Chapter 2

Improving Nitrogen and Phosphorus Efficiency for Optimal Plant Growth and Yield

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Additional information is available at the end of the chapter

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Abstract

Nitrogen (N) and phosphorus (P) are the most important nutrients for crop production. The N contributes to the structural component, generic, and metabolic compounds in a plant cell. N is mainly an essential part of chlorophyll, the compound in the plants that is responsible for photosynthesis process. The plant can get its available nitrogen from the soil by mineralizing organic materials, fixed-N by bacteria, and nitrogen can be released from plant as residue decay. Soil minerals do not release an enough amount of nitrogen to support plant; therefore, fertilizing is necessary for high production. Phosphorous contributes in the complex of the nucleic acid structure of plants. The nucleic acid is essential in protein synthesis regulation; therefore, P is important in cell division and development of new plant tissue. P is one of the 17 essential nutrients for plant growth and related to complex energy transformations in the plant. In the past, growth in production and productivity of crops relied heavily on high-dose application of N and P fertilizers. However, continue adding those chemical fertilizers over time has bad results in diminishing returns regarding no improvement in crop productivity. Applying high doses of chemical fertilizers is a major factor in the climate change in terms of nitrous oxide gas as one of the greenhouse gas and eutrophication that happens because of P pollution in water streams. This chapter speaks about N and P use efficiency and how they are necessary for plant and environment.

Keywords: nitrogen use efficiency, phosphorus, yield, phosphorus and agriculture

1. Introduction

Crop nitrogen use efficiency (NUE) in world cereal production has been estimated to be inefficient with only an average of 33% of fertilized N being recovered during production [1]. Denitrification caused by excessive amount of rainfall and nitrate leaching are the leading causes of N loss in the soil. Loss of N to ground and surface water has resulted from ongoing fertilizer management processes in the Corn Belt region of the USA [2–4]. Insufficient coordination between N applications and the requirement of the crops, applying excessive amounts of N before planting as an example, has been cited as one of the primary reasons for the low NUE of ongoing fertilizer management processes [5, 6]. According to the USDA, for the last two decades, close to 150 kg ha^{-1} has been the usual N application amount in the Corn Belt region of the USA [7], and around 75% of N applications, including the previous fall, was applied before planting [6]. The usual consumption rate of mineral N in the soil for corn for the first 3 weeks after emerging from the ground is less than 0.5 kg ha^{-1} a day. N consumption then increases exponentially to around 3.7 kg ha^{-1} a day after the first 3 weeks until the corn plant reaches the tasselling stage [8]. A recorded consumption of 6 kg ha^{-1} a day has been the highest rate recorded (J.S. Schepers, personal communication). Early season leaching of pre-plant N applications to areas below the crop-rooting zone before the plant reaches its peak N uptake phase is reliant on present soil and weather conditions [9]. The introduction of high amount of available N in the soil profile is risky as it is in danger of being lost to leaching, and the plant can take up denitrification over a period of several weeks before it during its active uptake phase. As the rate of N fertilizer applied in a single pre-plant N application increases, the efficiency of the N application will decrease [10]. However, NUE has been observed to increase when applied in-season as opposed to being applied pre-planting [11]. It has been suggested [12] that N should be applied when required by the crops to increase NUE. Farmer support of the practice of applying N in-season in the corn growing region is low, despite the improved NUE application strategies being supported by ample research [13]. Farmers are likely rejecting the practice of in-season applications in favor of the simpler strategy of applying pre-plant N applications due to the cost and practicality of the labor and equipment associated with in-season applications [6]. Despite the presence of spatial and temporary variables in different landscapes, N is applied in a uniform pattern onto the landscape, ignoring the variables and studies that have proven the economic and environmental benefits of spatially variable N applications, contributing to low NUE in the corn regions [14]. Due to the spatial variabilities in the interior of fields, different sections have varying levels of soil N content, different rates of crop N uptake, and different N responses [15]. Therefore, it is a risk to apply large uniform N pre-plant applications in ignorance of this variability within the field as N in the over-applied areas, or at-risk soils could be lost to environmental factors. Over application of N recommended by out of date N recommendations has been cited as another source of low NUE. Analysis of nitrate in the soil before planting and yield expectations is used as the basis for determining the recommended rate of N application for corn in North Dakota. However, corn will only benefit from these recommendations if they follow a rotation and if manure had been recently used [16]. About 30–60% N loss [17], sometimes N losses could go beyond 70% [18], have been proven by a handful of studies. In North Dakota, the different regional climates, the experience of farmers, and cultural practices are not taken into consideration when developing N recommendations for corn. N availability for corn and the rate of mineralization for residues and organic matter in the soil are dependent on regional climate variables such as the temperature and precipitation. N loss via leaching, the rate of N mineralization, or from denitrification caused by periods of excessive precipitation is affected by different soils in a field with variable traits such as soil texture, pH levels, and organic matter content (OM).

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In regard to phosphor the green revolution that followed World War 2, the use of chemical fertilizers increased to increase yields but at the expense of the environment [19]. The common usage of P fertilizers has led to P pollution in the waterways of the USA due to lack of preventative measures to prevent the erosion of P in bodies of water. As a result, wildlife and the environment are at risk. Studies carried out by the Environmental Protection Agency (EPA) has reported and confirmed the presence of P pollution in the Northeastern USA [20]. The application rates of major fertilizers containing N, P, and K have increased in all crops grown in the USA [21]. After 1989, consumption of P temporarily decreased after reports of P erosion in lakes and rivers were released [22] until consumption rates started to increase again in 2010, despite government regulations. Historically, the potato industry in the Northeastern USA was the primary source of P pollution. P fertilizer was applied when not needed, and the potato crops would only recover low amounts of P. It was recently discovered that P concentrations are increasing in lakes and rivers in the Northeast [20], raising concerns about the amount of P currently applied in the agricultural industry in the Northeast. In comparison to potato cultivation in other major potato growing regions, it was found that state-wide P consumption in Maine has declined. This could be attributed to a drop in land dedicated to potato growth over the last 20 years. Despite this, average yield has increased, with the last 2 years of potato production reaching record highs and growing still every year despite declines in P application. However, it was found that this decrease in P application had a nonsignificant reduction. Despite decreasing from 198 to 182 $kgha^{-1}$ (**Figure 1**), it is still very high. When low levels of P are found, the University of Maine Soil Testing Laboratory recommends 50 $kgha^{-1}$. In the agricultural industry, potato growers apply the maximum amount of fertilizers, making them a prime suspect of being the principal source of P pollution. P pollution in the St. Johns River in Florida has been directly linked to P loss in potato cultivation [23]. The United States Geological Survey found that 71% of the cropland in the USA had at least one of the four contaminations responsible for water quality degradation. Dissolved nitrates, fecal coliform bacteria, suspended sediments, and total P are the four contaminants. A total of 20,000 ha of agricultural land is dedicated to potato cultivation which has a production rate of 44 kg ha^{-1} [21]. The EPA in Maine has raised concerns over the

