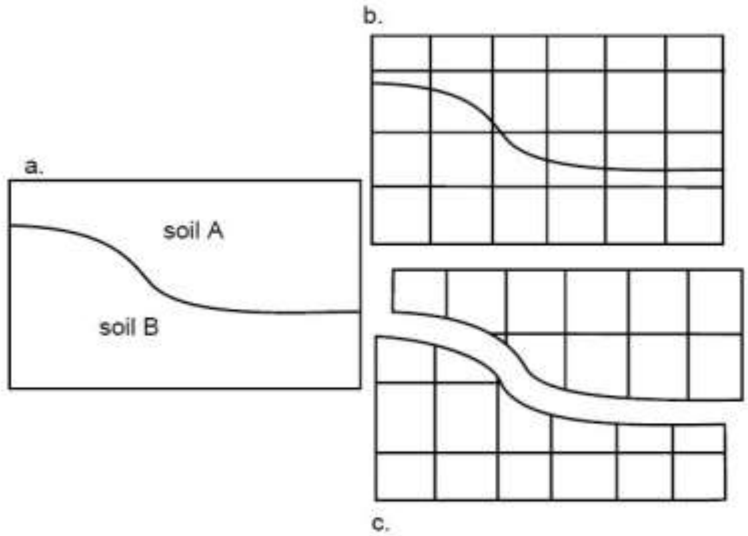

Figure 7: Process for creating hybrid grid/management zone scheme (Crozier and Heiniger 2001)

2.5 Traditional Soil Sampling Methods

Whole field composite sampling has been traditionally used as the best way to sample fields, and is still used by numerous farming operations. Soil probes are collected from various locations throughout the entire field and combined into one sample (refer back to Figure 4 for a visual representation, with the rectangle representing the whole field). The advantage to this method is that it tends to be quick and inexpensive, but there are some major drawbacks. This sampling technique can result in over- or under-fertilization on large areas of the field, potentially causing financial losses either from applying extra, unneeded nutrients or from yield loss due to under-fertilization (in addition to unnecessary and undesirable environmental impacts) (Gelderman, Gerwing and Reitsma 2006).

2.6 Precision Soil Sampling Guidelines

Guidelines for soil sampling have been established for multiple areas of the United States. These guidelines not only take into account the representation of the field that is obtained from sampling, but also the time and resources expended. Since this study will be conducted in northeastern North Carolina, the protocols established by the North Carolina State University Extension Agency and the North Carolina Department of Agriculture and Consumer Services are the best reference for the work at hand (Crozier and Heiniger 2001; Hardy, Myers and Stokes 2008). These guidelines can be summarized as follows:

1. All sample cores depths should be 6-8" for cultivated land and 4" for established no-till.
2. The number of probe cores should be:
   a. 8-10 per grid sample;
   b. 10-15 per management zone; and
   c. 15-20 for a traditional composite sample.
3. Grid size/density should be 2-2.5 acres, with 2.5 acres the most typical size.
4. Radius for probe collection around a point sample is not specified.
5. Size for management zones is not specified.

The protocol from another agricultural initiative in North Carolina was consulted to establish a value for the sample point radius. The North Carolina Hops Project (2010) conducts research on the potential of and key issues related to growing hops in North

Carolina. Initial grid-point soil sampling was performed to reveal soil variability at the research site. The protocol for the collection of samples around these point samples was 3 m (approximately 9-10 ft). Various sources from other geographical regions have also recommended or utilized a similar sample point radius (Wollenhaupt, Mulla and Crawford 1997; Reetz 1999b; Midwest Laboratories 2009). This value was replicated in this study.

Although a definite size for management zones is not given, the North Carolina Department of Agriculture and Consumer Services recommends using approximately 5 acre sampling areas for fields over 15 acres to evaluate variability (Hardy, Myers and Stokes 2008). Tidewater Agronomics, Inc. is an agricultural consulting company based out of Camden, North Carolina. They conduct management zone sampling and also use an approximate size of 5 acres per sample as their protocol. Taking this recommendation and protocol into consideration, the management zones in this study were established as contiguous areas of 5 acres or less.

CHAPTER 3: METHODS AND DATA SOURCES

North Carolina can be divided into three physiographic sections: the Mountains, the Piedmont, and the Coastal Plain (Figure 8). The Coastal Plain is the eastern-most region in North Carolina, with its waters and lands comprising approximately 45 percent of North Carolina. Elevation in this region ranges from sea level in the east to 300 feet above sea level near the border with the Piedmont (Gade et al. 2002).

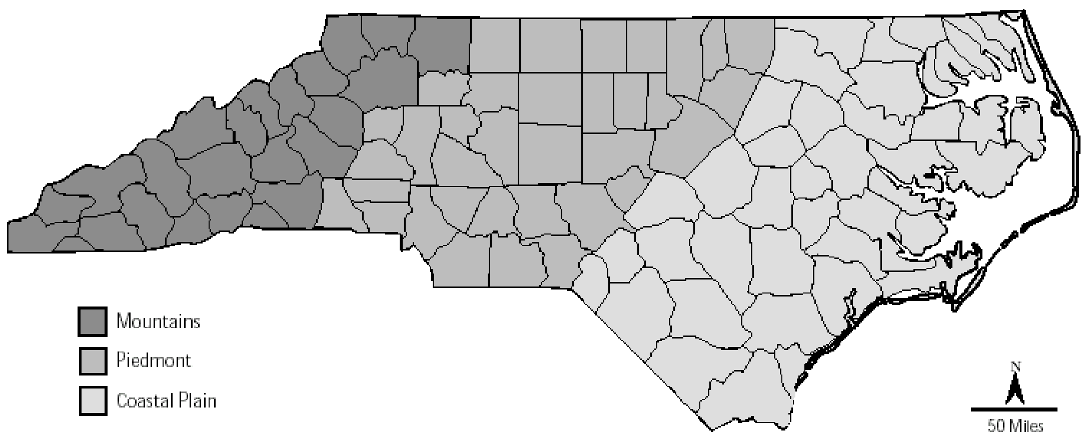

Figure 8: Physiographic regions of North Carolina (North Carolina Department of the Secretary of State 2012)

The Coastal Plain, in turn, can be roughly divided into three sections: the Tidewater area, the Atlantic Coast Flatwoods, and the Southern Coastal Plain (Crouse 2011). The interior portion of the Coastal Plain (the Atlantic Coast Flatwoods and the Southern Coastal Plain) is gently sloping and naturally well drained, whereas the Tidewater area is mainly flat and swampy (State Climate Office of North Carolina 2012).

The Tidewater region of the Coastal Plain is a narrow strip of land that extends approximately 30 to 50 miles inland along the Atlantic Ocean and includes the barrier islands, as well as various bodies of water. Figure 9 shows the location of the Tidewater region (and the Atlantic Coast Flatwoods and the Southern Coastal Plain combined and shown as the Inner Coastal Plain in this particular map). The physical soil samples for this study were obtained from the Tidewater region of the Coastal Plain.

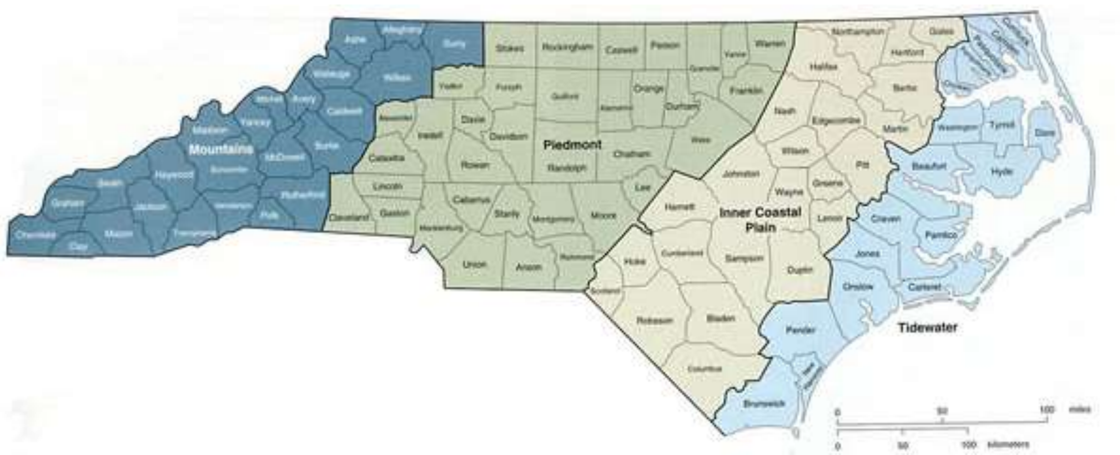

Figure 9: Sub-regions of North Carolina (Bluvias and DeMarco 2007)

3.1 Climate

North Carolina is located in a warm temperate zone and has a humid, subtropical climate. It has hot humid summers and mild winters, with frequent rain showers occurring in most areas. There are no distinct wet and dry seasons in North Carolina. Precipitation is usually greatest in summer, with July being the wettest month. Autumn is usually the driest season, with November usually being the driest month. East of the mountains, precipitation normally averages 40-55 inches per year (State Climate Office of North Carolina 2012).

