Improving Nitrogen Management in Potatoes with Active Optical Sensors

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IMPROVING NITROGEN MANAGEMENT IN POTATOES WITH ACTIVE OPTICAL SENSORS

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An Abstract of the Dissertation Presented
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Nitrogen (N) fertilizer rate is important for high yield and good quality of potato tubers. In this dissertation, I seek to study the response of different potato cultivars under different N fertilizer rates and how that can impact tuber quality, examine the performance of active optical sensors in improving a potato yield prediction algorithm, and evaluate the ability of active optical sensors (GreenSeeker (GS) and Crop Circle (CC)) to optimize a N recommendation algorithm that can be used by potato growers in Maine. This research was conducted at 11 sites over a period of two years (2018–2019) in Aroostook County, Maine; all sites depended on a rainfed system. Three potato cultivars, Russet Burbank, Superior, and Shepody, were planted under six rates of N (0-280 kg ha^{-1}), ammonium sulfate and ammonium nitrate, and were applied in a randomized complete block design (RCBD) with four replications. Active optical sensor readings (normalized difference vegetation index (NDVI)) were collected weekly after the fourth leaf stage began. The coefficient of determination (R^2) between soil organic matter (OM) content and total tuber yield for all sites combined was 0.78**. Sites with ≥ 30 g kg^{-1} of soil OM produced higher total tuber yield, marketable yield, and tuber weight per plant (39.45%, 45.22%, and 54.94%, respectively) than sites with ≤ 30 g kg^{-1} of OM. Specific gravity increased by 0.18% in the sites with ≥ 30 g kg^{-1} of OM. The total tuber yield for the three cultivars was maximized at 168 kg N ha^{-1}. Vegetation indices measurements obtained at stages of 16 or 20 fully expanded leaves were significantly

correlated with tuber yield, which can be used in the yield prediction model. Sensor measurements obtained at the 20th leaf stage were significantly correlated with tuber yield, with the exponential model showing the best fit for the regression curve. The recommended N rate calculated based on in-season sensor readings was reduced by approximately 12–14% compared to the total N rate that growers currently apply based on the conventional approach.

DEDICATION

First of all,

Thank God (Allah) for guiding me to the right path, especially being far from my country.

and then,

my parents,

wife and her parents,

brothers and sisters,

anyone encouraged me to be successful,

for their supplications, love, support, and encouragement.

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LIST OF ABBBREVIATION

CC: Crop Circle

CI: Chlorophyll Index

GBAO: Ground Based Active Optical

GDD: Growing Degree Days

GS: GreenSeeker

INSEY: In-Season Estimated Yield

K: Potassium

N: Nitrogen

NDVI: Normalized Different Vegetation Index

NIR: Nir-Infrared wavelength

OM: Organic Matter

P: Phosphorous

r: Coefficient of correlation

R: Red wavelength

R^2: Coefficient of determination

RCBD: Randomized Complete Block Design

SPAD: Single-Photon Avalanche Diode

CHAPTER 1

INTRODUCTION

1.1 Potato: Benefit, Growth, and Factors Affecting Production

Potato (*Solanum tuberosum* L.) is a vital crop in agricultural production systems because it combines high nutritional value with remarkably high yield potential. However, while countries with high-input agriculture, such as the USA, France, and Germany, can attain average potato yields higher than 40.38 Mg ha^{-1}, potato yields of other countries are considerably lower, resulting in an average of about 18.14 Mg ha^{-1} worldwide.

Potatoes are a good source of energy, proteins, minerals, fats, and vitamins (Ekin, 2011; Drewnowski and Rehm, 2013; King and Slavin, 2013). Furthermore, potatoes are not just an essential food source (Andre et al., 2014) but they are also used as feedstock for industrial products but they are also used as feedstock for industrial products (Izmirlioglu and Demirci, 2015; Jagatee et al., 2015). Hence, unlike most other crops, potatoes have an extraordinarily high utilization potential, which makes the production of this tuber more attractive.

The yield of a potato crop is principally determined by specific genetic properties (Evans and Fischer, 1999). However, there is usually a gap between the actual yield and the yield potential (Van Keulen and Stol, 1995; Michel et al., 2015), where the potential yield is never completely accomplished in natural production systems since biotic and abiotic factors negatively affect plant and tuber growth. Major biotic stress factors in potato production include late blight (*Phytophthora infestans*) (Nowicki et al., 2012) and fungal diseases, such as silver scurf (*Helminthosporium solani*), early blight (*Alternari solani*), and black scurf (*Rhizoctonia solani*), as well as Verticillium wilt and Fusarium (Rich, 1983). Moreover, other species of pathogens such as plant-parasitic nematodes can influence potato yield and production. The yellow potato cyst nematode

(*Globodera rostochiensis*) and the white potato cyst nematode (*Globodera pallida*) are the main economically influential nematode species (Eves-van den Akker et al., 2016). Additionally, there are several bacterial and viral diseases which influence potato yield and production (Rich, 1983).

The abiotic stresses that diminish yield include high radiation (Jansen, 2002), cold stress (Oufir et al., 2008), heat stress (Herman et al., 2017), and air pollutants such as ozone and nitrogen dioxide (Bahl and Kahl, 1995). The most critical abiotic factor influencing yield and quality is drought stress (Obidiegwu et al., 2015).

Growers can reduce the harmful effects of environmental impacts by using balanced agronomic practices. In addition to the selection of cultivar, plant protection, and constant water supply, a significant agronomic factor in potato production is satisfactory nutrient management. An adequate supply of mineral nutrients can fortify the potato plant against unfavorable growth conditions, is critical for obtaining high yield, and is necessary for producing potatoes that meet desired quality specifications.

The most prominent yield response law is the law of the minimum, developed by Carl Sprengel and, later, published by Justus von Liebig in the early 19th century. According to the law of the minimum, optimal crop growth can occur only if all the required nutrients are at an excellent level (Van der Ploeg and Kirkham, 1999). At the beginning of the 20th century, much additional work was conducted to study relationships among production factors, such as the nutrient supply of the plant, and the yield of crops (De Wit, 1994).

In particular, the law of the minimum affirms that plant growth is regulated not by the total quantity of nutrients available but by the quantity of the scarcest nutrient. This law denotes the importance of balanced nutrition for optimal plant growth. The law of diminishing yield increase, first formulated by Eilhard Alfred Mitscherlich (McNall, 1933), is of comparable significance.

This law declares that the higher the nutrient supply, the lower the yield increase achieved from the increase in fertilization, which indicates that yield response to fertilization mimics a saturation model (Spillman, 1923). The third important law is the law of the optimum formulated by Georg Liebscher (Liebscher, 1895). Liebscher indicates that at any instant, there is simply one factor that restricts production, which is the minimum supply. If its supply is progressed, production will progress proportionally up to a peak where a second factor takes into minimum supply and, in turn, restrict output (Nijland et al., 2008). These laws are the foundation for modern approaches to developing strategies for efficient resource use in plant production. Based on emerging difficulties in modern agriculture, De Wit (1992) suggested that the laws developed by Liebig, Mitscherlich, and Liebscher could be used as distinct options in one dynamic model. He presumed that both agriculture and environment should focus on the minimum production resources required for maximum usage of other resources (De Wit, 1992).

Although numerous studies focused on yield response, nutrient uptake, and the removal of nutrients by grain crops, which is the most available data. However, for the potato crop, due to the lack of data, they depend mainly on data produced from previous studies of several years, indicating a demand for further research. Nitrogen (N), phosphorus (P), and potassium (K) are the nutrients that are most commonly applied in potato production (Davenport et al., 2005).

1.2 Role of Nitrogen on Potato Production

Many scientists have reported that the optimal response to N fertilizer application varies among varieties and soil types (Kleinkopf et al., 1981; Johnson et al., 1995). Fertilizer application operates best if a soil test has been performed (Shadrack, 2018). Further research into newly released potato varieties regarding N response is required to develop the most suitable management recommendations for N fertilization in addition to optimizing tuber yield and quality (Saeidi et al., 2009). Nitrogen is the mineral nutrient that is most commonly deficient in agricultural soils. As a result, growers in developed countries apply comparatively high quantities of N fertilizers. The imperfect compatibility of the soil-plant system prevents comprehensive utilization of the N, leaving remaining N in the soil, which is a waste of natural resources and is grounds for environmental concern (Hopkins et al., 2008). Additionally, the application of fertilizers above optimum levels often creates a risk of nitrate-contamination of groundwater (Westermann, 2005; Ierna et al., 2011). Approximately 50% of crops globally do not directly utilize the applied N, and the overall nitrogen use efficiency (NUE) has diminished with increasing application of N fertilizer (Dobermann, 2005).

Conversely, in developing countries the amounts of fertilizers applied to potato crops are meager and insufficient. For example, in research conducted by Gildemacher et al. (2009), the quantities of farmyard manure (FYM), N, and P applied to potato crops were estimated to be 4327 kg FYM ha^{-1}, 43.3 kg N ha^{-1}, and 101.4 kg P ha^{-1}, respectively, in Kenya, 2207 kg FYM ha^{-1}, 37.6 kg N ha^{-1}, and 46.9 kg P ha^{-1}, respectively, in Uganda, and 3006 kg FYM ha^{-1}, 30.6 kg N ha^{-1}, and 33.4 kg P ha^{-1}, respectively, in Ethiopia. Fertilizer requirements differ among locations, for example, due to the spatial variation of soil types, nutrient availability of the soil, moisture supply, cultivars, and economic factors of the area (Zelalem et al., 2009).

1.3 Potato and Nitrogen Fertilizer

1.3.1 Nutrients Uptake and Partitioning

The NUE in crops is defined in numerous forms in the literature (Fageria and Baligar, 2005). In simplistic terms, efficiency is the ratio of output (yield) to input (fertilizers) for a process or complex system (Fageria, 2009). Agronomic efficiency may be described as the nutrients accumulated in the aboveground part of the plant body or the nutrients recovered inside the whole soil-crop root system (Roberts, 2008). Several indices are commonly used in agronomic research to evaluate the efficiency of applied N, especially for objectives that emphasize crop response to N. Quantifying the status of NUE in agriculture is a complicated task because definitions used in articles and explanations of different NUE indices vary, and reliable data needed to calculate NUE indices are usually not available, especially at national, regional and global scales(Dobermann, 2005). The N is initially concentrated in the stems and leaves of the plant, especially if it has been applied during the tuber growth stage. More than 80% of the assimilated N is found in the tubers at the beginning of the crop maturation stage. Therefore, a significant improvement in N fertilizer efficiency would result from split N fertilizer applications made according to crop growth demands (Westermann et al., 1988).

1.3.2 Nutrient Management in Potato

Numerous opportunities exist to improve potato yield and quality by improving nutrient management. The potato crop demands a high level of soil nutrients because of an inadequately developed and shallow root system (Perrenoud, 1993). The efficient management of nutrients is imperative for potato production, as tuber yield and tuber quality are directly influenced by the quantity and timing of nutrient applications. Research conducted by Love and Stark (2004) affirmed that each potato cultivar exhibits individual characteristics and, consequently, presents specific management challenges. These varietal differences can influence each aspect of production, from seed production to storage condition. Several factors that negatively influence efficiency should be considered. Split application of N is preferred to avoid losses through leaching, denitrification, volatilization, utilization by other competitive weeds, erosion by runoff water, and sedimentation (Shadrack, 2018). Another factor that can minimize the issue of soil as and nutrient loss, is the incorporation (e.g., by intercropping) of suitable indeterminate legume cover crops into potato cropping systems (Nyawade et al., 2016). Advancing N efficiency is a high priority in potato cropping systems, where N is the most limiting nutrient (Hopkins et al., 2008).

Applying the correct N fertilizer at the precise rate, time, and place is significant for proper N management. For best results, N should be applied only when required using calibrated application equipment to assure its appropriate placement. Additionally, source, rate and timing should be adjusted to meet N needs and to avoid seed or seedling injury (John et al., 2009). Nitrogen is applied according to market classes (e.g., table stock, French fries, and potato chips), which requires various quality parameters to be considered (Blumenthal et al., 2008). It is achievable to enhance crop yields and consequently (NUE) through utilizing soil and crop management practices. These practices include maintaining proper soil acidity, ensuring a suitable source, rate, and timing of N applications, supplying sufficient soil moisture, rotating crops, conserving or reducing tillage, using cover crops and animal manures, using N-efficient crop species or genotypes within species, and controlling insects, diseases, and weeds (Fageria, 2009).

Noura et al. (2016) reported that the method of utilizing controlled-release N fertilizers, such as polymer-coated urea, could reduce N losses and increase NUE by matching the N release process with potato N uptake. The management of organic matter is based on crop rotations, solid and liquid animal manures, green manures, and compost (Finckh et al., 2006). The release of N from most of these fertilizers is slow and is highly dependent on soil temperature and soil moisture influencing mineralization processes (Van Delden, 2001). Furthermore, two of the most significant difficulties for organic potato growers are producing N for optimal yield and quality and selecting cultivars that are both high yielding and have suitable quality when grown under an organic system. Consequently, N management is difficult in organic production practices.

1.3.3 The Role of Nitrogen in Potato

In potato production, N is used more frequently and in larger quantities than other nutrients (Bowen et al., 1999). This indicates that N is an indispensable nutrient for crop growth, and that the need for N in the potato crop is comparatively high. Möller et al. (2006) reported that in organic potato management, N availability is one of the most critical yield-limiting factors. Due to its significance, the optimum amount of N should be applied to utilize the highest possible potential of a given genotype within a particular area. In addition to its function in the synthesis of proteins, N is an essential component of the chlorophyll molecule (Tisdale and Nelson (1975). The report of FAO (1978) emphasized that N constitutes 10 g kg^{-1} to 40 g kg^{-1} of the dry weight of the plant; it is taken up from the soil in the form of nitrate (NO_3^-) or ammonium (NH_4^+) and combines with composites of carbohydrate metabolism in a plant to produce amino-acids and proteins.

Proper N fertilization is significant for optimizing potato yield and quality. According to Jatav et al. (2017), the application of N exerted a considerable impact on all growth parameters that prompted positive increments, where excessive N could reduce specific gravity in addition to yield. A similar result was achieved in a study by Kołodziejczyk (2014) in which each treatment of N doses induced a marked increase in potato plant productivity compared to a smaller dose. Inadequate available N leads to diminished growth and light interception (Millard and Marshall, 1986), early crop senescence (Kleinkopf et al., 1981), and decreased yields (Westermann and Kleinkopf, 1985). However, excessive available N can postpone tuber formation (Kleinkopf et al., 1981), decrease yields (Lauer, 1986), and reduce tuber dry matter content (Millard and Marshall, 1986). Furthermore, excessive N increases the potential for environmental contamination by nitrate leaching or runoff (Westermann et al., 1988).

1.3.4 The response of Potato to Nitrogen Supply

The response of a potato plant to the available N supply is an essential determinant for N fertilizer recommendations. Taking into account the residual soil NO_3-N concentrations, the rate and amount of N mineralized from soil organic N sources, and the effectiveness of the N fertilizer are needed to ensure success (Westermann and Kleinkopf, 1985). Researchers have proposed several factors that could limit crop yields. According to Downs and Hellmers (1975) and Tisdale and Nelson (1975), factors restricting crop yield (in both quality and quantity) can be divided into four significant categories: soil genetic, climatic, and management practices. Another parameter involves regulating the genetic response of the cultivar to the length of the photoperiod (Gastelo et al., 2014). Furthermore, the yield response to the mineral nutrient application in potato crops, as in other crops, was found to be limited by soil, plant, management, and climatic factors (Tuku, 1994). Maintaining an adequate level of soil fertility has been acknowledged as one of the management practices that influences growth, development, and yield of plants (Tisdale and Nelson, 1975). Potato plants have been described to have a high demand for mineral nutrition (Harris, 1978). Depending on the circumstances, an average potato crop has been observed to remove 50 to 80 kg N ha^{-1}, 20 to 30 kg P_2O_5 ha^{-1}, and 80 to 100 kg K_2O ha^{-1} from the soil in tropical regions (Sikka, 1982). However, these amounts can vary under different environmental conditions depending on soil characteristics, cultivar, crop rotation, soil moisture, and other management practices.

1.3.5 Effects of Nitrogen on Yield Related Parameters of Potato

1.3.5.1 Stem Number

Stems are generally considered to be the basic structure of the potato plant (Burke, 2017). Moreover, Burke (2017) revealed that potato plants grown from seeds have one main stem, but when proliferating from a tuber, the potato produces several stems. The stems are categorized either as main or secondary stems; main stems rise from the tuber eye, or because the eye may contain several buds, more than one stem may arise. According to Beyene (1998), a significant difference was observed in the mean stem number of potato plants due to N application. Refuting this theory, conclusions drawn by (Allen, 1972; Gray and Hughes, 1978) highlighted that the increment in stem number occurred as a result of planting larger tuber sizes or the mistakenly using more tuber numbers per unit area. Furthermore, various researchers (Lynch and Rowberry, 1977; Lynch and Tai, 1989; De la Morena et al., 1994) have emphasized the lack of a close relationship between mineral nutrition and the number of stems per plant. The yield difference due to N treatment was not suggested to influence stem density as the number of stems was not significantly affected by N treatments.

1.3.5.2 Tuber Size, Shape and Number

Gray and Hughes (1978) stated that potato tuber size and shape are varietal characteristics, with elongated tuber traits being dominant over a round tuber shape. In some cultivars of potato, the shape is also affected by cultural and environmental circumstances. Gray and Hughes (1978) demonstrated that high levels of applied N and irrigation combined with a low level of K increases the length of potato tubers comparative to their width. Likewise, Blumenthal et al. (2008) reported that N supply to potatoes impacts tuber size, dry matter, and sugar content. Contradicting results have also been reported by other researchers regarding the impact of mineral nutrition on the number of tubers set per plant. For example, Sharma and Arora (1987) suggested that there was no significant variation in the total number of tubers per area resulting from N, P, and K fertilizer application. However, Lynch and Rowberry (1977) reported a significant variation in tuber numbers due to N fertilization. Similarly, Wilcox and Hoff (1970) affirmed that N fertilizer influenced yield by influencing the number of tubers produced per plant and the average weight of tubers. Wilcox and Hoff (1970) also reported that yield increase due to N fertilizers was positive up to a particular level, beyond which yield decline was noticed.

1.3.5.3 Average Tuber Weight

Average tuber weight has been described to be the third most significant yield element determining total tuber yield (Lynch and Tai, 1989; Noura et al., 2016). Environmental factors that favor cell division and development such as mineral nutrition, and optimum water supply were stated to improve tuber size (Reeve et al., 1973). Sharma and Arora (1987) highlighted that an improvement in tuber weight with an increase the supply of fertilizer could be due to stronger growth, larger leaf area, and higher accumulation of photosynthate that encouraged the production of larger tubers, and then higher yields. The application of N and K was also suggested to extend the canopy life, therefore prolonging the tuber bulking stage (Harris, 1978; Petr et al., 1988). Burke (2017) also discovered a complicated relationship between seed tuber weight and seed tuber size, which differed among cultivars due to fluctuation in tuber shape among years, and even between batches grown at different positions in the same year. The result of a study conducted by De la Morena et al. (1994) highlighted that fluctuations in tuber yield and tuber weight were due to different N treatments. Sharma and Arora (1987) revealed that the improvement in the yield of tubers with applied N and K was associated with an increase in the number of tubers in the medium and large grades at the expense of small tubers.

1.3.5.4 Effects of Nitrogen on Potato Tuber Quality Traits

Two key quality characteristics influenced by N are specific gravity (dry matter content of the tuber) and reducing sugar (glucose) content. Insufficient N results in very small tubers, high sugar levels, low dry matter, over-mature tubers, and increased susceptibility to disease. Excessive N results in slightly smaller tubers, high sugar levels, medium-dry matter, and susceptibility to disease and bruising (Blumenthal et al., 2008). Blumenthal et al. (2008) also noticed that P fertilizer applications promoted quality (skin maturity and dry matter content) of tubers at harvest when N fertility levels were high. High uniform specific gravity in potato tubers is a necessity for the grower and processor (Kleinkopf et al., 1987). High values of specific gravity contribute to a higher recovery rate and better characteristics of the processed product (Tony, 2010). Kleinkopf et al. (1981) stated that the specific gravity of tubers decreased with increasing rates of N fertilizer. Likewise, (Westermann, 2005) reported that tuber specific gravity decreased when more N was available than required for growth, especially when available during late tuber bulking due to the lengthening of vegetative growth and delay in maturity (Sanderson and White, 1987).

Other researchers, however, noted that there was no significant variation in the specific gravity of tubers due to different N treatments (Roberts and Cheng, 1988; Joern and Vitosh, 1995).

The application of mineral nutrients has been observed to influence the size of potato tubers by affecting plant establishment, the number of tubers produced, and the growth rate of tubers and duration of bulking (Kleinkopf et al., 1981; Harrison et al., 1982; Sharma and Arora, 1987). Nitrogen and K application have been repeatedly emphasized to increase the proportion of medium and large-sized tubers (Reddy and Rao, 1968; Sharma and Arora, 1987). Sharma and Arora (1987) stated that increasing the N rates from 0 to 250 kg ha^{-1} resulted in a decrease in the number of small grade tubers (less than 25 g), and an increase the number of medium (25–75 g) and large (above 75 g) grade tubers.

1.4 Growth and Nitrogen Uptake Pattern

There is an apparent relationship between plant N uptake and total dry matter accumulation (Vos, 1995). Westermann (1993) classified the growth of the potato crop into five general stages, with each stage having its own N requirement. The duration of each stage depends on cultivar, as well as climatic/environmental circumstances. A generalized growth and N uptake pattern for a 'Russet Burbank' potato crop with an abundant fertilizer N supply under Midwest USA conditions is shown in Figure 1.1.

Stage I is the sprout development stage that occurs within the first 30 days after planting. At this stage, the seed tuber is the primary source of nutrients and energy for the developing shoot while soil N uptake is minimal. Growth stage II, occurring between 30 and 55 days after planting, is the vegetative growth period. During this stage, roots start providing nutrients for vines, and photosynthesis occurs in the leaves to produce energy for growth. High N supply during the first and second growth stages leads to a delay in tuber bulking (Biemond and Vos, 1992). Only approximately 20% of the crop N uptake has occurred by the end of Stage II (Figure 1.1). Consequently, high rates of N fertilizer applied before or early in this stage may increase the opportunity for nitrate leaching and nitrous oxide emission. The timing of N application is, therefore, essential from both a production and environmental protection perspective.

In growth Stage III, tuber initiation and setting ordinarily occurs between 50 and 70 days after planting, although it may be sooner in early maturing varieties. Vegetative growth and N uptake increase at a fast pace throughout this growth stage. As mentioned previously, environmental conditions such as temperature, soil moisture, N nutrition, and diseases, in addition to the physiological age of the seed at planting, can affect tuber initiation. Because of this interaction among factors, N fertilization has been explained to affect tuber number per plant either positively, negatively, or not at all (De la Morena et al., 1994; Bélanger et al., 2002).

Growth stage IV is the tuber bulking stage. Rates of vegetative growth and N uptake decrease during this stage or cease completely in early-ripening varieties. Carbohydrates and N, in addition to other nutrients, are translocated to the tubers. This stage occurs between 60 and 90 days after planting for the early-ripening varieties and between 70 and 120 days after planting for the late-ripening varieties. Although the need for N is highest during this growth stage, application of N late in the season can encourage vegetative growth, but at the expense of tuber bulking. This is especially true for indeterminate cultivars such as Russet Burbank (Westermann, 1993).

Growth stage V is the tuber maturity stage when vines begin to wilt and nutrients are solubilized in the leaves and roots, and then transported to the tubers. There is insignificant or no N uptake during this growth stage (Figure 1.1).