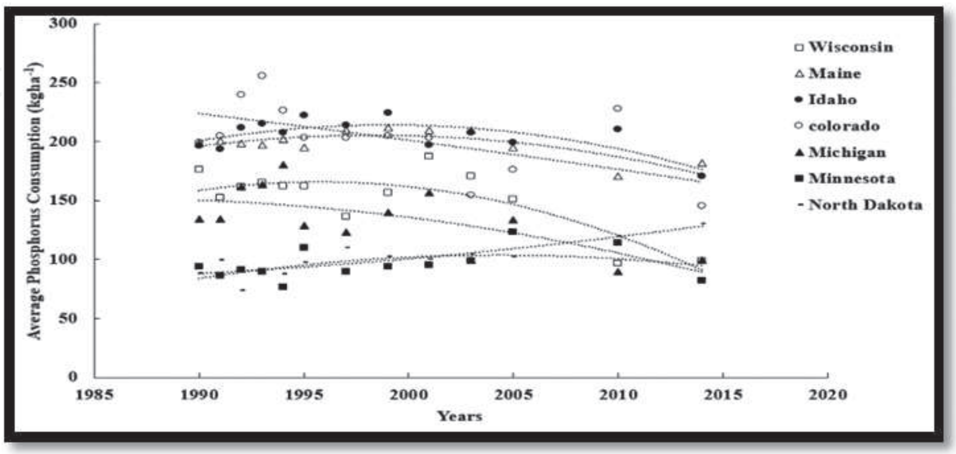

Figure 1. The trend of average P (kg ha^{-1}) used under potato in the key potato-growing states. The polynomial regression analysis was utilized to a potential relationship between years and P use. USDA, National Agricultural Statistics Service, and New England Ag Statistics.

nonpoint source of P that is increasing P pollution in water bodies; 14,407 ha of land has been impaired by P pollution [24]; 3350 t, with an average of 182 $kgha^{-1}$, of P, was applied to potatoes in 2014. Potatoes have a low P uptake at an average of ~28 $kgha^{-1}$ [25]. Only 10% of P applications are available to potatoes, resulting in a lowered efficiency and loss of P to erosion [26].

In Maine, out of ~3600 t of P that was applied, only 612 t was taken up by potatoes with only 1.12 kg ha^{-1} of it mineralized (fertility and fertilizer book). In Maine, there is P efficiency of ~17%, with applied P only has an efficiency of 16%. P can enter the water via run-in, runoff, or leaching. Water quality degradation is primarily caused by P pollution [66]. Soil runoff and leaching cause an estimated 10–40% of P pollution from agricultural land [46]. Severe eutrophication of water can occur if P concentrations exceed 0.02 ppm [27, 28]. Need for P management to mitigate eutrophication was brought to attention after high levels of P were recorded in the river and lakes of Maine [29]. Despite growers, receiving specific recommendations from soil testing, P pollution is still rising; suggesting growers are still applying excessive P. Because of different parent material, various soil types have different abilities when it comes to releasing available P in soil. Available Ca, Al, and Fe affect the soil ability to hold moisture and the availability of P in soil [30]. There is no clear answer to P requirements, especially in the case of potatoes, despite several studies had been carried out since the 1940s [30–37].

2. Soil and plant analysis

A few studies [38, 39] with the goal of applying the amount of N needed with spatial variables in mind, recommended marking spatial variable management zones (MZ) as part of a soil-based method for variable N applications and for bettering NUE. MZs are defined here as areas within a field with homogeneous characteristics in regard to soil conditions and landscapes. Traits within an MZ such as similar crop yields, electrical conductivity (EC), and producer-defined areas make zones homogenous [40]. Impact of fertilizers on the environment, input-use efficiency, and yield potential are some of the similarities that the attributes have. To define borders for MZ's, a range of methods were put forth by researchers as viable approaches. Geo-referenced data layers (i.e., soil color, electrical conductivity, yield, and topography) are statistically clustered or combined using geospatial statistical analyses within geographic information systems (GIS) to delineate zone boundaries [41]. Soil mapping units [42], remote sensing [41, 43], topography [44], yield maps, and soil EC [45] have been successfully used to delineate the MZ. Static and inconsistent (because of effects of temporal variations on yields) sources is what the MZ relies on for much of the delineation [14]. Because of their static and inconsistent nature, they are likely inappropriate in accounting for all the variability of N requirement within a field.

3. Use of tissue analysis for N management

N concentrations in critical states can be used as an indicator of crop N status. Critical N is the minimum amount of N required to provide the maximum amount of growth at a particular time [46]. The concentration of N is high when the corn plant first starts to grow and develop but eventually decreases as the corn plant matures. Critical N dilution is the graphical depiction of this process [47]. The ratio of actual N in the plant to the critical N set by experiments in the past is called the N nutrition index (NNIN) [58]. The value of NNI more or less than 1 relates to a non-limiting growth or deficient situation of the crop, respectively. Wheat (*Triticum aestivum* L.) [48], grain sorghum (*Sorghum bicolor* L.) [49], rapeseed (*Brassica napus* L.) [50], Rice (*Oryza sativa* L.) [51], and grasses [52] have been used in the NNI approach. Suggested to be the result of competition between corn plants [53] at the early stages of growth, the advent of critical N does not contribute to a solid estimate of crop N status [54]. In what is referred to occasionally as "dilution," an increase in crop biomass will lead to a decrease in N concentrations [53].

4. Spatial variation

Variations in traits such as soils, soil management techniques, production history, movement of water and nutrients, and spatial variation are to classify types of fields for commercial corn production. Because of the spatial variations, changes in N requirements of plants, vulnerability to stress, and productive plant variations across a landscape can occur. Slope changes in the interior of landscape and soil depth and drainage can have huge impacts on grain yield variability and corn grain yield, respectively [55]. Because of the flow of water and deposition of soils containing clay and organic matter into depressions and foot slopes in the landscape in areas of commercial corn production, these landscape features have a high level of N fertility in comparison to the rest of the landscape. The downward shift of these nutrient-rich materials has a noticeable effect on the soil in the upper landscape positions as they have been found to be low in OM [56]. This downward movement also affects P and potassium (K) concentrations as they can be found in higher levels of availability in footholds and depressions. High levels of crop production history naturally lead to higher rates of crop removing, potentially resulting in P and K that are lower than anticipated [44]. This suggests that unlike OM, the redistribution and deposition of soil P and K may not be as strongly related to variations in slope, suggesting a resistance to movement [62]. A loss in growth and yield could be a reaction to crop stress. In some different landscapes, seasonal weather conditions exert an influence on crops. Variations in yield caused by differences in landscape position during dry or wet growing seasons are amplified. High levels of OM or a high water holding capacity can increase the resilience of a landscape to the extreme conditions caused by droughts in comparison to upland areas [56]. Yields can drop if large amount of precipitation causes ponding to occur in depressions in the landscape [56].

5. Fertilizer placement and timing

N application can guarantee the high level of N availability that the crops with high NUE need are required. Injected UAN (urea-ammonium nitrate solutions) has better yield results than the yields that are a result of broadcasting UAN, especially on landscapes with surface residue [58]. Utilizing broadcast UAN applications can result in N loss a variety of ways, including the volatilization of ammonia in the urea portion of the UAN and N immobilization with the surface residue of the landscape [59]. Because of this, the application of fertilizer beneath the surface of the soil may be more efficient. The V7 growth stage in modern corn hybrids accounts for around 15% of total N uptake, as well as 5% of the total dry matter build up [60]; 40% of the total dry matter build up and 60% of the total N uptake have happened by the time the corn plant reaches its silking phase. This means that the period of 30 days between the V7 stage and the VT stage accounts for 40% of the corn plants total N uptake. With no risk of a reduced yield, N synchronization can be enhanced by holding off on in-season applications of N until the V7 stage [61, 62]. At 28 locations with a variety of soils in which timing of N fertilizer application was the experimental variable experimented. At the planting stage, V7 stage, V14 stage, and the silking stage, a single application of ammonium nitrate was put down at a rate of 180 kg N ha^{-1}. At most, of the sites, there was a positive response in corn yield to the N fertilizer. Out of all 28-study sites, only one site experienced slight yield loss when the application of N was held off until the V14 stage. With delayed N applications, there is a possibility that the climate could affect the relative risk of yield loss. Maximum yield was achieved in many locations during dry years by withholding N surface applications until the V14 stage in water-stressed corn. However, the amendment of many of the study sites with animal manure, the use of soybeans as an earlier crop, and the implementation of a variety of tillage systems across the sites have complicated this study. Two locations will be included where corn sites were tilled with the application of manure. The severity and timing of N deficiency due to N mineralization rates and soil N-supplies were affected by the previous crops that were used, manure management, and tillage management. In contradiction to the conclusions in [57, 62], unchangeable yield loss was experienced after N was applied during or after the V6 stage at one of the sites, implicating that at the location, N availability has to be sufficient before side dressing to guarantee that the maximum yield is achieved. There was a decrease in the yield response of the grain to N as N deficiency decreased the longer delay in side-dress N applications, implying that the N deficiency levels were positively interacting with the corn yield at the time of N application.

