Precision Agriculture's Impact on Nutrient Management in Agronomic Crops

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Abstract

The world population is exponentially growing and is expected to reach over 9 billion people by 2050. In order to feed the growing population, producers will have to rely on new technologies to increase yields. Globally there is focus on global warming and pollution that can damage ecosystems. A way to solve both of these conundrums is through understanding of nutrient cycles and the implementation of precision agriculture techniques to create a nutrient management system that meets the needs of the plants, but yet prevents unnecessary losses from the cycles. Studies show promise in the implementation of precision agriculture systems, with increased yields and better nutrient use efficiencies. However, studies show that there is variation between plots and areas, proving that more studies need to be conducted to determine the impact of precision agriculture on nutrient management.

The Affect of Precision Agriculture on Nutrient Management in Agronomic Crops

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INTRODUCTION

The world population is exponentially growing and is expected to reach over 9 billion people by 2050 (World Population, 2017). Population's rapid growth has caused agriculturalists to develop new and innovative ways to feed the growing population. In the early 20th century, the Haber- Bosch process was created which allowed for the synthetic production of fertilizers (Lu, 2017). During the 1950's and 1960's our country experienced the Green Revolution. The Green Revolution in the United States led to high- yield seeds, intensive irrigation techniques, herbicides, pesticides, mechanization, and petrochemical fertilizers, which increased agronomic yields across the country (Melillo, 2012). New technologies increased rapidly in the agriculture sector over time, causing increases in yields.

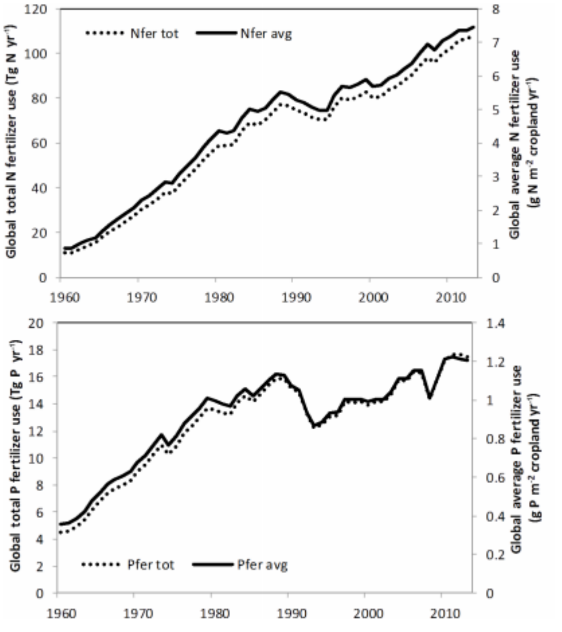


Figure 1: Global nitrogen (N) and phosphorous (P) fertilizer use in terms of total amount (tot) and average rate on per (Lu, 2017).

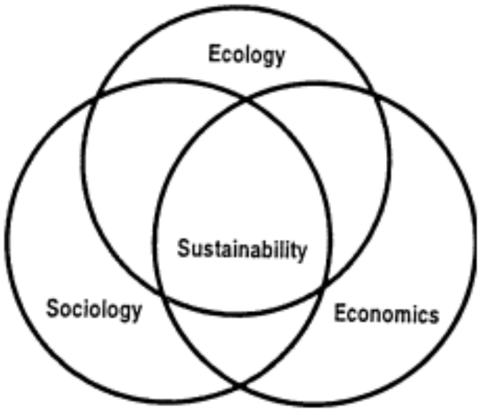
Figure 1 shows the use of synthetic fertilizers increased since the 1960s. The use of nitrogen fertilizer consumption increased from 11.3 Tg N yr^{-1} in 1960 to 107.76 Tg N yr^{-1} in 2013 and phosphorus fertilizer increased from 4.6 in 1960 to 17.5 Tg P yr^{-1} in 2013 (Lu, 2017). While fertilizer is necessary in producing high yields, synthetic fertilizers have environmental consequences, such as altering the global nutrient budget, affecting water and air quality, and ultimately contributing to climate change through greenhouse gas emissions (Lu, 2017).

With fertilizer use and environmental awareness both at an all time high, agriculturalists are looking for new and innovative ways to produce crops for the rising population and be good stewards of the land and environment. Precision agriculture techniques could be the solution agriculturalists need to have high yielding crops and to be environmentally friendly.

PRECISION AGRICULTURE

Definition

During the 20th century, fields were treated uniformly with fertilizers, pesticides, and herbicides due to economic pressures. After the Green Revolution, many areas were still undergoing uniform applications of fertilizers, pesticides, and herbicides, which lead to water and air pollution, erosion, and other environmental disturbances. Precision agriculture is linked to sustainability, "the ability to maintain constant consumption or productivity by substituting between natural resources and manmade capital in production" (Bongiovanni, 2004). Figure 2 illustrates the relationship between ecology, sociology, and economics intersecting and forming



the idea of sustainability. Ecology is a branch of science that studies how organisms relate to their natural environments; it can be broken into many levels including the individual organism, the population, the community, and the ecosystem (Hurd, 2018). The study of human societies and their interactions and the processes that preserve and change them is known as sociology (Faris, 2015). This field explains social movements and social change as humans develop. Economics, the final concept forming sustainability, is the "social science that seeks to analyze and describe the production, distribution, and consumption of wealth (Blaug, 2018)." Where these ideologies intersect you have society pushing for better environmental practices that are economical for producers and consumers.

The United States Department of Agriculture defines precision agriculture as, "a management system that is information and technology based, is site specific and uses one or more of the following sources of data: soils, crops, nutrients, pests, moisture, or yield, for optimum profitability, sustainability, and protection of the environment (McLoud, 2007)." Site-specific management is the thought of treating a specific area or problem instead of uniformly applying fertilizers, pesticides, and herbicides to an area (Bongiovanni, 2004). Site- specific management techniques and precision agriculture practices are directly related to sustainability. Precision agriculture aims to use technology to produce high yields, while only applying fertilizers, pesticides, and herbicides to areas, as they need treatments based on a problem; this is more environmentally sustainable.

Precision Agriculture Technologies Related to Nutrient Management

Agriculturalists have more technologies available to utilize than ever before. Many of these technologies are geared towards precision agriculture and allow the farmer to more easily apply site- specific treatments to areas within their fields. Some of these technologies include global positioning satellites (GPS), lightbar guidance systems, precision-based soil sampling techniques, remote sensing, yield monitors, and variable rate applications.