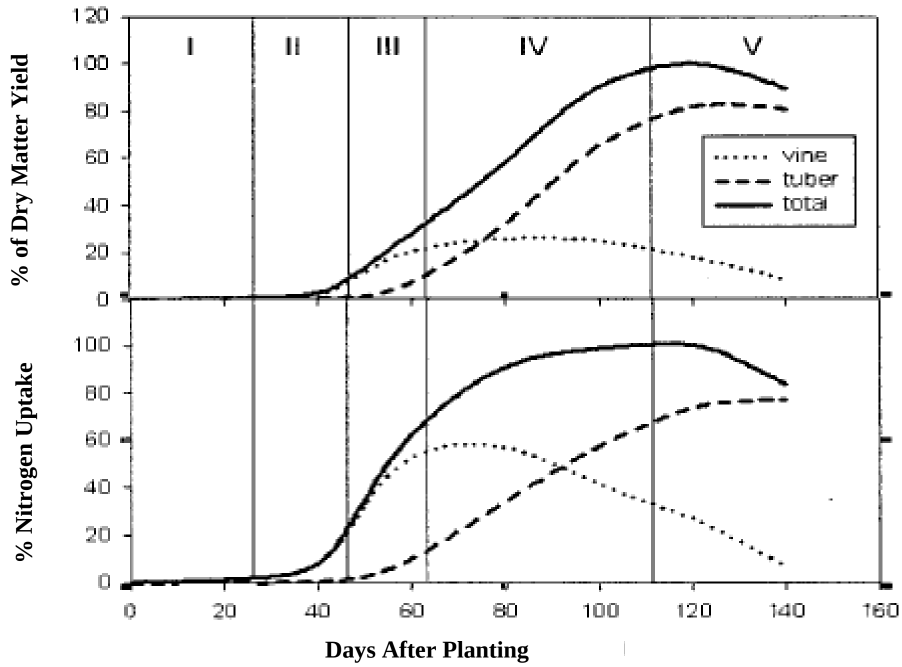

Figure 1.1. The percentage of the vine, tuber, and total dry matter accumulation and N uptake by potato (Russet Burbank) cultivar. The crop was fertilized with 270 kg N ha^{-1} applied in three split applications (46 kg N ha^{-1} at day 0, 112 kg N ha^{-1} at 31 days after planting and 112 kg N ha^{-1} at 45 days after planting) and grown under irrigation on sandy soil in Becker, Minnesota, USA. The five growth stages are denoted by I= sprouting, II= vegetative, III= tuber initiation, IV= tuber bulking, V= maturation. Reprinted with permission[4780550620413]:[American Journal of Potato Research] (Zebarth and Rosen, 2007).

1.5 Nitrogen Use Efficiency

The global population is forecasted to rise by 75 million people per year, reaching 9 billion by 2050, increasing the demand for food production (Buttriss and Riley, 2013). To meet these demands, it is predicted that rates of synthetic fertilizer application may have to rise threefold if past methods are used to accomplish the required 50 % increase in food production (Tilman et al., 2001). Due to ever-increasing dependence on non-renewable chemical fertilizers (which are associated with significant adverse environmental consequences), the sustainability of arable crop production in the future faces rising uncertainty (Tilman et al., 2002). Although past improvements in yields have resulted from higher applications of synthetic fertilizer (an approximate ten-fold increase between 1950 and 2000 (Ghorbani et al., 2009) and pesticides, further increases are unlikely to provide such sufficient yield gains as a result of diminishing returns (Tilman et al., 2002). Currently, only half of the applied N fertilizer is taken up by the plant (Smil, 1999; Cassman et al., 2002). The loss of N from the rhizosphere and its detrimental influence on the environment is of significant concern; inorganic N (in particular NO_3) can leach into the groundwater, leading to eutrophication (Vitousek et al., 1997).

The manufacture of N fertilizers depends upon the use of fossil fuels in an energy-intensive production system that releases greenhouse gases (in particular, N_2O) as a by-product (CHANGE-IPCC, 2006). Organic matter-based fertilization managements (legumes and composted manures) are alternatives currently being utilized in organic and low input agriculture, which for some crops or cropping systems, can have comparable yield potentials as mineral fertilizers (if applied at the same levels of NPK) (Herencia et al., 2007; Hepperly et al., 2009). Additionally, it can benefit plants through the repression of plant diseases and can improve various biodiversity indicators (Eyre et al., 2009; Ghorbani et al., 2010). Regrettably, the plant availability of the quintessential macronutrients N, P, and K in organic fertilizers is usually considerably lower than in mineral fertilizers (Van Bueren et al., 2011), whereas environmental guidance, such as the Water Framework Directive (2000/60/EC) and the Nitrates Directive (91/767/EC) restrict the total annual usage of livestock manure. This means that farming systems that rely on organic nutrient sources, (especially organic farming systems) usually have lower levels of productivity. Recent studies indicate that organic arable yields reach 80% of conventional production yields (De Ponti et al., 2012); consequently, there is a need to improve the efficiency of nutrient use from organic sources by optimizing agronomic management systems and varietal choice.

The need for sustaining constant arable crop production for upcoming generations and preserving the environment from further degradation is resulting in a reduction in mineral fertilizer input or a replacement with alternative fertilizers, whilst conserving or improving the current crop yield and quality levels (in other words, improving nutrient use efficiency) (Tilman et al., 2002). The most common definition of NUE is the ratio of the yield of a given crop to the unit of available nutrient. The term can be used to evaluate the efficiency of nutrient use of a given cropping system, on a seasonal or multi-year basis. The NUE can be influenced by plant genotype due to variations in nutrient utilization (e.g., maturation type and translocation efficiency) or nutrient uptake (e.g., root properties). Reducing fertilizer application and breeding plants with high NUE is one of the fundamental intentions of research conducted on plant nutrition (Hirel et al., 2007).

There is the possibility to enhance NUE through agronomic innovation and selection of the most beneficial practices. Precision agriculture can be utilized to improve the timing and rate of N application so that it coincides more closely with crop need (Raun et al., 2002; Dawson et al., 2008). For example, Semenov et al. (2007) worked on a crop model to confirm that NUE could be improved by 12% by merely regulating the date of N application, while Baeckström et al. (2006) explained the significance of residual soil fertility (legume residue) in improving NUE in organic production operations.

Weather conditions are the third factor that influence NUE and are related to the potential of the crop for optimal growth, especially where water can be limiting (Semenov et al., 2007). There are several further parameters which can be measured to contribute further insight into the NUE of a given production method. In potatoes, NUE can be understood if nutrient uptake and biomass partitioning at multiple stages of growth are included. For instance, a measure of total N uptake at growth stage GS66 (mid-flowering), affords an indication of the potential of the crop to take up N early in its growth and may reflect differences in physiology or morphology in the root system (Fageria and Baligar, 2005).

The measured total N uptake at GS85, an indicator for the maximum total N that has been taken up by the crop, provides a useful measure of the total available N for translocation to the tubers.

Dry matter (DM) distribution is measured by the harvest index (HI) and is an essential characteristic for yield improvement in field crops (B Zebarth et al., 2004; Fageria et al., 2008). The HI values of modern crop varieties are usually higher than those of traditional varieties for the main field crops (Ludlow and Muchow, 1990), due to increased dry weights in modern potato varieties. The distribution of nutrients in the parts of the plant (root, shoot, and tubers) explains their use efficiency, with higher N accumulation in the crop enhancing yield and leading to a higher NUE (Fageria and Stone, 2006).

As an example, wheat (*Triticum aestivum* L.) biomass partitioning of N applications at different growth stages can be useful and economical. The life cycle of the wheat crop can be divided into three phases: foundation, construction, and production phase (Sylvester-Bradley et al., 2008). Measuring the total N uptake at the end of the foundation stage (GS31) produces an indication of early plant development, tillering, and primary root development (Sylvester-Bradley et al., 2008). The construction stage of wheat development includes the development of yield forming leaves, fertile florets, stem reserves, and deep roots. The total N uptake at the end of this stage (anthesis, GS61) is principally associated with the size and activity of the root system and the availability of N within the rhizosphere. Biomass partitioning at the end of anthesis stage can render insights into variations in wheat N storage and translocation strategies (Cox et al., 1986).

Traditionally described harvest elements at maturity contribute insights into the efficiency of translocation of assimilated N from the stem and leaves to the grain. Ideally, scientists are looking for wheat genotypes and management operations that support maximum uptake of N and storage in stems and leaves during the foundation and construction stages, which is then efficiently translocated to the grain during the final production stage of formation. Further gains in NUE can be accomplished with varieties that possess the ‘‘stay-green’’ attribute which postpones senescence and enables N uptake and translocation to continue during the grain filling stage (Bogard et al., 2011).

1.6 Soil Organic Matter-Agronomic Benefits

To improve soil organic matter (SOM) content, the rate at which organic matter is applied to the soil must be greater than the rate at which it is lost through microbial decomposition, leaching, or erosion. Pasture and cropping management strategies that produce adequate quantities of high-quality residues are essential to rebuilding and maintaining SOM. Practices that improve soil structure support more abundant and more diverse microbial communities, which, in turn, promote soil fertility (Hoyle, 2013). Soil organic matter content can be improved, but it is necessary to study the economic expenses of doing so. For instance, the SOM content can be raised considerably by adding high amount of organic supplements such as compost and manure; however, this is likely to require significant transportation expenses. Increasing SOM content will be more economical in farming systems and environments that support high production and produce on-farm supplies of organic soil supplements. Johnston et al. (2009) showed that the constant use of farmyard manure over ten decades approximately tripled organic carbon in the soil and produced higher yields in long-term experiments.

1.6.1 How to Improve Organic Matter Content in Soil

Soil management approaches that promote soil health through impacts on SOM content include additional multiple crop rotations (particularly in crops with high-residue), reduced tillage practices, the intense practice of cover crops, and the incorporation of a variety of organic complements (Magdoff and Weil, 2004).

These approaches, in multiple modifications and combinations, achieve one or more of the following purposes: increase inputs and decrease outputs of carbon (C), attack pests present in the soil, and promote beneficial organisms (Table 1.1). Additionally, enhanced soil properties as a result of these practices, such as reducing soil compaction, more available water, better timing of nutrient availability to crop demands, and production of growth-promoting materials, are supporting the growth of plants and protecting themselves from stress and pests (Magdoff and Weil, 2004).

1.6.1.1. Increasing Carbon Inputs to Soil

The quantity of C inputs considerably impacts the accumulation of organic matter (OM) in the soil (Magdoff and Weil, 2004). Paustian et al. (1997) highlighted that the variation in SOM is linearly correlated to the level of C inputs in each of seven long-term trials when the variation in C was averaged across the duration of the trial. Campbell and Zentner (1993) observed a primary association between the amount of crop residue and its N content to SOM during 24 years of a crop rotation practice in Saskatchewan, Canada. Reductions in the duration of uncovered fallow periods and increases in the duration of perennial crops in rotations are models of approaches that can enhance C inputs. Both of these approaches improve long-term water and nutrient use efficiency of crops and therefore multiply C inputs to the soil (Paustian et al., 2000).

Table 1.1 Influence of Soil and Crop Management Practices on SOM, adopted from (Magdoff and Wei, 2004) with permission.

Practice	**Increased Gains**	**Decreased Losses**	**Increased Beneficials or Decrease Pathogens, Parasites, and Weeds**
Rotation			
High-residue crops included	Higher average annual residue	If a higher amount of residue leads to higher water infiltration and less runoff and erosion (especially if maintained on the surface)	Regardless of the effect on POM or total SOM levels, soil biology usually more favorable to crops in rotation
Perennial forages	Higher average annual residue	Soil continuously covered leads to reduced raindrop impact and physical holding of soil by roots	Same as above, especially because these are usually longer rotations
Cover crops	Increase production of biomass when otherwise no primary production POM increased or maintained	Same as above	Weeds smothered or suppressed (allelopathy) Higher AM inoculation of following crop Nematode or diseases suppressed
Use of organic amendments	Significant amounts of organic material usually applied along with nutrients (as with compost and dairy or beef manure)	If causes higher infiltration and drainage less water runs off, less erosion occurs	Diseases sometimes suppressed Plants might acquire systemic resistance to diseases Insects might find plants less attractive
Reduced tillage	Increased water infiltration can increase yields and residues, especially on medium to coarse soils	More residue on the surface (because of reduced tillage) reduces runoff and erosion	Reduced weed seed survival and emergence

1.6.1.2. Rotations and Crop Residue Management

Cropping techniques affect SOM in several ways (to be discussed later). Some crop rotations leave substantial amounts of residue, which contribute considerably to increase the addition side of the gains–losses model. Some crop rotations, such as legume or grass-legume forage crops provide a lot of root dry matter; they can contribute to increasing soil residue content. Also, tillage reduction and continuous soil cover of such crops decreases SOM losses either by erosion or by soil respiration (Magdoff and Weil, 2004). The quality of the crop residue (C/N) also influences SOM, where the higher the nitrogen content, the easier it is for microorganisms to produce decomposition. Crop rotations affect soil biology and overcome problems with numerous plant pests. Compared to monoculture cropping systems (no rotation), crop rotation can result in approximately a 10% increment in yield (Karlen et al., 1994). Consequently, more residue regularly settles in the soil after harvest. In a comprehensive review of the literature, West and Post (2002) noticed that performing crop rotations, such as shifting between corn and soybean crops, can enhance C in the soil by an average of 20 ± 14 g C m^{-2} $year^{-1}$. Including perennial forage crops in the crop rotation is one of the most efficient methods for increasing the level of SOM and advancing soil quality. The inclusion of pastures in a rotation system can reduce the soil-degrading consequences of conventional cropping and tillage applications. An examination was performed with a long-term crop rotation operation by practicing conventional tillage on soil with a 2% slope (Studdert et al., 1997). Procedures were consecutive for cropping and crop pasture (50:50 and 75:25) rotations. All soil characteristic indicators (bulk density, aeration, compaction, root penetration) declined with more cropping and increased and developed with more pasture in the rotations. For example, soil organic C declined by 4.4 g kg^{-1} during 6 to 7 years of a hard (monoculture) cropping system and flourished to the original level (37.2 g kg^{-1}) after 3 to 4 years of practicing pastures system. Studdert et al. (1997) concluded that three years of pasture was enough to fix soil quality that had been under seven years of conventional cropping within acceptable limits and met the goals of sustainable agriculture. Likewise, six years of unharvested grass (tall fescue) increased the soil organic carbon (SOC) content in the upper 15 cm of a sandy loam soil in Maryland from 10 to 20 g kg^{-1} (Weil et al., 1993). Improvements in soil structure and N fertility were obtained by practicing three years of perennial pasture, which approximately matched the degree of deterioration that occurred during three years of row cropping. These results suggest that similar lengths of cropping and pasture seasons are required to sustain soil properties in these poorly structured silt loam soils.

The practice of animal grazing on perennial grass vegetation can improve soil quality in comparison with ungrazed grassland. For instance, an 11-year study conducted by Manley et al. (1995) on a mixed-grass prairie in Wyoming showed that soils gained higher quantities of C and N within a 30 cm depth on grazed pastures compared to native rangeland where livestock was neglected. A distinct procedure of increasing SOM levels from the accumulations side of the balance is the conservative management of plant residues, roots, and over-ground parts. Globally, 1.4×10^9 ha of arable land is determined to return 3.44×10^9 Mg of crop residue annually, including 45% C or 1.5 P g year^{-1} of total C (Reicosky et al., 2000). Only a small portion of this crop residue C is preserved in SOM, the majority being returned to the atmosphere as CO_2 by microbial respiration processes within 1 to 2 years of its addition to the soil. Larson et al. (1972) mentioned that following 11 years of cropping, SOC content was linearly correlated to the quantity of crop residue added (alfalfa hay or corn stover). Approximately 5.5 Mg/ha of residues was required with conventional plowed tillage to keep the SOC content at its primary level of 1.8% C (Follett et al., 1987). For rotation research, including a legume phase followed by three wheat crops in Ferric Luvisol on poorly structured soil in New South Wales, Whitbread et al. (2000) stated that the quantity of labile soil C was significantly enhanced in the treatments with a maintained wheat stubble batter than the removed residue. It was recommended that the application of legume species is more reasonable to develop the overall fertility of the farming system when mixed with cereal stubble retention.

1.6.1.3. Use Different Sources of Organic Materials

Organic amendments and crop residues have distinct properties and can have different influences on chemical, physical, or biological characteristics of soils. Therefore, a procedure utilized in SOM management is the application of a variety of organic materials. Monoculture, i.e. the growing of the same crop in the same area for several years without organic supplements, would expose the soil fauna and flora to the same types of residues annually (Magdoff and Weil, 2004). This repeated exposure to the same residue promotes the presence of organisms that are detrimental to the plants. Over time, this can be moderated by improving populations of biological control organisms to reduce disease-inducing organisms to lower levels. Besides, different varieties of residue settle on a field when cover crops and crop rotations are practiced. Furthermore, multiple types of organic supplements can be imported from off the field, including various types of crop residues, animal manure, grass clippings, tree leaves, sewage sludges, and food processing waste. These substances can be applied directly or can be composted alone, mixed, or with other substances such as woodchips or bark, which are added as bulking factors. In addition to the added amount of C, the variety of substances in which C is combined with the soil also affects SOM accumulation (Magdoff and Weil, 2004). The application of 250 and 500 g C m^{-2} $year^{-1}$ to moderately-coarse textured soils in Canada and Sweden, respectively, in the order alfalfa < straw < manure < peat improved the OM content (Paustian et al., 2000).

Manure generates a higher increment in SOM because it consists comparatively of recalcitrant composites, with the most readily oxidized composites in the original plant tissue broken down by the livestock digestive system before the secretion of the manure. Hence, manure treatments have been understood to influence SOM for multiple years after treatments have added, can not be lost quickly as the mineral fertilizer (Jenkinson and Johnston, 1977). The amount of organic material required to be applied to soils to sustain or improve SOM can be substantial. The application of supplements such as animal manure is particularly essential when growing crops that leave a small amount of residue in the soil. In an examination of silage corn production, in which nearly all green vegetation residue was harvested using normal tillage on clay soil, researchers observed that approximately 44 Mg of dairy manure ha^{-1} $year^{-1}$ (wet weight) were required to keep SOM content at the initial level of 5.2% that produced from the long-term cropping manner to combined grass-legume hay (Magdoff and Amadon, 1980). Where the first level of SOM (5.2%) represented as a steady-state following the prior cropping to a combined legume–grass hay. The manure and livestock groundcover (bedding) input per hectare necessary to maintain this SOM level was nearly equal to the annual quantity expected from 2.2 large (636 kg) dairy cows. Approximately 2.5 ha are required to provide all the feed (forage and grain) for 2.2 lactating cows (Magdoff et al., 1997). Thus, 2.5 ha are required to produce the feed for a cow that generates an enough manure to maintain SOM levels of 1 ha of silage corn.

Additionally, compost has been observed to offer improvements over raw organic substances for such environmental purposes as bioremediation, artificial wetland construction, and slope stabilization (Alexander, 1999). However, this study, in addition to similar research on compost supplement, failed to create an ecologically appropriate comparison of the future of a given amount of organic C either applied directly or employed to make compost that is then added to the soil. In one research study in which supplements were added based on the same quantity of C in original substances, significantly higher N, C, and CEC levels were obtained following 199 days of incubation when hardwood sawdust and uncomposted sludge were added immediately to the soil, compared with composting of the sludge-sawdust compound before application (Chromec and Magdoff, 1984).

1.6.14. Decreasing Soil Organic Matter Losses from Soil

A reduction in SOM can occur due to discharge of plant material after harvesting, erosion damages by wind and water, or C losses (CO_2) by microbial respiration processes. Agricultural harvesting practices are aimed at ensuring careful preservation of as much of the residue of the plants as possible, as explained in the prior section (Magdoff and Weil, 2004). The loss of SOM through erosion processes is higher than what might be concluded from losses stated for planted soils (approximately 5 to 50 Mg ha^{-1} $year^{-1}$) because SOM is enriched in the eroded substance compared to the bulk soil in degraded areas. This enrichment of the soil is logical because erosion occurs at the soil surface where the accumulation of SOM is highest and because the organic portion of soils usually erodes more quickly than the mineral portion. Consequently, SOM content is typically higher in soils with a small degree of slope (lower landscape positions), because these soils experience minor erosion and might obtain SOM through sedimentation from the upper landscape positions. For instance, in Minnesota, the average SOC contents for soils at slope degrees of 0–2%, 3–5%, and 6–12% were 22.3, 13.5, and 8.9 g kg^{-1}, respectively. Mean seasonal erosion damage of SOC from these soils was between 273 and 758 kg C ha^{-1} for conventionally tilled soils and between 94 and 274 kg C ha^{-1} for non-tilled soils (Follett et al., 1987). With a lack of significantly hastened erosion, microbial respiration comprehensively controls SOC losses. SOM breakdown by microbial action is very sensitive to changes in drying and wetting conditions, and temperature (Birch, 1958). The availability and solubility of SOM when soils are moistened after a dry condition has been shown to be the reason for accelerated microbial respiration and SOM breakdown (Bartlett, 1981). Nevertheless, the tillage process is the management system with the potential for a vast impact on the loss of the SOM balance layer. A combination of mechanisms could justify the stimulation of SOM loss by tillage. First, practicing tillage on slope areas tends to transfer topsoil enriched with OM downhill (Magdoff and Van Es, 2000). Second, crop residues decompose more rapidly when incorporated into the soil because the soil maintains moisture, temperature, and N availability which facilitates microbial decomposition (Wilson and Hargrove, 1986).

Moreover, varieties of microbial communities of soil decomposers are in direct association with the residues tilled into the soil. Reicosky et al. (2000) stated that the practice of using a moldboard plow to plow wheat stubble prompted one third more C to be lost from the soil surface within 19 days of plowing than was included in the crop residue to begin with. The practice of using no-till planting systems can considerably reduce SOC losses in addition to damages from erosion due to these processes. Measurements of ^{13}C natural abundance have shown that the average residence interval of SOM was approximately doubled under no-till practices compared to absolute tillage (Paustian et al., 2000). Tilled soils are typically drier, warmer, and more sensitive to erosion than untilled lands, and these three factors have previously been considered as accelerators of the loss of SOM. In some cropping practices, the consequences of tillage application might be confounded by the impacts of biomass input, for example, when a wheat-fallow order is compared to the order of wheat pasture. If the soil is kept bare by continued tillage, the fallow interval represents a lost possibility for plant residue production and a higher number of tillage services per year. This is why during five long-term studies conducted in the United States (Nebraska, North Dakota, South Dakota, and Colorado) alternatives included less intensive tillage processes and less fallow durations than the standard wheat-fallow system with the production of 25 to 45% higher SOM levels within the upper 7.5 cm of the soil profile (Gajda et al., 2001).

1.7. Spectral Properties of Plants and Agricultural Management

The total amount of solar energy absorbed by the surface of plant leaves is directly associated with the total photosynthetic pigment present in the tissues of the leaves (Gates et al., 1965), while the photosynthetic potential of the plant is directly correlated with chlorophyll content (Hatfield et al., 2008). Total chlorophyll content varies due to plant developmental stage or stress. Therefore, the measurement of chlorophyll content in the leaves can be utilized for evaluating the physiological health of a plant. Gitelson and Merzlyak (1997) assessed the vegetative indices of various species of plants and concluded that reflectance and absorption of light in the 530–630 nm and near 700 nm wavelengths were correlated to chlorophyll content. The light reflectance of plant tissues at specific wavelengths of 550 and 700 nm was highly associated with chlorophyll content ($r^2 > 0.97$). Wavelengths in the near-infrared spectrum (NIR) (750–900nm) were comparatively insensitive to chlorophyll content.

Gitelson and Merzlyak (1997) established an index (chlorophyll index (CI)) for predictive computations using the ratio of the 750 nm light reflectance to the 550 nm wavelength. Similar research was carried out on corn (*Zea mays*, L.) (Ciganda et al., 2009), where individual leaves were sampled every two weeks. The red-edge (R-edge) wavelength (720–730 nm) was used to determine the total chlorophyll content of the leaves ($r^2 > 0.94$).

Crop reflectance is defined as the ratio of the amount of incident light to the amount of reflected light from the body of the plant (Schröder et al., 2000). Active sensors contain modulated light-emitting diodes that emit light at particular wavelengths in a special pulsing sequence onto a plant canopy (Shaver et al., 2010). The sensor estimates the amount of emitted and reflected light from the device in the same pulse flow rather than ambient sunlight (Shaver et al., 2010). (Raun et al., 2001; Raun et al., 2002) used the active optical sensors GreenSeeker (GS) and Crop Circle

(CC) for in-season N management in winter wheat fields (Gupta, 2018). The strategy employed during the study involved dividing the normalized difference vegetative index (NDVI, see below for details on calculation) by growing degree days (GDD) accumulated from planting to sensing. This value was described as the in-season estimate of yield (INSEY) which was correlated to the growth rate of the plant. The INSEY is a more reliable indicator of plant health in comparison to the sensor reading alone (Raun et al., 2001).