In the summer, the Coastal Plain is typically cooler than inland locations with an average temperature in August just below 90ºF (Bencivenga 2012). Severe thunderstorms commonly affect this region in the warmer months, along with an occasional tropical storm or hurricane.

3.2 Soil Characteristics

Soils of the Coastal Plain are relatively uniform compared to the Piedmont. They consist of soft sediment, with little or no underlying rock at the surface (State Climate Office of North Carolina 2012). Most soils are deep and coarse or sandy in texture with heavier sandy clay subsoil (Gade et al. 2002). Over thousands of years, ocean and river deposits have been laid down to make sand and clay the primary sediment types in this region (Gilliam, Osmond and Evans 1997).

Soils in the Tidewater region are usually 3 to 4 feet in depth, shallower than in the remainder of the Coastal Plain. Many soils in the Tidewater region are classified as organic and tend to be poorly drained. Moderately well to well drained (more mineral/sandy) soils can be found along the edges of flats and slopes leading down to a body of water (Gilliam, Osmond and Evans 1997). They range in color from the dark hue of highly organic soils to the tans of sands (Gade et al. 2002).

3.3 Agricultural Practices

The Coastal Plain of North Carolina has deep soils, abundant flat land, and a long growing season with plenty of sunlight. This area routinely grows a wide variety of crops, including soybeans, wheat, corn, cotton, potatoes, sweet potatoes, peanuts, cucurbits, and other small grains. Much of the area is irrigated, even though precipitation is normally sufficient for plant growth. This abundance of moisture through irrigation and natural precipitation allows for several crops to be harvested twice in the same calendar year (State Climate Office of North Carolina 2012).

3.4 Research Location

The research site for this study is located on a farm in Camden County, near the community of South Mills, which is part of the Tidewater region of northeastern North Carolina. This farm uses a continuous planting rotation of field corn and double cropped wheat and soybeans. The section of the farm selected for this study is 44.76 acres and contains multiple soil types (Figure 10). It was planted in field corn for the 2012 growing season, and double cropped wheat and soybeans in 2013.

3.5 Sampling Scheme Creation

The primary goal of this study was to evaluate the effectiveness of sampling methods in representing field lime and fertility needs. The nine sampling methods discussed previously were chosen for evaluation at this research location because they are common methods used throughout the US. Before samples could be physically collected, the sampling schemes needed to be created.

Figure 10: Research location map showing soil survey map units

3.5.1 Traditional Sampling Scheme

As discussed previously, whole field composite sampling has been the sampling method of choice for many farming operations. For this study, the research area was divided along the ditches and a composite sample was taken from each of these six sections. This sample procedure is shown in Figure 21.

3.5.2 Grid Sampling Schemes

Using the recommendations for North Carolina discussed earlier (Crozier and Heiniger 2001; Hardy, Myers and Stokes 2008), a 2.5 acre grid size was used in this study for the grid-based sampling schemes. This grid size is considered the industry standard and is also incorporated in grid sampling recommendations throughout other regions of the US (Mallarino and Wittry 2001; Thom et al. 2003; Gelderman, Gerwing and Reitsma 2006; Ferguson and Hergert 2007; Midwest Laboratories 2009; Grisso et al. 2011; Peters and Laboski 2013).

The 2.5 acre grid size was slightly modified to accommodate the dimensions and physical placement of ditches within the field. The resulting grid size (for full sized grid blocks) is approximately 2.58 acres. Figure 11 shows the final grid structure. From this, the grid sampling procedures (center point, staggered start, random point, and composite cell), used to collect physical samples at the research location, were created. These final procedures are illustrated in Figures 22 through 25.

Esri's ArcGIS software was utilized to create the center and random point sampling procedures, using the "Feature to Point" and "Create Random Points" tools, respectively. AgStudio (agricultural-based GIS software created by MapShots) aided in creation of the staggered start and composite cell sampling procedures.

3.5.3 Management Zone Sampling Schemes

The purpose of establishing management zones is to potentially isolate areas of variance, while keeping in mind the number of samples to be physically taken. Management zone soil sampling incorporates information supplied from various data sources to guide the creation of a sampling scheme. For this study, management zones were created by considering areas of soil change along with areas of significant yield difference. This was accomplished by using the US Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) soil survey as well as 2012 harvest data, recorded by the combine's yield monitor.

Figure 11: Final grid structure for study site

The soil survey was used as the foundation layer for management zone delineation. Overlaying the harvest data onto the soil survey, surprisingly, showed that areas of significant yield difference very nearly correlated with a portion of the already established soil survey regions. These soil survey regions were slightly adjusted to accommodate neighboring areas of similar yield.

Other sections of the research location contained a range of yield measurements within a single soil survey region. Loosely distinguishable areas of similar yield could be defined within these single survey regions and were divided accordingly, while not exceeding the previously discussed recommendation of 5 acres per management zone. These modifications can be seen in Figure 12. The final management zone sampling procedures are illustrated in Figures 26 and 27.

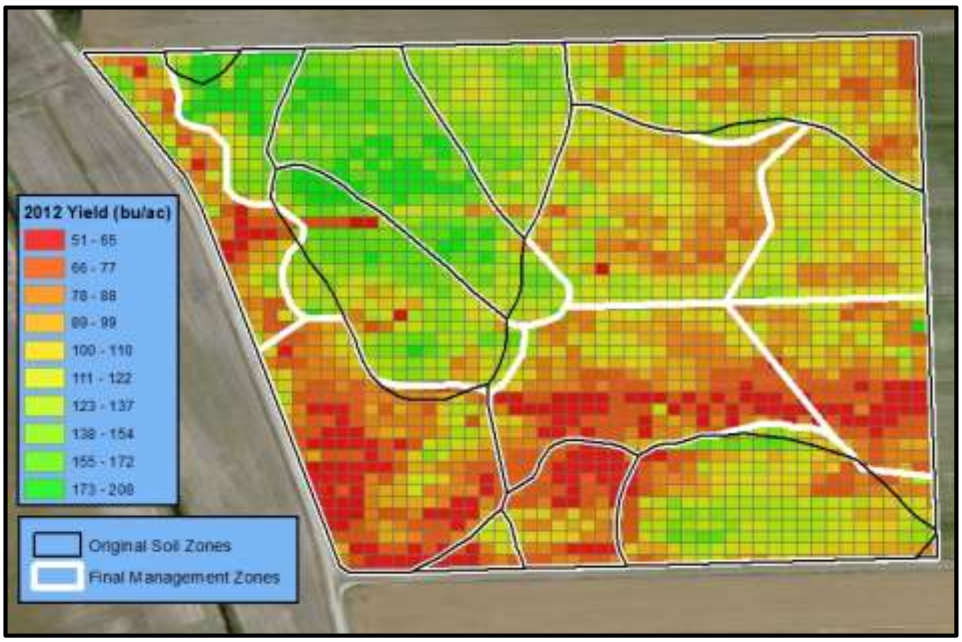

Figure 12: Creation of final management zones

3.5.4 Hybrid Sampling Schemes

To create the hybrid sampling schemes, the final management zones (Figure 12) and the 2.5 acre grid (Figure 11) were intersected. This intersection divided the management zones into smaller polygons. Obtaining physical samples from all of these polygons would create a sizeable workload because a large number of diminutive polygons were created. To mimic a realistic soil sampling scheme, polygons 0.25 acres or less were merged with a neighboring polygon without hindering the general grid structure of the scheme. Figure 13 shows all of the polygons created by the intersection mentioned above. Neighboring polygons of the same color were merged to form the hybrid sampling scheme. The final hybrid sampling procedures can be seen in Figures 28 and 29.

Figure 13: Hybrid sampling scheme creation

3.6 Physical Sample Collection

Physical soil samples for this study were collected on 17-18th November, 2012. The weather on these two days was partly cloudy and windy (average 15-20 mph; gusts up to

30 mph) with drizzle on the 18th November. The average temperature was 53ºF. As seen in Figure 14, the study area had been cultivated but the 2013 wheat crop had not been planted at the time of collection.

Figure 14: Field condition

To ensure consistency within each sampling procedure, an automated soil probe (Figure 15) was used to collect the soil samples (Figure 16). It was calibrated to obtain six inch sample cores and this depth was regularly examined throughout the sample collection process (Figure 17).

The samples were processed for lab analysis on the same days that they were collected. The varying colors of the soil samples can be seen in Figures 18 and 19. All samples were shipped to the NCDA&CS soil lab in Raleigh, North Carolina on 19th November, 2012. NCDA&CS soil test results for each sample procedure can be seen or downloaded at http://sdrv.ms/12VjQQH.

Figure 15: Automatic soil sampler mounted on ATV

Figure 16: Automatic sampler obtaining a soil probe

Figure 17: Assuring a 6" sample core: a full 6” core was normally obtained in the study samples. In the above photograph, the lower ½” of the core was lost due to the abrupt stop from using the “Emergency Stop/Kill Switch” button.