The United States Department of Defense led the way in pioneering technologies that aided in finding the location of military equipment. These systems have lead the way for the modern Global Positioning Satellites (GPS) system that is still owned by the Department of Defense (Dunbar, 2015). The current GPS system includes 31 operational satellites placed into 6 stationary orbits around earth forming a 27-slot constellation (Space Segments, 2018). With at least 3 satellites available at all times the GPS receiver is able to triangulate the users' location. Now civilians have access to this technology for their personal navigation needs. In 2005, the United Nations formed the International Committee on Global Navigation Satellite Systems, encouraging coordination among global navigation satellite systems (GNSS) (International Committee, 2018). Current provides include China: Compass/ BeiDou Navigation Satellite System (CNSS), European Union: European Satellite Navigation System (Galileo), Russian Federation: Global Navigation Satellite System (GLONASS), and the United States: Global Positioning System (GPS) (International Committee Members, 2018). These satellite networks can be utilized with the correct software and proper instruments. GPS systems are particularly useful in agricultural practices, including lightbar guidance systems and yield monitor systems.

In the early 1990's farmers began to utilize GPS technology to track locations and plan for crop applications (Spielmaker, 2014). Lightbar guidance systems are cab-mounted devices that use GPS signals to aid farmers by providing directions. Lightbars can vary in display options; simple displays include a single horizontal row of lights, with a center light that indicates the tractor is on the right path. More advanced options have graphic displays that have two-dimensional images of the tractor and path, where the operator must keep the vehicle on the path displayed. Some models have audio signals to alert the operator when they deviate from the path (Stombaugh, 2002). Lightbar guidance system helps the applicator align the equipment up with rows and stay in line to prevent over-application (McLoud, 2007). With these systems on the equipment, there is less human error and overlap in applications, making applications more site- specific.

As we gain a deeper understanding of soils and push for site-specific applications, improved soil sampling methods have also been utilized by agriculturalists. Grid soil sampling involves dividing a field into uniform sections and taking samples from each section. This method can be costly and time consuming but allows farmers to develop an extensive nutrient map (McLoud, 2007). A nutrient map divides an area into different categories based on fertility and soil type. Directed sampling involves taking samples based on special patterns. Patterns can be determined based on past grid samples, soil types, previous management, crop yields, or even aerial photos. Directed sampling can provide an accurate nutrient map based on patterns (McLoud, 2007). Each of these sampling techniques can be used to examine the nutrient needs of specific areas instead of a generalized prescription for a field.

Remote sensing is a technique picking up momentum within the agriculture community. Traditionally, airplanes or satellites are used to collect light reflectance. Light reflectance data can be used to isolate areas of a field that may be of concern (McLoud, 2007). Drones can now be used to help isolate areas within a field due to the lower cost. This technology allows growers to get an aerial view of a field and isolate potential problem areas. This viewpoint is different from the ground where problems may not be as obvious. Once an area is isolated it can be treated independently from other areas allowing for site-specific treatments.

Yield monitoring systems are mounted systems that measure the volume of a crop harvested while a GPS receiver works to track the special coordinates. Yields are then used to create a map based on the location they were harvested and can be used for future nutrient management programs (McLoud, 2007). Growers are able to take under-performing areas into consideration when soil sampling and creating nutrient management plans. This is an efficient way to analyze the fields and see what areas may have underlying deficiencies, soil structures issues, or even pest problems.

In conjunction with GPS systems and data collected through soil samples or yield maps, farmers are able to use variable rate applications. Computers are programed with a prescription for a field and doses are applied as the equipment travels through the field. GPS systems recognize coordinates and send signals to application equipment that varies the dose given to an area (McLoud, 2007). This technology allows for more site-specific applications than was previously possible. Farmers are able to give areas specific dosages based on their needs, allowing for practices to be more efficient and sustainable.

These technologies would not be useful if farmers did not keep accurate records of crop land from soil test, yield maps, and crop rotations. These are valuable resources that allow the farmer to track the nutrient uptake of an area, isolate areas of concern, and track the progress of their efforts. Producers can take this knowledge and use it to make decisions regarding nutrient management (McLoud, 2007). With data and technologies available to producers, they are able to have more precise applications and accurate with dosages applied to meet plant needs than ever before.

Nutrient Management and Nutrient Cycles

Nutrient Management

Nutrient Management is the management of fertilizers (synthetic and organic) to agriculture landscapes as plant nutrients. To accomplish sustainable nutrient management goals, the "Four Rs" are used and include using, right amount, right source, right placement, and right timing (The Global "4Rs", 2009). The right amount refers to a proper application rate, which can be derived from soil and plant tissue tests and along with recommendations specific to each crop. The rate at which fertilizers are applied depends on yield goals and crop removal balance. Record keeping is key in determining and monitoring the rate applied. Applying balanced fertilization and the chemical form of nutrients applied is part of the right source (The Global "4Rs", 2009).). In order for fertilizers to be utilized by plants, they must be applied properly. The right place considers the application method, incorporation of fertilizer into the soil, and maintenance and calibration of application equipment. Finally, right timing refers to the application of fertilizers at the appropriate point in the plant life cycle with consideration to fertilizer release, and urease and nitrification inhibitors (The Global "4Rs", 2009). In order to properly manage nutrients you first must understand the nutrient cycles. Plants take up nutrients in specific forms; within the nutrient cycle nutrients can be converted to other non- plant available forms or exit the system. Once the cycles are understood producers then can consider rates, application timing, and application methods for specific crops and fertilizer types.

The Nitrogen Cycle

Nitrogen is an essential element in plant systems and is often applied to crops. Understanding how the nitrogen cycle functions is key to understanding how the nutrient can be lost in fields. Nitrogen lost from the nitrogen cycle is a major concern, as it causes atmospheric pollution, groundwater pollution, and surface water pollution. Figure 3 diagrams the nitrogen cycle as nitrogen transitions between different chemical forms of nitrogen and as nitrogen moves through ecological systems.

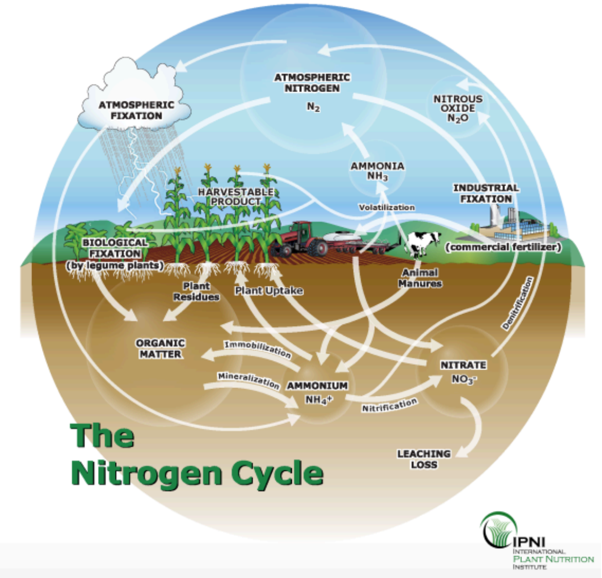


Figure 3: The Nitrogen Cycle (Generalized Nutrient Cycles, 2013).

