Proper fertilizer placement through better soil sampling with precision agriculture

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Abstract

Fertilizer use and proper nutrient management are key components to stay economically competitive in agriculture. Fertilizer that is removed from fields during harvest must be replaced to ensure nutrient availability for crop production. Soil sampling is the best way to determine the amount of nutrients need, but where they are needed depends on the type of sampling. Traditionally samples were collected so that one sample represented 20 acres, sometimes samples are grouped by soil series, A Veris 3100 EC cart (Veris Technologies, Salina, KS; http://www.veristech.com/) was used to map soil texture and sampled on a 100 ft X 100 ft grid to compare the different methods. Results from the study demonstrated significant spatial variability was present between whole field composite sampling, traditional field sampling, zone sampling, and zone 2.5 acre grid sampling.

Table of Contents

Introduction

In Virginia, over 1.3 million acres of cropland are farmed with soybeans, corn, wheat, and hay as the largest acreage commodities (Ellison, 2019). Proper nutrient management programs and fertilizer use are essential for Virginia to remain a viable and economically competitive agricultural state. Large amounts of nutrients are exported from fields in the harvested commodities and must be replaced to ensure adequate nutrient availability for sustainable crop production. Due to this nutrient need, over 76 million pounds of phosphorus fertilizer is added to farm production systems in Virginia yearly (VDACS, 2018). Roughly 49% of phosphorus nutrient inputs are from animal manure sources, but the remaining 51% of fertilizer use is from inorganic fertilizer sources (McGuire, 2017).

Enhanced nutrient management of soluble inorganic fertilizer sources in these farm systems would have a far-reaching impact for reducing overall nutrient loads. Computer programs, GPS technology, precision soil sampling, methods for developing soil nutrient management zones, and precision fertilizer application equipment are now more affordable than in past years (US Bureau of Labor Statistics, 2015). These technologies can be used in fields with historic manure or inorganic fertilizer applications to identify both deficient and excessive nutrient concentration areas. Research conducted in the mid-1990's in Virginia concluded that blanket phosphorus (P) fertilization based on composite soil samples had over-applications 28% of the time, and could be reduced to 10% by simply basing soil samples on soil series (Anderson-Cook et. al., 1999). Potassium (K) fertility followed suite and was over-applied by 37% (Anderson-Cook et. al., 1999). Unfortunately, most farmers in Virginia use one composite soil sample to represent 20-acres or more of their fields, if they soil sample at all. With increasing fertilizer prices and lowering commodity prices, farmers now have an opportunity to expand use of precision technologies to increase profits, improve yields and reduce nutrient loads.

This project used precision agricultural technology and fertilizer recommendation techniques to reduce P use by adjusting fertilizer on-the-go as variable rate applicators moved across the field. Phosphorus fertilizer was precisely placed in areas where needed, and reduced or deleted when soil conditions deemed phosphorus fertilizer unnecessary for economical crop production. Potassium fertilizer also assisted with overall economics of the precision agricultural technology by also increasing or reducing K fertilizer use as needed. Lime and soil pH have significant impacts on P nutrient availability and efficient plant uptake and crop yields, and overall soil health. The overall goal is to have all parts of a field testing in the "High +" soil test category as these soil tests will not likely see a yield increase with more fertilizer use and will also not see a yield reduction if fertilizer is not applied. Soils testing high have a crop replacement value recommended to replace nutrients removed with grain or plant biomass (VCE, 2000). By using precision soil sampling and variable rate application technologies, nutrient over-applications could be reduced.

Technology, such as global positioning systems (GPS), compatible computer software, and variable rate application trucks, are *shelf-ready* and can significantly improve nutrient fertilizer use and agronomic efficiency for inorganic fertilizer sources that are land applied (Torbett et. al., 2007). The idea behind this technology is that fertilizer is applied at higher rates in field locations that have severe nutrient deficiencies while areas with higher nutrient concentrations receive little or no fertilizer, i.e. rates are optimized for each area of the field. This technology will prove especially useful in fields with long histories of manure applications as nutrient concentrations vary substantially due to non-uniform manure applications. Effectively, variable rate fertilizer applications ensure that the entire field has the necessary, but not excessive nutrient concentrations for crop production. However, there is a considerable learning curve for farmers, applicators, extension, government stakeholders and others as technology evolves rapidly and data collection capabilities far exceeds data manipulation and recommendation capabilities. Farmers and other interested parties often gloss over in the excess information available today and most data goes unused for lack of understanding and tools necessary to properly manipulate data. Farmers, business, and other stakeholders need to be cognizant economically to ensure that money is not wasted on technology they are not willing to learn and use to better their or their clienteles' production practices.

Methods and Materials

This project focused on methods to design small nutrient management zones of varying sizes versus the traditional soil sampling methodology that is used by farmers today. Currently, Virginia Cooperative Extension recommends 20 soil samples to represent 5 to 10 acres (VCE, 2000). For this 5 to 10-acre sample, samples should be taken from like areas, but most farmers and consultants simply sample similar geographic areas together without regard to soil and landscape features. Soil sensor technologies were used to map fields to test for correlation to Mehlich-1 soil extractable nutrients, soil pH, and current soil maps. From these data layers, appropriate nutrient management zone areas were defined to soil sample for precision nutrient and lime applications. Different soil sampling area sizes were tested to find the differences in nutrient management recommendations and what area would be considered over or under applying fertilizer.

The data collection implementation area for this project was on the Eastern Shore of Virginia in Accomack County. A 158-acre farm was selected to soil sample using the methodology at the finest scale. Electrical conductivity readings were utilized for soil mapping to generate nutrient management zones, then sampled within that zone to establish a zone-specific soil test value and nutrient recommendation. Traditional grid soil sampling was also utilized on a 2.5-acre basis to generate soil sampling maps, as well as 2.5-acre grid samples based on SSURGO soil map data.