Figure 18: Processing the samples

Figure 19: Processing the samples

3.7 Method Used to Compare Sampling Procedures

No soil sampling method will create a perfect representation of a field's fertility needs, but representation tends to be more accurate when sampling density is increased (lower acres per sample/higher number of samples per acre). Increases in sample density cause the sampling process to be much more intensive in time and resources, making less dense methods (i.e. the methods previously discussed) more practical and appealing for sample collection (Franzen 2011).

A previous study from Illinois attempted to establish a soil sampling density that would be a "true" representation of field fertility needs (Franzen and Peck 1995; Franzen 2011). This study examined systematic aligned grid sampling at densities of 220 feet (1 acre) and 330 feet (2.5 acres), and determined that a grid sampling density of 220 feet was the best representation of fertility needs. Other research has concluded similar results (Wollenhaupt, Wolkowski and Clayton 1994; Ferguson and Hergert 2007). Therefore, the 1 acre systematic aligned grid was replicated in this study (Figure 20) as a basis for comparison and control ("gold" standard) in evaluating the effectiveness of each of the previously discussed sampling methods. The samples for this 1 acre method were obtained and processed in the same time frame as the other sampling methods.

Figure 20: One acre systematic aligned sampling procedure used as "gold" standard

CHAPTER 4: RESULTS AND DISCUSSION

The NCDA&CS soil results for each sample were linked and saved as attributes within each sample procedure layer using AgStudio. The attributes directly involved in precision fertility and lime management are the pH, the Phosphorus-Index (P-Index), and the Potassium-Index (K-Index). A general summary of the importance of these attributes in agriculture was provided in Table 3. For simplicity purposes, the pH attribute was chosen as the focus for this study because soil pH is directly correlated with the lime applications delivered by growers.

4.1 Measurements

Table 5 offers a summary of the pH results and the corresponding map results for each sampling procedure are presented in Figures 21-30. The minimum and maximum pH show large variability across the sampling methods in this study, but the differences across the mean pH values are minimal. When compared to the "gold" standard (i.e. the one acre grid), the mean pH values estimated with the other sampling methods are similar, with six falling within a ±0.2 unit difference from the mean pH of the one acre grid. The largest mean pH difference from the one acre grid was just 0.4 pH units lower.

The statistics summarized in Table 5 suggest there were three sets of sampling methods that produced similar results: (1) the center point, staggered start, and composite management zone sampling methods; (2) the random point, hybrid point, and hybrid composite methods; and (3) the management zone point and 1 ac. grid generated roughly similar minimum, maximum, and mean pH values. However, a quick perusal of the maps corresponding to these sampling methods points to substantial within field variability.

Table 5: Summary of sample results

Sampling Method	**Map Result**	**Number of Samples Taken**	**Minimum pH**	**Maximum pH**	**Mean pH**
Traditional	Figure 21	6	5.8	6.2	6.0
Center Point	Figure 22	20	5.4	6.5	6.0
Staggered Start	Figure 23	20	5.5	6.3	5.9
Random Point	Figure 24	20	5.1	6.6	5.7
Composite Cell	Figure 25	20	5.6	6.8	6.0
Management Zone Point	Figure 26	14	5.5	7.4	6.0
Management Zone Composite	Figure 27	14	5.3	6.2	5.8
Hybrid Point	Figure 28	34	5.0	6.8	5.9
Hybrid Composite	Figure 29	34	5.3	6.7	5.8
1 Ac. Grid	Figure 30	43	5.2	7.5	6.1

Visually, the pH result maps reproduced in Figures 21-30 show that some of the sample procedures produced similar results in specific parts of the study field. The management zone point and 1 acre grid, for example, pointed to an area of high pH in the northeastern part of the field, but none of the other sample methods produced the same result. Similarly, the random point, composite cell, hybrid composite, and 1 acre grid sampling methods pointed to an area of high pH approximately midway along the western boundary of the field. The other sample methods in this study found nothing unusual in this part of the field.