Nitrogen is all around us, in the atmosphere, soil, and in living organisms, it is estimated that on every square mile of earth there is 20 million tons of nitrogen. Seventy eight percent of all elemental nitrogen is found in the atmosphere in a gaseous state (Markov, 2013). The nitrogen present on earth circulates through the earth, plants, animals, and atmosphere. In order for plants to utilize nitrogen, it must be in inorganic forms (NO_3^- and NH_4^+); however, the nitrogen cycle converts nitrogen into organic forms as well (N_2, NO_2^-, and NH_3,) (Weil, 2010).

Within the nitrogen system major nitrogen processes occur: nitrogen fixation, ammonification, nitrification, denitrification, mineralization, and immobilization (Markov, 2013). Nitrogen fixation occurs when *Rizhobium* bacteria reduce atmospheric nitrogen (N_2) to ammonia (NH_3). Bacteria can live on the roots of plants in a symbiotic relationship or as free-living bacteria in the soil (Markov, 2013). Nitrogen fixation is a complicated reaction ($N_2 + 8e^- + 8H^+ + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16P$) that requires electrons and hydrogen ions to be transferred to the atmospheric nitrogen molecule through an enzyme called nitrogenase (Gossett, 2017; Markov, 2013). This reaction requires energy stored as ATP (adenosine triphosphate) in cells. Nitrogenase has two subunits; one subunit transfers electrons and hydrogen ions to the second subunit that binds with the ATP; through hydrolysis the ATP releases energy. The energy released makes passing the electrons and hydrogen ions to the nitrogen molecule possible resulting in the formation of ammonium. Before plants can use fixed nitrogen, ammonia must be converted to a plant soluble form nitrate (NO_3^-) (Gossett, 2017). With atmospheric nitrogen being readily available, nitrogen fixation is an important process of the nitrogen cycle.

Ammonia (NH_4^+) is also created through ammonification by living organisms. Ammonia is produced through waste of animals and fish through decomposition of organic nitrogen waste (Markov, 2013). This process is aided by bacteria in the soil or in the digestive system of animals. Ammonia can even be formed through the decomposition of plants (Markov, 2013). At this point in the nitrogen system ammonia can be converted through nitrification or could potentially be lost from the cycle through volatilization or converted into organic mater.

Nitrification is a two-step process that results in the formation of nitrite (NO_2^-) as a mediatory product. Through this process, two groups of bacteria, ammonia- oxidizing bacteria and nitrite- oxidizing bacteria, work in steps to convert the ammonia to nitrite through mineralization (Markov, 2013). The first step requires nitrifying bacteria convert ammonium into nitrite through the chemical equation $NH_4^+ + O_2 \rightarrow NO^{-2} + H_2O + H^+$. Nitrifying bacteria then oxidize the nitrite to form nitrate ($NO_2^- + O_2 \rightarrow NO_3^-$) (Markov, 2013). Bacteria often live in water and soil where the concentrations of ammonia are high. Nitrification creates a form of nitrogen that can be used by plants; however, if not used quickly it can be lost through immobilization, converted to organic matter, or lost to leaching (Weil, 2010).

In the Nitrogen Cycle, nitrogen can be lost from the system through nitrate leaching, denitrification, and volatilization, having significant consequences. Nitrate anions do not attach to the predominantly negatively charged soil colloids, so nitrate is able to move freely with water and leach from the soil, as the water drains through the soil profile (Weil, 2010). When nitrogen is lost it can lead to acidification of soil and co-leaching of other minerals, creates poor ecosystems, and the nitrate can move into ground water causing pollution downstream. Ammonium based fertilizers, such as ammonium sulfate and urea, are oxidized by soil microbes and produce strong inorganic acids. Positive hydrogen ions are consumed by bicarbonates, which are released as plants uptake anions, resulting in acidification. Acidification occurs as a result of over fertilization. Acids displace cations, such as Ca^{2+}, Mg^{2+}, and K^{2+}, which leach out of soils. In aquatic ecosystems if the nitrogen exceeds critical levels (dissolved N above 2 mg/L) aquatic plant populations can increase. Nitrogen levels are more likely to cause issues in salt-water ecosystems and can cause eutrophication (over fertilization). Dissolved nitrate in water can cause unsafe drinking water for humans and animals and dissolved ammonia creates toxicity to fish. Nitrate mineralized in highly weathered soils, Oxisols and Ultisols, can be lost from the root zone before annual crops can even take it up (Weil, 2010).

Denitrification is the process of soil bacteria converting nitrate into gaseous nitrogen (NO, N_2, N_2O) (Markov, 2013). Nitrogen can be lost from the cycle by denitrification, which occurs when nitrate ions are converted to gaseous forms through biochemical reduction reactions when oxygen is unavailable. Most commonly, anaerobic bacterial heterotrophs are responsible for this reaction; however, some denitrifying bacteria are autotrophs. The general series of reduction is as follows: Nitrate ions ($2NO_3$-) → Nitrite ions ($2NO_2$-) → Nitric oxide gas ($2NO\uparrow$) → Nitrous oxide gas ($N_2O\uparrow$) → Dinitrogen gas ($N_2\uparrow$) (Weil, 2010). In order for each reduction to take place organic residue or sulfides must be available for denitrifiers. Denitrification occurs when soil oxygen levels are below 10% oxygen. Optimum temperatures are between 25 and 35 degrees Celsius. Denitrification can cause atmospheric pollution, dinitrogen is an inert gas but nitrogen oxides are highly reactive. Acid rain can be created, when NO and N_2O are released into the atmosphere and creates nitric acid (Weil, 2010). Ground level ozone can be created through nitrogen oxides, causing air pollution. NO can contribute to the greenhouse effect when it is in the upper levels of the atmosphere and absorbs radiation. N_2O can react in the stratosphere resulting in the destruction of the ozone layer. Destruction of the ozone destroys the protective layer of the atmosphere that protects us from ultraviolet radiation from the sun (Weil, 2010). Agriculture applications are not the only source of N_2O, as vehicles can also contribute to this source of pollution. Denitrification tends to occur mostly in wet, poorly drained soils; in areas with these poor soils and large amounts of nitrogen fertilizer is applied the loss through denitrification can be 30 to 60 kg N/ ha/ yr. In flooded areas such as rice paddies, losses from denitrification can be high when they undergo alternate wetting and drying. During dry periods nitrates are formed through nitrification and when wetted denitrification occurs due to the lack of oxygen. In riparian areas significant levels of denitrification take place as contaminated groundwater travels through the area, the nitrate is lost to the riparian vegetation like a filter. The nitrate is then lost through denitrification in these zones. The water is cleared of half of the nitrates before it reaches the streams (Weil, 2010).

Ammonia gas can be formed as organic materials and fertilizers (anhydrous ammonia and urea), through the following equation: $NH_4^+ + OH^- \leftrightarrow H_2O + NH_3\uparrow$. Ammonia volatilization occurs more frequently at high pH levels and with soils with fewer soil colloids, as ammonia gas can be absorbed to soil colloids and lack would allow them to be lost. By incorporating manure or fertilizer the amount of ammonia volatilization can be reduced 25 to 75% (Weil, 2010). These losses are important to understand in order to apply fertilizers properly to ensure higher nitrogen use efficiency and to prevent pollution.