For the precisely sampled test field, soil was sampled in a grid pattern in a 100 ft. × 100 ft. grid. At each grid point, 20 independent samples were collected in a circle at a 10 ft. radius from the center at a 4-inch depth for a no-till field. These 20 soil cores were mixed together to represent this 10,000 $ft.^2$ area (0.23 acres). Zones consisted of the traditional method, with 5-10 acres max per soil sample and was divided by geographic dividers such as field roads and ditches. Soil samples were also grouped together by SSURGO soil maps, which is not intended to be used at this finite scale, but is often used by consultants. Soil points were also grouped by EC ranges of 4.21 to 6.00 mS/m, 6.01 to 8.20 mS/m, and 8.21 to 13.00 mS/m. Soil texture generally increases in loam and clay content as EC increases. Soil extractions were conducted using the approved soil testing guidelines (Mehlich-1) of the Virginia Tech Soil Testing Laboratory (Maguire and Heckendorn, 2015). Samples were analyzed using an inductively coupled atomic emission spectrometer (ICP-AES) for P, K, magnesium (Mg), etc. quantification. Electrical conductivity (EC) data was obtained to demonstrate the ease that an Order 1 soil survey map can be produced to refine nutrient management zones over the standard soil survey map. A Veris 3100 EC cart (Veris Technologies, Salina, KS; http://www.veristech.com/) was used to collect soil EC readings from 0-1 ft. and 0-3 ft. depths to estimate changes in soil texture across the field spatially. Data maps were manipulated using ESRI ArcGIS 10.4 software (ESRI, Charlotte, NC; http://www.esri.com/). Overall economic advantage or disadvantage of varying methods were estimated by using 5-year average nutrient and lime prices as reported by the USDA-Economic Research Service (2016).

Sampling was more concentrated and precise than traditional soil sampling techniques used by farmers, whether using precision ag techniques or not. For the precisely sampled test field, soil was sampled in a grid pattern in a 100 ft. × 100 ft. grid. At each grid point, 20 independent samples were collected in a circle at a 10 ft. radius from the center at a 4-inch depth for a no-till field. In comparison, most precision ag samples are sampled at a minimum of 2.5 acres in size for nutrient management zone. Traditional farmers may sample per 20 acres or more per sample. Extension currently recommends only 6 to 8 samples per circle around a point (Virginia Tech Soil Testing Lab, 2016; http://www.soiltest.vt.edu/PDF/farm-sampling.pdf) and this study used 20 samples per point. Therefore, sample frequency was sufficient and stricter than general guidelines for making project claims and meeting needs. In the raw form, the sampling is not comparable to real life situations as no farmer or consultant would sample a grid on a 0.23-acre basis. However, the samples do give a nice example of potential field variability and can be pooled together to represent different scenarios that would potentially be used by farmers and consultants in Virginia.

Soil sampling procedures followed protocol as outlined at: http://www.soiltest.vt.edu/PDF/farm-sampling.pdf. Sampling was conducted using a stainless-steel soil tube to a desired depth of 4 inches for no-till crop fields. Samples were placed in a clean plastic bucket and mixed thoroughly in the field. Samples were air dried in a forced air oven with no heat, ground to pass a 1-mm sieve, and stored in a dry area until extraction. Extraction protocols, ICP-AES instrumentation methodologies, and calculation examples can be found on the Virginia Tech's Soil Testing website at: http://www.soiltest.vt.edu/Files/other-lab-info.html. Official Extension recommendations per soil testing level can also be found at this link in the publication by Maguire and Heckendorn (2014). The chain of custody for soil samples resided primarily within the Eastern Shore AREC Soils and Nutrient Management program. Eastern Shore staff collected samples in field, were responsible for drying, grinding, extraction, and storage. After extraction, solution was delivered to the Virginia Tech soil testing lab for ICP-AES analysis. Data was transmitted electronically via email for analysis. Quality control of laboratory work was considered by extracting blank tubes and a standardized soil sample with similar textural, pH, and nutritional properties. The ICP-AES analysis had blind quality control samples analyzed within the extraction analyses runs. The ICP-AES data was first reviewed by the staff operator by verifying blind sample tests. The blanks and the standard soil were verified to ensure an accurate extraction procedure was conducted. Final data analysis and presentations were only completed after ensuring all data was accurate as compared to standards and checks. Field measurements (Veris 3100 EC, etc.) were verified by following manufacturers recommendations before collecting data in-field and in the office prior to analysis and reporting.