Figure 21: Traditional sampling pH results

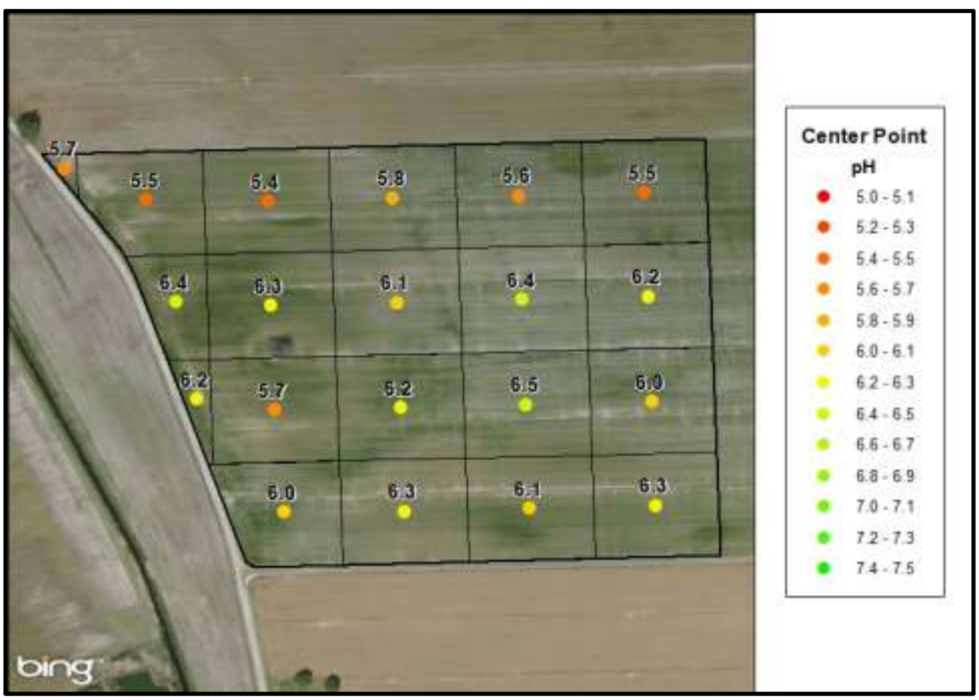

Figure 22: Center point sampling pH results

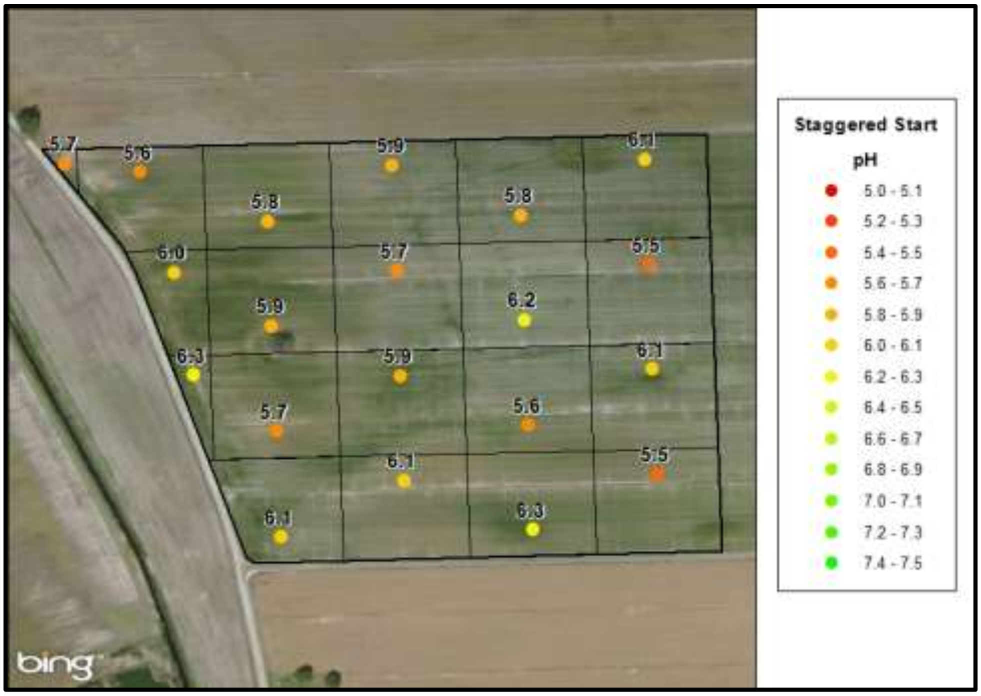

Figure 23: Staggered start sampling pH results

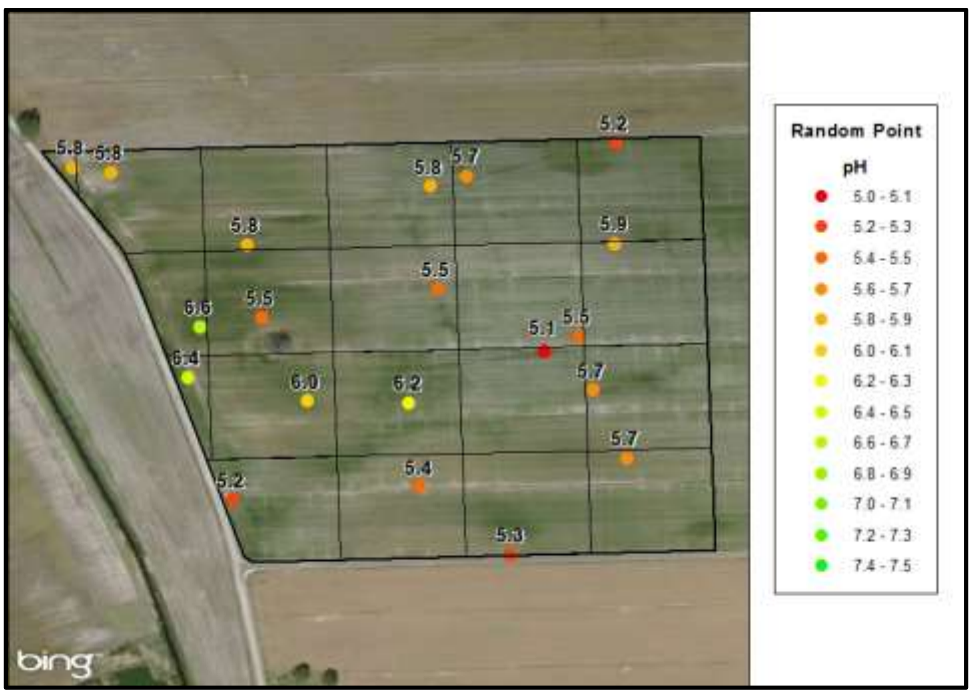

Figure 24: Random point sampling pH results

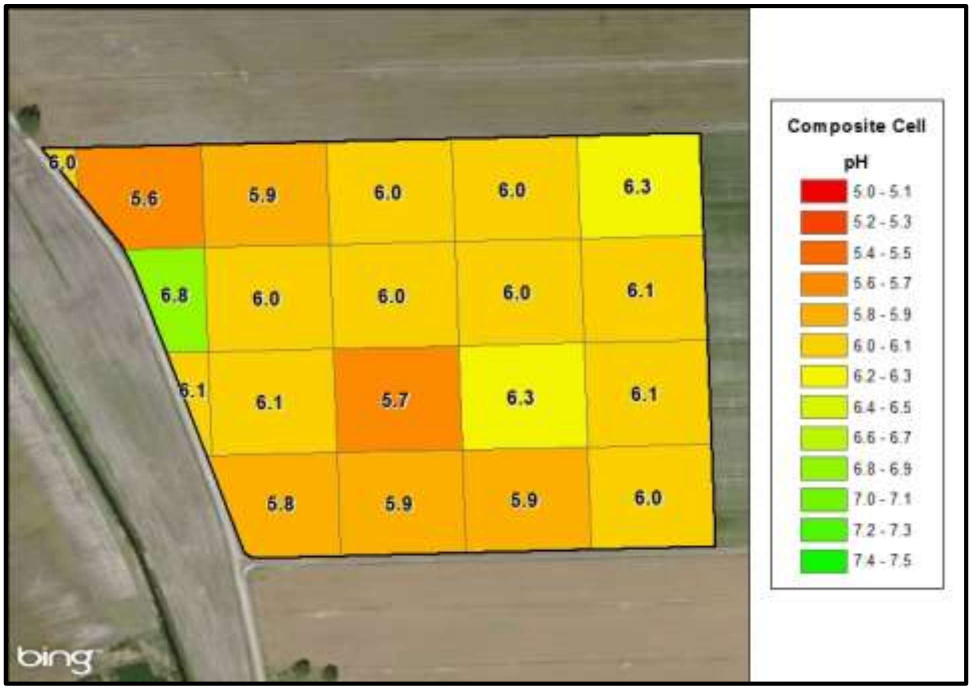

Figure 25: Composite cell sampling pH results

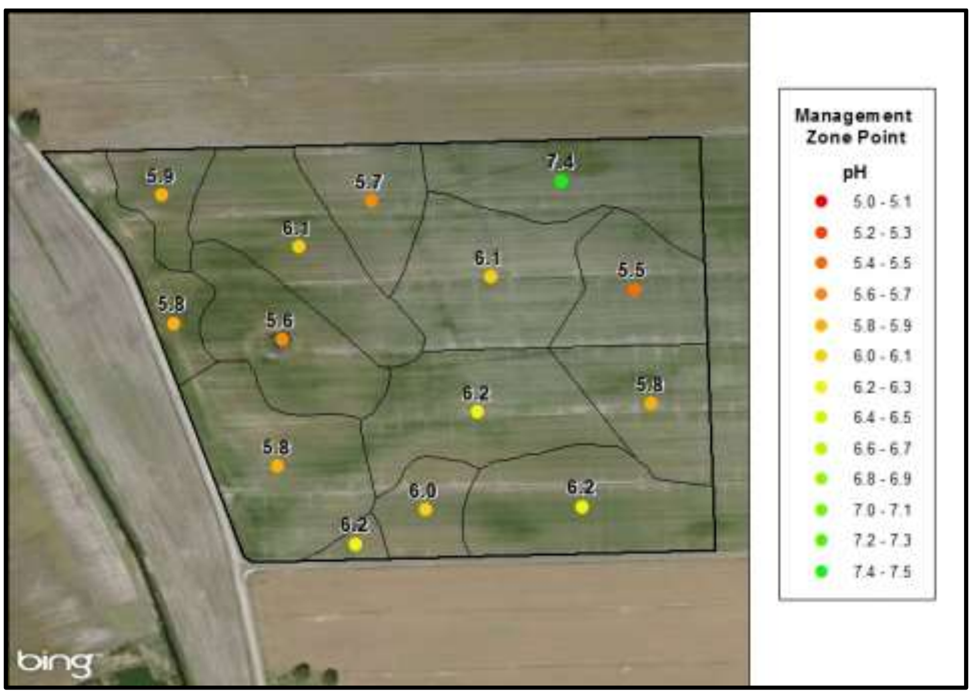

Figure 26: Management zone point sampling pH results

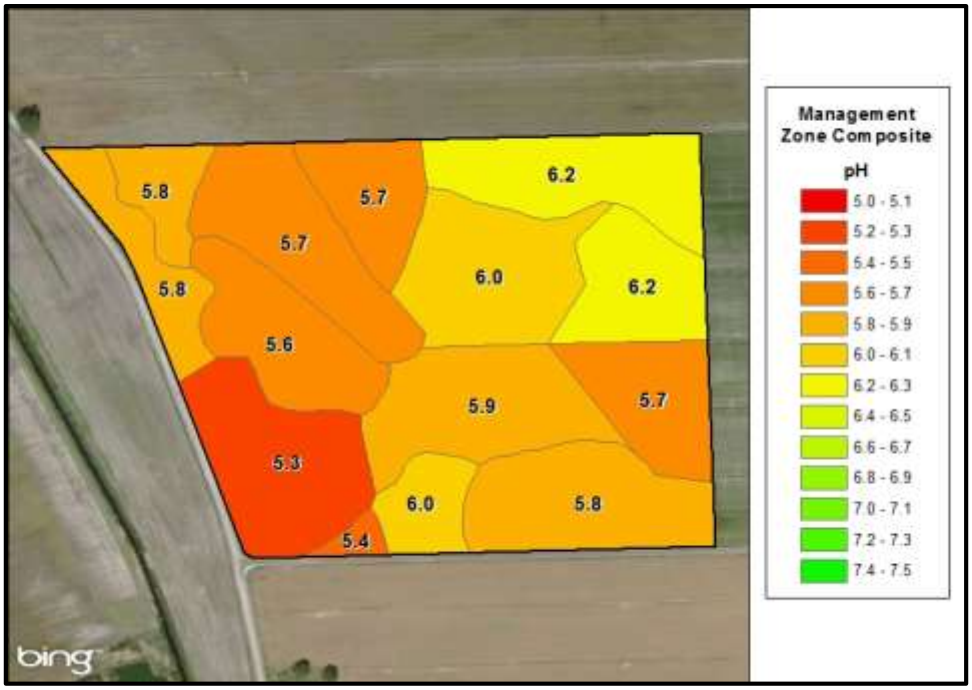

Figure 27: Management zone composite sampling pH results

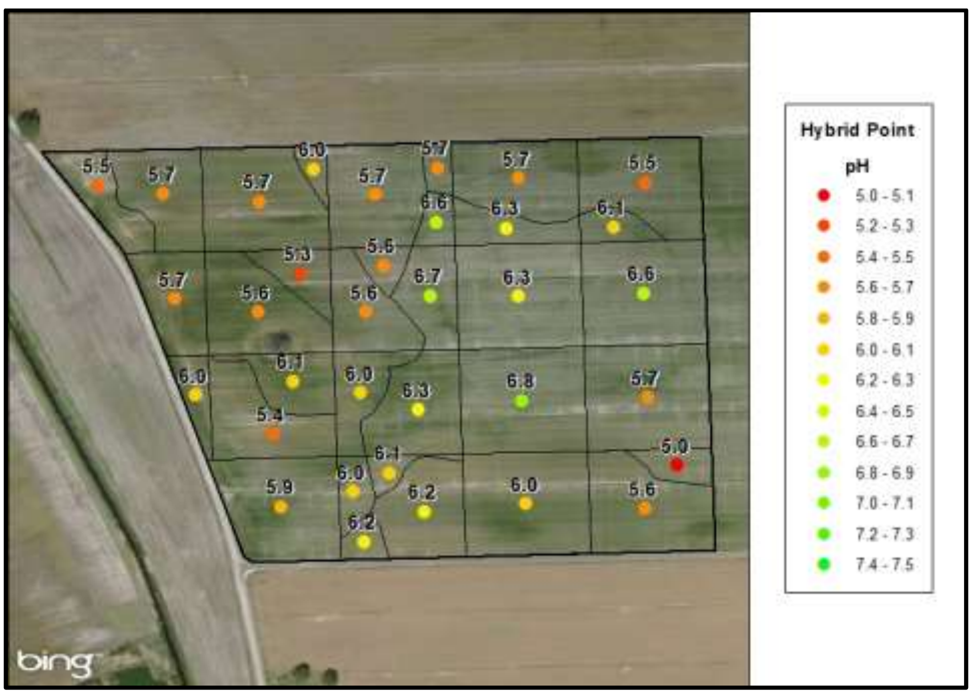

Figure 28: Hybrid point sampling pH results

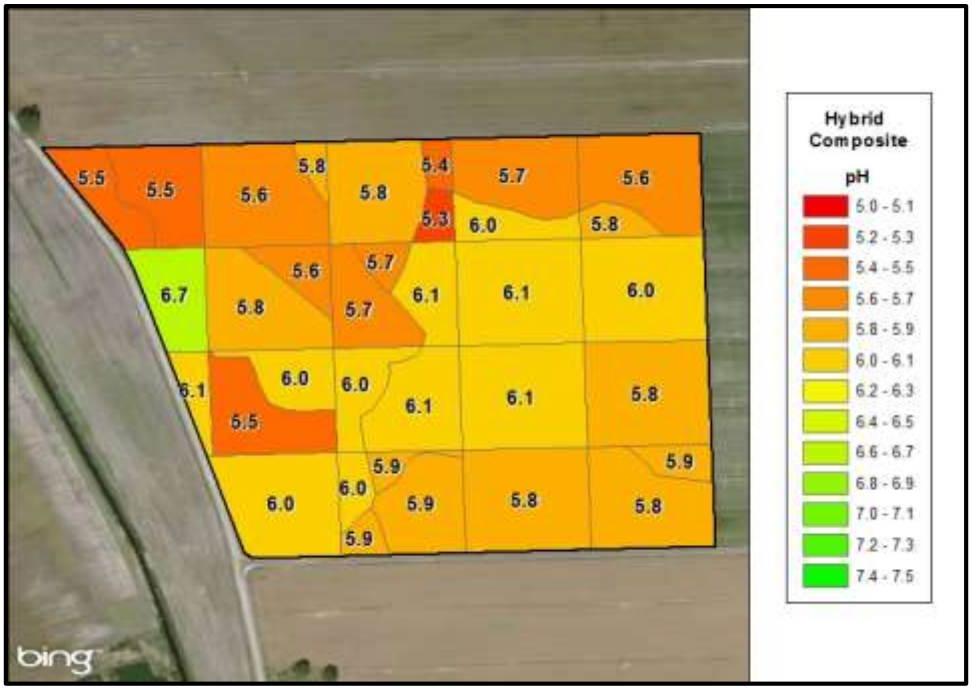

Figure 29: Hybrid composite sampling pH results

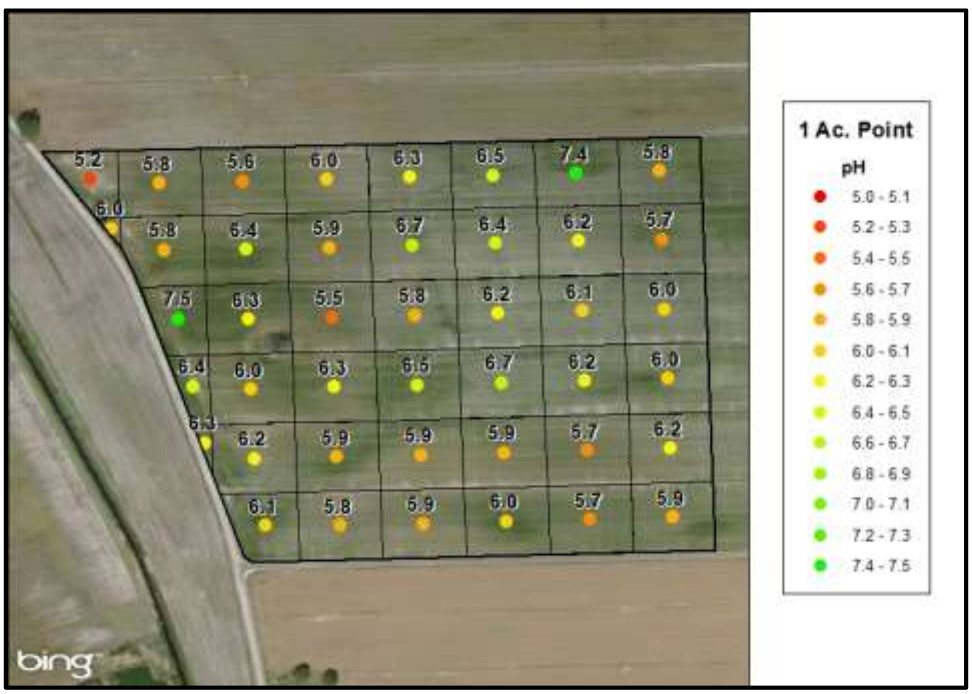

Figure 30: 1 acre grid point sampling pH results ("gold" standard)

The two sampling methods that are the most visually different from the others are the center point and random point (Figures 22 and 24). The random point sampling method shows lower pH values in much of the field, whereas the center point shows the opposite. When compared to the other sampling methods, the center point method produced higher pH values over much of the research area.

Visually observing the study field as a whole, the composite cell, management zone composite, and hybrid composite sampling approaches generated the most similar results. For these sampling methods, most of the field was represented with roughly similar spatial patterns of pH values ranging from 5.6 to 6.1 (cf. Figures 25, 27, and 29).

Based on the map observations, the effectiveness of the traditional method in representing the pH values of the field can be questioned. When visually compared to the "gold" standard, the 1 acre grid shows a wide range of pH values in all six of the sample strips of the traditional method (Figures 21 and 30). Visually, one can see that this would provide an inadequate representation of the field for the purpose of making fertilizer and lime recommendations.

Precision agriculture is concerned with describing patterns of variability across a field. The effectiveness of each sampling method to represent the true patterns of variability needs to be evaluated. This can be accomplished by comparing each sampling method against the "gold" standard.

To achieve this comparison, the sample method and the "gold" standard method were merged into a single layer using the "Intersect (Analysis)" tool in ArcGIS. This tool allowed each of the resulting polygons to be assigned the two pH values from the source sampling methods. The difference in pH value from the “gold” standard, for each resulting polygon, was calculated and these differences were classified into a series of ranges. The ranges used and the percentage of the field covered by these differences in the study field are reported in Table 6. This approach assumed that point samples were representative of the zones or grid cells used to organize the sample designs (although this assumption was relaxed when selected sample values were interpolated to a variety of outcomes in Section 4.2).