6. Leaf area index

The ration of the leaf surface area to the ground surface area is called the Leaf Area Index (LAI) [66] and is a direct depiction of the photosynthetic capacity of vegetation [63]. LAI has a direct link to the productivity of vegetation in some species and communities; however, for some, the link between productivity and LAI is dependent on variables such as the canopy extinction coefficient, light, NUE, and the amount of light cut off by the canopy top [64]. C4 plants growing in thick stands having higher NUE and higher leaf area production than C3 plants that are in the same environment is an example of this [64]. Remote sensing has been used to develop approaches for determining LAI. Inversions of canopy radiative transfer models [65] and the empirical relationships between spectral vegetation indices and LAI [66]. A short-coming of algorithms based on vegetation indices is the difficulty in extrapolating their results to larger regions or different canopy types [67]. Vegetation index predictions are often confounded with atmospheric and background effects, canopy architecture, solar-target-sensor geometry, and to lack of spectrum difference when measuring moderate to high levels of LAI [65].

7. Environmental interaction

Environmental stress is the primary influence on crop productivity. Corn yields can drop up to and over 70% under negative environmental conditions [68]. Corn hybrids created by breed programs today have shown the ability to withstand environmental stresses, as well as higher plant densities [69]. It is important to note that only 50% of the increases in yield during the modern age of breeding can be attributed to genetic improvements in corn [68], as the other half is a result of better management practices. Corn yield results drop sharply when available soil moisture at depths of 40 cm drops below 25% [70]. Yield can be doubled, however, with the introduction of water via irrigation. During the silking stage, barren ears can occur during drought conditions [71]. Crop yield can drop up to 20% if drought conditions occur after the silking stage [72]. Another study found that moisture stress before silking can cause yield to drop up to 25% and can drop 50% if moisture stress is present during the silking stage [73]. There can be a 21% reduction in yield if soil moisture stress is still present after silking [73]. Moisture stress can cause a plethora of negative symptoms in corn plants such as reduced grain yield, reduced cob length, reduced leaf area, and reduced stem elongation [73]. High temperatures are another source of crop stress. At temperatures of 45° Celsius (113° F), the rate of photosynthesis in corn can be restricted up to 95% during these extreme conditions [74]. Tassel initiation can be postponed by corn stress caused by excessive heat [74]. An increase in high air temperatures to around 32–27°C from a more moderate range of 22–17°C can, respectively, reduce the rate of photosynthesis and the rate of total biomass production by 11 and 32% [75].

8. Spectral response

The spectral properties of leaves can change because environmental stresses [76] observed similar changes in spectral responses across multiple species with changes in plant competition, disease interaction, insufficient ectomycorrhizal infection, senescence, herbicide damage, increased ozone, dehydration, and presence of saline soils. The basis of these responses was that stress reduces chlorophyll content. In regard to the red and green spectrums, chlorophyll α has a low rate of absorbency. Even small changes in chlorophyll concentration can cause increased reflection at these wavelengths [77]. Zhao et al. [78] found more than a 60% reduction in chlorophyll A in leaves after 42 days of emergence, resulting in increased reflectance near 550 and 710 nm. Stress caused by deficiencies in micronutrients is similar to stress caused by N deficiencies. After an evaluation of deficiencies of Fe, S, Mg, and MN, Masoni et al. [79] discovered that decreasing the concentrations of micronutrients caused a decline in chlorophyll concentrations in corn leaves. Chlorophyll a concentrations were 22% less, when Fe, Mg, and Mn were deficient in comparison to unstressed plants. Chlorophyll α concentrations dropped up to 50% when there are deficiencies in sulfur. Because of the decreased concentrations of chlorophyll, there is a decrease in light absorbency, increasing reflectance to around 555 nm and 700 nm [79].

9. Use of spectral properties of plants

The total photosynthetic pigment in a leaf is linked directly to the total amount of solar energy that is absorbed the leaf surface [80]. The photosynthetic potential is directly related to chlorophyll content [81]. Total chlorophyll content changes in response to plant developmental stages or stress. Therefore, measuring chlorophyll content can be a tool for evaluating the physiological health of plants. Gitelson and Merzlyak [82] assessed vegetative indices of a variety of species, leading to a conclusion that the absorption and reflectance of light in the 530–6300 nm and near 700 nm wavelengths were related to chlorophyll content. The light reflectance of plant tissue at the specific wavelengths of 700 and 550 nm was highly correlated with chlorophyll content ($r^2 > 0.97$). Wavelengths in the near infrared spectrum (750–900 nm) were relatively insensitive to chlorophyll content. The ratio of the 750 nm light reflectance to the 550 nm wavelength was used to create an index to be used for predictive measurements [82]. A similar study was conducted on corn [83]. Individual leaves were sampled every 2 weeks. To determine the total chlorophyll content ($r^2 > 0.94$), the red wavelength was used. Crop reflectance is defined as the ratio of the amount of incident light as the denominator to the amount of light reflected back as the numerator [9]. In-season N management was done with active optical sensors by [13] and in the winter wheat fields. During the approach, the NDVI was divided by the growing degree days accrued between planting and sensing. This value was defined as the in-season estimate of yield (INSEY) and was related to the growth rate of the plant. In comparison to solitary sensor readings, INSEY is a better indicator of plant health [13]. To be valid when just using the instrument reading, readings must be done at the same growth stage every year. For developing improved relationships for readings done within a year and over a period of years, time differences between seasons are normalized by INSEY during readings. Blue and red spectra have weaker penetrative properties than green and red-edge spectra when it comes to the capability of light to penetrate into leaves. Eighty percent and higher incident leaf absorption occur in the range of 400–700 nm during the process of photosynthesis [84]. There is a set or range of values, which are not high and narrow in range, in the absorption coefficient in the green and red-edge spectra called saturation, allowing the light in these spectra to be more responsive to changes in the chlorophyll content, especially more than any other wavelength [85]. The ability of leaves of some plant species to absorb light from the visible spectrum increased as plant leaves change their tint from a lighter green to a darker green [80]. The minimum rate of absorption by chlorophyll is 550 nm, while the maximum is 680 nm. Radiation absorption is also influenced by the angle of incident light on the leaf. The comparison of the amount of red light to the amount of near-infrared light absorbed underneath the plant canopy is the most commonly used method of spectral plant analysis [86]. As LAI increases, the amount of light absorbed in the red spectrum and light reflected in the near-infrared [86] increases. LAI could indirectly determine by using a light ratio (675/800) not over but beneath the canopy of the forest. Despite being able to estimate LAI remotely, the authors came to the conclusion that measurement accuracy could be affected by environmental conditions like the angle of incident sunlight and cloud cover. In the evaluation of grass canopies, like approaches have been used [87]. The absorption rate of incident light in spectra (630–690 nm) increases when green biomass increases. Irradiance near the infrared spectrum is defined as lack of absorption or reflection of chlorophyll [87]. Several ratios of the red and near-infrared spectrum are related to the mass of plant greenness [87]. There is a group of ratios that are responsive to physiological parameters and environmental parameters called vegetative indices. Common spectral vegetative indices include chlorophyll indices (Clgreen = $(RNIR/R\ green)^{-1}$) for estimating chlorophyll content [88] and the soil-adjusted vegetation index (SAVI = (RNIRRred) (I + L)/(RNIR + Rred + L)) for LAI estimation [89]. The normalized vegetative index (NDVI) is a widely used vegetative index [13]. Chlorophyll a and b are the most active in the process of photosynthesis, absorbing light (in the red and the blue spectra) and reflecting green spectra [90]. There is more reflectance in the near infrared (700-1400 nm) spectrum of light [90]. Biomass measurements and nutrient deficiencies can be found using these traits in plant leaves [91]. Specialists and researchers prefer to use the Normalized Difference Vegetation Index (NDVI) when they are predicting plant biomasses [91]. NDVI is the ratio of in the red wavelength to NIR light [92]. NDVI = (NIR − red)/(NIR + red), where "NIR" is the reflectance in the near infrared region of the spectrum and "red" is the reflectance in the red region of the spectrum. Because of its usage of the two light spectra and the easiness of its calculations, researchers embrace the NDVI [93].