Results and Discussion

Variation among the project field was significant and did allow demonstration of precision nutrient management's utility for improving fertilizer application accuracy and improving overall farm economics by placing lime and nutrients where needed. Overall, pH values ranged from 4.73 to 7.68 (Table 1) on this historically manured sandy loam textured field on the Eastern Shore of VA. Soils with pH values with this much variation will likely have crop damage and yield loss from aluminum toxicity (low pH) and micronutrient deficiencies (high pH). It is interesting to note that the sample mean was 6.18; which is the accepted target value for Virginia Tech Extension Recommendations for most crops of 6.2 (Maguire and Heckendorn, 2014). Phosphorus values range from 7.6 lbs. P/acre to 444.4 lbs. P/acre with a mean of 163.8 lbs. P/acre (Table 1). With these values, one would expect to see severe crop loss if not fertilized at the low value and the high value exceeds the established DCR threshold for further P applications of 270 lbs. P/acre (DCR, 2014). Potassium had similar variation with a range from 44.5 lbs. K/acre where severe crop loss will occur to 560.2 lbs. K/acre where further fertilizer applications are not warranted as fertilizer will be wasted and likely leached out of our upper soil horizon on these sandy loam soils. Other nutrients and elements of concern, such as calcium (Ca), Mg, zinc (Zn), manganese (Mn), boron (B), and aluminum (Al), showed similar variations and may cause significant crop injury (i.e. Al) or yield loss (B, Zn, etc.) by being the most limiting nutrient for that specific point. While this project focused on pH, P, and K, data indicates that further investigation should continue for variable rate applications for other macro and micro nutrients. For the minimum, maximum, and mean values, the resulting lime and fertilizer recommendation is outlined in Table 2 using traditional stair-stepped soil test recommendations from VCE. Using current VCE recommendations, these fields should have lime applications that vary from 0 to 3 tons/acre, P_2O_5 applications from 0 to 100 lbs. P_2O_5/acre and K_2O applications from 0 to 100 lbs. K_2O/acre. Overall, the field had sufficient Mn concentrations, but Zn may need to be added in certain parts even though Zn was continuously applied to the field via poultry litter.

Spreader truck technology now allows varying amounts of fertilizer to be applied as the equipment operates across the field. Therefore, traditional stair-stepped soil test recommendations can be improved upon by using regression equations. Due to differing soil chemical reactions for each nutrient in this project, different models were developed using the existing VCE soil test recommendations. Lime application projections best fit a linear model (R^2 = 1.00) where: lime recommendation in tons/acre = -2.2637(soil pH) + 13.8 and no lime recommendations are made with a soil pH above 6.0 if the target pH is 6.2. Phosphorus fertilizer recommendations best fit (R^2 = 0.96): lbs. P_2O_5/acre = -28.37(soil test P) + 153.73 and no P fertilizer recommendations are made when soil test P is greater than 110 lbs. P/acre. Potassium's correlation best fit a polynomial function (R^2 = 0.98) where: lbs. K_2O/acre = 0.0009(soil test K)^2 – 0.6215(soil test K) + 128.7 and no K fertilizer recommendations are made when soil test K is greater than 310 lbs. K/acre. These equations were used in estimates and referred to as regression soil test recommendations.

Producing accurate nutrient management zones is a task that requires significant manipulation of data sets to ensure accurate zones are made. A whole field composite sample, traditional soil testing field size, soil series based on soil survey maps, soil series grid sampled in 2.5-acre grids, EC maps (Fig. 2), and EC maps grid in 2.5-acre grids were compared to a small grid to see how overall lime and fertilizer rates were impacted (Table 3). Overall, pH had the most drastic changes when nutrient management zones were established as compared to traditional soil sample field size. With the 20-acre traditional soil sample, no lime was recommended. However, lime rates increased up to the smallest scale with no major differences in soil series or EC maps in total recommendation. Accuracy was increased when EC zones were grid sampled in a 2.5-acre grid within zone. However, data indicated that the lowest pH values requiring the most lime were predominantly in the 8.21 to 13.00 mS/m EC range (Fig. 2). Soils with more silt and clay have a higher buffering capacity that requires more lime per acre to change the pH value. Since these high EC areas are small, only 10% of the entire field, the majority of the field masked these areas needing lime. Another detriment to overall yield potential is that these higher EC areas also generally contain more water holding capacity that would allow higher yields in dry years.

Phosphorus applications would be only 47% of overall application if the farmer used traditional soil testing sampling methods versus the most precise grid we sampled (Table 3). Interestingly, P samples were generally grouped together within EC zone, but overall need for P fertilizer was masked due to very high soil testing levels in other parts of the same zone (Fig. 3). This masking demonstrates the need for soil maps to be reduced into smaller grids within similar larger zones as 38% of the farm had a P fertilizer recommendation when sampled on the smallest grid (Table 4). Similar to pH, groupings of P fertilizer need on heavier textured soils indicated possible higher yields due to more nutrient availability and higher water holding potentials;

which equates to higher crop removal amounts. From a poultry litter perspective assuming approximately 3% P_2O_5, using properly defined zones and sample sizes may allow up to 43.3 tons of manure being applied for 1 crop versus no-manure if based on a composite whole farm soil sample.

Overall, K was the least variable nutrient in the study with all methods requiring potassium fertilizer (Table 3). However, data clearly shows that higher EC zones generally had higher soil test K than lower EC zones (Fig. 4). Higher EC is correlated to soil with higher silt and clay, and therefore also has a higher cation exchange capacity (CEC). Therefore, these higher EC areas had more exchange sites for retaining K in the upper horizon. Potassium leaching is commonly experience on sandy loam soils in Virginia and have researched this in other corn/wheat/soybean rotations (Stewart, 2015; Williams et al., 2016). Potassium leaching is another reason there was less variation on test sites as all sandy loam soils retained little K on the upper horizon, requiring similar K fertilizer application rates regardless of how the soil sample was collected. Although overall K fertilizer recommendations are similar, K is being applied more appropriately to areas of the field that need it versus blanket applications.

A preconceived notion of precision ag soil sampling is that less fertilizer will be applied to a farm and reduce the farmer's overall fertilizer bill. This was true for the soil series and EC defined nutrient management zones for lime and P fertilizer as they required less inputs and therefore less costs than our traditional field size sampling method (Table 5). Meanwhile, K was only slightly higher (about 15%) for these two methods than traditional field sizes. However, data clearly demonstrated that if all parts of the field received the needed input for optimal production then lime and fertilizer prices would be significantly higher than traditional methods. For instance, looking at the entire lime, P, and K fertilizer plan costs, fertilizer bills increased by 78, 81, and 111% for 2.5-acre grid samples, SSURGO soil map 2.5-acre grid samples, and EC map 2.5-acre grid samples, respectively, as compared to traditional methodologies. It is important to note that fertilizer and lime inputs will likely go up on fields once nutrient management zones are properly outlined and suspect they may then decrease over time as the field is balanced by using appropriate precision ag techniques.