If used solely, the apparatus reading must be taken at precisely the same growth stage in the following years for a valid and matching growth relationship. Therefore, the INSEY normalizes the reading for time differences between the growing seasons, resulting in better relationships for readings taken within a year and among years. Light waves in the green (G) and R-edge spectra can penetrate the leaves of the plant greater than the blue (B), and red (R) spectra do. During photosynthesis, more than 80% of incident spectral light absorption was recorded in the range of 400 to 700 nm (Moss and Loomis, 1952). Thus, light in the G and R-edge spectra ranges would be more sensitive to any fluctuations in chlorophyll content than other spectra ranges because the absorption coefficient in these spectra produces a range of values, rather than a high or narrow spectral range of values (A. A. Gitelson et al., 2003).

Absorbance in the visible spectrum by leaves of different plant species increased when changing from a lighter green to darker green color (Gates et al., 1965). Maximum chlorophyll absorbance was observed at 680 nm, whereas the minimum absorbance was noted at 550 nm. The most basic method of spectral plant analysis involves examining the amount of R light to NIR light absorbed underneath a plant canopy to that on top of the canopy (Federer and Tanner, 1966). As leaf area index (LAI) (the proportion of leaf area per unit area of soil (Zheng and Moskal, 2009)) increases, the amount of light absorbed in the R spectrum and light reflected in the NIR (Federer and Tanner, 1966) also increase. Jordan (1969) established that by using a light ratio (675/800 nm) underneath the tree canopy rather than above, LAI could be measured indirectly. While LAI could be estimated remotely, environmental conditions such as the angle of incident, sunlight, and cover significantly influenced the efficiency of the measurements. Similar procedures have been utilized in assessing grass canopies (Tucker, 1979). With progressing green biomass, incident R light (630–690 nm) is increasingly absorbed. Several ratios of the R and NIR spectra are associated with the biomass of plants (Tucker, 1979), where R reflects the plant pigment condition and NIR reflects the cell structure condition (mesophyll).

Many proportions are collectively known as vegetative indices, which are specific to various environmental and physiological parameters. These include standard spectral vegetative indices such as chlorophyll indices (Cl_{green}= (R_{NIR}/R_{green})-1) for computing leaf chlorophyll content (Gitelson et al., 2005), the soil adjusted vegetation index (SAVI = (NIR–R) (I L)/(NIR+R L)) for computing LAI (Huete, 1988), and the normalized difference vegetation index (NDVI) which is a broadly handled vegetative index (Raun et al., 2001).

The plant pigments that are most involved in the photosynthetic process are chlorophylls type a and b, which absorb the R and B spectral light and reflect the G light (Slaton et al., 2001). Furthermore, there is more reflectance in the NIR light (700-1400nm) (Gausman, 1977; Slaton et al., 2001). This property of plant leaf 'reflectance' is employed to detect nutrient deficiencies and for biomass estimation (Osborne et al., 2002). The NDVI is the standard vegetative index used by researchers for forecasting plant biomass and yield (Stone et al., 1996; Osborne et al., 2002).

The NDVI is the proportion of in the R band to the NIR (Deering et al., 1975) described in the following equation:

$$NDVI = (NIR–R) / (NIR+R) \quad \text{(Eq. 1.1)}$$

Where,

NIR is the near-infrared region of the spectrum and

R is the red region of the spectrum

The NDVI achieved large-scale acceptance among researchers due to ease of calculation and the utilization of two light spectra (Deering, 1978), it does not require multiple wavelength bands or complicated calculations. The NDVI has been correlated to N status of the leaves, green leaf biomass, chlorophyll content, and grain yield (Shanahan et al., 2001; Shanahan et al., 2003; Solari et al., 2008). However, the there are some restrictions with the NDVI which include saturation whereby the absorption of all the visible light results in a value close to 1 if the density of green biomass is high. As a result, the NDVI is not appropriate as a stand-alone index for yield prediction studies (Gitelson et al., 1996; Myneni et al., 1997). The R wavelength exhibits a flat response after LAI values exceed 2, whereas the NIR reflection continues to respond even at high values of LAI ranging from 2 to 6 (Gitelson and Merzlyak, 1997). To overcome this restriction, Gitelson (2004) suggested that by multiplying the NDVI values by a weighting coefficient, a, the correlation between crop reflectance and the crop biomass might improve, where a can be used to enhance the sensitivity of the NDVI to NIR by introducing a weighting coefficient, $a < 1$, to decrease the variation between the contributions of NIR and R to the NDVI. This equation was termed the wide dynamic range vegetative index (WDRVI) as follows:

$$(a * \rho NIR - \rho R)/(a * \rho NIR + \rho R) \quad \text{(Eq. 1.2)}$$

Where,

a is a coefficient ranging from 0–1. When a is 1, then equation 1.2 would be equal to equation 1.1. The improvement in the active sensors has made sampling comparatively insensitive to variations in ambient light and environmental limitations.

1.8. Site-Specific Technologies for Nitrogen Management

Remote sensing is defined as the means of identifying and observing the physical properties of an object by measuring its reflected and released radiation at a distance from the targeted region (Christopherson et al., 2019). Examples of remote sensors include satellite imagery, aerial imagery, ground-based active optical sensors (GBAO), ground-based reflective sensors, and leaf chlorophyll sensors (Hatfield et al., 2008). Remote sensing has been employed in the agricultural field for evaluating land use, land cover, and crop biomass (Sala and Austin, 2000; Kogan et al., 2004; Henebry et al., 2005). Earlier studies examined the use of remote sensing techniques such as the single photon avalanche diode (SPAD) (Konica-Minota Americas, Ramsey, NJ), the chlorophyll meter, canopy reflectance, and color photography (Blackmer et al., 1996; Schepers et al., 1996), which have been successfully employed to estimate spatial variability in crop canopies (Blackmer et al., 1993; Blackmer et al., 1996; Schepers et al., 1996). Remote sensing techniques are now employed to identify in-season spatial crop N status (Osborne et al., 2002). Further research has resulted in the development of the relationship between physiological properties of plants (chlorophyll content, crop N status), and spectral reflectance (Bausch and Duke, 1996; Osborne et al., 2002).

1.9. Use of Sensors and Normalized Difference Vegetation Index

Most crop growers are taking into consideration the prior crop, soil management, and soil drainage when applying N. However, they do not generally use in-season instruments for diagnosing an optimal N rate (Kitchen et al., 2001). Additionally, farmers tend to apply higher rates of N fertilizer than recommended to assure the highest yield (Scharf et al., 2006). Adding excessive N rates for the yield attained often results in unutilized N flowing to surface water in the form of nitrate (NO_3) (Scharf et al., 2006). Utilizing proximal plant canopy sensors allows farmers to adjust N requirements according to the crop demands. The concept of “need basis” using sensing instruments was introduced by Schepers et al. (1995) to help overcome environmental pollution from excess nitrate. This strategy involved the use of single photon avalanche diode (SPAD) chlorophyll meter estimations, which helped determine the crop N status against a standard color and then N was added as required. This technique helped to sustain the optimum yield with less fertilizer (Varvel et al., 1997). The disadvantage of this strategy was that it was necessary to physically gather tedious readings from numerous leaves and to standardize the data among different varieties.

The SPAD chlorophyll meter is an active optical sensor that estimates transmitted light through the plant leaves at two distinct wavelengths (the NIR and the R range of the spectral radiance) and calculates a value that is defined by the manufacturer. The meter is a non-destructive technology that assists in examining leaf tissue for the N status or nutrition status of the plant. Research has revealed that chlorophyll meter readings are positively associated with real chlorophyll content (Schepers et al., 1992). The SPAD meter, however, is placed onto one individual leaf per measurement, which makes taking multiple readings in the field time-consuming. Chlorophyll meter research has focused on isolating areas with a positive response to N fertilizer from areas with low response potential and on indicating if and when N supplementation is required (Scharf et al., 2006). Crop characteristics confound chlorophyll meter calibration and reduce the effectiveness of the apparatus in predicting N availability across large areas (Schepers et al., 1992; Bullock and Anderson, 1998). Nevertheless, it is not difficult to normalize the meter data for a specific crop and growth stage against a high N control. If accurately calibrated in several crops, the apparatus can allow comparisons across areas and growth stages.

The commercial application of chlorophyll meters needs a reference strip, which is usually an appropriately fertilized area planted within the field following local growing recommendations (Schepers et al., 1992)

Since chlorophyll (CHL) does not have a direct effect on the spectral reflection of the crop, estimations were utilized to predict grain yield (Kanning et al., 2018). Consequently, an indirect procedure based on chlorophyll calculations from the obtained hyperspectral image data using partial least-squares regression was utilized. Resulting models showed reliable predictability (R^2 CHL=0.77, RMSE–CHL [$\mu g\ cm^{-2}$] =7.02). Chlorophyll predictions were employed afterwards to calibrate a multiple linear regression model to predict grain yield (R^2 yield=0.88, RMSE-yield [dt ha^{-1}]=4.18). A pixel-wise forecast of the hyperspectral image was carried out. The resulting yield calculations were validated and contrasted with various N treatments. The final result showed that above a particular amount of applied N, any additional fertilization did not result in a larger yield (Kanning et al., 2018).

Miri (2009) stated that the chlorophyll content index (CCI) was significantly and positively associated with grain yield and a harvest index of wheat. Chlorophyll is not only utilized in agriculture as a substitute for leaf N content, but also as an important indicator of N efficiency (Cerovic et al., 2012). The correlation between CCI and real measured chlorophyll has been observed to be linear in wheat and the Asian pear tree (*Pyrus pyrifolia* L) (Ghasemi et al., 2011; Kaur et al., 2015; Lunagaria et al., 2015). Furthermore, the CCI for relative chlorophyll content can be used as a decision-making assistance tool for N fertilization of crops and for improving the estimation of crop yield and biomass.

Bullock and Anderson (1998) did not discover a correlation between chlorophyll meter readings and yield at the V7 stage for corn. However, the results of the study demonstrated an improved correlation between leaf N concentration and yield at advanced stages (R1 and R4) when the meter data were better associated with the grain yield than with leaf N content.

Hyperspectral vegetation indices estimated from reflectance in the R-edge spectral wavelength and the adoption of a broader field of view (25° FOV) were the most appropriate indices for detecting potato crop N stress (Morier et al., 2015). Among those indices, the chlorophyll index (R-edge chlorophyll index) was highly sensitive to potato N content and accounted for 76% of the variability in total tuber yield at 55 days after planting (Morier et al., 2015). A robust association between potato tuber yield and chlorophyll content was also observed for Russet Burbank and Shepody potato cultivars. Additionally, a comparable trend was reported for the association between chlorophyll content and leaf nitrate concentration (Botha et al., 2006).

The CHL that obtained by SPAD (CHL-SPAD) was the only characteristic exhibiting a concurrent changing trend (slope) with yield, particularly in field conditions. The rate of senescence or greenness loss was slower in the higher water limitation treatments, which means that the stay-green impact (delayed senescence) occurs in some potato cultivars. CHL-SPAD was high and negatively associated with final yield at the loss of half the highest plant cover during senescence (between 1040 and 1170.C days) in all irrigation treatments (Ramirez et al., 2014).

Leaf chlorophyll fluorescence-based techniques are also being studied for crop N control (Tremblay, 2004a). These techniques are based on leaf chlorophyll fluorescence influenced by ultraviolet radiation and visible radiation, and on computations of the absorbance of ultraviolet light by epidermal leaf polyphenolic composites (Campbell et al., 2007). These procedures are currently being studied at Walloon Agricultural Research Center in Gembloux, Belgium and have a potentially higher sensitivity to crop N status because a variance in the concentration of polyphenolics was correlated to the crop N status, and, consequently, fluorescence can be discovered before chlorophyll concentration and LAI are modified (Cartelat et al., 2005).

The noninvasive and hand-held Dualex and Multiplex devices (Force-A, Paris, France) were recently developed for evaluating crop N status. The devices were studied by Tremblay et al. (2007) and Zhang and Tremblay (2010) for the evaluation of corn N status, and they are currently being studied at Walloon Agricultural Research Centre (CRA-W) for the evaluation of potato crop N status.

At the canopy scale, most of the practical approaches for crop monitoring are noninvasive and are based on computations of light transmitted beneath the canopy or reflected above it. They refer to the remote sensing methodology (based on spectral canopy features) that can be performed at various spatial scales such as ground-based, or airborne (Tremblay, 2004a; Jongschaap, 2006; Hatfield et al., 2008). Each methodology attempts to estimate canopy formation parameters, (especially LAI), based on the information that plant N, leaf chlorophyll, and LAI, are completely associated variables (Lemaire and Gastal, 1997).

Common instruments being studied for ground-based remote sensing for potato crops include the Cropscan field hand-held passive radiometer system (Cropscan, Rochester, MN), which was first used to examine potatoes in Europe by Booij and Uenk (2004) However, it is still under examination at CRA-W. Also, the N-sensor (Yara) examined and developed in Europe (a canopy reflection-based system with four tractor-mounted passive or active sensors; (Link et al., 2003) and the GS (NTech Industries, Ukiah, CA,) or CC (Holland Scientific, Lincoln, NE) with active sensor examined in the United States (Samborski et al., 2009).

Using leaf or canopy reflectance at various wavelength bands allows vegetation indices to be calculated and utilized for crop N status evaluation. Ground-based canopy light reflectance data with ground-based Cropscan radiometers have the advantage of combining a broader sampling region at each reading and including less laborious efforts than the use of the chlorophyll meter. Nevertheless, especially for the potato crop, vegetation indices must also account for the fact that canopy spectral responses are adjusted according to the proportion of vegetation cover and bare soil, and that the architecture of stems and leaves differs with plant growth stages. Specific vegetation indices such as the SAVI (Huete, 1988), transformed-SAVI (Wiegand et al., 1991), and the optimized-SAVI (Rondeaux et al., 1996) have been evolved to diminish or eliminate background soil impact. However, hand-held ground-based radiometers are usually not easy to utilize as they were designed for experimental use rather than for farmers. Some easy to use commercial devices can measure crop light reflectance at similar wavelength bands (R and NIR) utilized for the chlorophyll meter. This is the case with the hand-held equipment known as Grande Paroisse Azote (GPN; AZF-Europe Sol, Toulouse, France). The device is a hand-held ground-based radiometer employing a 1-m-long probe provided at its edge with a sensing head, designed for easy and prompt use in the field. The disadvantage of this device is that its sensitivity is somewhat lower than that of the chlorophyll meter (HNT and SPAD 502 (J.P. Goffart, unpublished data)). Its main advantage is its feasibility because immediate data can be produced while walking through the canopy (Goffart et al., 2011b).

Based on canopy reflectance characteristics like ground-based near remote sensing, airborne and space-based remote sensing depend largely on obtaining satellite and aerial images, either at the regional or field scale. Airborne and space-based remote sensing technologies are quick advancing fields of investigation for platforms (manned or unmanned crafts and airplanes, and satellite platforms) and for spectral, spatial, radiometric, and temporal resolutions. The practice of high-spatial-resolution satellite sensors such as the Satellite Pour l'Observation de la Terre-5 (SPOT-5 (10m for multispectral image)) is currently being examined at CRA-W (Goffart et al., 2011a) for evaluating potato crop N status.

Bowen et al. (2005) explained that NDVI obtained from GS (GS-NDVI) could be used to apply N to malt barley (*Hordeum vulgare* L.) and potato variably. The overall relationship between yield and N rate was robust with R^2 values between 0.87 and 0.99. The relationship between yield and NDVI was mostly strong, with R^2 values between 0.82 and 0.9. The correlation between NDVI and specific gravity was not as strong as the correlation between NDVI and yield, with R^2 values between 0.47 and 0.89.

1.10. Most Common Active Optical Sensors

1.10.1. Greenseeker and Crop Circle

The GS and CC sensors were tested in a study by Barker III et al. (2016), in which it was determined that they were not significantly influenced by ambient light. Sebastian et al. (2014) described a technique for measuring early chlorophyll in winter wheat with the aid of the GS and CC sensors. RGB image analysis was also adopted as a reference plan and a novel index, the early plant vigor index (EPVI) utilizing single wavelength states (670 nm, 750 nm, and 862 nm), was devised. Samborski et al. (2015) employed the GS Model 505 (R (656 nm) and NIR (774 nm)) and CC-ACS-210 (amber (590 nm) and NIR (880 nm)) to obtain R and amber canopy NDVI values of winter wheat at three growth stages. The results showed that genotype had an impact on both R NDVI values and amber NDVI values at Zadoks growth stages 37 to 39, and only on amber NDVI values at growth stages 55 to 71.

The sensors CC-ACS-210 and ACS 430 (R (630 nm), R-edge (730 nm) and NIR (780 nm)) were examined by Taskos et al. (2015). Various NDVI values were calculated and analyzed in each waveband. The results showed that ACS-430 indices and R-edge-based indices were robustly associated with leaf chlorophyll of vineyards. The new CC-ACS-470, provided with filters to select various wavelengths and vegetation indices, were also highly correlated to plant N (Padilla et al., 2014), and R-edge-based indices showed a better correlation than the NDVI and ratio vegetation index (Taskos et al., 2015). However, plant height, measuring distance, temperature, and reflectance from soil or adjacent rows influenced the work of active sensors. It was discovered that the optimal measuring distance should be modified depending on plant structure and growth stage, and a distance of sensors more than 40 cm from the canopy was suitable (Stamatiadis et al., 2010; Raper et al., 2013; Kipp et al., 2014; Li et al., 2014).

Reflectance indices were less sensitive at the late growth stages of plants, with the decline in the NIR reflectance from the plant canopy (Padilla et al., 2014; Sebastian et al., 2014; Samborski et al., 2015; Taskos et al., 2015; Barker III et al., 2016). Among all the active-type and passive-type spectral sensors, GS and CC are the most commonly adopted sensors for on-the-go, real-time measurement of plant chlorophyll. Each of the sensors can be installed on a platform and are suitable for high-throughput phenotyping.

Raper et al. (2013) examined the sensors GS Model 505 and CC-ACS-210 and noticed that CC-ACS-210 was less sensitive than GS Model 505 at the initial growth stage of plants when the NDVI values were small, while CC-ACS-210 had a more reliable performance than the GS Model 505 at the late growth stage when NDVI values were greater than 0.6.

1.11. Potato Nitrogen Recommendation

The standard N recommendations for most crops (except some legumes) depends on the yield potential and amount of nitrate (NO_3-N) at a depth of 30 cm in the soil profile (Franzen, 2018). Neglecting the 60-cm nitrate-N analysis results in arbitrary numbers for N recommendation. Nitrogen recommendations are not adjusted based on the method of adding fertilizers; they are modified by taking into consideration the previous crop and soil sampling depth.

In Maine, due to heavy rain and snow that potentially drains nutrients from the root zone there is no spring or fall soil analysis available for the prediction of N availability along the growing season, thus, nutrient recommendations are approximated to total seasonal requirement for a specific crop (Hoskins, 1997). It is expected that an average soil will provide a modest amount of N during the growing season, part of which will be lost through leaching and denitrification. The estimated N requirements are supposed to maximize the yield under Maine conditions for that crop. The recommendation additionally compensates for the loss of added chemical fertilizer N due to leaching and denitrification during the growing season. Adjustments are made in commercial potato crops when green manure or legumes have been incorporated into the soil from the previous year. Some N is recommended for legume crops in the seeding year but not in succeeding years because they can fix their N from the atmosphere via a biological relationship with a specific bacterium (rhizobia) after they are established. There are many issues associated with this procedure because it means the grower must predict yield from year to year, which is nearly unmanageable. Therefore, if farmers decide to develop NUE through split N application, the use of GBAOs may support the development of the N rate decision at the time of side-dress application.

1.12. Thesis Objectives and Organization

The general goal of the research was to develop a simple technique to aid commercial growers with N management in dryland potato production on different soils. In the dissertation, the individual objectives are addressed in separate chapters. The aims of Chapter 2 were to (1) determine whether the sites were N-responsive, (2) study yield and quality responses of different potato cultivars receiving different rates of N fertilizer, and (3) evaluate the impact of soil organic matter content on potential yield. The aim of Chapter 3 was to evaluate the performance of two active optical sensors for in-season potato yield prediction. The specific objectives were to (1) compare the performance of GS and CC sensors in yield prediction, and (2) evaluate the impact of chlorophyll index on improving a prediction algorithm. The main objective of Chapter 4 was to evaluate the ability of active optical sensors to optimize a N recommendation algorithm that can be used by potato growers in Maine.

CHAPTER 2

YIELD AND QUALITY OF THREE POTATO CULTIVARS UNDER SERIES OF NITROGEN RATES

2.1 ABSTRACT

Undesirable growth of potato crops under excessive nitrogen (N) fertilizer application is currently a significant issue. This research was conducted to investigate the response of different potato cultivars, i.e. Russet Burbank, Shepody, and Superior, and assess qualitative characteristics under a series of six rates of N fertilization (0–280 kg ha^{-1}). Ammonium sulfate (which was replaced by ammonium nitrate in the second year), was applied on 11 sites in a randomized complete block design, with four replications. Each subplot contained four rows with a total width of 360 cm. The N fertilizer affected the chlorophyll content, yield, and yield components significantly. The regression coefficient between soil OM content and total tuber yield for all sites combined was R^2=0.78**. Sites with ≥ 30 g kg^{-1} soil OM produced higher total tuber yield, marketable yield, and tuber weight per plant (39.5%, 45.2%, and 54.9%, respectively) than sites with ≤ 30 g kg^{-1} of OM. The specific gravity of tubers increased by 0.18% in the sites with ≥ 30 g kg^{-1} of OM. The total tuber yield for the three cultivars was maximized at 168 kg N ha^{-1}. Applying 168 and 112 kg N ha^{-1} at ≤ 30 and ≥ 30 g kg^{-1} of OM sites, respectively, achieved marketable specific gravity, starch, and dry matter content. Russet Burbank cultivars produced a significantly higher yield than Shepody and Superior cultivars; however, there was no significant difference among the cultivars regarding specific gravity of tubers. Excessive N application (>168 kg ha^{-1}) decreased potato tuber production and quality.

2.2 INTRODUCTION

Potato crops have high economic importance worldwide (FAOSTAT, 2015). The potato crop is the fourth most crucial crop after rice), wheat, and maize, which have historically contributed to global food security (FAOSTAT, 2015).

The potato is a common vegetable grown in the United States of America (USA) and ranks fourth in global potato production (Silver, 2013). At the beginning of the 18th century, potatoes were introduced into the USA from Ireland and were first grown in New Hampshire. Today, the USA produces more than 52.75 Mg ha^{-1} of potatoes annually on around 445154.2 ha, with an approximate annual value of $3.5–4.0 billion. The northeastern states account for around 40468.6 ha each year(Bogash et al., 2014). USDA (2018) showed that potato production has been increasing slowly in recent years. From 1960 to 1980, potato production increased by 10.54 Mg ha^{-1}, from 23.85 Mg ha^{-1} to 34.39 Mg ha^{-1}, however, from 2000 to 2018 potato production increased by only 8.15 Mg ha^{-1}, from 49.2 Mg ha^{-1} to 57.36 Mg ha^{-1}.

There are several challenges associated with the potato cultivation system, such as soil fertility and pest management. The effective management of N fertilizers is the first challenge involved in potato production(Fageria and Baligar, 2005). A high N rate has a positive impact on vegetative growth, which in turn increases tuber yield (Oliveira and Alberto, 2000). Conversely, N stress may restrict photosynthesis and negatively affect the partitioning of photosynthesis from leaves to tubers (Jin et al., 2015). Low N rates not only produce a lower yield but also decrease tuber size because of reduced leaf area and early defoliation. Furthermore, excess N will produce more dry matter yields in parts of the plant other than the tubers (Goffart et al., 2008; Fontes et al., 2010).

Considering that N is the most critical element in increasing crop yield, its use is increasing exponentially around the world (Fageria and Baligar, 2005). Potato tuber production consumes approximately 4.5–8.5 kg soil N Mg^{-1}, and plant tissues constitute 10–50 g kg^{-1} N (Kandi et al., 2011). The N could limit tuber yield, thus it is required in higher quantities than other plant nutrients (Haase et al., 2007; Poljak et al., 2007). To maximize potato yield, growers often apply higher amounts of N fertilizer than the required range (Lemaire and Gastal, 1997).