Overall, the percentages reported in Table 6 show substantial differences between the sampling methods. Perhaps the biggest similarity is that all of the sampling methods reported the largest percentage of acreage having pH values smaller than the 1 acre grid (larger percentage in the ranges below “0”).

Table 6: Difference of pH units estimated with the “gold” standard and each of the other sampling methods expressed as percentage of the field

		Figure								
		21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Difference in pH units from “gold standard”	**0.5 or larger**	4.1	10.3	2.2	2.6	8.4	17.3	4.0	9.9	1.1
	0.3 to 0.4	12.6	18.3	13.1	1.9	8.7	10.8	2.4	10.0	5.7
	0.1 to 0.2	22.8	14.6	13.7	4.5	20.3	12.9	19.2	17.6	13.4
	0	15.2	6.9	8.6	12.4	10.1	7.4	9.8	5.1	11.3
	-0.2 to -0.1	20.9	18.3	21.2	12.9	22.5	12.8	15.6	18.8	26.5
	-0.4 to -0.3	7.6	11.4	13.5	13.9	15.7	23.3	13.0	14.1	18.6
	-0.5 or larger	16.8	20.2	27.8	51.9	14.3	15.5	36.1	24.4	23.4

The percentages reported in Table 7, on the other hand, show the spread of pH values either side of the zero difference result. These results suggest that the traditional

(Figure 21), composite cell (Figure 25), and hybrid composite (Figure 29) sampling methods produced the best results and that the random point sampling method (Figure 24) produced the least satisfactory results. Earlier, after visually comparing the pH maps, the effectiveness of the traditional sampling method (Figure 21) was questioned. Surprisingly, this sampling method produced the best results in Tables 6 and 7, recording the highest percentage of acreage (15.2 percent) with no difference from the 1 acre grid ("0" range in Tables 6 and 7) and the highest percentage of acreage falling within ±0.2 and ±0.4 pH unit differences from the 1 acre grid, with values of 58.9 and 79.1 percent, respectively. The random point sample method (Figure 24), on the other hand, looked to produce the worst results based on the values reported in Tables 6 and 7. In this method, 78.7 percent of the research area acreage had pH values smaller than the pH values in the 1 acre grid (negative values in Table 6) and more than one-half of the acreage within the study field fell at least -0.5 pH units away from the pH results produced with the 1 acre grid sampling method. Table 7 shows that the random point sampling method had the smallest percentage of research area acreage falling within ±0.2 and ±0.4 pH unit differences from the 1 acre grid. This seems to correspond with the visual observations of the random point sample method discussed earlier.