Table 1. Minimum, maximum and average Mehlich-1 extract soil testing values from the 158 acre historically manure applied sandy loam field on the Eastern Shore of Virginia.

Amount	pH	P	K	Ca	Mg	Zn	Zn Index	Mn	B	Al
		--------------------lbs./acre--------------------						---------lbs./acre-------		
Min	4.73	7.6	44.5	257.6	49.0	0.6	78.0	5.2	0.1	220.3
Max	7.68	444.4	560.2	3665.5	1288.1	28.9	1134.0	128.3	1.7	2216.4
Mean	6.18	163.8	198.0	930.4	246.9	2.5	207.0	34.5	0.4	696.1

Table 2. Fertilizer recommendations made from the minimum, maximum, and average soil test levels (STL) for each point.

Amount	pH	Lime	P	P_2O_5	K	K_2O	Ca	Mg	Zn	Mn
		tons/acre		lbs./acre		lbs./acre				
Min	L	3.00	L	100	L	100	L	L+	DEF	OK
Max	H	0.00	VH	0	VH	0	VH	VH	OK	OK
Mean	OK	0.00	VH	0	H-	40	M-	VH	OK	OK

Table 3. Comparison of different nutrient management zone methods for sandy loam soils on the Eastern Shore of Virginia. The small grid method with regression based fertility recommendations was used as the base for calculating deviation on the 158-acre farm.

Zone Method	Lime	Lime Deviation	P_2O_5	P_2O_5 Deviation	K_2O	K_2O Deviation
	tons/farm	%	lbs./farm	%	lbs./farm	%
Whole Field Composite	0	-100	0	-100	6,320	-10
Traditional Field Sizes	0	-100	1,380	-47	5,354	-23
2.5 acre grid	27	-22	1,781	-31	6,445	-8
Soil Series	17	-66	546	-79	6,133	-12
Soil Series, 2.5 acre grid	25	-49	2,166	-17	6,495	-7
EC Zones	16	-68	0	-100	6,097	-13
EC Zones, 2.5 acre grid	53	8	833	-68	6,172	-12
Small Grid Traditional	57	16	2,449	-6	6,428	-8
Small Grid Regression	49	0	2,598	0	6,986	0

Table 4. Percentage of fields testing in each soil test category from a 0.25-acre grid along with traditional P and K soil test recommendations and total fertilizer to be recommended for a sandy loam soil.

Soil Test Level	P	K	P_2O_5	K_2O	P_2O_5 Fertilizer	K_2O Fertilizer
	--------%--------		--------------------lbs./area--------------------			
L-	0	0	120	120	0	0
L	0	0	100	100	31	31
L+	0	1	80	80	50	174
M-	4	7	80	80	499	897
M-	6	20	60	60	561	1,869
M+	2	16	40	40	112	1,010
H-	7	17	40	40	449	1,047
H-	10	26	30	30	467	1,206
H+	9	6	20	20	280	193
VH	62	7	0	0	0	0
				TOTALS	2,449	6,428

Table 5. Comparison of different nutrient management zone methods for sandy loam soils on the Eastern Shore of Virginia. The small grid method with regression based fertility recommendations was used as the base for deviation calculation on the 158-acre farm.

Zone Method	Lime Cost†	P_2O_5 Cost	K_2O Cost	Total Cost	Deviation
	----------------------------$/farm----------------------------				---%---
Whole Field Composite	0	0	3,350	3,350	-62
Traditional Field Sizes	0	800	2,838	3,638	-59
2.5 acre grid	2,025	1,033	3,416	6,474	-27
Soil Series	1,275	317	3,250	4,842	-46
Soil Series, 2.5 acre grid	1,875	1,256	3,442	6,573	-26
EC Zones	1,200	0	3,231	4,431	-50
EC Zones, 2.5 acre grid	3,975	441	3,271	7,687	-14
Small Grid Traditional	4,288	1,420	3,407	9,115	2
Small Grid Regression	3,708	1,507	3,702	8,917	0

†Fertilizer prices based on a 5-year average of $0.58/lb. for P_2O_5, $0.53/lb. for K_2O, and $75/ton for dry lime (USDA-ERS, 2016).