10. Estimation of vegetative indexes

10.1. Nutrient status

After developing active sensors, the impact of factors such as environmental constraints and ambient light on sampling has been reduced. A plethora of techniques such as destructive plant analysis and soil testing have been used in the past to determine the nutritional status of plants, but recent developments have introduced nondestructive sensors as an alternative [94]. Much of the work done with nondestructive sensors is used to determine the N status of crops [95]. Leaf photosynthesis is negatively impacted and reduced when there is a deficiency of N. Low N availability in corn affects overall production by reducing all components of the corn yield such as kernel dry weight [96]. Crucial for determining the N status of corn, there is a group of wavelengths associated with the N status of corn [97]. Shanahan et al. [98] proposed using NDVI and Green NDVI (GNDVI). In the GDVI, the two spectrums used were NIR, and the other was in the range of 500–600 nm. The light in this spectrum is green; therefore, it was named as green NDVI. The basis for their finding was an experiment of four corn hybrids under irrigation using 5 N rates. Active-optical sensors emitted light in four bands: blue (460 nm), green (555 nm), red (680 nm), and NIR (800 nm). Differences in NDVI were related to N rate and sampling date. N was correlated to increased chlorophyll content ($R^2 > 0.96$). Also, Ref. [99] found that NDVI could be used successfully in evaluating growth and development of small grains.

10.2. Yield estimation

Kitchen and Goulding [104] found it hard to use sensors to establish estimations of yield, even with the established links between green leaf biomass and vegetative indices. In wheat, sensor readings at Feekes growth stage 5 tended to be more correlated with grain yield than any other stage of development [100]. Raun et al. [13] found that sensor-based estimated grain yields were able to explain 83% of grain yield variability. The relationship between sensor reading and yield may be variable over space and time [101]. Inconsistencies have been found in hybrid variations, sampling, seasonal changes, dates, N fertilization, and spatial differences, when determining an estimation of yield [101].

10.3. Nitrogen management using site-specific technologies

Destruction of an area or object is avoided when data are measured via remote sensing methods such as the use of satellite imagery, ground-based active-optical sensors, ground-based reflective sensors, leaf chlorophyll sensors, and aerial imagery or photography [100]. In the agricultural industry, the estimation of land use, land cover, and crop biomass has been done using remote sensing [102]. The in-season status of spatial crop N is now determined using remote sensing [91]. The link between spectral reflectance, crop N status, and chlorophyll content has been better developed as a result of a few studies [91]. Canopy reflectance/color photography, SPAD®(Konica-Minota Americans, Ramsey, NJ), and chlorophyll meters were some of the very first methods of remote sensing used in studies [103]. A plethora of geospatial technologies have been accessible since the mid-1990s for the agricultural market and industry. Crop reflectance, color photography, and GBAO sensors have been successfully used to measure spatial variability in crop canopies.

10.4. Use of sensors and NDVI

When preparing N applications, many farmers use factors such as previous crop, soil management, and soil drainage properties when determining the optimal N rate. However, they commonly do not use in-season tools during these determinations [85]. Farmers apply excessive amounts of N fertilizer in an attempt to guarantee that they will get maximum yield in their fields [105]. Excessive N application leads to problems such as the loss of unused N in the form of nitrate to surface and groundwater, causing environmental problems [105]. Use of proximal plant canopy sensors offers an opportunity for corn producers to adjust N requirement according to the crop requirement. The optimal N rate for any variety of corn and fields is challenging to determine. In order to diminish environmental impact of excess nitrate originating from the production of corn, Schepers et al. [106] suggested that sensing tools to determine to exact amount of N needed instead of applying excessive amounts of N. By estimating crop N status against a standard, the SPAD chlorophyll meter measurement method can help farmers apply N as needed. As a result, farmers still get their maximum yields while using less N fertilizer [107]. However, the SPAD approach requires a laborious process of compiling data from a large number of leaves and then finding a way to standardize N deficient plants from ones that are not deficient with a more significant number of varieties. Active optical sensors are utilized by the SPAD chlorophyll meter to measure two different wavelengths of light (NIR and RED) through the plant leaf. Then, as determined by the manufacturer, a value is computed. The SPAD chlorophyll meter assesses the status of N/nutrition of the plant by analyzing leaf tissue in a nondestructive manner. A positive correlation between chlorophyll content and SPAD chlorophyll meter readings has been proven in multiple studies [108]. However, measurements are done on a one-leaf-at-a-time basis, requiring large of amounts of time to take multiple readings in a field with the SPAD chlorophyll meter. Bullock and Anderson [109] discovered a lack of correlation between V7 stage yields and chlorophyll. An improved correlation between yield and N concentrations in leaves, however, was found at the more advanced stage of R1 and R4. Chlorophyll meter readings at the R1/R4 stages were more closely linked to grain yields than they were to N concentrations in leaves. Correlation coefficients between leaf N and meter readings in the early stages of corn were initially positive ($r^2 = 0.23$), but as the crops grew, there was a drop in value ($r^2 = 0.20$). N recommendations for irrigated corn systems that use irrigation water as a method of N delivery have been successfully made using relative chlorophyll meter readings made by comparing sensor readings from normal farmer fields to readings from plots with high N. Continuous examination of the N status of corn with the chlorophyll meter enabled the additional low N applications when the readings of the chlorophyll meter indicated that N levels had fallen below a set value that determined to be critical [110]. Relative recommendations using the chlorophyll meter require a location where nonlimiting rates of N were applied. Corn grain yield predictions were more accurate when made with relative chlorophyll meter readings rather than predictions using absolute meter readings [105]. Corrective N applications can only be made in a single application in a dryland corn production system, and there are no simple relationships between the application of N that the crop needs and the chlorophyll meter readings [105]. In comparison, low fixed amounts of N can frequently be applied when required in irrigation systems, while guiding N application rates are only active when done with a chlorophyll meter if the meter is the basis for a single N application recommendation [105]. Sripada et al. [113] have analyzed active optical sensors and their possible use at a field scale to determine irrigated corn N status. Variations of growth were manipulated by altering time applications and the rate or amount of N applied. A chlorophyll index (CI) at 590 nm and a NDVI at 590 nm were the two evaluated vegetative indices. Both indices were related to N rate, hybrid, and growth stage. The chlorophyll content during the vegetative growth stages had a stronger relationship to sensor readings than the vegetative reproductive stages. A group of studies has evaluated two available commercial active optical sensors and their efficiency. The two sensors studied were the GS Model 505 (Trimble Inc., Sunnyvale, CA) and the CC ACS-210™ (Holland Scientific, Inc., Lincoln, NE), and they were both used to predict corn yield. The two sensors were differentiated by the wavelengths that they used to calculate NDVI. Both sensors utilized visible and near-infrared wavelengths but the GS Model 505 utilized reflectance measurements from 660 nm and 770 nm, while the CC ACS-210 emitted and detected light at 590 nm and 880 nm. Both sensors are sensitive to crop growth differences ($r^2 > 0.89$). The GS Model 550 exhibited saturation at later stages of growth in comparison to the CC ACS-210, as the different wavelength used by the CC ACS-210 to predict yield reduced its sensitivity and allow usage at the later stages of growth [92]. The GS was also found to be sensitive to the rate of the sensor movement and row spacing [111]. Once again, the CC ACS-210 outperformed the GS by displaying stability during the early and late stages of growth, as well as over multiple row spacing and speed of sensor movement [112]. Therefore, while choosing an appropriate sensor variable N management, the red-edge (680–730 nm) and green wavelength (590 nm) provide a better estimation of canopy development [111]. The hand-held GS 505 is a GBAO sensor, which, unlike the chlorophyll meter, measures reflected light. Satellite imagery, chlorophyll meters, and aerial photography have disadvantages in comparison to the GS when it comes to corn N nutrient management on a field scale regarding speed and labor intensiveness. Ultra-high resolution and fully canopies are needed for aerial photography, while it is not necessary for the GS [113]. Deficiencies of N in plants result in decreased photosynthetic activity, resulting in a higher reflectance of the visible segment of the spectra (400–700), while the stress caused by the N deficiency results in reduced leaf surface area, causing a decrease in NIR (>700 nm) reflectance [114].