Randall and Mulla (2001) reported that fertilizer N management, especially the rate and time of application, plays a robust role in the loss of nitrate far from the rhizosphere. The challenge is to manage N availability before, during, and after the maximum crop demand. Nitrogen fertilizers are susceptible to denitrification, volatilization, leaching, and immobilization processes within the soil; the risk of N losses due to these transformations increases as the time between N application and crop uptake increases (Magdoff, 1991). Limiting the amount of inorganic N in the soil profile at the end of a growing season, and also before establishing an extensive root system for the next crop, is a crucial factor for reducing N losses (Power and Schepers, 1989).

Although the method of N application, timing, and the accounting for mineralizable soil N are essential for reducing potential nitrate leaching, scientists have concluded that the most critical factor is the addition of the correct amount of N fertilizer (Power and Schepers, 1989). With soybean (*Glycine max* L.) crops, the N leaching potential is minimized, especially when it is between growth stages V4 and R5, however, N leaching can be quite high in the early spring if a large amount of N remains following the corn crop.

Zebarth et al., (2004) explained that a combination of moderate residual soil NO_3, plus the N made available through the growing season by mineralization of soil OM, could afford adequate N fertility to produce potato yields (Russet Burbank) within 15% of the maximum obtained by applying 196 kg ha^{-1} of used N. Kelling and Wolkowski (1991) found the N requirements of early-maturing determinant cultivars such as Russet Norkotah were considerably higher than slower-growing indeterminant cultivars such as Alpha and Russet Burbank. The study results implied that in early-maturing cultivars, tuber growth and development occur at the expense of root growth, producing a weak root system with low nutrient recovery capability and correspondingly high N fertilizer demands. In many circumstances, the yields achieved soslely with residual soil N (50–75 kg ha^{-1}) were approximately 15% of the maximum achieved with supplemental N. Fertilizer use efficiency of potatoes has been identified to be weak and limited yield responses to N fertilizer are common in both research experiments and commercial fields (Johnson et al., 1995).

Crop rotation may influence crop yield and improve soil properties, including soil nutrient availability and OM (Guertal et al., 1997). Crop rotation may focus on a primary crop such as the potato crop, while the other crops of the rotation may be selected for fertilizer, and diversity and nutrient management. Potato cultivation systems generally involve excessive tillage and the production of low levels of crop residue, which is the essential factor in soil quality (Carter and Sanderson, 2001). A key concern in potato farming is the sustainability of the production system. Therefore, it is essential to maintain soil quality to achieve a higher income for the invested capital. Schulte et al. (2005) reported that growing corn after corn produced 9.5 Mg ha^{-1} when 224 kg of N ha^{-1} was applied. In contrast, growing corn after alfalfa produced 10.56 Mg ha^{-1} with no added N.

Cover crops could minimize both the mass of N leached and the nitrate concentration of the leached amount from 20 to 80% in comparison with no cover crop (Meisinger et al., 1991). Grasses and brassicas were found to be two to three times more efficient than legumes in reducing N leaching (Meisinger et al., 1991). Cover crops have been used to enhance soil quality and reduce nonpoint sources of nutrient pollution, e.g., nitrate (Daliparthy et al., 1994). Thus, it is essential from both an economic and environmental standpoint to determine how cover crop systems influence soil OM characteristics and also the biogeochemical cycling of carbon (C) . The content and characteristics of soil OM are a function of agricultural practices and the quantities and species of plant residues returned to the soil (Campbell et al., 1998; Ding et al., 2002).

Soil OM content is very reactive, a ubiquitous component in soils. It is an essential soil quality characteristic, which impacts the physical well-being of soils and productivity. Soil OM content has been shown to improve soil bulk density, the proportion of soil occupied by air and water, porosity, root penetration, water and nutrient use, and microbial activities in the soil (Khaleel et al., 1981; Lampurlanés and Cantero-Martinez, 2003). Barmaki et al. (2008) highlighted that the total yield of plots in which manure was applied increased by about 15.6% compared to plots that received only chemical fertilizers, where OM content was 9.0 g kg^{-1}.

McCauley et al. (2009) stated that soil OM decomposition decreased soil pH significantly. The micronutrients (e.g., zinc (Zn), copper (Cu), iron (Fe), manganese (Mn)) bind firmly to the surface of soil particles, where, at high pH (base, low H-concentration), these metal ions precipitate with calcium (Ca) compounds. The metals are not readly available in the soil solution and, thus, are inadequately available for plant uptake. In contrast, at low pH (acidic, high H-concentration), fewer metal ions stick to the soil surface or precipitate with Ca compounds, making them more accessible for plant uptake.

Mousavi et al. (2007) reported that zinc sulfate improved the total number of tubers, size per plant, and weight of tubers per plant. Puzina (2004) mentioned that Zn is essential to improve the indole-3-acetic acid (IAA)/abscisic acid (ABA) and cytokinin/ABA ratio, which induces the formation and growth of stolons primarily due to reducing ABA content with an increase in the gibberellin content of the plant. However, root development decreased with the decline in alcohol dehydrogenase enzyme under a low level of zinc because the molecule of the enzyme consists of two atoms of Zn (Sati et al., 2017).

Murthy et al. (1979) reported that the photosynthetic rate was increased by 72% and 80% in the presence of 10 mg kg^{-1} of Zn and Mn, respectively, and suggested that this occurred to increase the amount of chlorophyll and carotenoids in the leaves. Roques et al. (2013) showed that Cu is involved in processes related to the reduction of nitrate-N to ammonium in plants; therefore, plants that suffer from Cu deficiency can have a significant accumulation of nitrate, carbohydrate, and polyphenols in vegetative tissue. Copper is an essential component of many proteins that are required for a reduction and oxidation processes within metabolic pathways such as respiration, photosynthesis, and the regulation of plant hormones (MAFF, 1976). Trehan (1999) reported that the application of Fe increased the yield of the fourth size class of tubers but decreased the yield of the first size class, where Fe is a component of hemoglobin structure and cytochrome (Tisdale et al., 1985; Mousavi et al., 2007).

Given the significance of supplying an optimum rate of N to potato crop, this study was conducted to determine whether the sites were N-responsive study the response and qualtitative properties of different potato cultivars under different rates of N fertilization, and evaluate the impact of soil properties (OM) on potential yield.

2.3 METHODS

2.3.1 Description of The Study Area

The experiment was conducted at Aroostook County, Maine, during 2018 and 2019. A total of 11 research sites were chosen. In 2018, six sites were established: Presque Isle, Aroostook Farm (AF1) (Lat.46.66134° and Long.-68.01808°), Frenchville (FV) (Lat.47.21676° and Long.-

68.41153°), New Sweden-1 (NS-1) (Lat.46.95156° and Long.-68.14779°), New Sweden-2 (NS-2) (Lat.46.95271° and Long. -68.14572°), Caribou (CA1) (Lat. 46.88227° and Long. -68.02895°), and Wood Land (WL) (Lat.46.88520° and Long.-68.12577°). In 2019, five additional research sites were selected: Presque Isle, Aroostook Farm (AF 2 and 3) (Lat.46.66134° and Long.-68.01808°), Limestone (LM) (Lat: 46.96186° and Long.-67.83333°), two in Caribou (CA2) (Lat: 46.89628° and Long.-68.07750°), and (CA3) (Lat: 46.89180° and Long.-68.04055°).

All sites had different average annual rainfall and temperature. Sites AF1, AF2, and AF3 had an average annual rainfall of 91.0 cm and an annual mean temperature of 5.15℃. Sites WD, NS-aand NS-2, and CA1,CA2, and CA3 had an average annual rainfall of 97.9 cm and an annual mean temperature of 4.3ºC, while FV had an average annual rainfall of 85.5 cm and an annual mean temperature of 3.6ºC (United States Climate Data, 2018).

2.3.2 Experimental Materials

The experiment included three potato cultivars: Shepody, Russet Burbank, and Superior. Shepody and Superior were selected depending on the availability of seeds at Aroostook farm, while Russet Burbank was planted depending on farmers' choice. The Shepody and Superior cultivars were planted at AF1 in (2018) and AF2 in (2019), respectively, while the Russet Burbank cultivars were planted at the rest of the sites during 2018 and 2019. Planting space between seeds (tubers) was 30 cm within the rows, and the width of each row was 90 cm.

2.3.3 Experimental Treatments and Design

Six rates of N, 0, 56, 112, 168, 224, and 280 kg ha^{-1} of ammonium sulfate were applied at all the sites in the first year, in a randomized complete block desgin (RCBD) with four replications, and ammonium nitrate was applied in the second year (because ammonium sulfate can increase soil acidity, where most of the sites already have a low pH). Phosphorus (P), potassium (K), and sulfur (S) were applied as recommended by the University of Maine Soil Laboratory. In the experimental design at each site, each subplot measured 9.14 m in length × 3.65 m in width and had four rows. A distance of 1.50 m was maintained between replicates as a buffer zone. All management practices, such as weeding, insect, pest, and disease control, were applied for all sites. Planting was completed between the middle and end of May, and harvesting was conducted between the end of September and the beginning of October.

2.3.4 Soil Properties

Prior to the fieldwork, soil samples were collected from each site for soil chemical analysis using a hand probe (2.5 cm diameter) to a depth of 20 cm. Soil samples were sent to the University of Maine Soil Laboratory for chemical testing, and the USDA-Natural Resources Conservation Service was used to obtain soil taxonomy data (Table 2.1). The sites NS-1, NS-2, and WL had three years of crop rotation (potato-grain-cover crop), whereas the sites CA1 and FV had two years of crop rotation (potato-grain). A crop rotation system was not applied to the AF1, AF2, and AF3 sites , and the grass was planted continuously over seven years. The sites CA2, CA3, and LM had two years of crop rotation (potato-mustard (*Brassica nigra* L)-radish (*Raphanus sativus* L)), (potato-red clover (*Trifolium pratense* L) and white clover (*Trifolium repens* L))-rye (*Secale cereale* L)), and (potato-clover-oat (*Avena sativa* L)-grains), respectively, (Table 2.1).

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Table 2.1. Soil chemical properties, soil series, and crop rotation duration. Data adopted from (Ahmed et al., 2020).

Site	pH^2	OM	NO3	NH4	P	K	Ca	Mg	S	Bo	Cu	Fe	Mn	Zn	CEC	Crop Rotation	Soil Series
		$g\ kg^{-1}$	$mg\ kg^{-1}$												me/100g		
AF1	6.5	27	7.0	4.0	21.5	271	1258	250	4.0	0.2	0.42	2.0	2.9	0.3	7.0	>3 yrs	Fine-Loamy, mixed, Frigid Typic Haplorthods
AF2	6.5	18	6.0	9.0	17.0	201	1122	259	4.0	0.1	0.38	3.3	2.7	0.7	6.2	>3 yrs	Fine-Loamy, mixed, Frigid Typic Haplorthods
AF3	6.0	18	12.0	8.0	15.0	167	721	167	5.0	0.2	0.57	8.9	4.9	0.5	6.3	>3 yrs	Fine-Loamy, mixed, Frigid Typic Haplorthods
CA1	6.5	37	6.0	1.0	23.6	395	1376	172	8.0	0.3	0.67	5.0	3.2	1.3	7.9	2 yrs	Fine-Loamy, mixed, Frigid Aquic Haplorthods
CA2	5.0	41	8.0	3.0	19.4	271	431	92	19.0	0.4	1.69	23	8.1	2.6	7.8	2 yrs	Gravelly loam, Isotic, Frigid, Typic Haplorthods
CA3	6.0	30	7.0	2.0	19.5	195	1205	95	9.0	0.3	0.95	6.2	1.3	1.4	6.2	2 yrs	Gravelly loam, Isotic, Frigid, Typic Haplorthods
FV	5.9	49	5.0	1.0	19.8	266	1184	121	15.0	0.3	0.85	10.0	4.2	1.3	7.3	3 yrs	Fine-Loamy, mixed, Frigid Aquic Haplorthods,
LM	6.0	33	3.0	2.0	19.0	240	1089	108	7.0	0.2	2.96	8.7	3.4	0.8	6.5	2 yrs	Gravelly loam, Isotic, Frigid, Typic Haplorthods
NS-1	5.4	45	21.0	6.0	18.2	157	893	135	10.0	0.3	1.12	8.4	7.3	1.9	8.7	3 yrs	Fine-Loamy, mixed, Frigid Typic Haplorthods
NS-2	5.6	41	16.0	6.0	19.3	204	1038	132	6.0	0.3	1.33	11.0	8.8	1.7	7.9	3 yrs	Coarse-Loamy, Isotic, Frigid Oxyaquic Haplorthods
WL	5.8	41	15.0	5.0	16.5	283	1319	131	9.0	0.3	0.71	6.0	8.4	1.6	7.3	3 yrs	Fine-Loamy, mixed, Frigid Aquic Haplorthods

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[2] [2] Soil pH was measured in a 1:1 ratio of soil to deionized water (Watson and Brown, 1998), organic matter was measured using loss on ignition (LOI) method (Ball, 1964), micro and macronutrients and were extracted using modified Morgan extraction method (McIntosh, 1969), and measured by ICP-OES (Inductively coupled plasma optical emission spectroscopy)(Hendershot and Duquette, 1986), but phosphorus was measured using colorimetric (Knudsen and Beegle, 1988), NO_3 was extracted using KCL (Keeney and Nelson, 1982), cation exchange capacity (CES) was measured using ammonium acetate method (Hendershot and Duquette, 1986).

2.3.5 Measurements

2.3.5.1 Yield Data Collection

2.3.5.1.1 Yield Harvesting and Calculation

A random selection of 3.0 m length from the two middle rows (6.0 m in total) of each subplot was harvested mechanically using a potato digger machine; potato tubers were collected into special paper bags of 23.0 kg capacity. Potato tubers were cleaned of soil and plant residues and then graded to four different sizes using a potato grading machine (HAINES), which was manufactured by Potato Handling Equipment, Presque Isle, Maine. The two middle rows (total of 6.0 m length) of each subplot were converted to 3.0 m length by dividing them on two and those were then used to calculate total yield production using the equation provided by North Dakota and Minnesota, (Equation 2.1) (Donavon et al., 1946).

$$\text{The certain weight/acre (cwt/acre)} = \left[\frac{lb}{10\ ft}. \times \text{Multiplication Factor}\right] \qquad \text{(Eq. 2.1)}$$

The multiplication factor depends on the row width, which is equal to 14.5 when planting a row with a width of 36 inches (90 cm). Equation 2.1 was used to calculate the total yield per area which was then converted to the standard unit, which is Mg ha^{-1}. The total weight per plant was calculated by dividing the total weight of tubers from each subplot by the number of plants in the row.

2.3.5.1.2 Marketable Tuber Yield

Potato tubers were classified according to their diameters into <45 mm, 46-65mm, 65-85 mm, and >85 mm by passing them through a grading machine. Potato tubers with a diameter of <45 mm were considered as unmarketable tubers, while marketable tubers had a diameter greater than 45 mm.

2.3.5.1.3 Specific Gravity, Starch And Dry Matter Content

The specific gravity of tubers was calculated using the weight in air and weight in water procedure (Eq. 2.2). Ten tubers of all sizes and shapes were randomly selected from each treatment and were weighed first in the air and then in water. The specific gravity of tubers was measured using the following equation (Kladivko et al., 1986).

Specific gravity (g cm^{-3}) $=[(\text{weight in air} / (\text{weight in air} - \text{weight in water})]$ (Eq. 2.2)

Several studies proved that there is a robust correlation between the specific gravity of tuber with starch and dry matter content. This correlation was used to calculate the total starch and dry matter content, where three references (Equations 2.3-2.6) were statistically evaluated to determine which one was a more precise calculation. In addition, dry matter and starch content were estimated from the calculated specific gravity of tubers using established procedures (USDA, 1997) (DEPI, 1995).

Starch (%) = 17.546 + 199.07 × (X – 1.0988) (Yildrim and Tokuşoğlu, 2005) (Eq. 2.3)

Dry matter (%) = -214.9206 + [218.1852 × (X)] (McDole et al., 1987) (Eq. 2.4)

Starch (%) = [112.1 × (X)] - 106.4 (Kawano et al., 1987) (Eq. 2.5)

Dry matter (%) = [158.3 × (X)] -142 (Kawano et al., 1987) (Eq. 2.6)

Where X is the measured specific gravity of potato tuber.

The standard deviation used to evaluate the accuracy of equations. It was high (1.3 and 1.5) when using equations 2.3 and 2.4, respectively. However, equations 2.5 and 2.6 revealed the lowest standard deviation, 0.7 and 1.1, respectively, which have been adopted in the calculations.

2.3.5.2 Vegetative Growth Characteristic

2.3.5.2.1 Chlorophyll index

Chlorophyll content of leaves, as an index, was measured using the Crop Circle^{TM} (Holland Scientific, Lincoln, NE) active optical sensor. The sebsor depends on red-edge and near-infrared (NIR) wavelength bands to calculate the index, which are sensitive to a wide range of chlorophyll, (Equation 2.7) (Gitelson et al., 2005).

$$Cl_{RE} = (NIR/RE) - 1 \qquad \text{(Eq. 2.7)}$$

Where,

NIR: near-infrared wavelength band 850 nm

RE: Rededge wavelength band 730 nm

2.3.6 Data Analysis

Yield, specific gravity, starch content, and dry matter were analyzed using analysis variance (ANOVA) to test the variance among means values in each site using IBM-SPSS V-25 (SPSS-IBM-Corp., 2017). Mean separation was employed following the significance of mean squares using least significant difference (LSD) at 5% probability. Linear regression analysis was used to determine the relationship between specific gravity, dry matter, and starch content of which specific gravity was considered as the independent variable and dry matter and starch as the dependent variables (response). Linear regression was conducted between the highest yield production from each site and soil chemical properties to understand the impact of soil properties on the potato yield data. Linear regression was also conducted to investigate the response and availability of soil micronutrients under different degrees of soil reactions. A correlation analysis was conducted between total tuber yield and leaf chlorophyll index to understand how chlorophyll content associated with the yield variation within different potato cultivars.

2.4 RESULTS

2.4.1 Analysis of Variance and Mean Performance of Varieties

To better understand the response of potatoes to N, a multiple regression analysis was conducted (data not shown) between soil properties and potato yield, where OM was found to be the predominant factor that had a high correlation (P<0.01) and impact on crop yield (r^2=0.77**), (Figure 2.1). There was an apparent effect of OM content on tuber yield production, where the sites with more than 30 g kg^{-1} of OM showed a significant disparity compared to sites that had less than 30 g kg^{-1} of OM (Figure 2.2). As a result,, all the sites were categorized into two groups ≤ 30 and ≥ 30 g kg^{-1} of soil OM content. The sites NS-1, NS-2, FV, CA1, CA2, CA3, LM, and WD, were classified as having ≥ 30 g kg^{-1} OM, while AF1, AF2, and AF3 were classified as having ≤ 30 g kg^{-1} OM. It is important to mention that Shepody and Superior potato cultivars hade only one site each that was classified as ≤ 30 g kg^{-1} OM.

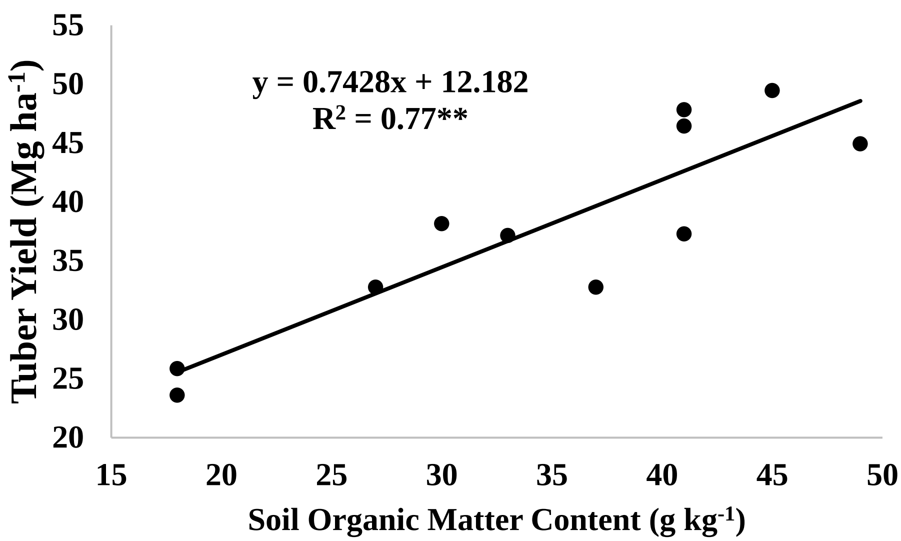


Figure 2.1. The effect of soil OM content on total tuber s yield produced from all sites during the two growing seasons 2018-2019, P< 0.01.

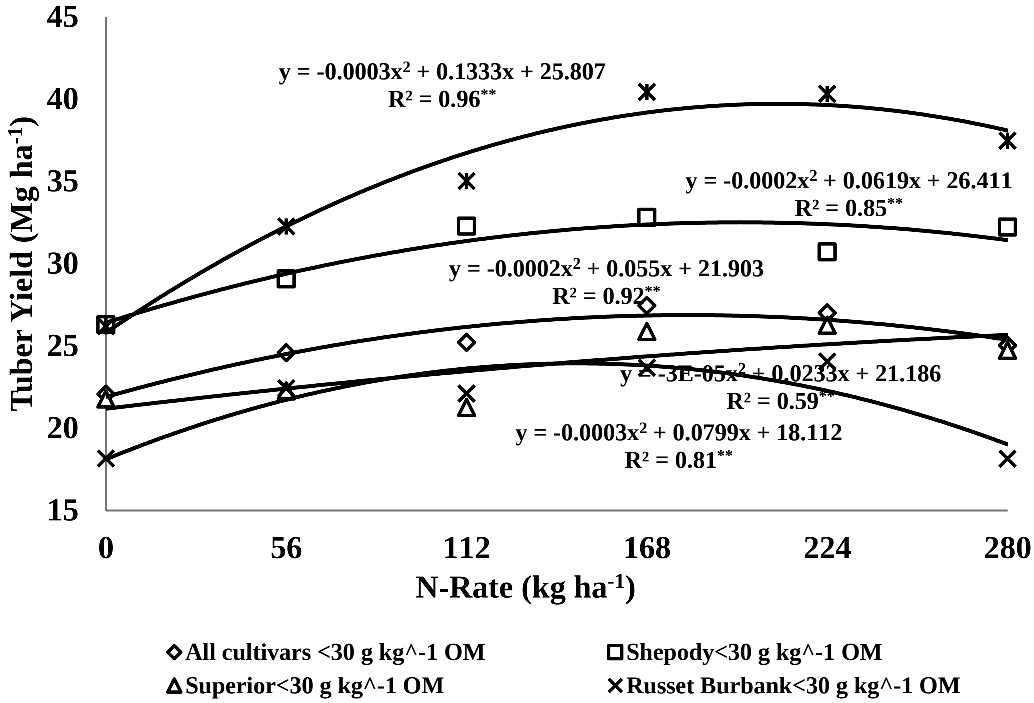


Figure 2.2. Potato yields from all cultivars and how they have been affected by N rates and soil OM content, P< 0.01.

2.4.2 Vegetative Growth Characteristic (Chlorophyll Content)

2.4.2.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

The chlorophyll content index of the plant leaves significantly interacted with N fertilizer rates in most of the sites, where chlorophyll content increased with increased N rates. Significant regression relationships between N rates and leaf chlorophyll index were found with all sites combined, Shepody, Superior, and Russet Burbank cultivars, where R^2= (0.39**, 0.25*, 0.75**, and 0.66**), respectively (Figure 2.3 a, b, c, and d), respectively.

The analysis of variance showed that chlorophyll index means for all cultivars combined ranged between 1.0 to 1.45. N rate of 280 kg ha^{-1} resulted in the highest chlorophyll index mean of 1.45, while 0 kg ha^{-1} of N resulted in the lowest chlorophyll index mean of 1.0. Statistically, Post Hoc-LSD (P ≤0.05) showed that 0 kg ha^{-1} of N differed significantly compared to other N rates, while 112 kg N ha^{-1} did not differ significantly from N rates of 56, 168, 224, and 280 kg ha^{-1} (Figure 2.4 a).