The results presented thus far rely on the assumption that the point samples represent the areal units used to construct the sample designs. This assumption may not be correct, especially in the case of the grid point methods. The purpose of sampling is to collect a relatively small and finite number of soil samples that characterize the variation of pH and other attributes in a field. In this study, soil survey mapping units and yield maps guided delineation of the sampling units used in the management zone and hybrid methods, but the grid procedures had no guidance. Given this approach, the management zone and hybrid methods should produce better results but thus far, there is little evidence to support this hypothesis.

Table 7: Absolute differences of pH units estimated with the “gold” standard and each of the other sampling methods expressed as percentage of the field

		Figure								
		21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Difference in pH units from “gold standard”	0	15.2	6.9	8.6	12.4	10.1	7.4	9.8	5.1	11.3
	$\leq \lvert 0.2 \rvert$	58.9	39.8	43.5	29.8	52.9	33.1	44.6	41.5	51.2
	$\leq \lvert 0.4 \rvert$	79.1	69.5	70.1	45.6	77.3	67.2	60.0	65.6	75.5

4.2 Interpolation Results

In hopes of creating an even better representation of variability within the study field, the point data were interpolated. Interpolation provides measurements for unsampled locations based on the results of the sampled points, creating continuous measurements across a study site. In this study, interpolation was achieved using AgStudio’s “Layer Surfacer” tool, in which the interpolation method used is Inverse Distance Weighting. The parameters for this tool were set to the following values:

1. Search Radius: 500 ft (this is the distance from each cell that was searched for measured values)

2. Plateau Radius: 0 ft (this value was used to keep close values within dense data from overwhelming the results; i.e. as might happen with harvest data)
3. Weighting: 2 (determines the influence of nearby measured locations versus measured locations further away; the value of “2” means the inverse square of the distance was used as the proximity and distance weighting measure in this work)
4. Cell Size: 45 ft. (the cell size used for resulting maps)

The 45 ft cell size was chosen due to the application equipment typically used in this region of North Carolina. Informal conversations with fertilizer companies and consultants in this region showed the most common swath of application to be approximately 45 ft. Table 8 shows a summary of the interpolation results and the respective maps are reproduced in Figures 31-36.

Table 8: Summary of interpolation results

Sampling Method	Map Result	Resulting Cells	Minimum pH	Maximum pH	Mean pH
Center Point Surface	Figure 31	1,033	5.4	6.5	6.0
Staggered Start Surface	Figure 32	1,033	5.5	6.3	5.9
Random Point Surface	Figure 33	1,033	5.1	6.6	5.7
Management Zone Point Surface	Figure 34	1,033	5.5	7.4	6.0
Hybrid Point Surface	Figure 35	1,033	5.0	6.8	5.9
1 Ac. Grid Surface	Figure 36	1,033	5.2	7.5	6.1