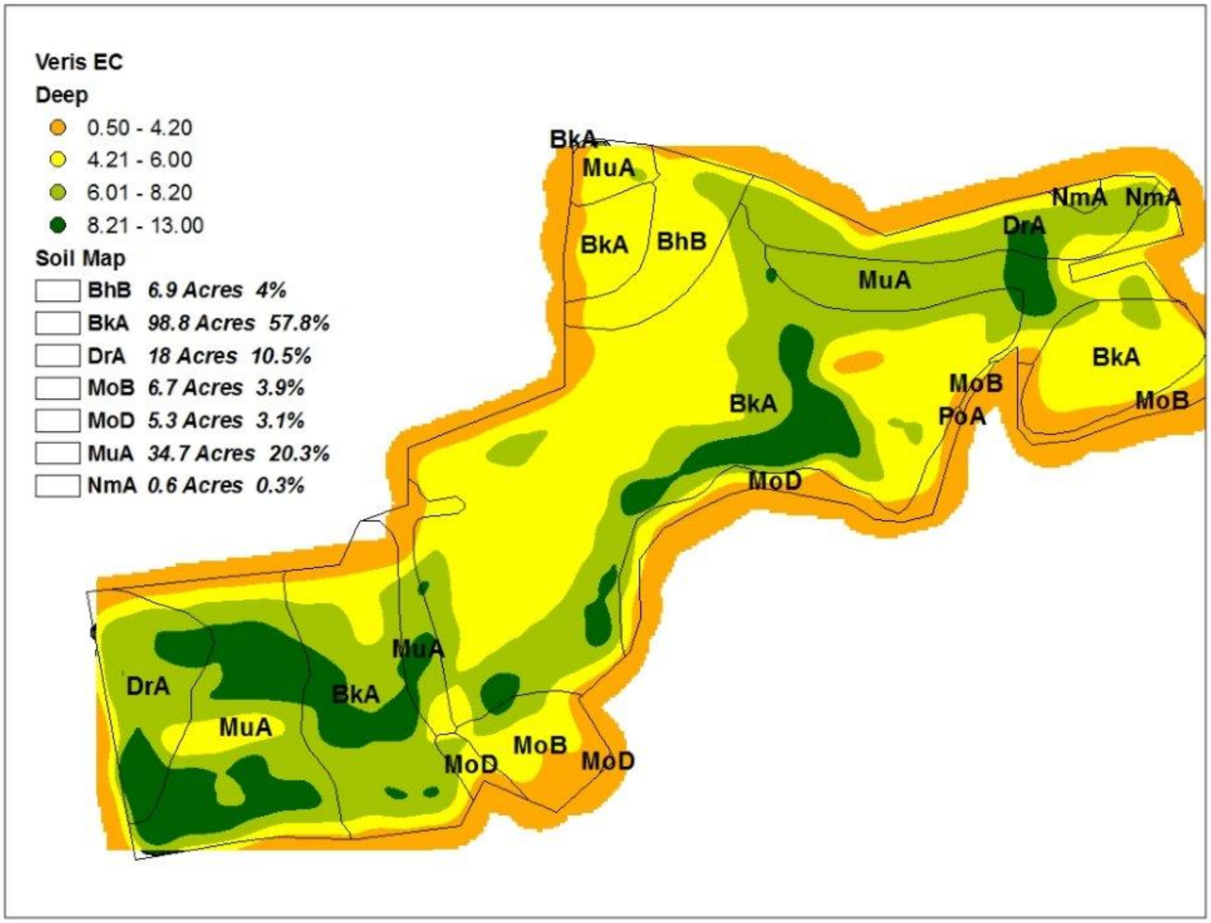
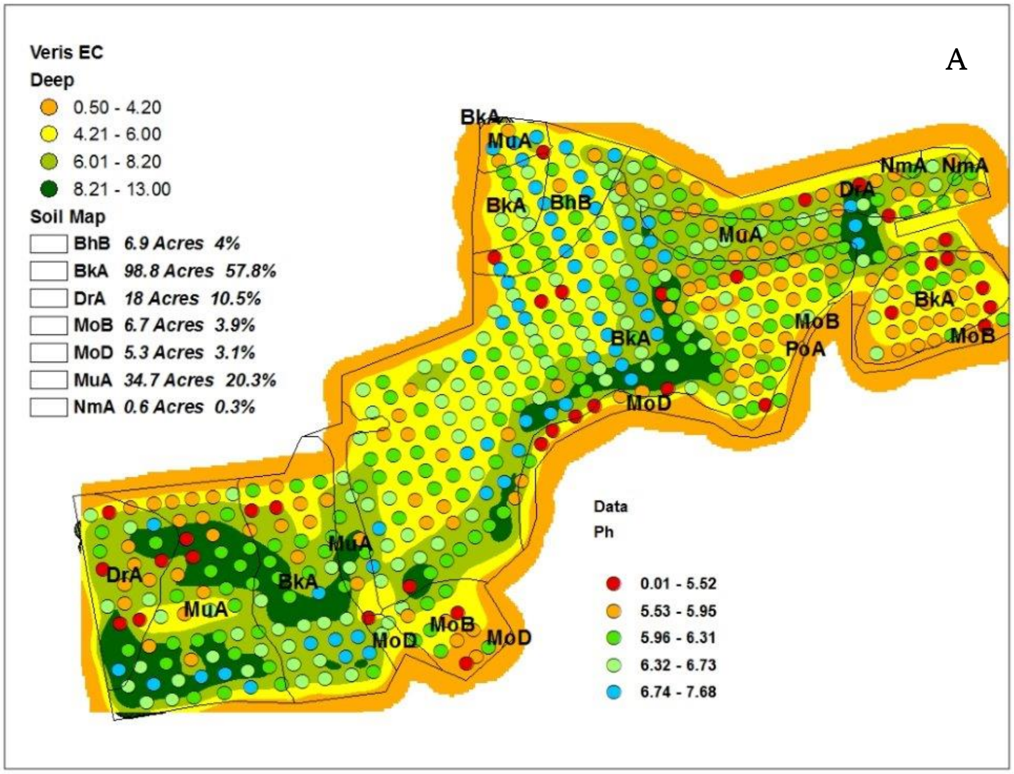


Figure 1. Soil EC field map created with a Veris 3100 EC cart (Veris Technologies, Salina, KS; http://www.veristech.com/).