10.5. Materials and methods for phosphorus

Three approaches for the study were considered. For the first approach, the last 10-year nutrient analysis data from UMaine Soil Testing Laboratory (UMSTL) were used. Loam, gravelly loam, sandy loam, and silty loam with a parent material of glacial outwash are the soils present in Aroostook County, Maine. Soil testing procedures recommended for the Northeastern USA with publication no.493 by 1:1 method were followed. Modified Morgan soil extracts with inductively coupled plasma (ICP) were used to measure P, Mg, K, Al, and Ca. Using 2874 mL glacial acetic acid mixed with 40 L carboy containing ~ 20 L of distilled water, a modified Morgan extractant (0.62 N NH4OH + 1.25 N CH3COOH) was prepared. Most laboratories did not do bulk density measurements to make it easier for farmers to understand as they convert PPM to pounds/acre. The formula for this is PPM × 2. For all soil testing, the universal assumption/conversion is 2 million pounds or 1000 tons dried and sieved soil per "acre plow layer." Fixed volumes were obtained by scooping rather than weighing by the laboratories to calculate PPM by volume (mg/dm^3) and multiplied by 2 to get a pounds/acre volume. A 1-year N and P study done in 2016 was used for approach 2. A farmer's field in Easton, Aroostook County, was used as the research site for this method. Isotic, frigid Aquic Haplorthods and gravelly loam, fine loamy, isotic, frigid Typic Haplorthods were the soil types used for this study. The Russet Burbank potato cultivar was utilized for this study and was planted 10 cm deep and with row spacing of 91 cm. At planting on the study plots, 6 N treatments, 0, 56, 112, 168, and 280 $kgha^{-1}$, was done for each of the N fertilizers that are being used in the study, ammonium nitrate (AN) and calcium ammonium nitrate (CAN). The Univ. of Maine Soil Testing Lab., potassium (KCI), gives following recommendations, and P applications were implemented. In the study plot, P was found at a sufficient range (45–49 $kgha^{-1}$) out of a required range of 24–56 kg ha^{-1} needed which eliminated the need of additional P application. However, the farmer still applied 224 kg ha^{-1} of P on his field leaving the study plot. A UMaine study done in 1996 found no response on the soils, with high P tests (>40 kg ha^{-1}) was cited as the reason for no P applications. The location site was 46 × 46 m and was divided into 3.7 × 9 m subplots. Four replications within a complete randomized block design were used, see **Table 1**.

Two 10 foot potato rows were harvest from each subplot, and each collected bag was graded. The P study from the 1999 master thesis and an article from [115] were reviewed with permission for the third approach (**Table 2**), as well as data from other studies. Maine P study recommendations were developed and critically examined in and near areas in the Northeastern USA and Canada. The Hochmuth study was done in Maine on 12 research locations in farmers in 1995 and 1996.

Location/Soil Sample Depth	OM	pH	P	K	Ca	Mg	N	S	B	Cu	Fe	Mn	Zn
	%	PPM											
Easton/0–15 cm	3.4	5.4	18	386	1065	125	26	133	0.5	1.25	4.9	5.4	1.0
Easton/0–15 cm	3.1	5.5	20	459	1062	114	18	167	0.4	1.19	4.6	6.1	1.0

Soil samples were collected from 0 to 15 cm deep and 15–46 cm deep from the study using a standard soil probe.

Table 1. Before planting at the Easton site, a comprehensive soil test was conducted.

Year	Parameter	pH	OM	P	K	Mg	Ca	Al	B	Cu	Fe	Mn	Na	S	Zn	CEC
			%	ppm												$cmol_c/kg$
2006	Mean	6	4	13	190	98	795	101	0	1	8	6	23	19	1	7
	Median	6	4	13	177	92	714	96	0	1	7	5	23	16	1	7
	Min Range	5	1	1	22	19	132	9	0	0	1	2	3	5	0	2
	Max range	8	9	66	706	262	7596	502	1	20	33	58	81	142	6	17
	Skew	1	1	2	2	1	6	2	1	7	2	4	0	3	2	2
2007	Mean	6	4	14	172	101	909	97	0	1	8	7	24	23	1	7
	Median	6	4	13	161	95	792	92	0	1	7	5	22	17	1	7
	Min Range	5	1	2	34	18	156	16	0	0	2	1	5	1	0	2
	Max range	8	10	34	671	259	21,616	308	1	6	65	152	211	220	25	19
	Skew	0	1	1	2	1	16	1	2	2	3	11	4	3	12	1
2008	Mean	6	4	16	180	101	802	109	0	1	9	7	21	26	1	7
	Median	6	4	16	172	94	731	106	0	1	9	6	20	18	1	7
	Min Range	4	1	3	38	19	116	8	0	0	1	1	7	5	0	3
	Max range	7	7	89	552	228	2770	333	1	11	33	46	82	174	106	15
	Skew	0	0	4	1	1	2	1	2	5	1	3	1	3	30	1
2009	Mean	6	4	17	180	101	896	113	0	1	9	6	27	19	2	7
	Median	6	4	16	170	95	822	110	0	1	8	5	24	15	1	7
	Min Range	4	1	1	28	16	134	19	0	0	2	1	6	4	0	3
	Max range	7	7	95	751	328	4106	301	2	8	37	41	87	240	149	20
	Skew	0	0	5	2	1	2	1	4	3	2	3	1	5	10	1
2010	Mean	6	4	16	182	101	867	108	0	1	9	7	25	20	1	7
	Median	6	4	16	173	94	772	102	0	1	8	6	23	15	1	7
	Min Range	4	1	1	47	10	84	6	0	0	2	2	5	4	0	3
	Max range	8	8	46	592	259	6821	433	2	12	52	49	72	211	29	17
	Skew	0	1	1	1	1	4	2	3	3	3	4	1	4	13	1
2011	Mean	6	4	16	191	111	888	106	0	1	9	6	27	16	1	7
	Median	6	4	16	183	107	795	103	0	1	8	5	25	13	1	7