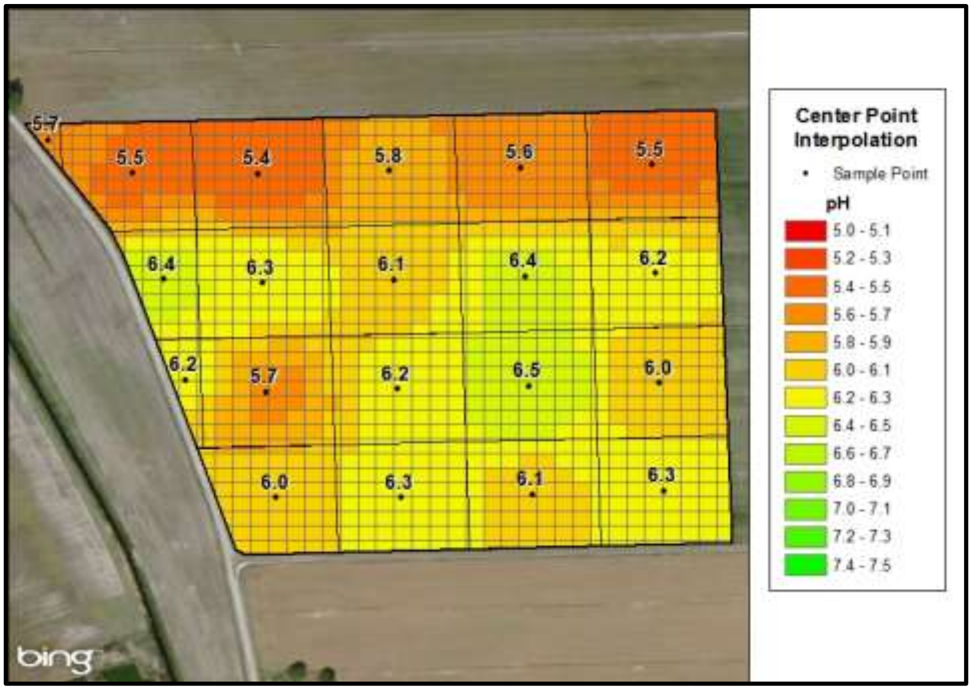

Figure 31: Center point pH interpolation results

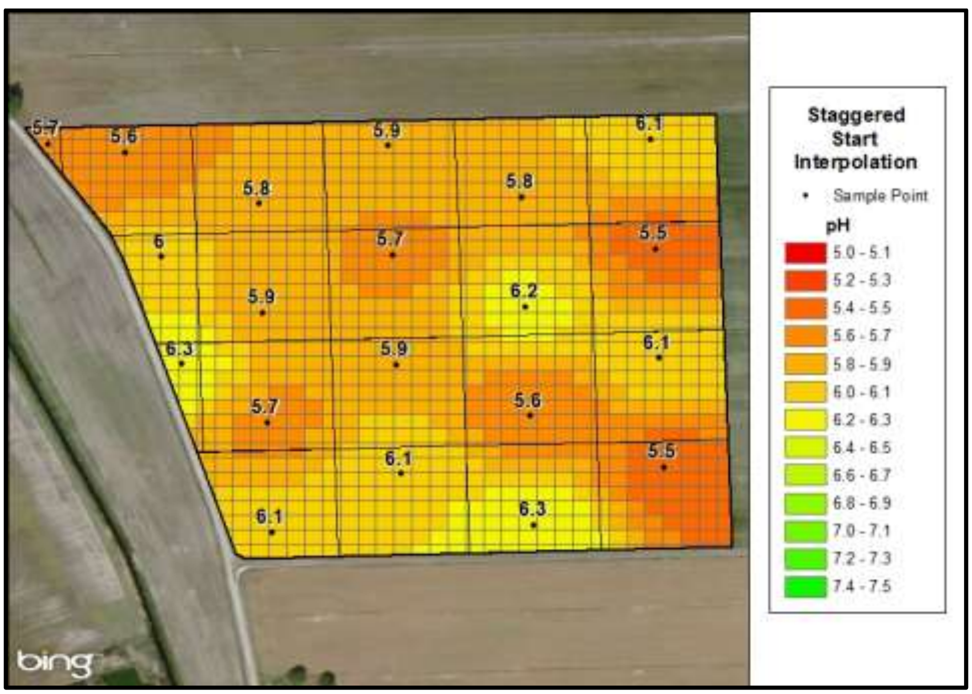

Figure 32: Staggered start pH interpolation results

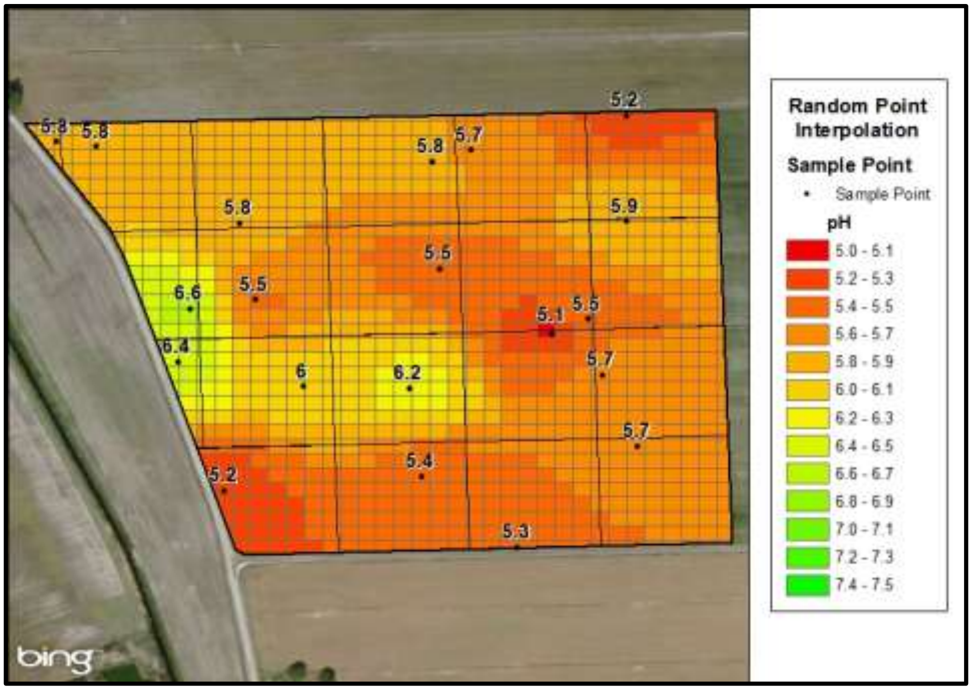

Figure 33: Random point pH interpolation results

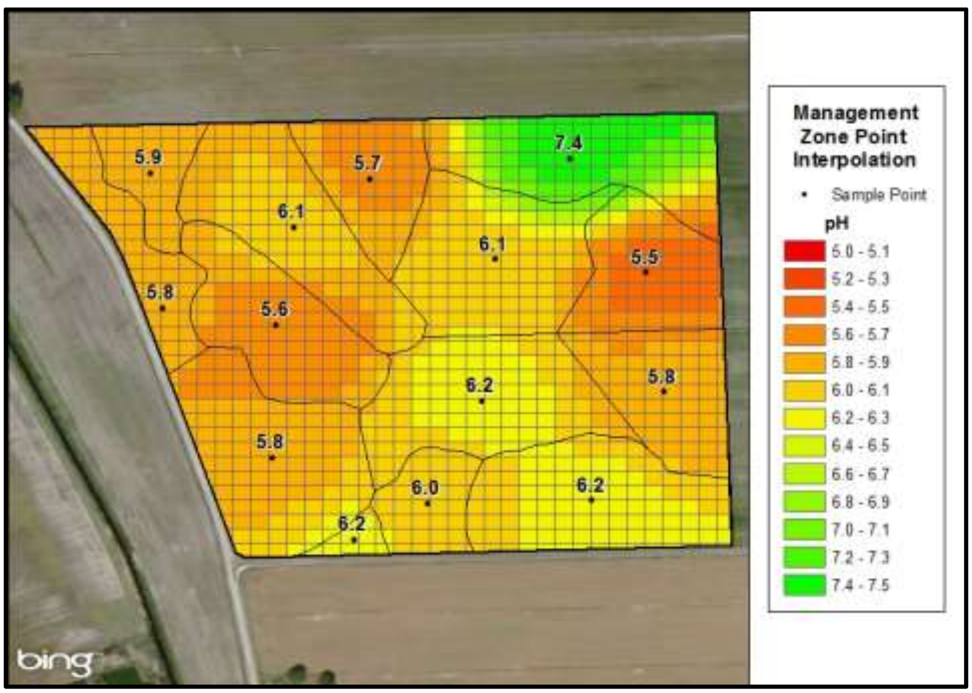

Figure 34: Management zone pH interpolation results

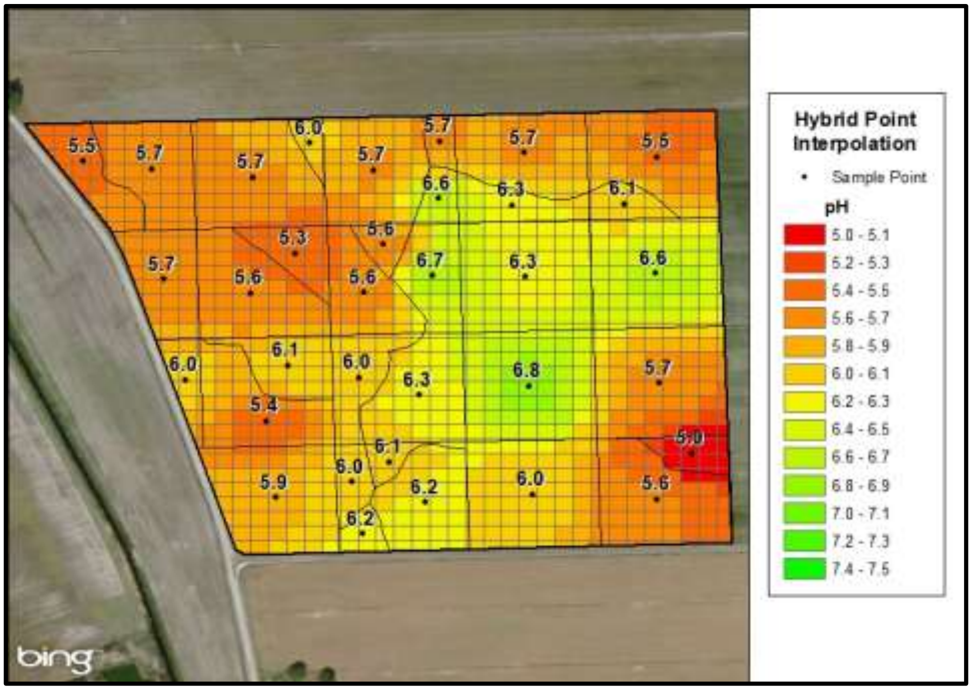

Figure 35: Hybrid point pH interpolation restults

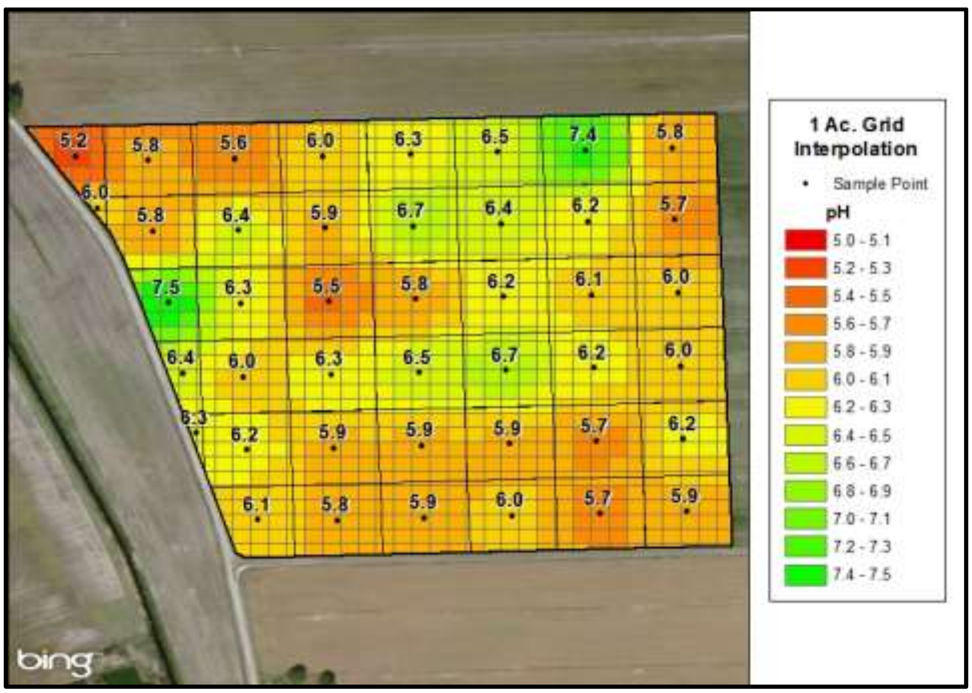

Figure 36: 1 acre grid pH interpolation results ("gold" standard)

In order to assess the validity of the interpolations, cross validation was used for each point sampling method. To achieve this cross validation, first, a single sample point was removed and the interpolation was repeated with this point removed. Then the value at the removed sample point was predicted as part of the new interpolation. This is repeated for each sample point and the differences between the predicted and observed values for each sample point were compared using a one-sample t-test. This approach was used to test whether the differences were significantly different from zero or not. All six of the one-sample t-tests performed for this study showed that the differences between the observed and predicted values were not significantly different from zero.

To compare the interpolated data of the various sampling methods to the 1 acre grid interpolation results, the same comparison approach discussed in the last section was reproduced. The results from this comparison are presented in Tables 9 and 10.