Phosphorus Cycle

Phosphorus, like nitrogen, is an essential element and is of concern due to potential avenues of pollution. Phosphorus moves through earth through soils, rocks, water, and the atmosphere making its cycle very complex (Schlom, 2015). The phosphorus cycle differs from the nitrogen cycle because it does not include a gaseous state, as shown in Figure 4; the inorganic forms are absorbed to the mineral surface (Weil, 2010). However, some phosphorus can be lost into the atmosphere when dust is dissolved into water, having negative consequences (Schlom, 2015).

Phosphorus reserves are mainly found in sedimentary rocks; weathering occurs which removes the phosphorus from the rocks and deposits them in the soil and water. When in the form of phosphate, plants can take up the phosphorus for cellular use (Phosphorus, 2015). Animals can then consume plants and the phosphorus is deposited back into the environment through waste. After an animal's death phosphorus can also be retuned to the soil through decomposition (Phosphorus, 2015).

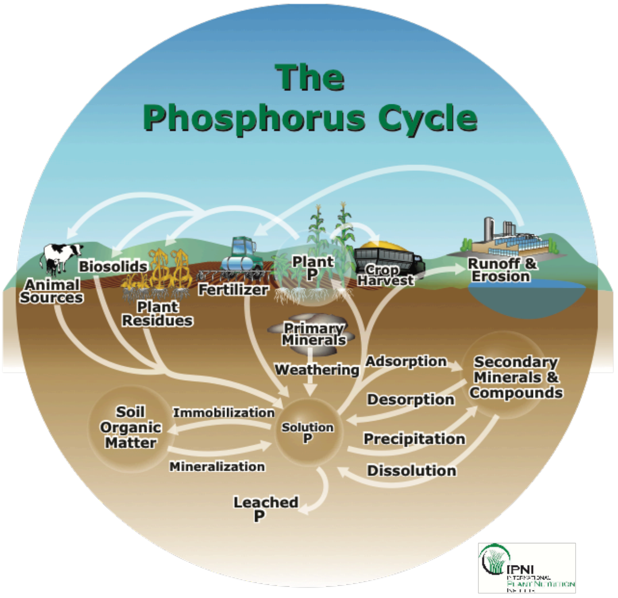


Figure 4: Phosphorus Cycle (Generalized Nutrient Cycles, 2013)

In the soil, phosphorus usable forms are highly insoluble, therefore plants cannot utilize the phosphorus. When soluble forms are added to the soil for agricultural purposes they become fixed and unavailable for plants (Weil, 2010). Understanding the different forms of phosphorus in the soil is key to proper management. Plant roots as phosphate ions, HPO42- in alkaline soils and H2PO4- in acidic soils, absorb phosphorus. However, soluble organic forms can be taken up (Weil, 2010). As plants decompose in the soil microorganisms decompose the plant residue; eventually a portion of the phosphorous is released back into the soil, through the process of mineralization. Some of the phosphorus from decomposing plants goes into soil organic matter. Organic forms mineralized slowly releasing phosphate ions into the soil for plant uptake, the cycle continues as the plant tissue senesces and decomposes (Weil, 2010).

Soil phosphorus can be grouped into three compounds: organic phosphorous, calcium-bound inorganic phosphorus, and iron- or aluminum- bound inorganic phosphorous (Weil, 2010). Calcium bound inorganic forms of phosphorus is mostly found in alkaline soils, whereas iron- or aluminum- bound inorganic forms of phosphorus is found mostly in acidic soils. These forms contribute slowly to the soil phosphorus but most forms lack in solubility making them unavailable for plant uptake (Weil, 2010).

In aquatic ecosystems, phosphorus enters the ecosystem through runoff, natural deposits, and even waste. Because phosphorus is not highly soluble it binds too tightly to soil particles and tends to settle to the floors of water bodies (Phosphorus, 2015). When the floor sediment is disturbed phosphorus may reenter the cycle or be used by aquatic species. From this point it will flow through the aquatic food chain (Phosphorus, 2015).

Phosphorus can be lost from the soil in the following ways: plant biomass removal (5 to 50 kg ha^{-1} yr^{-1}), soil erosion with bound phosphorus ions (0.1 to 10 kg ha^{-1} yr^{-1}), surface runoff (0.01 to 3 kg ha^{-1} yr^{-1}), and leaching (0.0001 to 0.4 kg ha^{-1} yr^{-1}) (Weil, 2010). In these estimates the higher ranges are those soils that are cultivated though agriculture practices. These losses can have negative impacts on the environment and show inefficiency in agriculture practices. By understanding how nutrient cycles function producers are able to more efficiently apply fertilizers, thereby protecting the environment and their bottom line.

Potassium Cycle

Potassium is also an essential nutrient, but unlike nitrogen and phosphorus is has little environmental concerns when lost from the soil, making it less focused on from a pollution standpoint. However, it is essential to plant development and its cycle is important to understand in order to properly manage (Weil, 2010). Potassium is only present in soil solution as a positively charged cation and does not have a gaseous state that can be lost. In the soil potassium is influenced by cation exchange properties and weathering, as seen in Figure 5 (Weil, 2010).

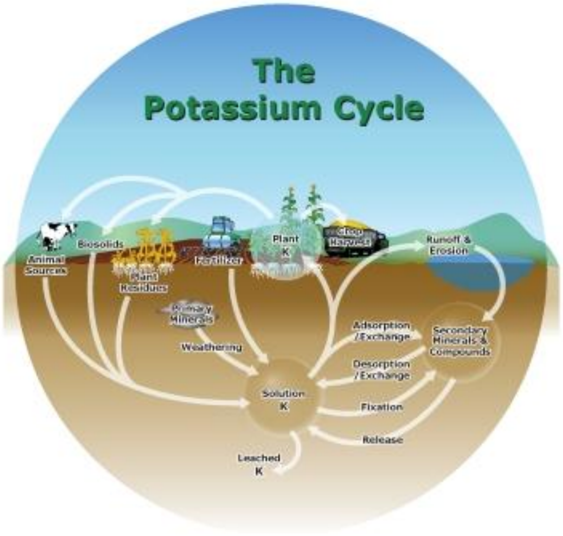


Figure 5: The Potassium Cycle (Generalized Nutrient Cycles, 2013)

Potassium is found in primary minerals like micas and potassium feldspar, as these minerals weather their lattice structure becomes more pliable. As the mineral slowly weathers more potassium is released from the minerals, first as nonexchangeable but as the mineral continues to weather available forms near minerals edge are released and soil solution forms are taken up by the plants (Weil, 2010). In the soil 90 to 98 percent of potassium is found in micas, primary minerals and feldspar, 1 to 10 percent is found fixed in clays (nonexchangeable forms), and 1 to 2 percent in exchangeable forms. In the soil primary mineral structures contain unavailable potassium, secondary minerals (clays and humus) are deemed slowly available, and exchangeable potassium on soil colloids or water (soluble potassium) is deemed readily available (Weil, 2010). Potassium ions in the soil solution can become absorbed to vermiculite, smectite, and other 2:1 minerals. These ions can become definitely fixed to soil colloids. Potassium ions fit between layers of crystals of clays. These ions become part of the structure and become nonexchangeable (Weil, 2010).