The chlorophyll index means for Shepody cultivar ranged from 1.36 to 1.60. The N rate of 112 kg ha^{-1} resulted in the highest chlorophyll index mean of 1.60, while 280 kg ha^{-1} of N resulted in the lowest mean of 1.36. Statistically, Post Hoc-LSD ($P > 0.05$) showed that 0 kg ha^{-1} of N did not differ significantly from other N rates (Figure 2.4 b).

For Superior cultivar, the means ranged from 0.25 to 0.77. The N rate of 224 kg ha^{-1} resulted in the highest chlorophyll index mean of 0.77, while 0 kg ha^{-1} of N resulted in the lowest mean of 0.25. Statistically, Post Hoc-LSD ($P \leq 0.05$) showed that 0 kg ha^{-1} of N differed significantly with other N rates, while 168 kg N ha^{-1} did not differ significantly from 224, and 280 kg ha^{-1} (Figure 2.4 c). For Russet Burbank cultivars, the mean ranged from 0.99 to 1.51. A N rate of 224 kg ha^{-1} resulted in the highest chlorophyll index mean of 1.51, while 0 kg ha^{-1} of N resulted in the lowest mean of 0.99. Statistically, Post Hoc-LSD ($P \leq 0.05$) showed that 0 kg $ha^{-1}$of N differed significantly compared to other N rates, while 168 kg ha^{-1} of N did not differ significantly compared to 112, 224, and 280 kg N ha^{-1} (Figure 2.4 d).

2.4.2.2 Sites with ≥ 30 g kg^{-1} of Organic Matter (Only Russet Burbank cultivar)

A significant statistical relationship, ($P < 0.01$) ($R^2 = 0.41^{**}$) was recorded between N rates and leaf chlorophyll index for Russet Burbank cultivars (Figure 2.3 e). The analysis of variance showed that the chlorophyll index mean for Russet Burbank cultivars ranged from 0.99 to 1.55. A N rate of 250 kg ha^{-1} resulted in the highest mean of 1.55, while 0 kg ha^{-1} of N resulted in the lowest mean of 0.99. Statistically, Post Hoc-LSD ($P \leq 0.05$) showed that 0 kg ha^{-1} of N differed significantly compared to other N rates. 224 kg ha^{-1} of N did not vary significantly with 280 kg N ha^{-1} but did differ with 0, 56, 112, and 224 kg N ha^{-1} (Figure 2.4 e).

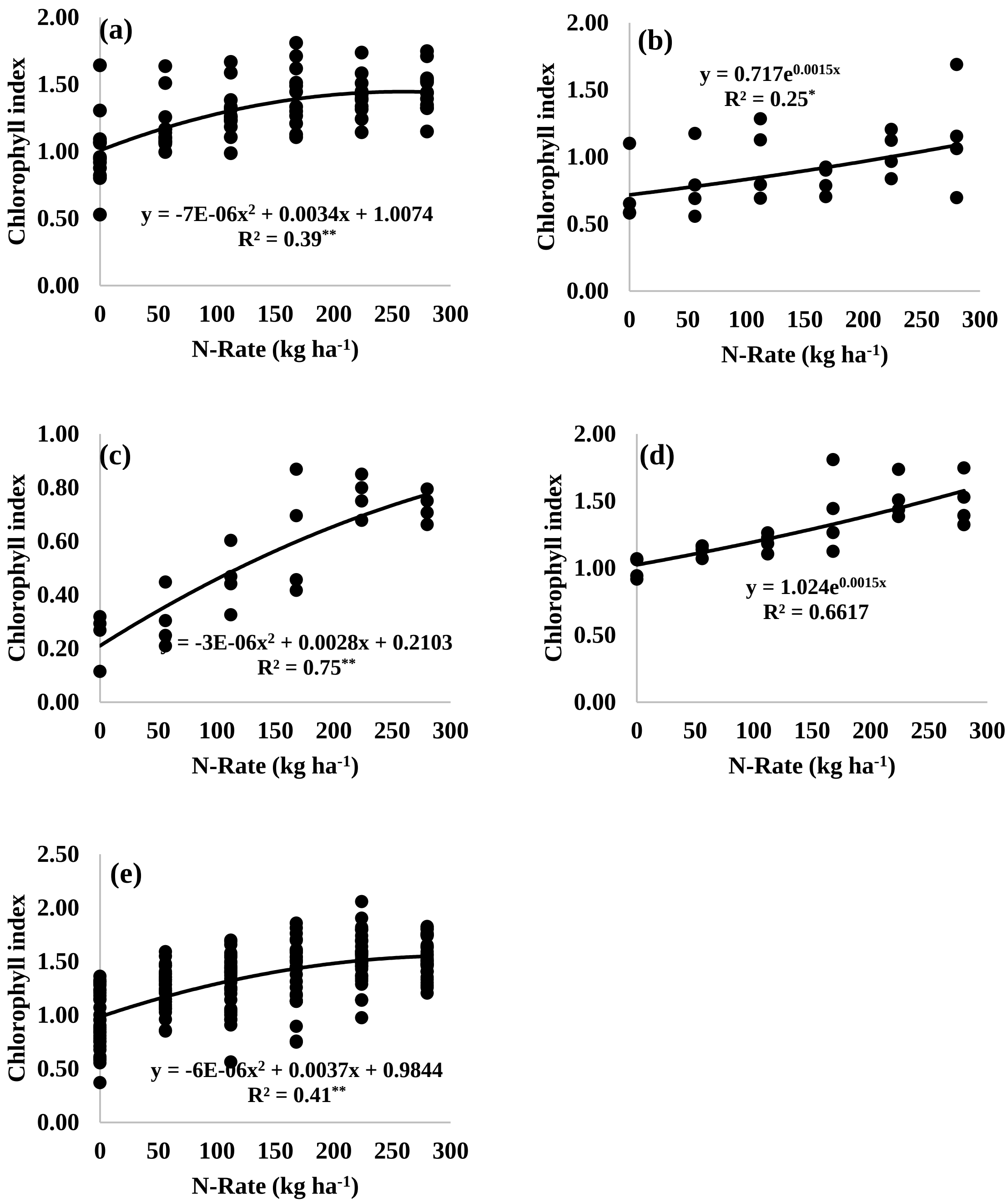


Figure 2.3 The relationship between N rates and chlorophyll Index, where (a) All sites combined with ≤30 g kg^{-1} OM. (b) Shepody cultivar in the sites with ≤ 30 g kg^{-1} OM, (c) Superior cultivar in the site with ≤ 30 g kg^{-1} OM, (d) Russet Burbank cultivar at the sites with ≤ 30 g kg^{-1} OM, and (e) All sites (Russet Burbank cultivar) combined with ≥ 30 g kg^{-1} OM, P< 0.01.

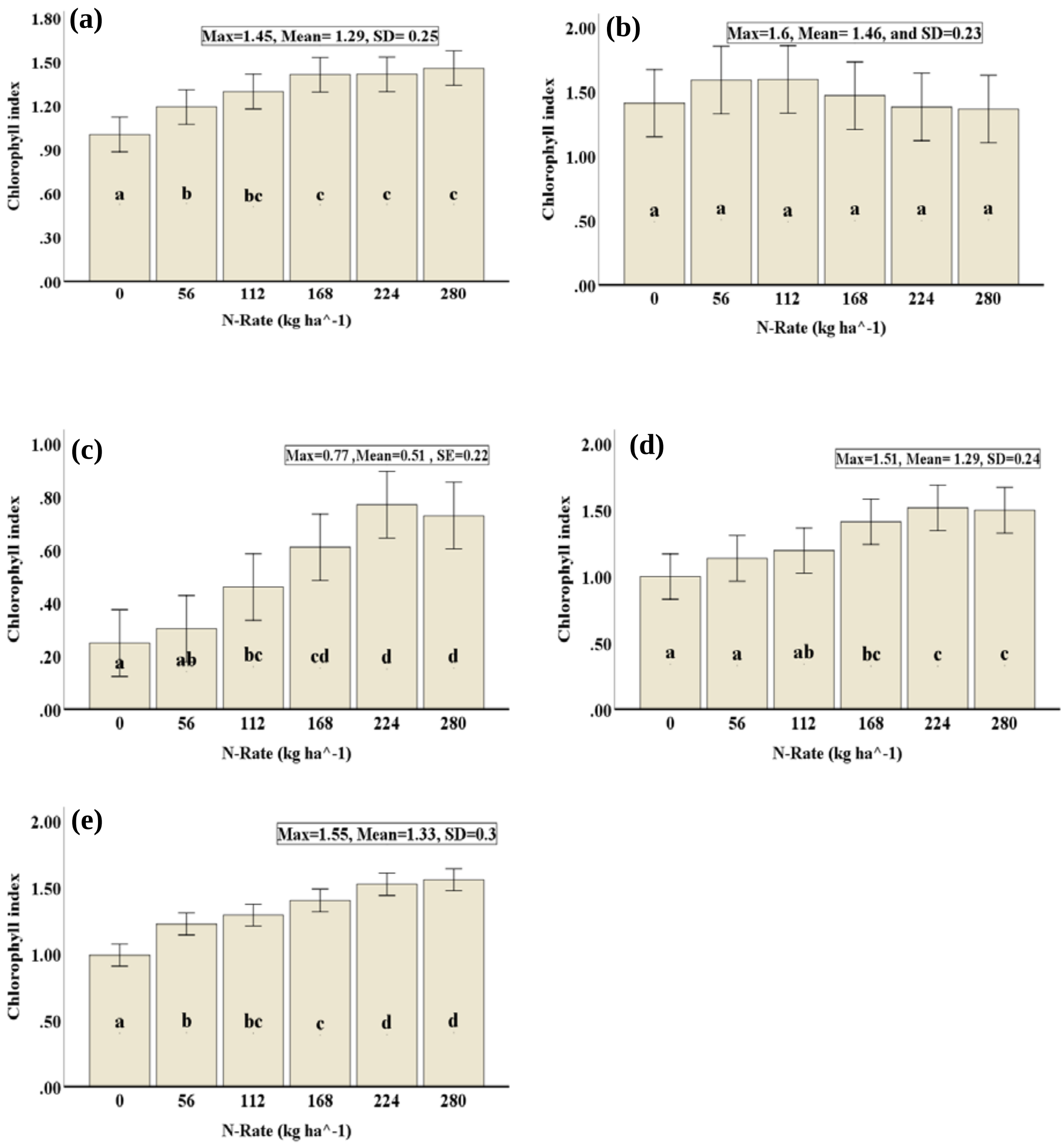


Figure 2.4. Chlorophyll response to N rates at the sites (a) all sites combined of ≤ 30 g kg^{-1} OM, (b) ≤ 30 g kg^{-1} OM-Shepody cultivar, (c) ≤ 30 g kg^{-1} OM-Superior cultivar, (d) ≤ 30 g kg^{-1} OM-Russet cultivar, (e) all sites (Russet Burbank cultivar) combined with ≥ 30 g kg^{-1} OM, ANOVA at $P< 0.05$.

2.4.3 Correlations Between Leaf Chlorophyll Content and Yield Data

A significant correlation was discovered between total tuber yield and leaf chlorophyll index for both potato cultivars and at all sites. The period between the end of July and the beginning of August showed the most significant correlation coefficient for the sites of ≤ 30 g kg-1 OM, the sites of ≥ 30 g kg-1 OM, and all sites combined of ≤ and ≥ 30 g kg-1 OM (R2= 0.69**, 0.61**, and 0.66**), respectively (Figure 2.5 a, b, and c).

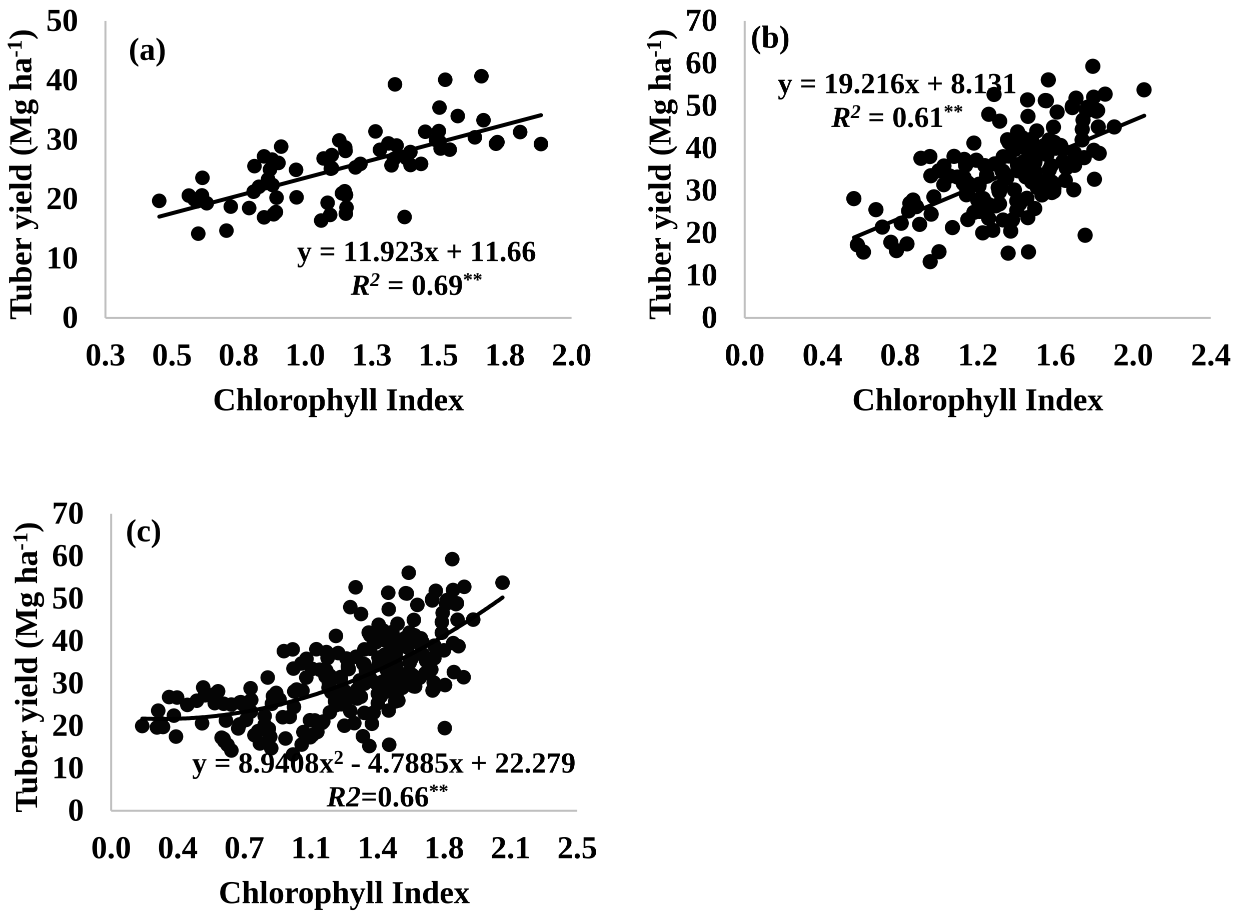


Figure 2.5. The correlation relationship between leaf chlorophyll index and tuber yield at the sites with, (a) ≤ 30 g kg^{-1} OM, (b) ≥ 30 g kg^{-1} OM, (c) all sites combined, P< 0.01.

2.4.4 Yield Data

2.4.4.1 Total Weight of Tubers Per Plant

2.4.4.1.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

Different rates of N significantly affected potato yield measurements. Tuber weight per plant for all cultivars combined ranged from 0.54 to 0.66 kg. The maximum tuber weight (0.66 kg plant^{-1}) was observed with 224 kg ha^{-1} of N, while the minimum tuber weights were observed with 0 kg ha^{-1} of N (0.54 kg plant^{-1}) and 56 kg ha^{-1} of N (0.60 kg plant^{-1}). There was no significant difference in maximum tuber weight with 224 kg ha^{-1} of N (Figure 2.6 a).

For Shepody cultivar, tuber weight per plant ranged from 0.65 to 0.81 kg. The maximum tuber weight (0.81 kg plant^{-1}) was observed with 168 kg ha^{-1}of N, while the minimum tuber weights were observed with 0 kg ha^{-1} of N (0.65 kg plant^{-1}) and 56 kg ha^{-1} of N (0.72 kg plant^{-1}). After the application of 168 kg ha^{-1}of N, the maximum tuber weight did not show any progress. However, there was no significant difference between all rates (Figure 2.6 b).

For Superior cultivar, tuber weight per plant ranged from 0.50 to 0.62 kg. The maximum tuber weight (0.62 kg plant^{-1}) was observed with 224 kg ha^{-1} of N, while the minimum tuber weights were observed with 0 kg ha^{-1} of N (0.50 kg plant^{-1}) and 56 kg ha^{-1} of N (0.53 kg plant^{-1}). After the application of 224 kha^{-1} of N, the maximum tuber weight did not show any progress. However, there was no significant difference between all rates (Figure 2.6 c). For Russet Burbank cultivars, tuber weights per plant ranged from 0.43 to 0.57 kg. The maximum tuber weight (0.57 kg plant^{-1}) was observed with 224 kg ha^{-1} of N, while the minimum tuber weights were observed with 280 kg ha^{-1} of N (0.43 kg plant^{-1}) and 0 kg ha^{-1} of N (0.431 kg plant^{-1}). After the application of 224 kg ha^{-1} of N, the maximum tuber weight did not show any progress. However, there was no significant difference between all rates (Figure 2.6 d).

2.4.4.1.2 Sites with ≥ 30 g kg^{-1} of Organic Matter

The tuber weight per plant of Russet Burbank cultivars for sites ≥ 30 g kg^{-1} OM was higher than the tuber weight per plant on the sites with ≤ 30 g kg^{-1} OM; the mean ranged from 0.99 to 1.55 kg. The maximum tuber weight (1.55 kg plant^{-1}) was observed with 168 kg ha^{-1} of N, while the minimum tuber weights were observed with 0 kg ha^{-1} of N (0.99 kg plant^{-1}) and 56 kg ha^{-1} (1.22 kg plant^{-1}). Although 168 kg ha^{-1} of N resulted in the highest yield per plant, it did not differ significantly from 224 and 280 kg ha^{-1} of N (Figure 2.6 e).

2.4.4.1.3 Different Potato Cultivars

The different potato cultivars (regardless of soil OM content) significantly affected potato yield. The maximum tuber weight (0.91 kg plant^{-1}) was found with Russet Burbank cultivars, while the minimum tuber weight was observed with Superior cultivars (0.55 kg plant^{-1}). Statistically there was a significant difference among the cultivars, Post Hoc-LSD ($p \leq 0.05$). Superior cultivar showed a considerable difference compared to each of the Russet Burbank and Shepody cultivars (Figure 2.7).

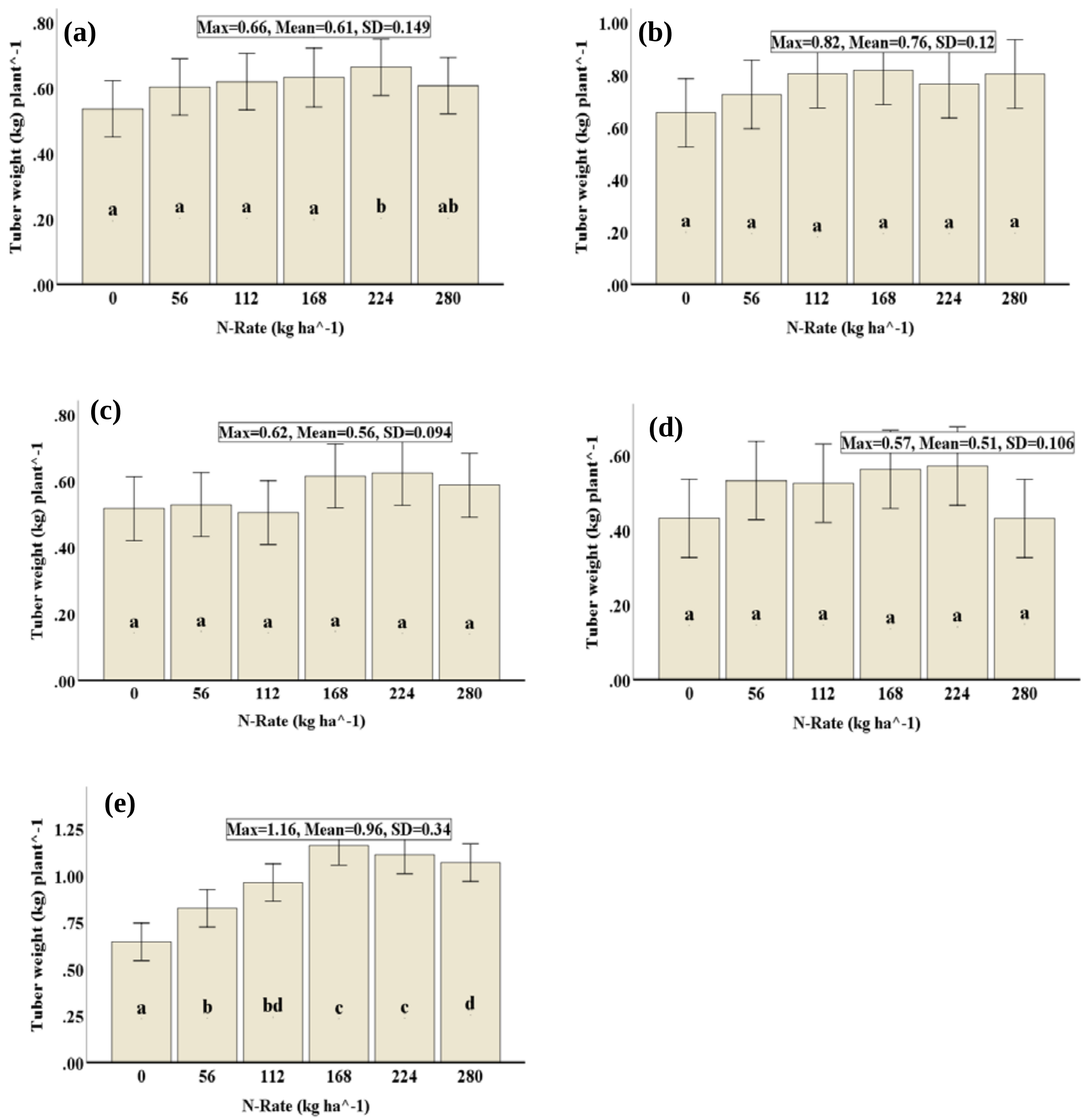


Figure 2.6. Effect of N fertilization rates on potato tuber's weight per plant at the sites with, (a) all combined cultivars of ≤ 30 g kg^{-1} OM, (b) Shepody cultivar with ≤ 30 g kg^{-1} OM, (c) Superior cultivar with ≤ 30 g kg^{-1} OM, (d) Russet Burbank cultivar with ≤ 30 g kg^{-1} OM, and (e) all combined Russet Burbank cultivar of ≥ 30 g kg^{-1} OM, ANOVA at P< 0.05.

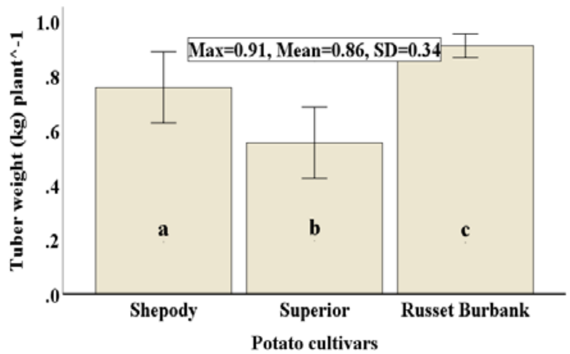


Figure 2.7. Effect of potato cultivars on potato tuber's weight per plant, ANOVA at P< 0.05.

2.4.4.2 Total Yield Per Area

Total yield increased significantly with N rate at all sites where a polynomial response function described the relationship between N rate and total tuber yield (R^2 = 0.85, 0.6, 0.85, and 0.98) for the sites with Shepody, Superior, and Russet Burbank cultivars that had OM ≤ 30 g kg^{-1}, and the sites with Russet Burbank cultivars that had OM ≥ 30 g kg^{-1} (Figure 2.2).