Table 9: Difference of pH units estimated with the "gold" standard and each of the other sampling methods expressed as percent of the field

		Figure				
		31	**32**	**33**	**34**	**35**
Difference in pH units from "gold standard"	**0.5 or larger**	5.6	1.3	1.0	8.7	5.7
	0.3 to 0.4	17.0	6.7	0.3	10.8	10.8
	0.1 to 0.2	20.1	14.1	7.2	20.4	17.8
	0	8.7	11.0	6.6	6.4	9.0
	-0.2 to -0.1	17.9	22.5	20.3	16.9	19.6
	-0.4 to -0.3	14.5	20.2	20.7	19.8	14.8
	-0.5 or larger	16.3	24.3	43.9	17.1	22.4

These results are similar to those in the last section in that there were more low than high estimates and the random point method (Figure 33), once again, provided the worst results. Similar to the comparison in the last section, the results from the random point method showed a sizable percentage (43.9 percent) of the field falling -0.5 pH units or more from the values estimated using the 1 acre grid sampling method. It also showed 84.9 percent of the research area having pH values less than the pH values estimated using the 1 acre grid.

Table 10: Absolute differences of pH units estimated with the "gold" standard and each of the other sampling methods expressed as percentage of the field

		Figure				
		31	**32**	**33**	**34**	**35**
Difference in pH units from "gold standard"	0	8.7	11.0	6.6	6.4	9.0
	≤ |0.2|	46.7	47.6	34.1	43.7	46.4
	≤ |0.4|	78.2	74.5	55.1	74.3	72.0

The poor performance of the random point sampling method (Figure 33) is highlighted again in Table 10 which shows how the interpolations with the other four sampling methods – the center point, staggered start point, management zone point, and hybrid point – produced roughly similar results overall. Based on the percentages in Table 10, an argument can be made that the center point and staggered start sampling methods (Figures 31 and 32) produced the best results based on the percentage agreement in map values using the ±0.2 and ±0.4 thresholds respectively.

The final two sets of comparisons look at the effect of interpolating fine-grained maps on the one hand and the effects of zone attribution versus statistical interpolation on the other hand.

Table 11 shows the absolute differences for the point sampling methods with and without interpolation. The values in this table show that, overall, the interpolated data produced better results than when the point pH values were assigned to the areal units used to construct the sample design. There were only two instances where this was not true: the zero difference cases for the random point (Figures 24 and 33) and the management zone point (Figures 26 and 34) sampling methods. Therefore, the interpolated point data was used in the final comparison of the sampling methods in Table 12.

Table 12 combines the composite sampling results from Table 7 and the interpolated point sampling results from Table 10. Based on this final comparison, the traditional sampling method (Figure 21) was shown to produce the best results overall, having the highest percentages in each row of Table 12. The composite cell (Figure 25) and hybrid composite (Figure 29) sampling methods provided the next best overall results. The percentages represented by these two sampling methods were consistently higher than other sampling methods in each row of Table 12.

Table 11: Absolute differences of pH units estimated with the "gold" standard and each of the other sampling methods with and without interpolation expressed as percentage of the field

		Figure									
		Point					Interpolated Point				
		22	**23**	**24**	**26**	**28**	**31**	**32**	**33**	**34**	**35**
pH Units from "gold standard"	0	6.9	8.6	12.4	7.4	5.1	8.7	11.0	6.6	6.4	9.0
	≤ |0.2|	39.8	43.5	29.8	33.1	41.5	46.7	47.6	34.1	43.7	46.4
	≤ |0.4|	69.5	70.1	45.6	67.2	65.6	78.2	74.5	55.1	74.3	72.0

Table 12: Combined composite and interpolated point comparison results

		Figure								
		Composite				Interpolated Point				
		21	**25**	**27**	**29**	**31**	**32**	**33**	**34**	**35**
pH Units from "gold standard"	0	15.2	10.1	9.8	11.3	8.7	11.0	6.6	6.4	9.0
	≤ |0.2|	58.9	52.9	44.6	51.2	46.7	47.6	34.1	43.7	46.4
	≤ |0.4|	79.1	77.3	60.0	75.5	78.2	74.5	55.1	74.3	72.0

4.3 Real World Application

An optimum soil pH level improves crop performance and makes certain nutrients more available for plant use. Lime is used to correct pH values that fall below or are more acidic than the optimum pH level of the soil. Based on the target pH, the amount of lime applied to the farm is a direct function of that measured from soil sampling.

The higher the percentage that falls below “0” in Tables 6 and 9, the greater the risk of over-liming the farm (assuming the 1 acre grid sampling method produced that most reliable estimates of the spatial patterns of pH in the study field). Over-liming leads to unnecessary application costs and can also cause spikes in pH, which will tie-up the availability of certain micronutrients in some parts of the field. The higher the percentage that falls above “0” in Table 6 and Table 9, on the other hand, the greater the risk of under-liming the farm. Under-liming can decrease the potential yield of the crop.

When compared to the pH results of the 1 acre grid, all of the sample methods evaluated in this study showed lower pH values on a higher percentage of the acreage for the study site. Ideally, a large percentage would fall in the “0” category or in the ranges closer to “0”.

CHAPTER 5: CONCLUSIONS

This study attempted to analyze the most common soil sampling methods to determine the method that was best suited for characterizing field variability in northeastern North Carolina. Nine of the most common soil sampling methods were chosen based on research in various regions of the US. These nine methods were evaluated against a "gold" standard sampling method, the 1 acre systematic aligned grid.

5.1 Final Thoughts

Although the traditional sampling method produced the best statistical results in this study, this sampling method is not designed to characterize variability within a field. It is meant more for ease and convenience of sampling, as well as providing a general pH and fertility condition of the farm.

Excluding the surprising results associated with the traditional sampling method, the results from this study showed that the composite cell and hybrid composite sampling methods provided results most comparable to the "gold" standard one acre grid. These two sampling methods produced very similar results in the final comparison (Table 12). In all ranges of Table 12, the percentages estimated using these two sampling methods were consistently first, second, or third highest among the evaluated sampling methods. The composite cell and hybrid composite sampling methods were especially impressive in the "$\leq |0.2|$" range, where they posted the top two percentages in the table, with values of 52.9 and 51.2 percent, respectively.

The random point sampling method consistently produced the worst results throughout this study. This is no different in Table 12 (Figure 33), where it produced the lowest overall percentages in all ranges.

5.2 Considerations for Future Research

Originally, the "gold" standard protocol that was proposed for this study relied on a different sampling method than the 1 acre grid as the "gold" standard. Recreating the study described in Franzen (2011) and Franzen and Peck (1995), a systematic aligned grid with grid cells measuring 82.5 ft on a side (i.e. 0.156 ac in areal extent) was imagined as the initial "gold" standard. Once in the field, it was obvious that acquiring such a large number of samples, without adequate resources, was not possible. The protocol was adjusted for the "gold" standard to be represented by a 1 acre grid, which reflected the findings of Franzen (2011) and Franzen and Peck (1995) instead of the original protocol. Future research involving an 82.5 ft systematic aligned grid as the "gold" standard has a high likelihood of providing a more concrete comparison of the various methods because of the high sampling density of this method.

This study involved using two types of data (soil survey and 2012 yield) from outside sources to define management zones. This is an efficient way to establish potential areas of variability within a field, but increasing the reliability of this technique is possible for future research. If possible, gathering multiple years of data can prove helpful in realizing the consistency across areas of variability. This is especially prominent in yield data and aerial photography. Including other datasets from outside sources may also help to delineate potential management zones (i.e. soil electrical conductivity, elevation, past management records, hydrology), so long as these data are reliable. Soil electrical conductivity mapping would improve upon the effectiveness of the soil survey data in showing variations in the soil. In turn, this would aid in management zone delineation.

In this study, the point data was interpolated using the Inverse Distance Weighting method. This interpolation method was chosen because it was standard in the software (AgStudio) used throughout this study. Future research may find value in evaluating other interpolation methods (i.e. kriging) against the Inverse Distance Weighting method for use in precision agriculture in northeastern North Carolina.

Studies need to be replicated numerous times before one can be confident of the results. A future replication of this study may choose to analyze composite and point sampling methods separately by having a point and a composite "gold" standard. This way the comparison is performed with sampling methods of a similar nature. The "gold" standard in this study was a point method itself, but the composite samples may have benefited from having a "gold" standard that was composite as well.

Future research may also benefit by including a cost-analysis evaluation for each sampling method. This cost-analysis can include the time, money, and resources it takes to obtain the samples, as well as apply the recommended amount of material. This will help to further delve into the effect of soil sampling on management practices within farming operations.

A number of samples in this study produced obscure and unusual values when tested by the soil lab. For example, the management zone point and 1 acre grid produced maximum pH values of 7.4 and 7.5 respectively, which is very high. This could be caused by natural pockets of high variability within the soil, potential errors in lab precision, contamination during collection, or another unknown reason. As discussed earlier, it can be assumed in this particular case that this value is a correct representation of pH at this location because these two samples were taken in such a close proximity to each other. In this case, there is no way to absolutely know. For future research, it would be advantageous to resample and retest any sample results considered obscure and unusual to reassure the validity of the soil test results.

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