Year	Parameter	pH	OM	P	K	Mg	Ca	Al	B	Cu	Fe	Mn	Na	S	Zn	CEC
			%	ppm												$cmol_c/kg$
	Min Range	5	1	2	48	23	176	10	0	0	2	1	2	1	0	1
	Max range	7	10	70	687	375	6854	320	2	8	48	37	88	110	20	15
	Skew	0	0	2	1	1	4	1	3	2	2	2	1	3	8	0
2012	Mean	6	4	17	181	113	1004	107	0	1	8	5	25	15	1	7
	Median	6	4	17	175	109	901	101	0	1	7	5	21	12	1	7
	Min Range	5	1	3	42	19	164	17	0	0	1	2	6	4	0	3
	Max range	7	9	80	558	271	4235	288	7	15	33	29	179	244	22	15
	Skew	0	1	2	1	1	2	1	21	5	2	3	2	10	11	0
2013	Mean	6	3	17	172	107	944	113	0	1	9	6	23	17	1	7
	Median	6	3	16	160	105	851	107	0	1	8	5	21	14	1	7
	Min Range	4	1	3	25	17	148	19	0	0	2	1	4	4	0	1
	Max range	8	10	61	488	285	10,358	329	1	6	91	151	77	212	127	13
	Skew	0	1	1	1	1	7	1	1	2	4	15	1	6	26	0
2014	Mean	6	3	17	189	114	989	110	0	1	8	5	20	16	1	7
	Median	6	3	17	178	109	900	106	0	1	8	5	19	14	1	7
	Min Range	5	1	1	31	17	171	20	0	0	2	1	4	4	0	3
	Max range	8	8	65	555	264	4599	358	2	14	43	27	171	225	6	12
	Skew	0	0	2	1	1	3	1	4	4	2	2	4	9	2	0
2015	Mean	6	4	17	198	114	1001	113	0	1	9	5	19	15	1	7
	Median	6	4	17	194	110	897	105	0	1	8	5	17	12	1	7
	Min Range	4	1	2	47	22	176	11	0	0	1	2	2	3	0	2
	Max range	8	10	61	613	392	10,966	515	13	6	53	37	61	90	243	14
	Skew	0	1	2	1	1	7	1	16	2	3	4	1	3	30	1
SR[†]		0.02	0.09	0.46	2.63	2.06	23.97	1.66	0.01	0.03	0.16	0.20	0.87	1.16	0.05	0.07

The number here is the average of ~1000 potato soil samples received by the laboratory each year.

Table 2. The chemical analysis of soil samples received by the UMaine Soil Testing Laboratory each year.

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Medium to high P levels was found at all the sites. Diammonium phosphate was applied at 5 P rates, 0, 56, 112, 168, 224 kg P_2O_5 ha^{-1}, using a randomized complete block design with five replications. The "Atlantic" potato cultivar was used for the experiment. All fertilizer was applied at planting. Only one site responded positively to an increase in P rates. To determine the correlation between several parameters of soil that changed with time, the coefficient of correlation (R^2) was used. SAS for Windows 9.2 using PROC REG was used to conduct regression analyses. To compare the N treatments with farmer field yield data and potato yield for approach 2, SAS GLM was used. The relationship between time and P levels was from the UMaine Soil Testing Laboratory who averaged the 10-year data set. The simple percent calculation method was used to calculate the percentage of P samples that were at or above sufficient P levels. The simple percent calculation method is as follows: X = number of samples with P levels above 35 kg/ha and Y = total number of samples.

11. Results and discussion

Of the total Maine soil samples in approach 1, 85% were found to have sufficient P (**Table 2** and **Figure 2**) in the range between 24 and 56 $kgha^{-1}$. However, farmers still applied P in the

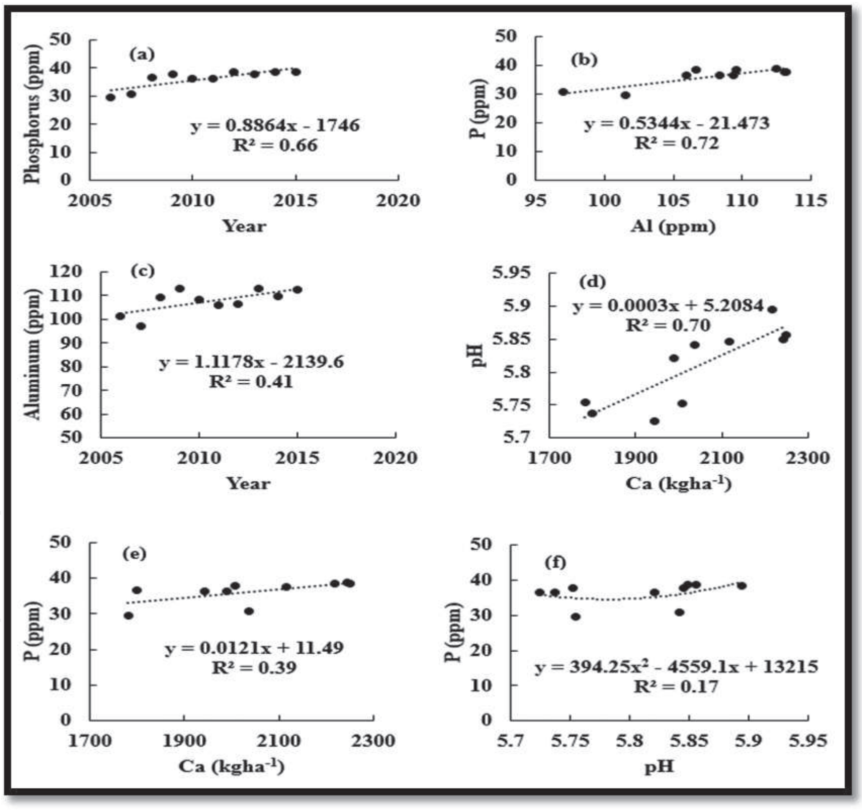

Figure 2. The AL and soil P levels in Aroostook County, Maine. The Univ. of Maine Soil Testing Laboratory has been receiving soil samples since 2006. (a) represents the change in phosphorous levels with time (p = 0.03), (b) represents the relationship between Al and P (p = 0.01), (c) accounts for the change in AL levels with time (p = 0.2), (d) represents the relationship between Ca and pH (p = 0.02), (e) represents the relationship between Ca and P(p = 0.2), and (f) represents the relationship between pH and P (p = 0.6). The polynomial model was used in 2 (f) because it was best suited. The trend was positive and properly depicted the significant association of soil P buildup with successive years.

range of 180–200 kg ha^{-1}. Since 2006, growers have been ignorant of recommendations and have been applying significant amounts of P, when the application is not needed, causing P pollution. About 5% of soil samples had more than 56 $kgha^{-1}$ of P, and 10% were P deficient. There may have been a steady build-up of P in the soil over the years ([116, 117]) due to steady P application. In 2016, 85% of the soil samples were found to have a higher range of P in comparison to ~70% in 1996. Growers apply excessive P to protect themselves from P deficiencies caused by soil fixation and erosion in an attempt to ensure that a sufficient supply of P is available to their crops. The low cost of P makes it easier to over apply P. Soil reactive aluminum (Al) that potentially fixes P has a great presence in soil with pH's of around 5–6 pH [118] and is cited by growers as an additional reason to apply excessive P. Maine soil has a general pH range between 4.9 and 6 pH. Al reacts with P to form Al phosphate, a crystalline structure that can transform again to form amorphous Al phosphate [118]. P is also lost to erosion.