Most soil potassium is found in minerals and in nonexchangeable forms. In fertile soils these forms can release potassium in exchangeable forms and soil solution forms that plants can use for optimum growth. However, plant removal removes these nutrients from the ecosystem causing a lack of potassium (Weil, 2010). Other soils that lack primary minerals may also lack potassium. These soils that lack potassium will need to be supplemented with fertilizers. In mature natural ecosystems, with diverse species and niches, only 1 to 5 kg/ ha of potassium is lost each year through leaching or erosion (Weil, 2010). Plants can also take up more potassium than needed, which is known as luxury consumption. Luxury consumption removes the potassium from the soil and if the plants or plant products are removed from the cropland the stored potassium is lost from the system, potentially causing deficiencies (Weil, 2010).

These losses are normally balanced out by the weathering of minerals. Compared to phosphorus, potassium is more susceptible to leaching, but less susceptible than nitrogen (Weil, 2010). Because potassium is a positively charged cation it is attracted to negatively charged clays and humus, reducing losses. Potassium is taken up in large quantities by plants (Weil, 2010). Rainwater can leach potassium from plant leaves and ultimately return it to the soil; plant residue can also decompose and return potassium to the soil. Potassium can also be returned to the soil in urine released from animals that have consumed the plants (Weil, 2010). Because potassium is found bound to mineral particles, potassium can be lost form the soil system through leaching and runoff through the weathering of the minerals. It is estimated that one fifth to nearly all of the potassium, taken up in agroecosystems, will be lost and not returned to soils in which it was taken (Weil, 2010).

Lime

The pH of the soil is a key factor in nutrient management; if the soil is too high or too low in pH, it can affect the nutrient availability and plant up take. The pH of the soil can be affected by acid rain and soil type making the pH too acidic for plants to properly take up nutrients (Weil, 2010). Ideally soils should be between 6 and 7 on the pH scale, depending on the crop, soil type, and nutrient availability; for most crops the pH should be between 6.2 and 6.5. Liming is a common agriculture practice especially in humid regions to raise the pH of acidic soils (Weil, 2010). Liming is done by amending soil with alkaline materials that provide a conjugate base of weak acid that are able to consume H^+ ions to form weak acids. Most commonly these bases are calcium and magnesium (Weil, 2010). Some agricultural limes contain oxides or hydroxides of alkaline earth metals, which react to water to form hydroxide ions (ex. $Ca + H_2O = Ca(OH)_2 = Ca^{2+} + 2OH^-$). Lime is applied to change the chemical makeup of the soil and is applied in smaller quantities compared to fertilizers (Weil, 2010).

When applied to acidic soils, lime reacts with carbon dioxide and water to form bicarbonate. Calcium and magnesium bicarbonates are more soluble, making them reactive to exchangeable and residual soil acidity (Weil, 2010). The calcium and magnesium replaces hydrogen and aluminum ions on soil colloids, decreasing the percent acid concentration raising the pH of the soil (Weil, 2010).

To determine the amount of lime required you must consider the following: the change of pH needed, soil buffer capacity, amount and depth of soil, chemical composition of lime, and fitness of lime. You must also consider soil textures when selecting lime, due to the buffer capacities of different soil types (Weil, 2010). Soil tests can be done to determine the soil type and pH levels, which should be considered before selecting lime type and the amount applied.

Lime slowly reacts, raising the pH over time to reach the desired pH; this could take a few weeks or even up to a year (Weil, 2010). The calcium and magnesium are consumed by plants and removed from the system or they are lost through leaching. They are replaced by acidic cations, slowly decreasing the soil pH (Weil, 2010). In order to maintain soil pH, lime applications must be done every three to five years and should be applied before a crop is planted to ensure the lime has time to raise the pH, because the process takes time to get the desired affects (Weil, 2010). Without consideration to soil pH and proper liming techniques, fertilizer applications would be pointless. Nutrient uptake is dependent on soil pH and is a key factor in nutrient management plans.

Importance of Nutrient Cycles

Understanding the nutrient cycles is key to nutrient management. Without a basic understanding of how key nutrients move through their cycles and how plants utilize them precision techniques would be less effective. Precision techniques allow farmers to apply fertilizers to specific areas and can allow farmers to prescribe applications based on nutrient needs in a specific area. For example, if an area of a field has high drainage a farmer would be able to assume this area may be prone to nutrient leaching based on their knowledge of the nutrient cycles. The farmer would be able to isolate the area and use soil-sampling techniques to check that specific area. The farmer would then be able to apply the prescribed application to the isolated area and monitor the area using precision technologies. Through the literature review we will explore the benefits of precision agriculture in relation to yields and nutrient use efficiency.

Review of Literature: Precision Agriculture in Relation to Nutrient Management

Introduction

Agriculturalists take into consideration many factors when producing commodities for the world; these concerns include stewardship, yields, and profitability. Producers work to prevent pollution, soil erosion, and greenhouse gas emissions in order to maintain the integrity of the environment that their livelihood relies on (Schimmelpfennig, 2018). Precision agricultural techniques allows farmers to accomplish these goals, by decreasing pollution emissions from equipment and losses from nutrient cycles while allowing for site specific treatments based on data collected. But how effective are these techniques in relation to nutrient management?

Long-term impact of a precision agriculture system on grain crop production

A study was performed by the Cropping Systems and Water Quality Research Unit through U.S. Department of Agriculture – Agricultural Research Services at the University of Missouri, to determine the long- term impact of a precision agriculture system on grain crop production on a 36 ha field in central Missouri. From 1993 to 2003 yield and soil mapping and water quality were assessed; in 2004 to 2014 they implemented a precision agriculture system that included no- till tillage system, growing winter wheat instead of corn where corn was not profitable, cover crops, and herbicide applications based on weed pressures (Yost, 2016). The study implemented site-specific nitrogen applications for wheat and corn; more specifically they applied nitrogen on odd years in variable rates through top dressing based on data collected using canopy reflectance sensors. Variable rates of phosphorus, potassium, and lime were applied based on grid sampling through broadcasting (Yost, 2016). The management system broke the field into 3 different zoned (A, B, and C): sections A and B are in the northern portion and C in the southern portion. Zones A and B are used to produce soybeans and wheat and zone C was used to produced corn and soybeans (Yost, 2016).