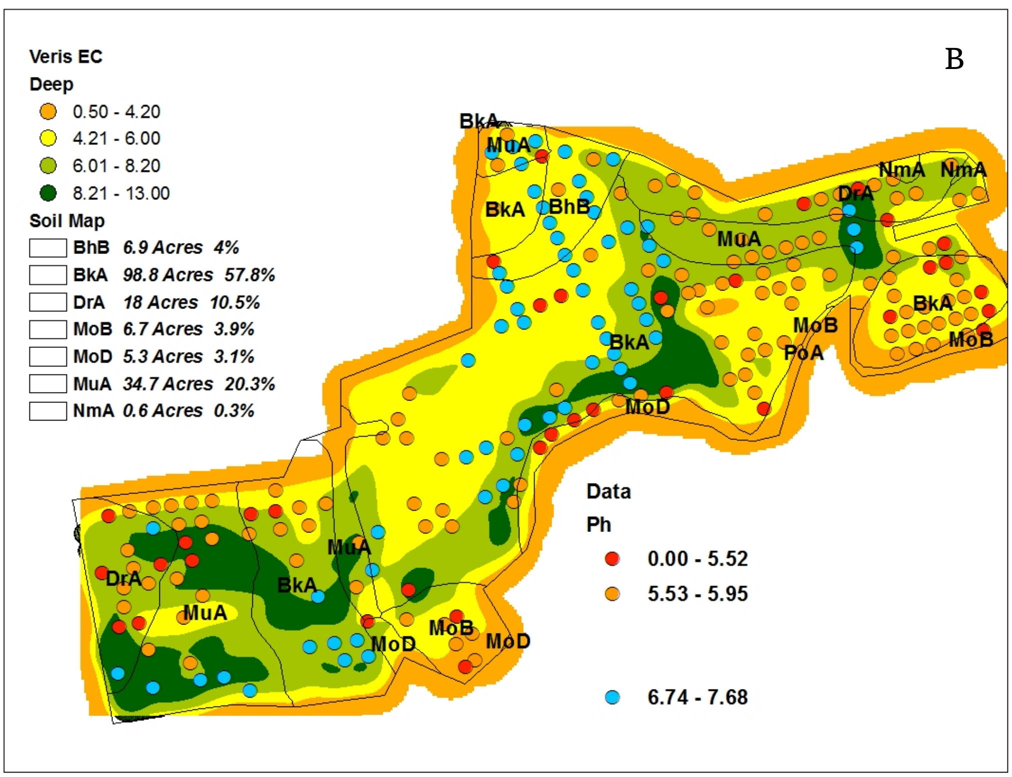


Figure 2. Soil pH field maps with all points (A) and with parts of the field requiring no lime removed, but with excessively high pH areas outlined in blue (B) for a sandy loam soil.