2.4.4.2.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

The total tuber yield from all cultivars combined ranged from 22.07 to 27.45 Mg ha^{-1}. Maximum total tuber yield (27.45 Mg ha^{-1}) was observed with 168 kg ha^{-1} of N, while the minimum total tuber yields were observed with 0 kg ha^{-1} of N (22.07 Mg ha^{-1}) and 56 kg ha^{-1} of N (24.59 Mg ha^{-1}). Statistically, Post Hoc-LSD (P≤ 0.05) showed that 0 kg ha^{-1} of N differed significantly from other N rates, while 168 kg ha^{-1} of N did not differ significantly from 224 and 280 kg ha^{-1} of N (Figure 2.8 a).

For Shepody cultivar, the total tuber yield ranged from 26.29 to 32.81Mg ha^{-1}. The maximum total tuber yield (32.81 Mg ha^{-1}) was observed with 168 kg ha^{-1} of N, while the minimum total tuber yields were observed with 0 kg ha^{-1} of N (26.29 Mg ha^{-1}) and 56 kg ha^{-1} of N (29.07 Mg ha^{-1}). After the appliation of 168 kg ha^{-1} of N, the maximum tuber yield did not show any progress. Statistically, Post Hoc-LSD ($P > 0.05$) showed that 0 kg ha^{-1} of N did not differ significantly from the other rates of N (Figure 2.8 b).

For Superior cultivar, the total tuber yield ranged from 21.78 to 26.26 Mg ha^{-1}. The maximum total tuber yield (26.26 Mg ha^{-1}) was observed with 224 kg ha^{-1} of N, while the minimum total tuber yields were observed with 0, 56, and 112 kg ha^{-1} of N (21.78, 22.26, and 21.26 Mg ha^{-1} respectively). After 224 kg ha^{-1} of N, the maximum tuber yield did not show any progress. Statistically, Post Hoc-LSD ($P > 0.05$) showed that 0 kg ha^{-1} of N did not differ significantly from the other rates of N (Figure 2.8 c). For Russet Burbank cultivar, the total tuber yield ranged from 18.14 to 24.0 Mg ha^{-1}. The maximum total tuber yield (24.0 Mg ha^{-1}) was observed with 224 kg ha^{-1} of N, while the minimum total tuber yield was observed with 280 kg ha^{-1} of N (18.14 Mg ha^{-1}). After the application of 224 kg ha^{-1} of N, the maximum tuber yield did not show any progress. Statistically, Post Hoc-LSD ($P > 0.05$) showed that 0 kg ha^{-1} of N did not differ significantly from other rates of N (Figure 2.8 d).

2.4.4.2.2 Sites with ≥ 30 g kg^{-1} of Organic Matter

For Russet Burbank cultivar, the total tuber yield ranged from 26.2 to 40.43 Mg ha^{-1}. The maximum total tuber yield (40.43 Mg ha^{-1}) was observed with 168 kg ha^{-1} of N, while the minimum total tuber yield was found with 0 kg ha^{-1} of N (26.2 Mg ha^{-1}). After the application of 168 kg ha^{-1} of N, the maximum tuber yield did not show any progress. Statistically, Post Hoc-LSD ($P \leq 0.05$) showed that 0 kg ha^{-1} of N differed significantly with other rates N, while 168 kg ha^{-1} of N did not vary significantly with 224 and 280 kg ha^{-1} of N, (Figure 2.8 e).

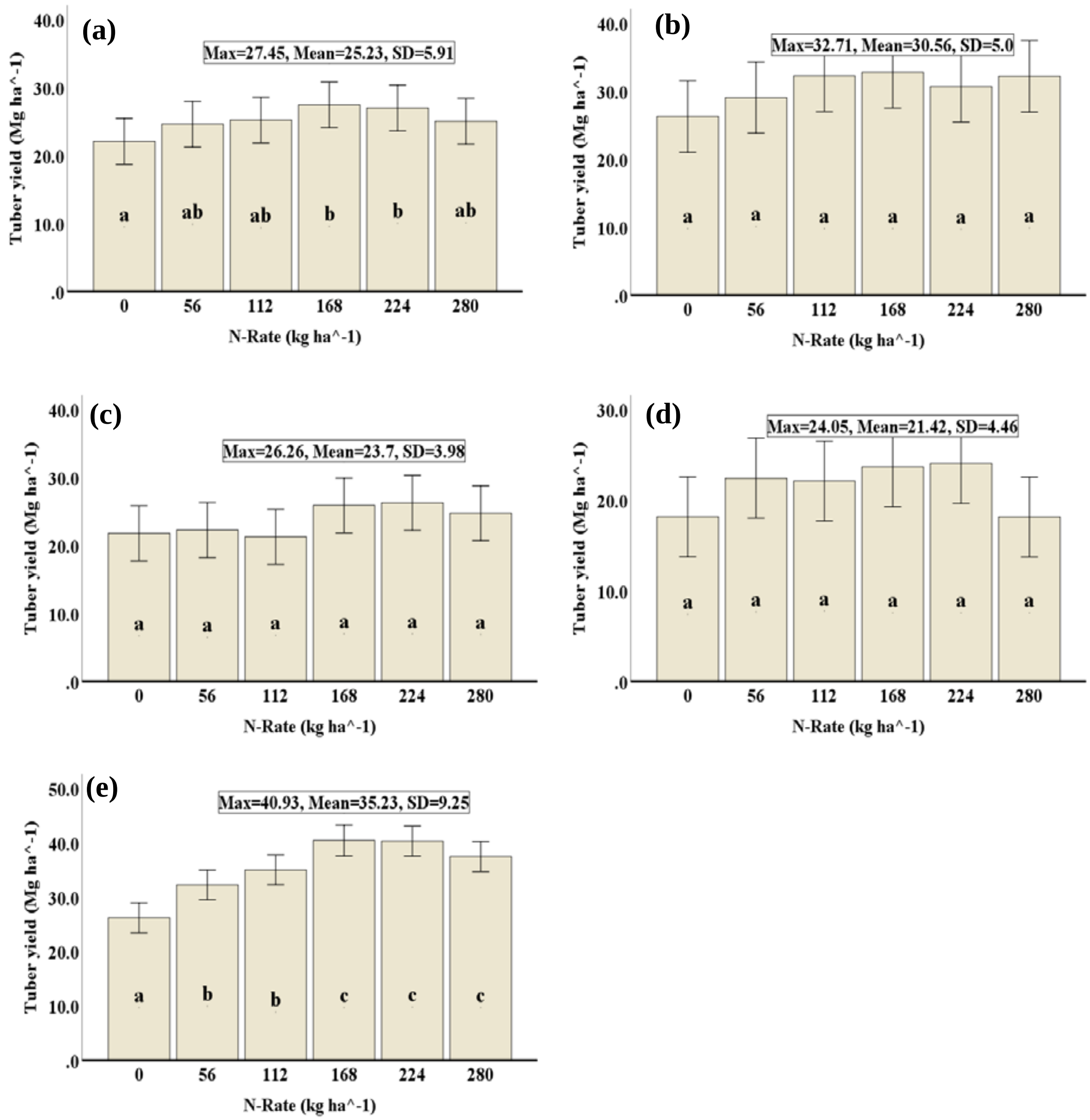


Figure 2.8. Effect of N fertilization rates on total tuber yield of potato at the sites with, (a) all combined cultivars of ≤ 30 g kg^{-1} OM, (b) Shepody cultivar ≤ 30 g kg^{-1} OM, (c) Superior cultivar ≤ 30 g kg^{-1} OM, (d) Russet Burbank cultivar ≤ 30 g kg^{-1} OM, and (e) all sites combined (Russet Burbank cultivar) ≥ 30 g kg^{-1} OM, ANOVA at P< 0.05.

2.4.4.2.3 Different Potato Cultivars

Regardless of soil OM content, the maximum total tuber yield (33.7 Mg ha^{-1}) was observed with Russet Burbank cultivar, while the minimum total tuber yield (23.3 Mg ha^{-1}) was found with Superior cultivars. Statistically, Post Hoc-LSD ($P \leq 0.05$) confirmed a significant difference among cultivars (Table 2.2 and Table 2.3). Shepody cultivar showed a significant difference compared to Superior cultivar but not compared to Russet Burbank cultivar. Superior cultivar showed a significant difference with each of the Russet Burbank and Shepody cultivars (Figure 2.9).

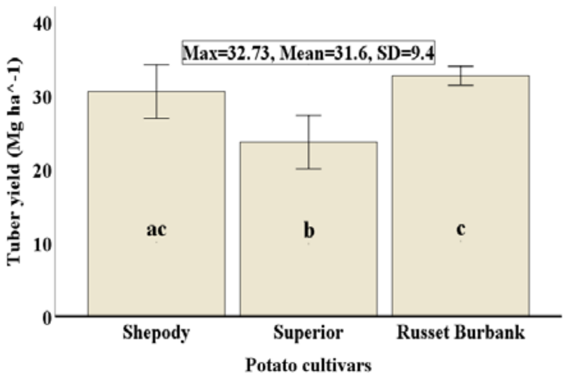


Figure 2.9. Effect of potato cultivars on total tuber yield of potato, ANOVA at P< 0.05.

Table 2.2. Analysis of variance (ANOVA) between yield data and potato cultivars, P< 0.05.

	Yield (Mg/ha)				
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2437.08	2	1218.54	14.72	.000
Within Groups	21440.75	259	82.78		
Total	23877.83	261			

Table 2.3. Multiple comparisons analysis between yield data and each potato cultivar, P< 0.05.

Dependent Variable: Yield (Mg/ha)				
LSD				
(I) Cultivar	(J) Cultivar	Mean Difference (I-J)	Std. Error	Sig.
Shepody	Superior	7.086*	2.627	.007
	Russet Burbank	-3.297	1.959	.093
Superior	Shepody	-7.086*	2.627	.007
	Russet Burbank	-10.384*	1.959	.000
Russet Burbank	Shepody	3.297	1.959	.093
	Superior	10.384*	1.959	.000
*. The mean difference is significant at the 0.05 level.				

2.4.4.3 Marketable Tuber Yield

2.4.4.3.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

The marketable tuber yield for all combined cultivars ranged from 18.57 to 22.18 Mg ha^{-1}, with a mean of 20.55 Mg ha^{-1}. The maximum value of marketable tuber yield (22.18 Mg ha^{-1}) was observed with 56 kg ha^{-1} of N, while the minimum value was observed with 0 kg ha^{-1} of N (18.57 Mg ha^{-1}). The maximum value did not show any increase with an increase N rate. Statistically, there was no significant difference between the means, where P > 0.05, (Figure 2.10 a).

The marketable tuber yield for Shepody cultivar ranged from 24.16 to 31.4 Mg ha^{-1}, with a mean of 28.50 Mg ha^{-1}. The maximum value of marketable tuber yield (31.4 Mg ha^{-1}) was observed with 168 kg ha^{-1} of N, while the minimum value was observed with 0 kg ha^{-1} of N. The maximum value did not show any increase with an increase in N rate. Statistically, there was no significant difference between means, where P> 0.05, (Figure 2.10 b).

The marketable tuber yield for Superior cultivar ranged from 17.58 to 22.68 Mg ha^{-1}, with a mean of 20.65 Mg ha^{-1}. The maximum value of marketable tuber yield (22.68 Mg ha^{-1}) was observed with 280 kg ha^{-1} of N, while the minimum value was observed with 0 kg ha^{-1} of N. The maximum value did not show any increase with an increase N rate. Statistically, there was no significant difference between means, where $P > 0.05$, (Figure 2.10 c). The marketable tuber yield for Russet Burbank cultivar ranged from 8.77 to 16.8 Mg ha^{-1}, with a mean of 12.47 Mg ha^{-1}. The maximum value of marketable tuber yield (16.8 Mg ha^{-1}) was observed with 56 kg $ha^{-1}$of N, while the minimum value was observed with 280 kg ha^{-1} of N. The maximum value did not show any increase with an increase N rate. Statistically, the only significant difference was noted between 0 and 56 kg ha^{-1} of N, (Figure 2.10 d).

2.4.4.3.2 Sites with ≥ 30 g kg^{-1} of Organic Matter

The marketable tuber yield for Russet Burbank cultivar ranged from 32.59 to 34.3 Mg ha^{-1}, with a mean of 29.35 Mg ha^{-1}. The maximum value of marketable tuber yield (34.3 Mg ha^{-1}) was observed with 168 kg $ha^{-1}$of N, while the lowest value was found with 0 kg ha^{-1} of N. The maximum value did not show any increase after the rate of 168 kg ha^{-1} of N. Statistically, there was a significant difference between 0 kg ha^{-1} of N and rates of 168, 224, and 280 kg ha^{-1} of N. However, the rate of 168 kg ha^{-1} of N did not differ significantly from 224 and 280 kg ha^{-1} of N, (Figure 2.10 e).

2.4.4.3.3 Different Potato Cultivars

Regardless of soil OM content, the maximum marketable tuber yield (28.4 Mg ha^{-1}) was found with Russet Burbank cultivar, while the minimum value was found with Superior cultivar (20.0 Mg ha^{-1}). Statistically, Post Hoc-LSD ($P \leq 0.05$) showed that Shepody cultivar exhibited a significant difference with compared to Superior cultivar but not compared to Russet Burbank cultivar. Superior cultivar showed a significant difference with each of the Russet Burbank and Shepody cultivars (Figure 2.11)

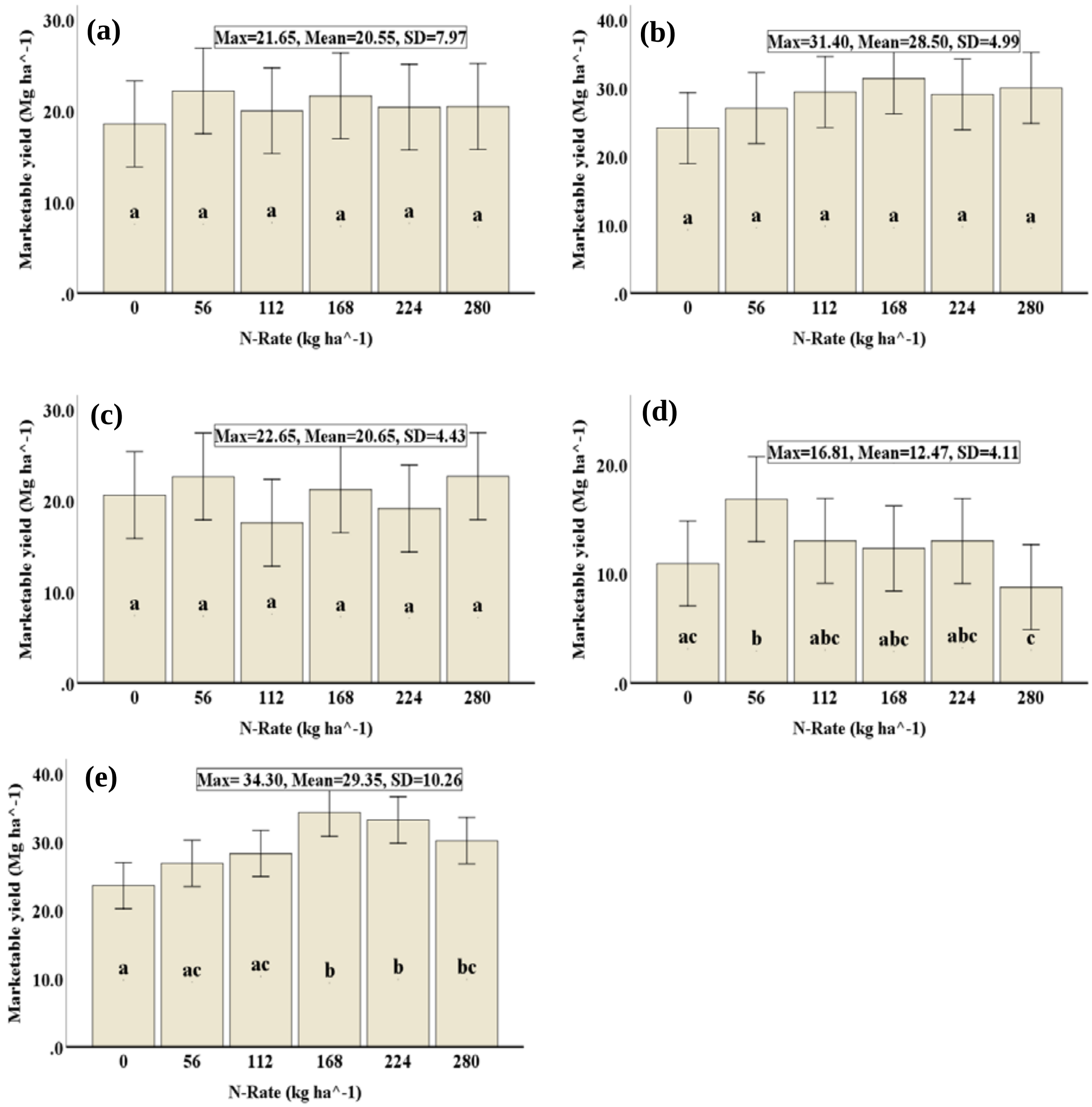


Figure 2.10. Effect of N fertilization rates on marketable tuber yield at the sites with, (a) all combined cultivars of ≤ 30 g kg^{-1} OM, (b) Shepody cultivar ≤ 30 g kg^{-1} OM, (c) Superior cultivar ≤ 30 g kg^{-1} OM, (d) Russet Burbank cultivar ≤ 30 g kg^{-1} OM, and (e) all sites combined (Russet Burbank cultivar) ≥ 30 g kg^{-1} OM, ANOVA at P< 0.05.

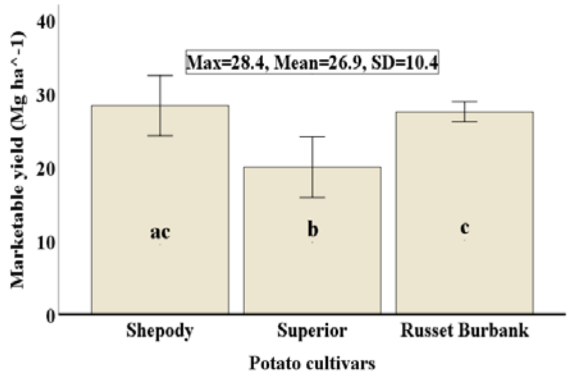


Figure 2.11. Effect of potato cultivars on marketable tuber yield of potato, ANOVA at P< 0.05.

2.4.4.4 Number of Tubers Per Plant

2.4.4.4.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

The number of tubers per plant for all cultivars combined ranged from 4.77 to 5.30, with a mean of 5.01 tubers per plant. The maximum number of tubers per plant (5.30) was observed with 112 kg ha^{-1} of N, while the lowest value was found with 280 kg ha^{-1} of N. The maximum value did not show any increase after the rate of 112 kg ha^{-1} of N. Statistically, there was no significant difference among all means (Figure 2.12 a).

For Shepody cultivar, the number of tubers per plant ranged from 3.5 to 4.8, with a mean of 4.05 tubers per plant. The maximum number of tubers per plant (4.8) was observed with 112 kg ha^{-1} of N, while the lowest value was found with 224 kg ha^{-1} of N. The maximum value did not show any increase after the rate of 112 kg ha^{-1} of N. Statistically, there was a significant difference among the means, where 112 kg ha^{-1} of N differed significantly from 168, 224, and 280 kg ha^{-1} of N, however, there was no significant difference observed with 0, or 56 kg ha^{-1} of N (Figure 2.12 b).

For Superior cultivar, the number of tubers per plant ranged from 4.62 to 5.31, with a mean of 4.84 tubers per plant. The maximum number of tubers per plant (5.31) was observed with 56 kg ha^{-1} of N, while the minimum value was observed with 280 kg ha^{-1} of N. The maximum value did not show any increase after the rate of 56 kg ha^{-1} of N. Statistically, there was no significant difference among all means (Figure 2.12 c). For Russet Burbank cultivar, the number of tubers per plant ranged from 5.41 to 6.71, with a mean of 6.18 tubers per plant. The maximum number of tubers per plant (6.71) was observed with 56 kg ha^{-1} of N, while the minimum value was observed with 280 kg ha^{-1} of N. The maximum value did not show any increase after the rate of 56 kg ha^{-1} of N. Statistically, there was no significant difference among all means (Figure 2.12 d).

2.4.4.4.2 Sites with ≥ 30 g kg^{-1} of Organic Matter

The number of tubers per plant for all sites combined (Russet Burbank cultivar) ranged from 6.35 to 6.85, with a mean of 6.63 tubers per plant. The maximum number of tubers per plant (6.85) was observed with 112 kg ha^{-1} of N, while the minimum value was observed with 0 kg ha^{-1} of N. The maximum value did not show any increase after the rate of 112 kg ha^{-1} of N. Statistically, there was no significant difference among all means (Figure 2.12 e).

2.4.4.4.3 Different Potato Cultivars

Regardless of soil OM content, the number of tubers per plant for all potato cultivars ranged from 4.1 to 6.6, with a mean of 6.2 tuber per plant. The maximum number of tubers per plant was observed with Russet Burbank cultivar, while the minimum value was observed with Shepody cultivar. Statistically, there was a significant difference among all of the cultivars, Post Hoc-LSD ($P \leq 0.05$), (Figure 2.13).

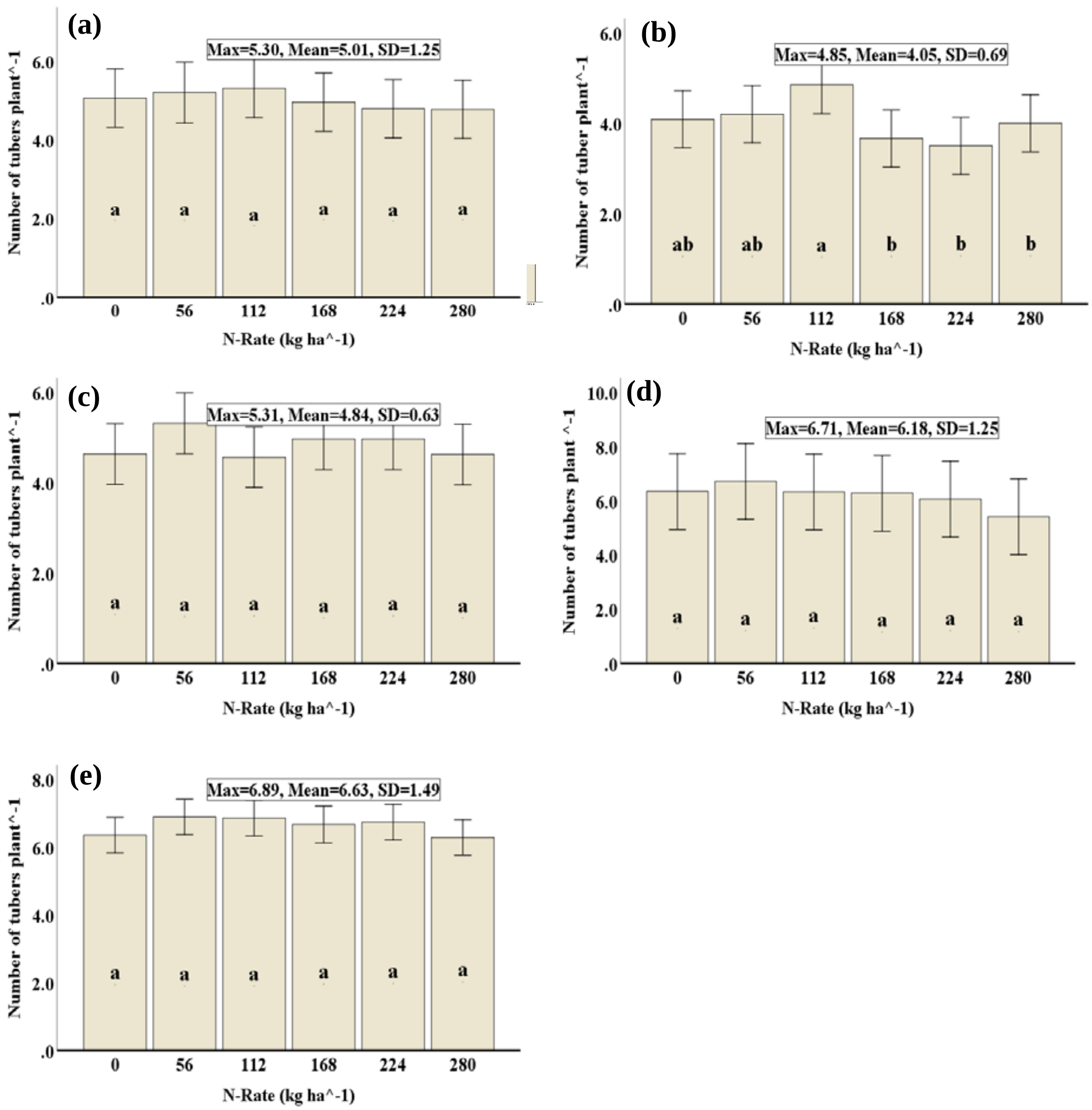


Figure 2.12. Effect of N fertilization rates on number of tubers per plant at the sites with, (a) all combined cultivars of ≤ 30 g kg^{-1} OM, (b) Shepody cultivar ≤ 30 g kg^{-1} OM, (c) Superior cultivar ≤ 30 g kg^{-1} OM, (d) Russet Burbank cultivar ≤ 30 g kg^{-1} OM, and (e) all sites combined (Russet Burbank cultivar) ≥ 30 g kg^{-1} OM, ANOVA at P< 0.05.