The possibility that P might potentially be fixed in high amounts in Maine's soil was confirmed by a gradual increase of Al levels with a coefficient of correlation ($R^2 = 0.41$) over time in the soils of Aroostook County. Despite a strong correlation, the relationship between P, Ca, P, and pH was not significant. However, it was found that P and Al had a very strong relationship with serious correlations ($R^2 = 0.72$). The maximum yield obtained in approach 2 where no P was applied was 59 t ha^{-1} in comparison to the average Maine potato yield of 44 t ha^{-1} [97] with an average P rate of 182 $kgha^{-1}$. Compared with the zero P application at the experimental plot, the farmer applied P at the rate of 224 $kgha^{-1}$ but got a maximum yield of ~53 t ha^{-1}. This confirmed that many farms in Maine potentially have enough P for maximum optimal potato yield. Due to crop and livestock production and high fertilizer applications, soil fertility in Maine may have improved [113]. Another source of improvement in soil fertility is manure application and organic agricultural practices. Over 50% of the annual soil tests in the Northeast States had results that showed high levels of plant-available P [110], indicating that the large P soil reserves could lead to excessive P application as many of the states in the Northeast have not calculated soil P tests results satisfactorily due to P sites that were nonresponsive. Consequently, they were not able to find the optimum P rate for optimal yield. The necessity of developing recommendations for different regions and crop to account for the effects of multiple soil types, climate, crop growth habits, and crop requires has increased the amount of work needed. A study on the effect of residual P in Northeast Florida on the Sebago potato by [107] discovered that soils with P levels greater than 20 mg P kg^{-1} (Mehlich I method) produced about the same yield as soils without P fertilizer. The experiments carried out by [107] were performed on acidic soils with a pH range of 4.5–6, similar to soil pH levels in Maine. Other differences (such as soil types and climate) make it unreasonable to use the results of their study as a basis for P recommendation revisions in Maine. P fertility experiments in the early 1800s in Northern Maine revealed results similar to Rhue's. P applications could potentially be reduced or eliminated without yield reduction on soils that have high amounts of plant-available P (modified Truog method). Potatoes require ~39–45 kg ha^{-1} of P for optimum yields [119, 120]. As potatoes do not use P in soil aggressively, fields with high P concentrations may not need an application of P for several years [121]. However, the variability in P in soil may cause yield to decrease across larger fields. As such, growers may not want to risk nonapplication of P in the soil as it may affect their profits. A study in Florida in 2002 determined that even though P was applied at rates of 0, 12, 24, 49, and 74, yields were not impacted significantly. This may have been due to P fixation in the soil that releases P during plant growth by mineralization or other means [120]. Only one site out of five showed a decrease in yield with a higher P concentration, but it was not significant. The P concentration in the leaves was highly correlated with yield, and only one site found to have an inverse relationship. When graphing all combined outcomes, they are weakly correlated, but individually, they show a strong correlation.

Several studies have indicated that variations in soil type could have an impact on P response regarding crop yield [122, 123] as demonstrated in the introduction. This deems it necessary to study the varying soil types in Maine and Aroostook County, Maine. There are 21 mapping units in Maine, and of these, 15 mapping units are located in Aroostook County, which is a major potato growing area. The soil behaves differently P response of crop yield, P supplying ability, and P retention, and they may vary further in P distribution throughout the landscape. **Table 2** explained that there are soils containing gravel and stones with loam to silt loam. The higher drainage portions of the gravel infused soil may move P into groundwater and nearby streams, whereas silty loam may retain more P. The primary soil order in Maine is Spodosols, susceptible to P deficiency with the third minimum distribution of P among the 12th order after Andisols and Vertisols [124]. A University of Kentucky study on P showed that testing soil P changed under different soils with the same rate of P application [123]. This study explained that different soils have varying rates of P absorption, which results in different levels of P soil tests despite the same rate of application, making it crucial to consider soil type when testing for P levels and recommending P rate for agronomic crops. **Figure 3** explains the rate of change of P concentration in soil depending on the initial test, showing variations in P soil tests with increasing P rates of 16 soil mapping units of large agronomic crops.

Soil pH is a key factor that regulates soil P in soil solutions. The pH range for maximum P availability is between 6 and 7 [112]. At pH levels lower than 6, the available P is fixed by Al and Fe ions and fixed by Ca at a pH higher than 7. Changes in pH were in the study due to its influence. The approach I was used to determine that change in pH over time. Other studies were also discussed to find the answer of the impact of P recommendation and pH on P pollution. Shaver et al. [112] concluded an experiment in Maine to develop P recommendations which proved that there was sufficient P available in Maine soils when only one site ($R^2 = 0.66$) out of 12 was found with positive P response, and the sites with no P response had high to too high P availability. There were not sufficient data to develop P recommendations, so researchers recommend a minimum of ~56 $kgha^{-1}$ when the P value is between 22 and 56 $kgha^{-1}$. Moreover, while the application is not too high, it may have an impact on P erosion to Maine's water sources. Soil pH rates in Maine have improved over the last 10 years (**Figure 4**), mostly after P recommendations were developed. Maine's potato soils have increased after the variety switch from round whites to scab resistant Russet Burbank potatoes and due to grains and other rotation crops that require a higher pH level. The current emphasis on growing grains has led to the increase in soil pH from 5 (20 years ago) to ~6 presently and is expected to continue to improve.

Crop response to an application of P depends on the P availability and crop uptake ability. The soil P can be slowly replenished, but it still depends on the uptake speed and overall crop behavior [125]. Once the crop has absorbed the P from the soil solution, the unavailable or stable form of P can slowly replenish it. The uptake ability also depends on root distribution [125]. P application in potatoes as a banded application that comes in direct contact with the roots ensures P availability later in the season. However, the rainfall before uptake could cause the P to move deeper into the soil or become fixed in unavailable or marginally available forms. In contrast, less movement of P could result in less availability in a banded