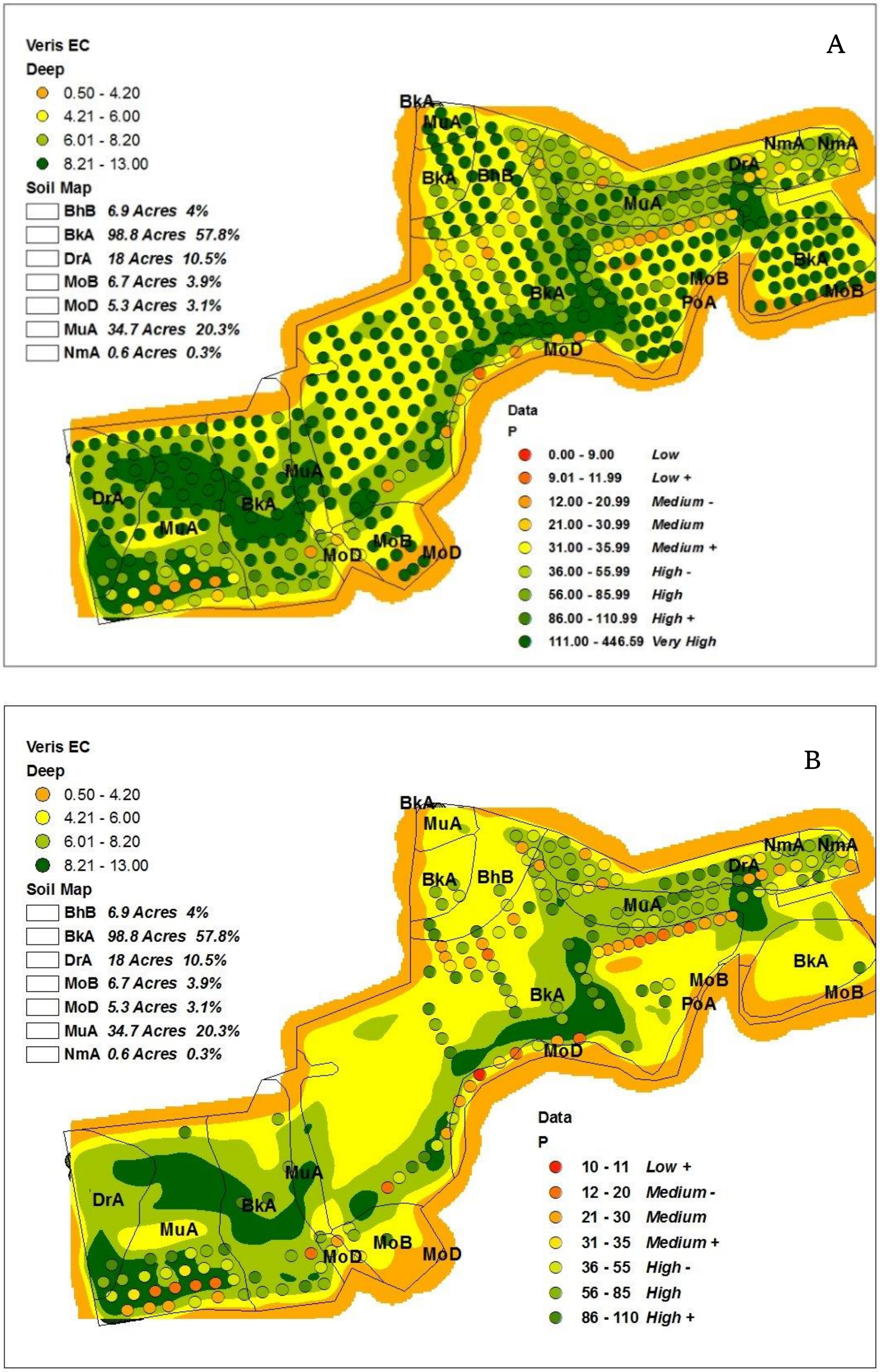
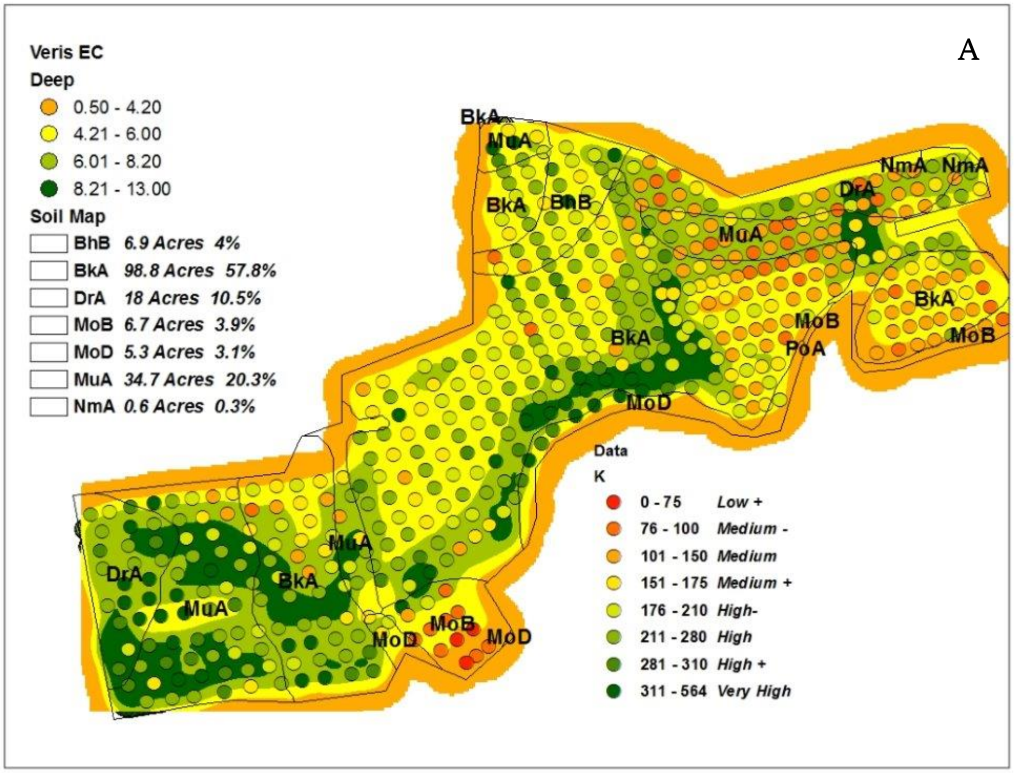


Figure 3. Soil phosphorus field maps with all points (A) and with Very High testing points removed (B) for a sandy loam soil



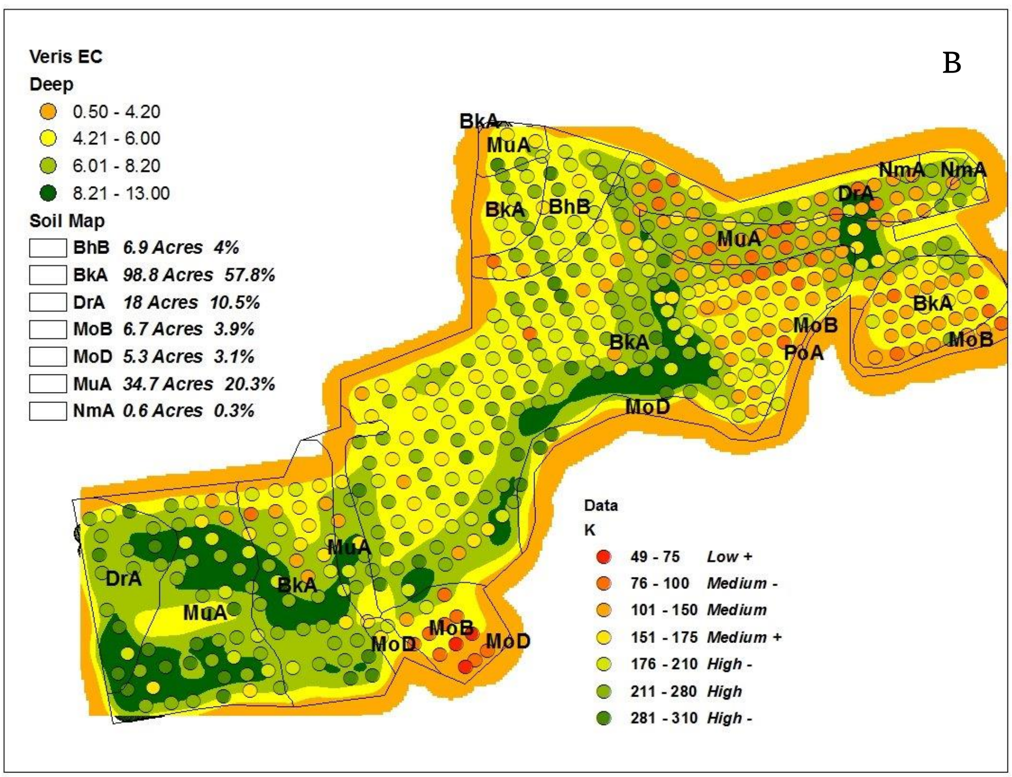


Figure 4. Soil potassium field maps with all points (A) and with Very High testing points removed (B) for a sandy loam soil.