To determine the affect of these precision techniques they used the data collected from the previous decade using conventional farming techniques that included whole field corn and soybean mulch tillage system. With the system in place for 11 years the study showed significant crop productivity changes (Yost, 2016). In the area of the field that has an eroded back slope and wheat was planted instead of corn showed the most significant change with a 22% increase in relative yields. In the southern portion of the field the relative corn temporal variation decreased 51% (Yost, 2016). Corn and soybean temporal variation with the precision agricultural system was reduced 22% in the southern portion and 30% overall. The improvements occurred despite weather deviations over 30 years (Yost, 2016). With the precision agriculture system in place soybean and corn yields did not increase and special grain yield variability was not reduced, suggesting these techniques have limited ability to increase yields in these crops. The study suggests that this area may need more time in order or yields of soybeans and crops to increase based on the yield from adjacent land that went through a similar change but was not included in the study (Yost, 2016).

A Preliminary Precision Rice Management System for Increasing Both Grain Yield and Nitrogen Use Efficiency

In China researchers developed a preliminary integrated precision rice management system that incorporated site-specific nutrient management techniques with alternate wetting and drying irrigation and optimized transplanting density. The study aimed to increase yield and nitrogen use efficiency (Zhoa, 2013). The data was compared through plot experiments in the following categories: high efficiency system that optimized nutrient and water management, a high yield system that optimized transplanting density and water management, and a farmers practice. In this experiment there were 5 treatments, the first applied 0 kg ha−1 N, fields had mild drainage until leaf stage 7-8 and then was flooded (Zhoa, 2013). Treatment two applied nitrogen at the rate of 150 kg ha^{-1} at early basal and tillering stages, the experiment used the same irrigation methods as treatment one. The third treatment uses a site- specific nutrient management method by splitting a 100 kg ha−1 N treatment into four doses, with the third and forth based on data from chlorophyll meters and intermittent wetting of the soil (Zhoa, 2013). Treatment four used a total nitrogen application of 140 kg ha−1 N split into 5 doses and utilized intermittent wetting of the soil. The fifth treatment used a total nitrogen application of 110 kg ha−1 N split into 5 doses and utilized intermittent wetting of the soil (Zhoa, 2013).

The results from this study showed that the preliminary integrated precision rice management system (treatment 5) increased rice yields by 10% compared to farmers practice (treatment 2) systems and increased nitrogen use efficiency from 51 to 97% (Zhoa, 2013). The high efficiency system (treatment 3) optimized the nitrogen use efficiency from 46 to 63% compared to the farmers practice system and did not affect the yields. The high yield system (treatment 4) achieved similar yields compared to the preliminary integrated precision rice management system but the nitrogen use efficiency was 5 to 27% lower (Zhoa, 2013). Though few studies have been conducted to determine the affects of precision agriculture on yield and nutrient use efficiency in rice, the results from this study show that there is potential in incorporating these techniques in rice production. Producers could increase yield and more efficiently use nutrients without losses from the nutrient cycle (Zhoa, 2013).

Spatial Variability and Precision Nutrient Management in Sugarcane

Sugarcane is an important crop around the world, with India being the largest producers. A study took place in northern India on an 800 ha area where maximum temperatures range from 25 to 43 degrees Celsius in April and minimum temperatures range from 8 to 15 degrees Celsius in December, with the rainfall in the region being 540 mm annually (Patil, 2014). The study had two parts; the first was precision nutrient management in sugarcane and the second was an assessment of temporal and spatial variability in soil and sugarcane in the given plot. To determine the affect of precision agriculture they set up a plot and had ten fertilizer treatments with varying time and levels of fertilizers applied through fertigation compared to a control, which used furrow irrigation (Patil, 2014). To assess the temporal and spatial variability in soil and sugarcane thirty-two farmers were selected who followed practices by the University of Agricultural Sciences in Dharwad, India and yield of crops were recorded. Based on soil tests the recommended fertilizer rate was 250kg N, 32 kg P, and 156kg K per hectare (Patil, 2014). Ten treatments were applied to the different plots as shown in the following chart:

Treatment Number	Dosage of Treatment	Application Interval
1	187: 117 kg N &K ha^{-1}	Weekly
2	250: 156 kg N &K ha^{-1}	Weekly
3	312: 195 kg N &K ha^{-1}	Weekly
4	187: 117 kg N &K ha^{-1}	Fortnightly
5	250: 156 kg N &K ha^{-1}	Fortnightly
6	312: 195 kg N &K ha^{-1}	Fortnightly
7	187: 117 kg N &K ha^{-1}	Monthly
8	250: 156 kg N &K ha^{-1}	Monthly
9	312: 195 kg N &K ha^{-1}	Monthly
10: Farmer’s Practice	250: 32: 156 NPK ha^{-1}	

The surface irrigation with 250: 32: 156 kg NPK ha^{-1} (farmer's practice) acted as a control to compare the precision agriculture techniques to, yielded 124 Mg ha^{-1}.

The precision treatments varied in yield from 111 Mg ha^{-1} in the 187: 17 kg N&K ha^{-1} at weekly interval to 167 Mg ha^{-1} in the 312: 195 N&K ha^{-1} at fortnightly interval application (Patil, 2014). The higher yields in precision applications show that the correct nutrient prescription applied at the proper time and through the proper method can positively affect yields in sugarcane crops. Based on soil data after harvest the surface irrigation treatment had a higher fertility status compared to the fertigation techniques through flood irrigation, demonstrating a higher nutrient use efficiency using the precision techniques (Patil, 2014).

Variable Nitrogen Rate Determination From Plant Spectral Reflectance In Soft Red Winter Wheat

Previous studies have shown that a normalized difference vegetation index is more accurate at estimating biomass. Normalized difference vegetation index is calculated using the equation, NDVI= (NIR- R)/(NRI+R), where NIR is near infrared and R is red wavelengths (Thomason, 2010). In Virginia, researchers created a study to determine the potential of using crop canopy reflectance data, to apply variable nitrogen applications in soft red winter wheat. There were 14 small plot sites (3.6 by 5.8m) between 2000 and 2003 that were used to create the variable rate Virginia Wheat algorithm for Virginia soft red winter wheat. Sites were chosen to represent the diverse environments in Virginia that grow wheat and included different cultivars of soft red winter wheat grown in Virginia. Researchers used no irrigated fields and planted plots at approximately 400 seeds m^{-2}. Before planting nitrogen was applied at 34 kg N ha^{-1} in all plots. Two in season nitrogen top dressing applications were applied at Zadoks growth stage (GS) 25 and 30. Applications at GS 25 were based on tiller density with plots with higher densities receiving lower nitrogen rates and lower densities having higher nitrogen rates. At GS 30 the applications were based on tissue nitrogen concentrations. “Fixed nitrogen rates (0, 34, 68, 101, and 134 kg N ha^{-1}) were applied at GS 25 and GS 30 in factorial arrangement of treatments using a randomized compete block design with four replications at all sites in 2000 and 2001(Thomason, 2010).” One treatment was based on the preliminary version of the Virginia Wheat Algorithm and received variable rate applications, at GS 25, GS 30, or both, applied to each m^2 in the plot. The Virginia Wheat Algorithm is based on plant spectral reflectance. Using GreenSeeker® systems researchers were able to collect spectral reflectance data in each plot at GS 25 and GS 30, by scanning the center of the targeted 1 m^2 area, in the direction of the rows. Data was then used to calculate the normalized difference vegetation index. Grain was harvested and weighed to determine the grain yield. The mean yields were calculated and plotted against the yield projection index. Using data collected researchers began in 2005, large plot validation studies to determine if the algorithm created based on the small plots was accurate. Fifteen replicated large plots, in commercial fields, were used to validate the algorithm developed from the small plot studies. Before planting all sites had 34 kg ha^{-1} nitrogen applied and followed corn. The plots were managed using intensive wheat management before implementing nitrogen rich strip at GS 25 and treatments applied at GS 30. The nitrogen rich strip was established by applying 2 times the intended GS 25 rate. Strips varied in size sue to the field size and equipment used but was larger than 1200 m^2. GS 30 applications were conducted in individual plots 18.2 m by 100 to 122 m in size. Treatments were performed in a randomized complete block design, standard nitrogen rates were applied at GS 30 based on tissue nitrogen concentrations and variable rate treatments were applied using GreenSeeker® RT 200 system, each treatment was replicated 6 times. This experiment included 4 to 5 fixed rate treatments, replicated 3 times, to assess site responsiveness and optimum nitrogen rates. Using commercial combines the grain was harvested, and grain from each strip was weighed to determine the yield.