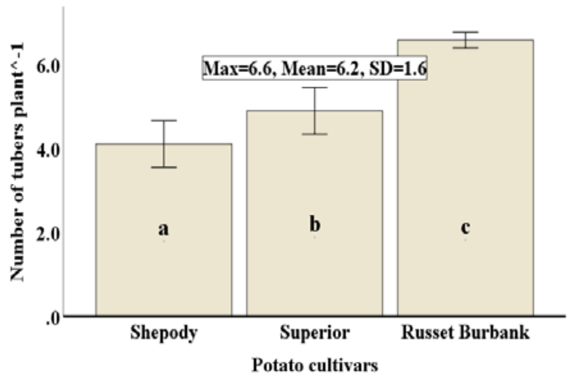


Figure 2.13. Effect of potato cultivars on the number of tubers per plant, ANOVA at P< 0.05.

2.4.4.5 Specific Gravity, Starch, and Dry Matter Content

2.4.4.5.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

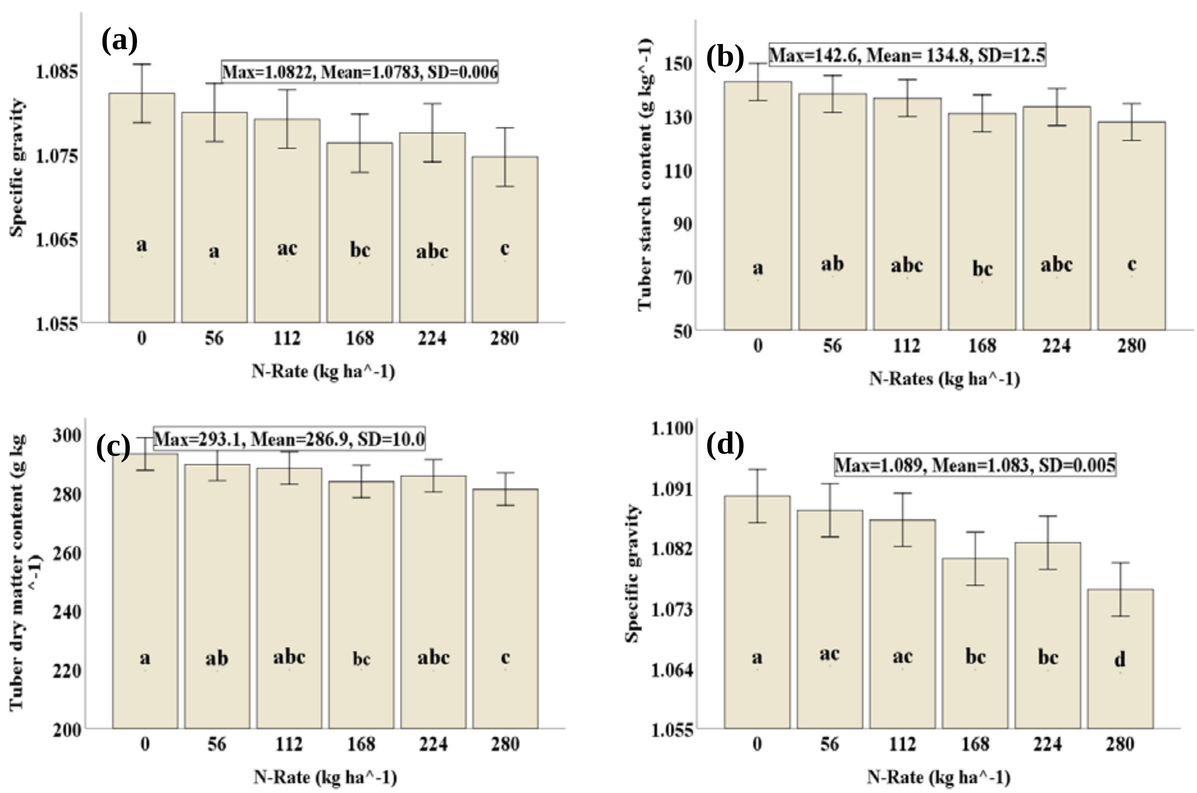
High rates of N led to a gradual decrease in tuber specific gravity, starch, and dry matter at all sites for all cultivars combineds. Rates of 0, 56, and 112, kg ha^{-1} of N produced the highest values of specific gravity (1.0821, 1.0799, and 1.0791, respectively), while 280 kg ha^{-1} of N reduced the specific gravity to 1.0746 (Figure 2.14 a). Starch and dry matter content showed higher values with the lowest N rates and decreased with an increase in N rates. Nitrogen rates of 0, 56, and 112 kg ha^{-1} resulted in the highest values of starch (142.5 g kg^{-1}, 138.1 g kg^{-1}, and 136.5 g kg^{-1}, respectively), and of dry matter (293.1 g kg^{-1}, 289.5 g kg^{-1}, and 288.3 g kg^{-1}, respectively). However, N rates of 168, 224, and 280 kg ha^{-1} led to the lowest values of starch (130.8 g kg^{-1}, 133.2 g kg^{-1}, and 127.5 g kg^{-1}, respectively) and dry matter (283.8 g kg^{-1}, 285.7 g kg^{-1}, and 281.1 g kg^{-1}, respectively) (Figure 2.14 b and c). Statistically, the rate of 0 kg ha^{-1} of N differed significantly the rates of with 168 and 280 kg ha^{-1} but did not differ significantly with the rates of 56 and 112 kg ha^{-1} for each of specific gravity, starch, and dry matter.

For Shepody cultivar, specific gravity, starch, and dry matter decreased with increasing N rates. Nitrogen rates of 0, 56, and 112, kg ha^{-1} produced the highest values of specific gravity (1.0897, 1.0875, and 1.0861, respectively) while 280 kg ha^{-1} of N reduced the specific gravity to

1.0757 (Figure 2.14 d). Starch and dry matter content showed higher values with the lowest N rate and decreased with an increase in N rate. Nitrogen rates of 0, 56, and 112 kg ha^{-1} resulted in the highest values of starch (157.5 g kg^{-1}, 155.1 g kg^{-1}, and 153.5 g kg^{-1}, respectively), and dry matter (305 g kg^{-1}, 301.6 g kg^{-1}, and 299.4 g kg^{-1}, respectively). However, N rates of 168, 224, and 280 kg ha^{-1} led to the lowest values of starch (147 g kg^{-1}, 149.8 g kg^{-1}, and 141.9 g kg^{-1}, respectively) and dry matter (290.1 g kg^{-1}, 293.1 g kg^{-1}, and 282.9 g kg^{-1}, respectively), (Figure 2.14 e and f). Statistically, the rate of 0 kg ha^{-1} of N differed significantly with rates of 168, 224, and 280 kg ha^{-1}, but did not differ significantly with the rates of 56 and 112 kg ha^{-1} of N for each of specific gravity, starch, and dry matter.

For Superior cultivar, the specific gravity, starch, and dry matter increased slightly with increasing N rates. Rates of N of 0, 56, and 112, kg ha^{-1} produced the lowest values of specific gravity (1.0771, 1.0764, and 1.0761, respectively) while 224 and 280 kg ha^{-1} of N produced higher values (1.0791 and 1.0777, respectively), (Figure 2.14 g). Starch and dry matter content showed higher values with the highest N rate and decreased with the lowest N rates. Nitrogen rates of 0, 56, and 112 kg ha^{-1} resulted in the highest values of starch (143.4 g kg^{-1}, 142.6 g kg^{-1}, and 142.3 g kg^{-1}, respectively), and dry matter (285 g kg^{-1}, 283.9 g kg^{-1}, and 283.4 g kg^{-1}, respectively). However, 168, 224, and 280 kg ha^{-1} of N produced 140.2 g kg^{-1}, 145.6 g kg^{-1}, and 144.1 g kg^{-1} of starch and 280.5 g kg^{-1}, 288.2 g kg^{-1}, and 286 g kg^{-1} of dry matter, respectively (Figure 2.14 h and i). Statistically, N rates did not result in any significant differences among the means of tuber properties.

For Russet Burbank cultivar, specific gravity, starch, and dry matter decreased with increasing N rates. Nitrogen rate of 0, 56, and 112, kg ha^{-1} produced the highest values of specific gravity (1.0798, 1.0758, and 1.0752, respectively) while 224 and 280 kg ha^{-1} of N reduced specific gravity to 1.0707 and 1.0705, respectively (Figure 2.14 j). Starch and dry matter content showed higher values with the lowest N rate and decreased with an increase N rate. Nitrogen rates of 0, 56, and 112 kg ha^{-1} resulted in the highest values of starch (146.5 g kg^{-1}, 142 g kg^{-1}, and 141.3 g $kg^{-1,}$ respectively), and dry matter (289.4 g kg^{-1}, 283.1 g kg^{-1}, and 282 g kg^{-1}, respectively). However, 168, 224, and 280 kg ha^{-1} of N led to the lowest values of starch (140.3 g kg^{-1}, 136.3 g kg^{-1}, respectively), and dry matter (136.1 g kg^{-1} of starch and 280.6 g kg^{-1}, 274.9 g kg^{-1}, and 274.6 g kg^{-1}, respectively) (Figure 2.14 k and l). Statistically, the N rate of 0 kg ha^{-1} differed significantly only to N rates of 224 and 280 kg N ha^{-1} but did not with 56, 112, and 168 kg ha^{-1} for each of specific gravity, starch, and dry matter.



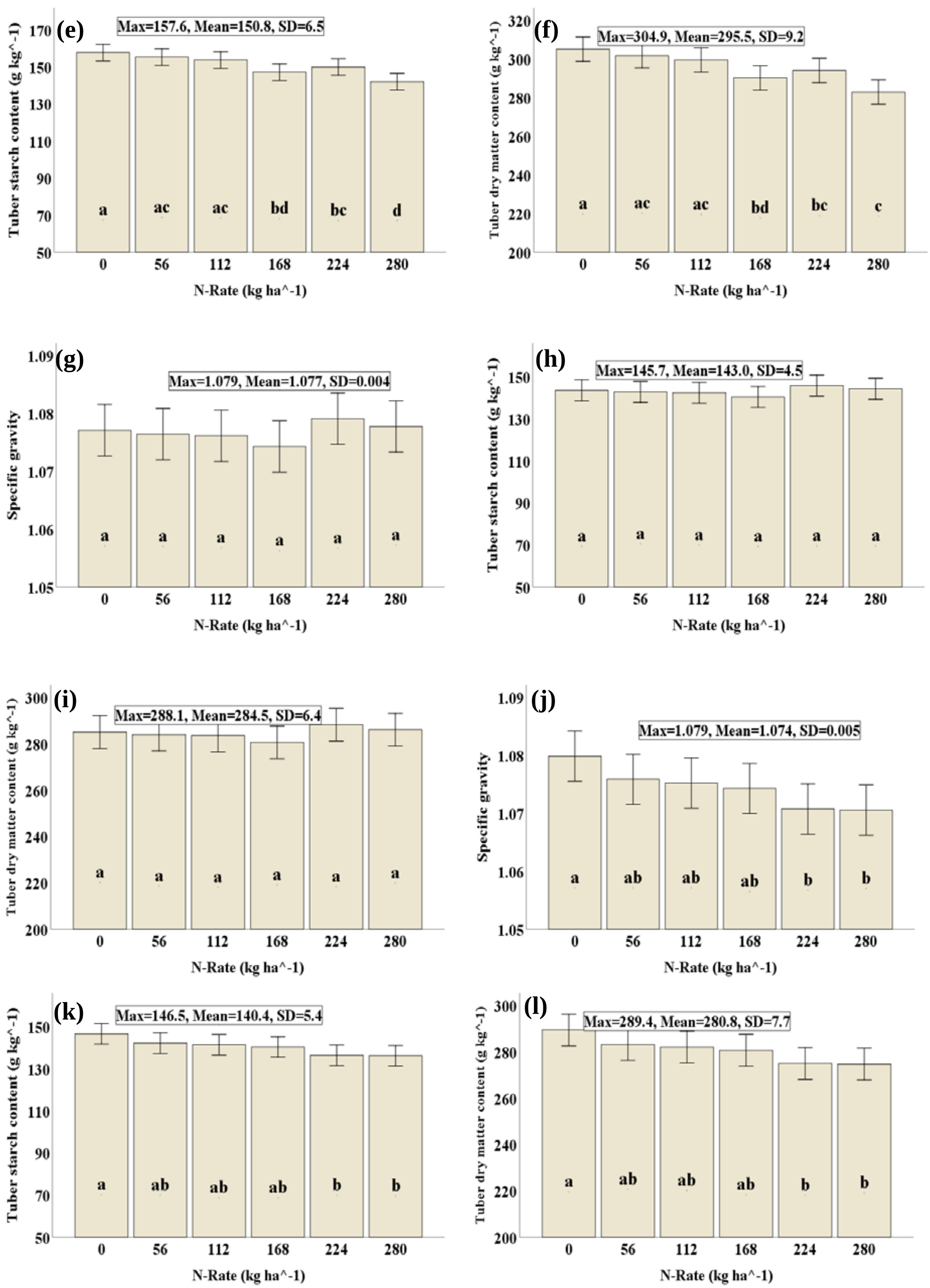

(e)
Max=157.6, Mean=150.8, SD=6.5
Tuber starch content (g kg^-1)
a
ac
ac
bd
bc
d
N-Rate (kg ha^-1)
(f)
Max=304.9, Mean=295.5, SD=9.2
Tuber dry matter content (g kg^-1)
a
ac
ac
bd
bc
c
N-Rate (kg ha^-1)
(g)
Max=1.079, Mean=1.077, SD=0.004
Specific gravity
a
a
a
a
a
a
N-Rate (kg ha^-1)
(h)
Max=145.7, Mean=143.0, SD=4.5
Tuber starch content (g kg^-1)
a
a
a
a
a
a
N-Rate (kg ha^-1)
(i)
Max=288.1, Mean=284.5, SD=6.4
Tuber dry matter content (g kg^-1)
a
a
a
a
a
a
N-Rate (kg ha^-1)
(j)
Max=1.079, Mean=1.074, SD=0.005
Specific gravity
a
ab
ab
ab
b
b
N-Rate (kg ha^-1)
(k)
Max=146.5, Mean=140.4, SD=5.4
Tuber starch content (g kg^-1)
a
ab
ab
ab
b
b
N-Rate (kg ha^-1)
(l)
Max=289.4, Mean=280.8, SD=7.7
Tuber dry matter content (g kg^-1)
a
ab
ab
ab
b
b
N-Rate (kg ha^-1)
0
56
112
168
224
280

Figure 2.14. Effect of different N rates on tubers quality, specific gravity, starch content, and dry matter content for different cultivars and at sites with < 30 g kg^{-1} of OM; (a) tubers-specific gravity for all cultivars combined, (b) tubers-starch content for all cultivars combined, (c) tubers-dry matter for all cultivars combined, (d) tubers-specific gravity for Shepody cultivar, (e) tubers-starch content for Shepody cultivar, (f) tubers-dry matter for Shepody cultivar, (g) tubers-specific gravity for Superior cultivar, (h) tubers-starch content for Superior cultivar, (i) tubers-dry matter for Superior cultivar, (j) tubers-specific gravity for Russet Burbank cultivar, (k) tubers-starch content for Russet Burbank cultivar, (l) tubers-dry matter for Russet Burbank cultivar, ANOVA at P< 0.05.

The specific gravity of Russet Burbank cultivar (1.079) was lower than that of Shepody cultivar (1.089). Figure 2.15 shows that Shepody cultivar can produce an accepted value of specific gravity marketably untill N rates reach 168 kg ha^{-1}. In contrast, Russet Burbank cultivar showed lower values of specific gravity within that rate. This result is the inverse of what observed in studies conducted by (Storey and Davies, 1992; Bélanger et al., 2002), in which RS produced higher values of specific gravity in comparison with Shepody cultivar. These conflicting results can be explained by the fact that the specific gravity for any cultivar is inversely related to increased N rates. Shepody is classified as an early-maturing cultivar, meaning that it will mature sooner than a Russet Burbank cultivar and subsequently, there is no additional uptake of N affect specific gravity values when the Russet Burbank cultivar is continually growing and taking up N.

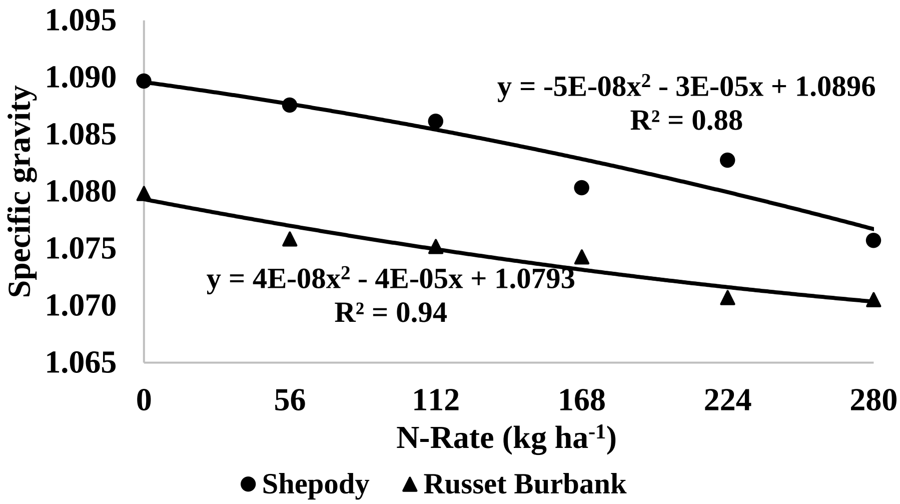


Figure 2.15. The response spesific gravity of Russet Burbank and Shepody cultivars to different rates of nitrogen, P< 0.05.

2.4.4.5.2 Sites with ≥ 30 g kg^{-1} of Organic Matter

For all combined Russet Burbank cultivars, specific gravity, starch, and dry matter decreased with increasing N rates. Nitrogen rates of 0, 56, and 112, kg ha^{-1} produced the highest values of specific gravity (1.1158,1.1067, and 1.0838, respectively) while 224 and 280 kg ha^{-1} of N reduced specific gravity to 1.0410 and 1.0401, respectively (Figure 2.16 a).

Starch and dry matter content showed higher values with the lowest N rate and showed lower values with increased N rates. Nitrogen rates of 0, 56, and 112 kg ha^{-1} resulted in the highest values of starch (181.2 g kg^{-1}, 165 g kg^{-1}, and 144.8 g kg^{-1}, respectively), and dry matter (338.4 g kg^{-1}, 323.1 g kg^{-1}, and 287 g kg^{-1}, respectively). However, 168, 224, and 280 kg ha^{-1} of N led to the lowest values of starch (102.8 g kg^{-1}, 95.5 g kg^{-1}, and 94.6 g kg^{-1}, respectively) and dry matter (227.7 g kg^{-1}, 217.4 g kg^{-1}, and 216.1 g kg^{-1}, respectively) (Figure 2.16 b and c). Statistically, the N rate of 0 kg ha^{-1} differed significantly only to 168, 224, and 280 kg ha^{-1} of N and did not differ significantly to 56 and 112 kg ha^{-1} of N for each of specific gravity, starch, and dry matter.

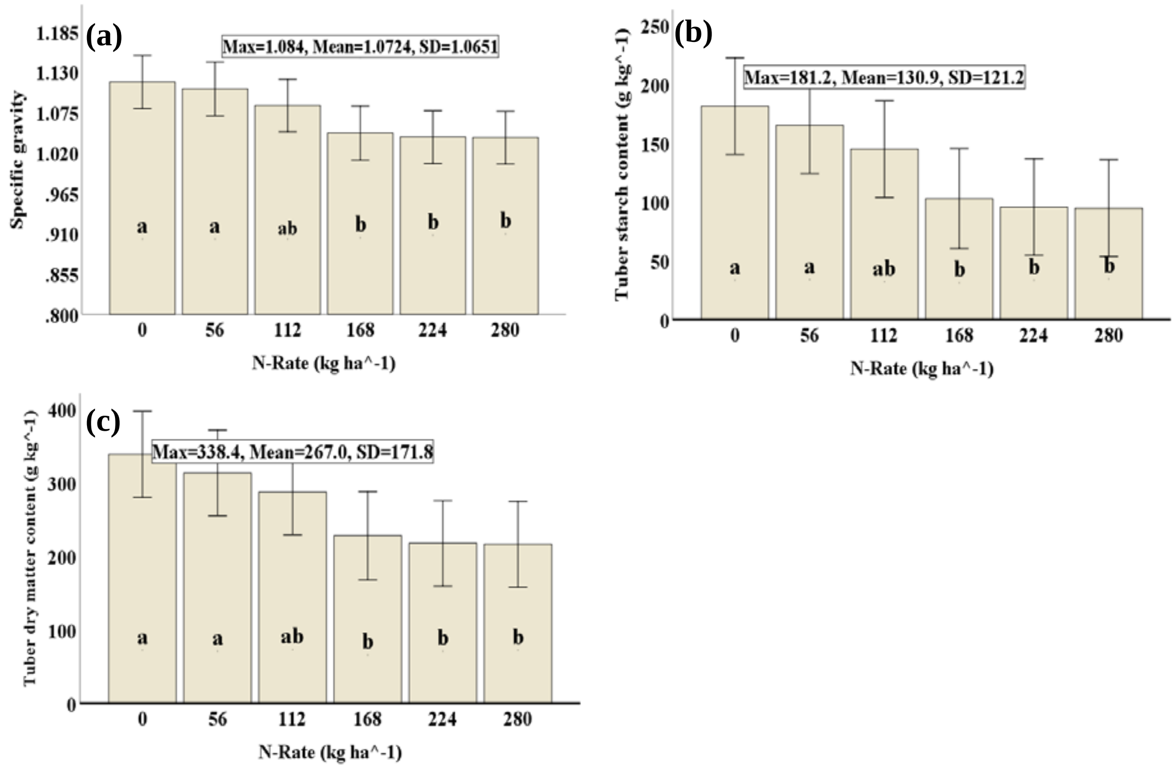


Figure 2.16. Effect of different N rates on tubers quality, specific gravity, starch content, and dry matter content for all combined sites with ≥ 30 g kg^{-1} of OM, where (a) tubers-specific gravity, (b) tubers-starch content, (c) tubers-dry matter, ANOVA at P< 0.05.

2.4.4.5.3 Different Potato Cultivars

Regardless of soil OM content, the maximum value of specific gravity for tubers (1.084) was found with Shepody cultivar, while the lowest value was found with Russet Burbank cultivar (1.067). Statistically, Post Hoc-LSD (P > 0.05) showed that the specific gravity of tubers was not affected by the potato cultivar factor (Figure 2.17).

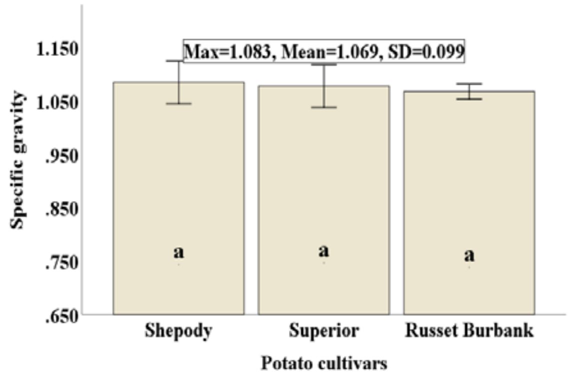


Figure 2.17. Effect of potato cultivars on the specific gravity of potato tubers, ANOVA at P< 0.05.