Conclusions and recommendations

In conclusion, this study demonstrated that significant variability is present within a small spatial area across the agricultural landscape. Using precision soil sampling on a fine scale clearly demonstrated that significant portions of a typical agricultural field suffers from yield loss due to soil pH issues or a lack of necessary macronutrients. Likewise, this same field may also contain areas that have excessive concentrations of soil test P that may lead to losses via leaching if the soil is P saturated or soil particles are lost via overland flow. Importantly, it was also demonstrated that precision ag soil sampling and fertilizer application may also increase overall fertilizer use, but the nutrients are applied in areas where necessary. In general, most of the sampling groupings used overall, recommended less lime and fertilizer than the most precise grid. Of the methods, both soil maps generated from EC zones and taken from the SSURGO database did refine recommendations when soils were grouped together and each hold potential. The most accurate method, defined as the method with the least deviation from the small grid, varied depending on soil measurement. Lime was best predicted using EC maps that were sampled in 2.5 acre grids within the same EC zone. Phosphorus fertilizer recommendations were most similar when SSURGO soil maps were divided into 2.5 acre grids. Potassium recommendations were most similar when the field was simply sampled on a 2.5-acre grid regardless of any other data layer or when grid was sampled within similar SSURGO zone.

Precision ag technologies for nutrient management should continue to be studied to further investigate nutrient zone establishment methods from various data layers. The next study point would be to aggressively sample a field each year, have fertilizer and lime applied based on a yearly prescription, and define the period of time when the soil pH and nutrient concentrations no longer warrant precision ag techniques. Another point to further investigate is deep soil sampling. Preliminary research demonstrated that sandy loam soils leach K fertilizer readily and a yield response is not always realized. Deep soil sampling on a refined precision ag basis would assist with determination of yield response or not. Overall, this study recommends that farmers in Virginia switch to precision ag soil sampling technologies to overall increase nutrient use efficiency by applying prescribed nutrients where needed and deleting fertilizer applications where very high and excessive nutrients exist.

Works Cited

Anderson-Cook, C.M., M.M. Alley, R. Noble, and R. Khosla. 1999. Phosphorus and potassium fertilizer recommendation variability for two mid-Atlantic coastal plain fields. Soil Sci. Soc. Am. J. 63(6):1740-1747.

DCR-Virginia Nutrient Management Standards and Criteria. 2014. [Online]. Available at: https://www.dcr.virginia.gov/document/standardsandcriteria.pdf (verified 10 September 2020).

Ellison, Herman. 2019. Virginia Agricultural Statistics 2019 Annual Bulletin [Online]. Available at: https://www.nass.usda.gov/Statistics_by_State/Virginia/Publications/Annual_Statistical_Bulletin/Annual%20Bulletin_19.pdf (verified 9 September 2020).

McGuire, Andrew. 2017. Can Manure Supply Nitrogen and Phosphorus to Agriculture? [Online]. Available at: http://csanr.wsu.edu/can-manure-supply-n-and-p-to-ag/ (verified 10 September 2020).

Maguire, R.O. and S.E. Heckendorn. 2015. Soil test recommendations for Virginia [Online]. Available at: https://www.soiltest.vt.edu/content/dam/soiltest_vt_edu/PDF/recommendation-guidebook-june-2019.pdf (verified 10 September 2020).

Stewart, A.B. 2015. Full-season and double-crop soybean response to potassium fertilizer. Thesis. Dept. Crop & Soil Environmental Sciences, Virginia Tech, Blacksburg.

Torbett, J.C., Roberts, R.K., Larson, J.A. *et al.* 2007. Perceived importance of precision farming technologies in improving phosphorus and potassium efficiency in cotton production. *Precision Agric* 8, 127–137

U.S. Bureau of Labor Statistics. 2015. Long-term price trends for computers, TVs, and related items. [Online] Available at: https://www.bls.gov/opub/ted/2015/long-term-price-trends-for-computers-tvs-and-related-items.htm (verified 11 September 2020).

USDA-Economic Research Service. 2016. Fertilizer use and price [Online]. Available at: https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx (verified 10 September 2020).

Virginia Tech Soil Testing Laboratory. 2016. Soil sampling instructions for the farm [Online]. Available at: https://www.soiltest.vt.edu/content/dam/soiltest_vt_edu/PDF/farm-sampling.pdf (verified 10 September 2020).

Virginia Cooperative Extension. 2000. Agronomy Handbook [Online]. Available at: https://www.pubs.ext.vt.edu/424/424-100/424-100.html (verified 10 September 2020).

Virginia Department of Agriculture and Consumer Services. 2018. Total fertilizer and nutrient tonnage by county fiscal year 2018. [Online] Available at: https://www.vdacs.virginia.goc/pdf/report-totalfertcounty17-18.pdf (verified 11 September 2020).

Williams, A.S., M.R. Parvej, D.L. Holshouser, W.H. Frame, and M.S. Reiter. 2016. Full-season soybean response to potassium on Mid-Atlantic Coastal Plain and Piedmont soils. Soil 1.