In the validation studies, the Virginia Wheat Algorithm yields were similar in sites, one site was higher yielding, and one site was lower, when compared to the standard GS 30 rates (Thomason, 2010). Virginia Wheat Algorithm treatments were 99.1 percent the yield compared to the standard approach and used 93.1 percent of the nitrogen applied. With GS 30 applications all sites responded positively, with one site excluded, rates were 8 and 3 kg ha^{-1} below economically optimum nitrogen rates for the Virginia Wheat Algorithm. This study shows that using the using GreenSeeker® RT 200 system to apply nitrogen based on the Virginia Wheat Algorithm was equal to standard fix rate applications.

Phosphorous and Potassium Fertilizer Recommendation Variability For Two Mid-Atlantic Coastal Plain Fields

Grid soil sampling and variable rate fertilizer applications are being used more in an effort to provide site- specific applications (Anderson-Cook, 1999). The relative effectiveness of these strategies is unproven. In an effort to determine the effectiveness of fertilizer recommendations for variable rate applications derived from grid soil sampling methods, researchers used two fields in the Virginia Costal Plains area. In the areas selected the alluvial soils range from Bojac 1A and 2A, coarse- loamy, mixed, thermic, Hapludults soils, to Wickam 3A and 4A, fine- loamy, mixed, thermic, Ultic Hapludalfs soil. Two fields, 21 ha in size, were used to collect soil samples using the grid soil sampling technique. Researchers tested each sample to determine the Mehlich I extractable phosphorus and potassium. Field one was divided into 7 rows 18.5m apart with 19 samples taken at 30.4m intervals equaling 133 soil samples taken. Field two was divided into 14 rows 18.5m apart with 20 samples taken at 30.4m intervals equaling 280 soil samples taken. Field one had less variability for both phosphorus (standard deviation 4.4 mg kg^{-1}) and potassium (standard deviation 15.7 mg kg^{-1}) across the field. Field two had greater differences across the field with phosphorus (standard deviation 15.9 mg kg^{-1}) and potassium (standard deviation 41.3 mg kg^{-1}) fertilizer needs (Anderson-Cook, 1999). Other methods tested included 0.83 ha grid with samples taken every fifth row and third column, 0.33 ha grids with samples taken every third row and second column, global composite calculated by sampling 20 locations in the test site, and composite-by-soil-type calculated by sampling 20 areas in well-represented soil type areas and 10 samples taken in scarce soil type areas. A second study was conducted to compare the variation at the core level to the variation at the sample level. Researchers used 4 core level measurements and 1 sample measurement at 4 locations within the Bojac and Wickham soil types. This was done to make sure the composite and composite-by-soil-type values were measured accurately.

Through this study researchers determined that grid sampling is not required for subsequent variable rate fertilizer applications (Anderson-Cook, 1999). Grid sampling done at 0.33 ha was more precise at estimating extractable potassium, but in only one field. When tested for appropriate fertilizer rates 67 percent of tested sites were at appropriate potassium levels. However, there was no improvement in either test fields for extractable phosphorus levels. When compared to the whole field composite sampling both grid sampling methods improved precision, with a lower average misapplication rate, for extractable phosphorus and potassium. Composite-by-soil-type method has a lower average misapplication and higher percentage of appropriate fertilizer rates applied, compared to whole field composite sampling. They found that composite-by-soil-type was the most precise method derived for fertilizer recommendations due to small systematic variation. Grid sampling was superior in precise fertilizer recommendations for large in field variations; however composite-by-soil-type method was not far behind. Through this study it is recommended that grid sampling only be used when there are strong trends in extractable phosphorus and potassium.

Differentiating Soil Types Using Electromagnetic Conductivity and Crop Yield Maps

Variable rate fertilizer applications based on soil types within a field are highly effective. However, it is impractical and expensive to correctly classify soils using Order I Soil Survey (Anderson-Cook, 2002). In the Coastal Plains of Virginia researchers created a study to determine if apparent electromagnetic conductivity alone or combined with previous year crop yields using GPS technology could provide an alternative to detailed soil mapping. Soils on the experimental site were determined using an Order I Soil Survey. The soils were all alluvial soils, including Bojac 1, Bojac 2, Wickham 3, and Whickham 4 soil types. Soil productivity and fertilizer requirements are determined by soil water holding capacity and soil texture. The experimental location was 24 ha in size. To determine the electromagnetic conductivity of the soils they used an EM38 induction meter, all measurements were standardized to equivalent electrical conductivity at 25 degrees Celsius (Anderson-Cook, 2002). Electromagnetic conductivity readings were taken on a grid at 30.4 m intervals along 21 strips that were 18.5 m apart. A GPS was used to record the location of electromagnetic conductivity readings and the standardized equivalent. Due to the area tested being part of a crop rotation study the study was broken into 4 crops: corn, barley, wheat, and soybean. The soil survey results were matched with the electromagnetic conductivity readings using the GPS readings. Yields for crops were determined using a Greenstar yield monitor and GPS receiver.

Using electromagnetic induction to classify soil type shows promise in the region. Based on the study 85 percent of the time the electromagnetic conductivity readings were able to differentiate subsoil texture differences (Anderson-Cook, 2002). Electromagnetic conductivity combined with crop yield locations, correct soil classification increased over 90 percent. The study found that it was more difficult to determine precise soil types, for example determining Bojac 1 or Bojac 2. Using only electromagnetic conductivity reading they were 62 to 81 percent correct in determining the difference; when combined with crop yield data they were 80 and 91 percent correct in determining the precise soil type. With this technology producers could economically determine soil type to develop variable rate fertilization systems.