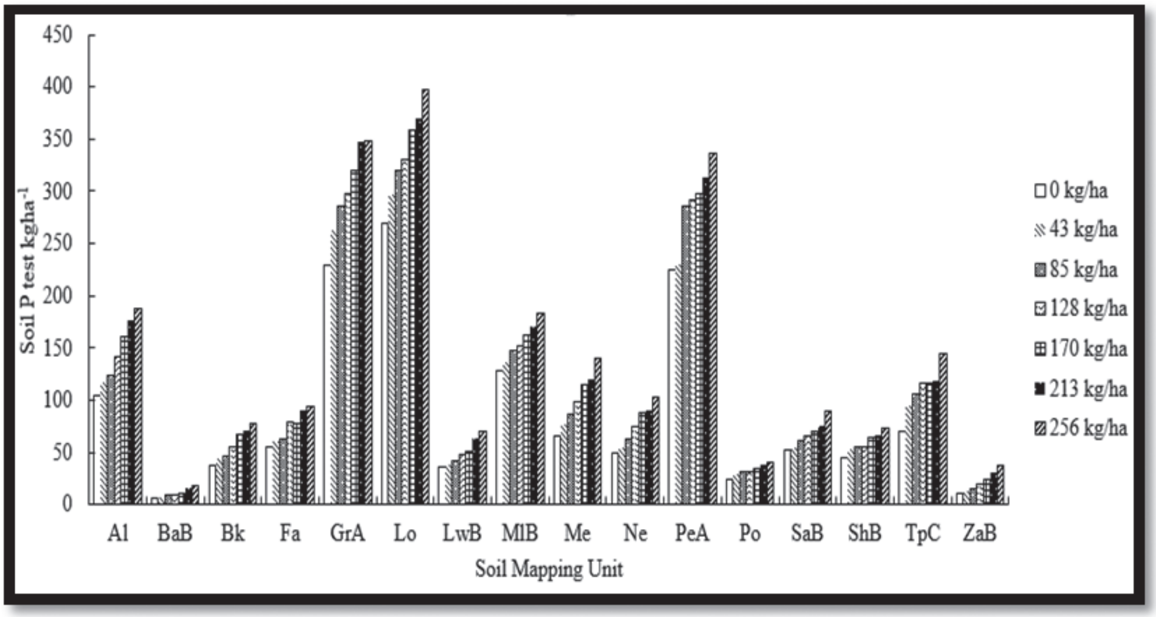

Figure 3. Representing the change in P levels with seven P rates under 16 different soil mapping units in Kentucky, United States. Source: Data adopted from Hochmuth et al. [115].

application as compared to a broadcast application. The potato planting in Maine happens in late May and early June, making the P application more susceptible to erosion due to rainfall. With rainfall in consideration, it is wise to apply P in high doses that are close to first of second hilling (tuber initiation), as the different soil moisture could severely affect the P uptake by the crop plants [122]. Several studies have documented the improvement of crop yields with P application [126]. However, the economic return and response were found only in places with low soil [127]. Inefficiency in soil P application leads to P build up in the soil, particularly when potatoes are used in crop rotation [127]. There is a gap between the rate of P application and the rate of P removal. Potatoes have a relatively high P requirement but a low P uptake behavior [128]. Water can be used as an extracting of P, but due to lack of major leftover undissolved P and analysis difficulties of water as an extracting, several other varieties of extractants have been suggested to extract forms of P in soils used by plants. The Truog Method (1930) is to dilute H_2SO_4 buffered to pH 3.0. The Bray Method is a combination of HCL and NH_4F used to extract acid soluble P forms (mostly Al and Fe bound P [129]) in North Central states. In 1953, another combination (Mehlich 1), HCL and H_2SO_4 acids were introduced to extract P and other nutrients in Southeastern soils. In 1984, Mehlich further expanded on his earlier extractants to Mehlich 3, a combination of acetic acid [HOAc] and nitric acids [HNO_3], salts (ammonium fluoride [NH_4F] and ammonium nitrate [NH_4NO_3]). The standard soil test for P is modified Morgan in Northeastern states due to its acidic soils and low (less than 20) cation exchange capacity (CEC). Modified Morgan used 0.62 M NH4OAc + 1.25 M CH3COOH at pH 4.8. Soil tests show an increase in soil pH in Maine overall with an average P application of ~32 kgha^{-1}. The average application of P is between 20 and 50 kgha^{-1}, but farmers still apply P to their soils making the excess erode into local water systems. P recommendation studies and their results have never been published making it difficult for growers and researchers alike to amend their practices for better P guidelines.

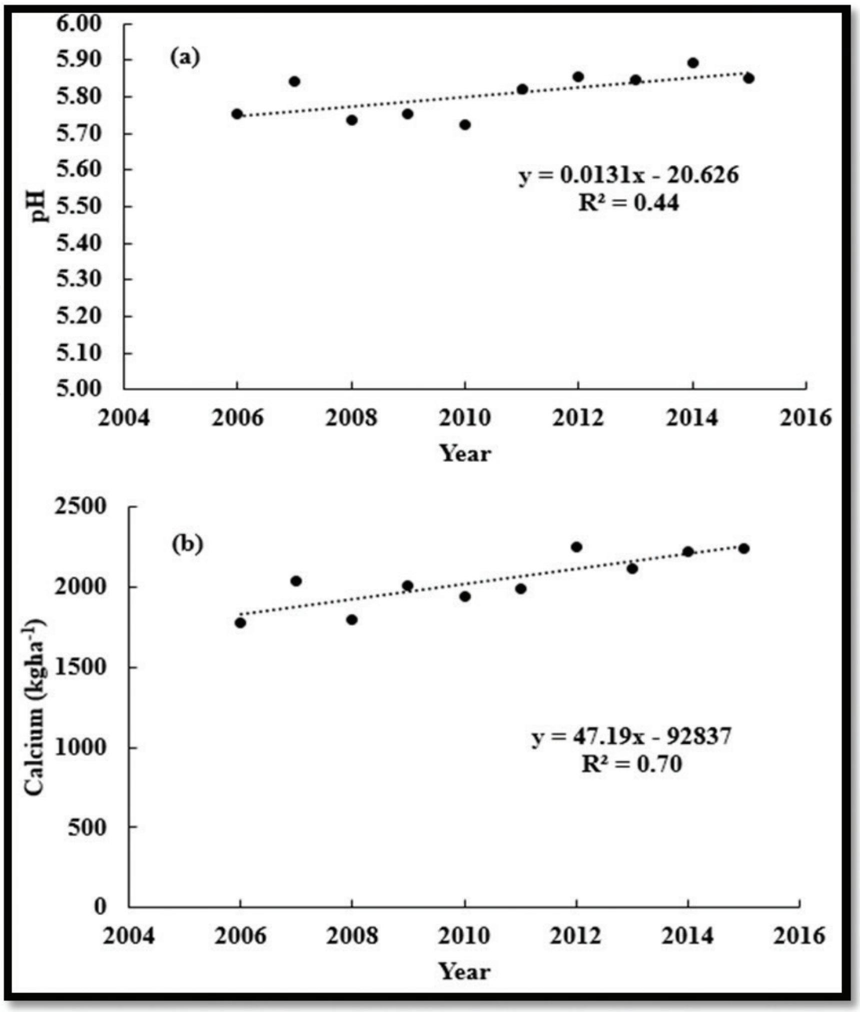

Figure 4. The trend of change in the soil pH and calcium level over time in Aroostook County. (a) The change in pH, and (b) a shift in calcium level with time.

12. Conclusion

Soils in Maine are highly variable and may already possess sufficient P to support the maximum yields of crops. Therefore, the recalibration of the recommendation equation is necessary, by newly inserting low, medium, and high P yield sites. While developing P recommendations, it is important to differentiate between soil types and regions, such as North Dakota State for sunflower, corn, and wheat [130–135]; because soil variability and soil moisture are a driving force toward plant, growth, and nutrient movement among plant roots. The study found that P recommendation needs revision to account for soil variability and a recalibration of the soil P test. The average soil P test has increased showing a buildup of P in Maine soils. Due to unnecessary applications of P, the study recommends a more robust recommendation from low, medium high, and above excellent P level sites. The study also found that types of growers need to be taken into consideration, e.g., table stock growers (not concerned with frying quality), seed producers (no concern of high yield or frying quality), and processing growers (need excellent frying quality with maximum yields) when developing P recommendations. It was also found that an examination needs to be done on the banded application according to the crops root system development as banded applications stay here are applied to the roots that grow beyond the reach of the application.

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