Conclusion

With the world's population exponentially increasing, producers will face many challenges and with societal pressures producers are focused on stewardship more than ever, especially with less than 2 percent of the worlds population being farmers. Precision agriculture could be a solution to both of these conundrums. Precision agriculture techniques will allow producers to apply site-specific treatments to an area of a field or to individual plants using technologies. Based on current studies precision techniques can produce higher yields than using traditional farming practices and can increase the crops' nutrient use efficiency. Based on the studies highlighted there is some variability from area to area where precision techniques were applied, demonstrating the need for more studies to compare the implementation of these practices compared to traditional methods. There is promise in implementing these techniques, but every area is different and will be trial and error in some areas to find techniques that work for each scenario. Using data and research producers have an excellent starting point to find the technologies and methods that work best.

LITERATURE CITED

Anderson-Cook, C. M., Alley, M. M., Roygard, J. K., Khosla, R., Noble, R. B., & Doolittle, J. A. (2002). Differentiating Soil Types Using Electromagnetic Conductivity and Crop Yield Maps. *Soil Science Society of America Journal,66*(5), 1562. doi:10.2136/sssaj2002.1562

Anderson-Cook, C., Alley, M., Noble, R., & Khosla, R. (1999). Phosphorous and Potassium Fertilizer Recommendation Variability for Two Mid-Atlantic Coastal Plain Fields. *Soil Science Society of America Journal,63*(6), 1740. doi:10.2136/sssaj1999.6361740x

Blaug, M. (2018, October 15). Economics. Retrieved from https://www.britannica.com/topic/economics

Bongiovanni, R., & Lowenberg-Deboer, J. (2004). Precision Agriculture and Sustainability. *Precision Agriculture,5*(4), 359-387. doi:10.1023/b:prag.0000040806.39604.aa

Dunbar, B. (2015, May 05). Global Positioning System History. Retrieved November 12, 2018, from https://www.nasa.gov/directorates/heo/scan/communications/policy/GPS_History.html

Faris, R. E., & Form, W. (2015, August 31). Sociology. Retrieved from https://www.britannica.com/topic/sociology

Generalized Nutrient Cycles. International Plant Nutrition Institute , 10 May 2013, www.ipni.net/article/IPNI-3326.

The Global "4R" Nutrient Stewardship Framework. International Fertilizer Industry Association, Aug. 2009, www.ipni.net/ipniweb/portal/4r.nsf/0/BAB4157B488871A385257DF100739D94/$FILE/The Global 4R Nutrient Stewardship Framework.pdf.

Gossett, D. R. (2017). Nitrogen fixation. *Salem Press Encyclopedia of Science*. Retrieved from http://login.ezproxy.lib.vt.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ers&AN=87324009&site=eds-live&scope=site

Hurd, L. E. (2018). Ecology. *Salem Press Encyclopedia of Science*. Retrieved from http://login.ezproxy.lib.vt.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ers&AN=88833194&site=eds-live&scope=site

International Committee on Global Navigation Satellite Systems (ICG). (2018). Retrieved from http://www.unoosa.org/oosa/en/ourwork/icg/icg.html

International Committee on Global Navigation Satellite Systems (ICG): Members. (2018). Retrieved from http://www.unoosa.org/oosa/en/ourwork/icg/members.html

Lu, C., & Tian, H. (2017). Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance. *Earth System Science Data,9*(1), 181-192. doi:10.5194/essd-9-181-2017

Markov, S. A. (2013). Nitrogen Cycle. *Salem Press Encyclopedia of Science*. Retrieved from http://login.ezproxy.lib.vt.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ers&AN=88953033&site=eds-live&scope=site

McLoud, P. R., Gronwald, R., & Kuykendall, H. (2007, June). Precision Agriculture: NRCS Support for Emerging Technologies. Retrieved October, 2018, from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043474.pdf

Melillo, E. D. (2012). The First Green Revolution: Debt Peonage and the Making of the Nitrogen Fertilizer Trade, 1840–1930. *The American Historical Review, 117*(4), 1028-1060. doi:10.1093/ahr/117.4.1028

Mississippi State University Extension. Phosphorus Cycle [Online image]. Retrieved November 15, 2018 from http://extension.msstate.edu/sites/default/files/topic-files/soils/phosphorus.gif

Patil, V. C., Nadagouda, B. T., & Al-Gaadi, K. A. (2012). Spatial Variability and Precision Nutrient Management in Sugarcane. *Journal of the Indian Society of Remote Sensing,41*(1), 183-189. doi:10.1007/s12524-011-0181-4

Phosphorus Cycle. (2015). Retrieved November 15, 2018, from https://enviroliteracy.org/air-climate-weather/biogeochemical-cycles/phosphorus-cycle/

Schlom, D. M., & Ness, B. (2015). Phosphorus cycle. *Salem Press Encyclopedia of Science*. Retrieved from http://login.ezproxy.lib.vt.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ers&AN=89407995&site=eds-live&scope=site

Schimmelpfennig, David. 2018. "Crop Production Costs, Profits, and Ecosystem Stewardship with Precision Agriculture" 50 (1): 81–103. http://login.ezproxy.lib.vt.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=eoh&AN=EP128223493&site=eds-live&scope=site.

Space Segment. (2018, December 21). Retrieved from https://www.gps.gov/systems/gps/space/#orbits

Spielmaker, D., & Mitsuoka, Y. (2014). Historical Timeline - Farm Machinery & Technology. Retrieved from https://www.agclassroom.org/gan/timeline/farm_tech.htm

Stombaugh, T. (2002). Lightbar Guidance Aids. Retrieved from http://www2.ca.uky.edu/agcomm/pubs/pa/pa3/pa3.pdf

Thomason, W. E., Phillips, S. B., Davis, P. H., Warren, J. G., Alley, M. M., & Reiter, M. S. (2010). Variable nitrogen rate determination from plant spectral reflectance in soft red winter wheat. *Precision Agriculture,12*(5), 666-681. doi:10.1007/s11119-010-9210-5

Weil, R. R., & Brady, N. C. (2010). *Elements of the nature and properties of soils*. New York, NY: Pearson.

World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100 | UN DESA Department of Economic and Social Affairs. (2017, June 21). Retrieved from https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

Yost, M. A., Kitchen, N. R., Sudduth, K. A., Sadler, E. J., Drummond, S. T., & Volkmann, M. R. (2016). Long-term impact of a precision agriculture system on grain crop production. *Precision Agriculture,18*(5), 823-842. doi:10.1007/s11119-016-9490-5

Zhao, G., Miao, Y., Wang, H., Su, M., Fan, M., Zhang, F., . . . Ma, D. (2013). A preliminary precision rice management system for increasing both grain yield and nitrogen use efficiency. *Field Crops Research,154*, 23-30. doi:10.1016/j.fcr.2013.07.019