2.5 DISCUSSION

The results showed increases in chlorophyll index with an increasing N rate of up to 224 kg ha^{-1} regardless, of soil OM content. Each cultivar within the group of ≤ 30 g $kg^{-1}$of OM showed continued increase in chlorophyll index with increasing N rate.. This could be attributed to the low SOM content, ≤ 30 g kg^{-1}, which encouraged the utilization of N fertilizer in metabolism and meristematic activities. These outcomes are in agreement with those obtained by El-Gizaw (2009). Chlorophyll index was observed to run compatibly with the potato yield pattern (Ahmed et al., 2009; Güler, 2009), and this could be attributed to the N affecting plant growth and as a result, affecting chlorophyll concentration (Parvizi et al., 2004). Moreover, total tuber yield was significantly correlated with leaf chlorophyll index. This could be attributed to the N influencing plant growth and yield. A study conducted on corn by Parvizi et al. (2004) highlighted that there was a highly significant correlation between leaf's chlorophyll readings and yield of dry matter.

The best fit of the polynomial function described the relationship between N rate and total tuber yield, where the coefficient of determination, R^2, ranged from 0.60 to 0.96. The highest response to N applications at the sites with OM ≥ 30 g kg^{-1} may be due to the robust effect of OM, which accumulated as a result of continuous crop rotation operations over 2 to 3 years. Sites with

≥ 30 g kg^{-1} of OM produced 40.93 Mg ha^{-1} as a maximum potato tuber yield, whereas sites with ≤ 30 g kg^{-1} of OM produced a maximum of 27.45 Mg ha^{-1} potato tuber, which is approximately 39.45% higher than the tubers yield produced from sites with ≤ 30 g kg^{-1} of OM. Additionally, sites with ≥ 30 g kg^{-1} of OM produced a higher total tuber weight per plant (50.2%) than sites with ≤ 30 g kg^{-1} of soil OM. The significant difference in tuber yield response among the sites was attributed to the practice different crop rotation systems, which consequently promoted crop residue accumulation, and also supported soil properties (Charles et al., 2009).

Tuber weight per plant responded positively to the N rates in the case of the combined sites. An N rate of 168 kg ha^{-1} produced the maximum tuber yield for the sites with ≥ 30 g kg^{-1} and ≤ 30 g kg^{-1} of soil OM. Russet Burbank cultivar at sites with ≥ 30 g kg^{-1} of OM showed a maximum tuber yield with a rate of 168 $kgha^{-1}$ of N and did not show a significant difference with 224 kg ha^{-1} of N. This result differs from results obtained in Maine by Porter and Sisson (1991) which showed that 96 kg ha^{-1} of N and 211 kg ha^{-1} of N were the most effective rates and resulted in the maximum total tuber yield for Russet Burbank and Shepody cultivars, respectively. This difference could be due to a high soil OM content > 65 g kg^{-1}, but a low quality and high C:N ratio. Consequently, soil microorganisms my have required a higher rate of N to accomplish OM decomposition (Miller, 2000). Russet Burbank cultivarin sites with ≤ 30 g kg^{-1} of OM produced a maximum tuber yield of 24.05 Mg ha^{-1}, which is approximately 52.0% lower than the tuber yield of Russet Burbank cultivar in the sites with ≥ 30 g kg^{-1} of soil OM.

The observedyield reduction after the application of a rate >168 N kg $ha^{-1}$of N in both groups (≤ 30 and ≥ 30 g kg^{-1} of soil OM) could be due to a delay in tuber growth as a result of the long vegetative (leaves and stems) growing period in comparison to tuber growth. The excessive applications of N encouraged a dense vegetative growth, which in turn reduced the amount of the carbohydrates expected to be available for tuber growth. As a result, photosynthesis supported the leaves of the plant more than the tubers and eventually reduced tuber quality (Porter and Sisson, 1989; Ahmed et al., 2009).

As for the effect of cultivars, Russet Burbank produced a higher yield than Shepody and Superior cultivars, which is in agreement with what discovered by (Feibert et al., 1998; Meyer, 2002). However, Superior cultivar may reach a high level of productivity (like Russet Burbank and Shepody cultivars) if planted under irrigated systems, as observed by Evanylo (1989).

As a comparison, the gap between marketable tuber yield and total tuber yield was attributed to subtracting unmarketable tubers. Within the marketable tuber yield itself, the gap between the yields in the sites that contained ≤ 30 g kg^{-1} and ≥ 30 g kg^{-1} of OM content was attributed to the benefits of OM toward soil physical properties i.e., bulk density. The higher the SOM content, the lower the soil bulk density and as a result, a soft bed was created around the tubers that allowed for size enlargement. This finding is in agreement with the result of a study conducted by Lynch et al. (2008).

The number of tubers per plant increased in the sites with ≥ 30 g kg^{-1} of soil OM content in comparison with sites with ≤ 30 g kg^{-1} of OM. This result is the opposite of results obtained in the first year of this research (2018. In 2018) ammonium sulfate was used as a source of N, while in the second year (2019) ammonium nitrate was used. These findings agree with those of studies conducted by (Polizotto et al., 1975; Davis et al., 1986; Maier et al., 2002), in which different sources of N(ammonium nitrate, ammonium sulfate, and urea) were compared. It was shown that ammonium nitrate produced a higher number of tubers per plant in comparison with the other sources that contained mostly ammonium as a source of N. The studies also demonstrated that nitrate is essential to support the growth of tops, roots, and tubers. Moreover, the results showed that some NO_3-N should be available to the potato for proper growth, development, and yield.

The average specific gravity, starch content, and dry matter content of all sites followed the same pattern of progress, where increasing N rates led to a decrease in potato quality. The values of specific gravity, starch, and dry matter content were lower in the sites with ≥ 30 g kg^{-1} of OM than sites with ≤ 30 g kg^{-1} of OM, and showed a reduction of 2.9%, 23.9%, and 21.9%, respectively at 168 kg ha^{-1} of N, which is the rate that produced the highest tuber yield.

High rates of N encouraged growth rates and prompted solids accumulated through photosynthesis to immediately be utilized to develop the vegetative growth (leaves and stems) instead of supporting the growth of the tubers.This resulted in the production of tubers with low values of specific gravity, dry matter, and starch content. These results are in line with results obtained by Schippers (1968), which demonstrated that increasing N rates reduced tuber quality due to an increase in tuber water content. However, other researchers (Teich and Menzies, 1964; Hermanson, 1965; Kelling et al., 2003; Kelling and Speth, 2004; B. Zebarth et al., 2004) did not observe any effect of N rates on specific gravity, starch content, and dry matter.

In some situations, specific gravity, starch, and dry matter levels may increase compared to the zero N rate; this can happen only when a reasonable rate of N is applied on infertile soils (Zvomuya et al., 2003). However, tuber quality will decrease when N rates reach excessive levels. The impact of N on reducing specific gravity appears to be a substantial factor when N rates surpass the requirements of the crop. The explanation for this issue is that any excessive N in the soil due to an extreme N, either from over-fertilization or credits from the previous cover crop, can cause a problem when combined with the amount of N from the regular application. Schippers (1976) demonstrated a high correlation between specific gravity and dry matter or starch.

Increasing the N rate may increase tuber yield, however, it simultaneosly decreases the tuber dry matter. This could be attributed to an increase in tuber water content due to an excessive N rate. Shepody cultivars showed higher values of tuber specific gravity than Russet Burbank and Superior cultivars, which agreeswith what was discovered by (Porter and Sisson, 1991; Wayumba et al., 2019). This could be attributed to the short growing season for Shepody and Superior cultivars which reduces the opportunity for the plants to consume more N, where excessive N mostly negatively affects specific gravity. Statistically, potato cultivars did not show a significant difference regrading tuber specific gravity values. Multiple regression analysis between soil OM content and soil micronutrients confirmed that the availability of micronutrients increased with an increase in soil OM content (where R^2= 0.47, 0.60, 0.31, 0.51, and 0.60 for S, B, Mn, Zn, and CEC respectively), (data not shown).

2.6 CONCLUSIONS

Monitoring soil OM content is essential for crop production, including potato crops. Among the series of N rates used, the rate of 168 kg ha^{-1} achieved the highest tuber yield production at all sites. Soil OM content supported tuber yield significantly at all sites but did not reduce the required N rate.

Although low soil pH was not beneficial regarding the availability of macronutrients, soil OM content improved the total potential yield. The issue induced by acidity is less if the soil is adequately supported with OM because organic matter serves to make Aluminum less toxic. Moreover, humus improves soil cation exchange capacity (CEC). Soil pH will not shift as quickly in soil with high OM content, where organic matter buffers soil pH and decrease acidification because it restrains hydrogen (H) tightly (Magdoff and Van Es, 2000).

An N rate of 168 kg ha^{-1} achieved the highest tuber yield with acceptable quality for Russet Burbank, Shepody, and Superior cultivars y, but taking into consideration soil tests. The concerns of low specific gravity, starch, and dry matter content are more significant when fertilization passes the N requirements, which growers are used to doing to reach maximum tuber yield.

Russet Burbank cultivar produced a higher yield than Shepody and Superior cultivars. However, Superior cultivar have the potential to reach a high level of productivity if planted under irrigated systems. For more precise results, regarding OM, cultivars should be planted in two different soils, where the effect of soil properties can be examined.

CHAPTER 3

IN-SEASON POTATO YIELD PREDICTION WITH ACTIVE OPTICAL SENSORS

3.1 ABSTRACT

Crop yield prediction is a critical measurement, especially during a time when parts of the world are suffering with farming issues. Yield forecasting provides an alert regarding economic trading, food production monitoring, and global food security. This research was conducted to investigate whether active optical sensors could be utilized for potato (*Solanum tuberosum* L.) yield prediction in the middle of the growing season. Three potato cultivars, Russet Burbank, Superior, and Shepody, were planted, and six rates of Nitrogen (N) (0, 56, 112, 168, 224, and 280 kg ha^{-1}) (ammonium sulfate was replaced by ammonium nitrate in the second year) were applied on 11 sites in a randomized complete block design (RCBD), with four replications. Normalized difference vegetation index (NDVI) and chlorophyll index (CI) measurements were obtained weekly from the active optical sensors, GreenSeeker (GS) and Crop Circle (CC). A N rates of 168 kg ha^{-1} produced the maximum potato yield. Indices measurements obtained at stages 16 and 20 of fully expanded leaves were significantly correlated with tuber yield. Multiple regression analysis (potato yield as a dependent variable and NDVI, and CI as independent variables) made a significant improvement to the accuracy of the prediction model and increased the determination coefficient. The exponential and linear models showed a better fit of the data. Soil organic matter (OM) content increased the yield significantly but did not affect the prediction models. Stages 18 and 20 of fully expanded leaves were the most effective stages to use the sensors for yield prediction.

3.2 INTRODUCTION

Potato crops contribute to global food security. Potatoes supplement or replace grain-based diets where wheat, rice, and maize availability has declined due to high cost (Camire et al., 2009). Potatoes are inexpensive to buy and are easy to grow. The potato crop can provide a steady yield under varying circumstances where other crops might fail (Lutaladio and Castaldi, 2009). Flexibility in a variety of environmental circumstances and productivity potential also makes the potato crop the foremost for food and nutrition security (Kyamanywa et al., 2011).

The volume of potato production ranked fourth in the world after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.), (Hirpa et al., 2010). Furthermore, it is the most famous crop among tuber and root crops, listing first in volume production followed by cassava (*Manihot esculenta* L.*Crantz*), sweet potato (*Ipomoea Batatas* L. Lam), and yam (*Dioscorea spp*.) (Cromme et al., 2010). The demand for potato crop production is increasing, especially with expanding diet diversity and a need for inexpensive foods. Potato consumption has increased universally due to its ability to grow in a wide range of climates and its adoption by a wide range of cultures (King and Slavin, 2013).

Consequently, the potato is the predominant vegetable for sales, production, and consumption (Kolasa, 1993). It is the most valuable crop in developing countries, and its production is increasing more quickly than other food crops (Scott et al., 2000). As a result, it is an important source of rural employment, income, and food for a growing population (Guchi, 2015).

Maine is one of the top ten production areas for potatoes in the USA, although yields are considerably lower than in the mid- and western USA (DeFauw et al., 2012). During the last ten years, potato yields in Maine have mostly remained constant at 38 $Mg.ha^{-1}$, except for 2016, when the yield was measured at 44 $Mg.ha^{-1}$. The same rate of production for consecutive years demonstrates the difficulty of improving the yield and quality of potatoes with traditional fertilization practices. Therefore, new agronomic procedures are necessitated to fulfill producers and industry-requirements (Lakesh Sharma et al., 2017). Prediction of potato crop yield prior to harvesting can be instrumental in pre-harvest and marketing decision making.

Research confirmed that traditional practices of crop yield estimation could lead to inadequate crop yield assessment and inaccurate crop area appraisal (Reynolds et al., 2000; Haverkort and MacKerron, 2012). Moreover, these methods typically depend on rigorous field data collection of crop and yield, which is a costly and time-consuming process.

Existing strategies are time-consuming and rely heavily on soil and plant analyses. Because of the restrictions of traditional yield prediction techniques, the development of a non-destructive, rapid, and convenient approach to estimate yields in a timely manner would aid in management decisions and fertilizer application control. Remote sensing technologies have been utilized extensively in agriculture for precise management, nutrition investigation, and in-season yield prediction (Caturegli et al., 2016).

Remote sensing can be utilized to estimate temporal variation in crop dynamics, including crop yield and spatial variability (Taylor, 1997). Visible (blue, green, and red) and near-infrared (NIR) parts of the electromagnetic spectrum can be utalized to obtaine information on crop type, crop health, soil moisture, N stress and crop yield (Magri et al., 2005; Hassaballa and Matori, 2011; Abdalla et al., 2013; Hassaballa et al., 2014). Numerous studies have highlighted the potential association between the vegetation indices provided by the remote sensing techniques and crop yield and biomass (Rasmussen, 1997; Liu and Kogan, 2002).

Several experiments have focused on crop growth analysis using NDVI to improve precision agriculture (Taylor, 1997; Baez-Gonzalez et al., 2002; Baez-Gonzalez et al., 2005; Funk and Budde, 2009). A study on plant life monitoring confirmed that NDVI is linked to the leaf area index (LAI) and the photosynthetic activity of crops. The NDVI is an indirect method for estimating primary productivity through its association with crop yield using the fraction of absorbed photosynthetically active radiation (FAPAR) (Prince, 1990; Los, 1998).

Numerous plant indices based on multispectral sensors, ratio vegetation index (RVI), perpendicular vegetation index (PVI), and the simple ratio (SR) have been confirmed to accurately correspond to plant physiological responses, such as leaf area, plant N response and biomass (Broge and Leblanc, 2001; Aparicio et al., 2002; Hansen and Schjoerring, 2003). Among these indices, the NDVI via the GS active optical sensor, is efficient in predicting the in-season yield of many crops (Raun et al., 2001; Prasad et al., 2007). NDVI measurements are used to identify the N condition or biomass development of plants, and are sometimes also employed to conduct nutritional monitoring of elements such as phosphorus (P) and potassium (K) in field crops (Samborski et al., 2009; Pimstein et al., 2011). The GS hand-held optical sensor is a portable and easy crop research and consulting instrument that provides useful data to monitor plant status (Govaerts et al., 2007).

Erdle et al. (2011) conducted a study to compare active and passive sensing systems in terms of their capability to identify agronomic parameters. Active sensors collect the reflected rays from objectives that were sent from the sensor itself, while passive sensors collect the reflected rays that originally came from sunlight (Wang and Xu, 2018). Passive satellite images and three active sensors (including GS, CC, and an active flash sensor (AFS)), were examined to assess six destructively determined crop parameters. The result showed that active spectral sensors are more flexible in terms of timeliness and illumination circumstances; however, to date, they are restricted to a limited number of indices.

The GS sensor emits beams (by its active light source) to the plant canopy at wavelengths of 671 ± 6 nm and 780 ± 6 nm ; the beams reflected from the canopy are then received again via the sensor and are used to calculate the NDVI value (Kipp et al., 2014). Previous studies revealed that the canopy reflectance to the visible beam (400–700 nm) fundamentally relied on the CI in the palisade layer of the leaf and the NIR reflectance relied on the formation of the mesophyll cell and the cavities between cells (Blackmer et al., 1994; Campbell and Wynne, 2011).

Olfs et al. (2005) reported that the visible reflectance was reduced while NIR reflectance was increased due to N fertilizer supplementation. Consequently, NDVI values measured in nutrient-deficient areas were lower than in the areas with sufficient nutrients. Additionally, the NDVI index could discriminate between N status and plant biomass, which can be employed to predict potential yield. In previous studies, NDVI values collected by the GS hand-held active optical sensor were shown to predict the in-season yield of several crops, such as winter wheat, corn, and rice (Lofton et al., 2012; Macnack et al., 2014; Cao et al., 2015). A robust relationship was noted between NDVI measurements and the yield of winter wheat. It has been found at Feekes stage 4 and 5 (Raun et al., 2001), while in the corn crop, the NDVI value taken by the GS at the V8 leaf stage showed a strong relationship ($R^2 = 0.77$) with the grain yield (Teal et al., 2006).

GreenSeeker and CC optical sensors have been successfully employed for predicting yields of grain crops, and the preliminary and accurate estimation of yields would provide valuable information for building decisions associated with N management (Yao et al., 2012). In Maine, there are vast hectares planted with potato crops and unfortunately, active sensors are not extensively used, while other states and countries are utilizing satellite images for potato yield prediction measurements (Newton et al., 2018). Ji et al. (2017) tested remote sensing tools for cabbage crop yield prediction and noted that the numerous varieties and comparatively complicated canopy architecture of cabbages resulted in uncertainty as to whether the instruments would be adopted for in-season yield prediction.

In Louisiana, Lofton et al. (2012) encountered difficulties with the yield prediction of a sugarcane crop due to a multi-year cropping cycle combined with a shorter growth period. A similar issue was observed with rice crop, and the robust association was not sustained throughout the growth stages. At the heading stage, the GS indices of rice became saturated. Consequently, GreenSeeker could not be used for estimation for in-season yield, while at the early growth stages (tillering stage) the rice canopy was not closed, however, the soil and water background had a substantial impact on canopy reflectance (Kamiji et al., 2011; Cao et al., 2016).

The goal of this study was to evaluate the performance of two active optical sensors for in-season potato yield prediction. The specific objectives were to compare the performance of GS and CC sensors in yield prediction, and evaluate the impact of chlorophyll index in improving the prediction algorithm.

3.3 METHODS

3.3.1 Measurements

3.3.1.1 Sensor Description and Sensing Procedure

Two hand-held active optical sensors were employed for this research: the GS sensor (Trimble Navigation Limited, Sunnyvale, CA, USA) and the CCsensor (A-470 sensor Holland Scientific, Inc., Lincoln, NE, USA). The GS sensor measures incident and reflected beams from the plant canopy at 660 ± 15 nm and 770 ± 15 nm, which are red and NIR bands, respectively (Sharma et al., 2015).

In the GS sensor, the beam is transmitted from diodes in alternating emissions at different intervals such that the visible source pulses come out to be 1.0 ms, and the NIR diode source pulses come out to be 1.0 ms at 40,000 Hz. Emission from a given source equals approximately 40 pulses before pausing for the other diode to release its radiation, which is another 40 pulses (Sharma et al., 2015). The area covered by the light is approximately 60 cm in width and 1.0 cm in length, with the long dimension positioned vertically in the direction of walking to take readings. The field of view is relatively steady for heights between 60 and 120 cm above the canopy of the plant; the output from the sensors is a red NDVI and simple ratio (red/NIR) (Sharma et al., 2015).

The CC sensor concurrently emits three bands red 650 nm, red-edge 730 nm, and the NIR 760 nm. The sensor collects approximately 2 to20 readings per second, so each recorded value in a 6.0 m length of the plot, walking at approximately 5.0 km hr^{-1} is the average of approximately 4000 readings. The output data of the sensor are reflectance values that allow for calculation of vegetation indices. NDVI involves red and red-edge bands, which is different from GS (Sharma et al., 2015).

The equation for red NDVI and red-edge NDVI are as follows:

Red NDVI $=\frac{NIR-Red}{NIR+Red}$ (Eq. 3.1)

Red Edge NDVI $= \frac{NIR-Red\ Edge}{NIR+Red\ Edge}$ (Eq. 3.2)

GS emits two bands: red (660 nm) and NIR (774 nm),

NDVI $= \frac{(774\ nm-660\ nm)}{(774\ nm+660\ nm)}$ (Eq. 3.3)

CC emits three bands: red (670 nm), red-edge (730 nm), and NIR (760 nm):

NDVI $= \frac{(760\ nm-670\ nm)}{(760\ nm-670\ nm)}$ (Eq. 3.4)

Or red-edge NDVI

NDVI = $\frac{(760\ nm - 730\ nm)}{(760\ nm + 730\ nm)}$ (Eq. 3.5)

The GS and CC sensors were used weekly during the growing season, once the plants completed the fourth leaf (4, 8, 10, 12, 16, 18, and 20). Readings were obtained at 60 cm over the top of the potato plant from the middle row of each plot. Approximately 40 to 60 readings were obtained from every single experimental unit. In-house macro programs for Visual Basic within Excel were used to calculate the mean of the sensing readings data (Franzen, 2012). Due to small differences in the growth stages between sites, NDVI data were normalized using the INSEY (In-Season Estimate of Yield) approach. The INSEY was particularly useful when combining NDVI data from different site-years. The INSEY (Raun et al., 2001) was computed by dividing the NDVI data by the growing degree days (GDD) which started from the planting date to the date of taking sensor readings data (United States Climate Data, 2018) used to calculate weather, equation (3.6).

GDD = $\frac{(Tmax + Tmin)}{2}$- C (Eq. 3.6)

Where,

T_{max} and T_{min} represent the daily maximum and minimum temperature, C represents the base growing temperature for potato, which is 10 ºC.

Sensing was conducted by placing the GS and CC sensors at an approximate distance of 60 cm above the plant canopy, resulting in a similar magnitude of reflectance at each site and each growth stage reading (Franzen, 2012).

3.3.1.2 Chlorophyll index

Leaf chlorophyll content, as an index, was measured using a CC active optical sensor. The CC sensor depends on red-edge and NIR wavelength bands to calculate the index which are sensitive to a wide range of chlorophylls (Equation 3.7) (Gitelson et al., 2005).

Cl_{RE} =(NIR/RE) -1 (Eq. 3.7)

Where,

NIR represents near-infrared wavelength band 850 nm,

RE represents red-edge wavelength band 730 nm.

3.3.2 Data Analysis

A correlation analysis via IBM-SPSS v.25 (SPSS-IBM-Corp., 2017) was conducted between total tuber yield and sensor data to understand how leaf chlorophyll content is associated with the yield variation within different potato cultivars. Regression analysis was used to determine the relationship between potato yield data as a dependent variable and sensor data as independent variables. Multiple regressions were conducted between potato yield data and sensors' data, NDVI, and CI to enhance the determination coefficient (R^2) of the yield prediction algorithm. The CI data were utilized with each group ($\geq$ 30 g kg^{-1} of soil OM, $\leq$ 30 g kg^{-1} of soil OM, and combined sites), and also with each type of sensor data (GS-red, CC-red, and CC-red-edge).

To avoid multicollinearity between independent variables, variance inflation factor (VIF) was used as an index to examine the association between independent variables. A VIF value of $\leq$ 5.0 is the recommended threshold value (Marquaridt, 1970; Rogerson, 2001), and values greater than 5.0 would negatively affect the results associated with a multiple regression analysis.

3.4 RESULTS

3.4.1 Yield Responses to Nitrogen Rates

There was a noticeable impact of OM content on tuber yield production, where sites with $\geq$ 30 g kg^{-1} of soil OM content revealed a significant disparity with sites that had $\leq$ 30 g kg^{-1} of OM (Figure 2.1). Hence, all the sites were classified into two groups, $\leq$ 30 and $\geq$ 30 g kg^{-1} of soil OM content. The sites NS-1, NS-2, FV, CA1, CA2, CA3, LM, and WD were classified as $\geq$ 30 g kg^{-1} of OM, while AF1, AF2, and AF3 were classified as ≤ 30 g kg^{-1} OM. Shepody and Superior potato cultivars had only one site for each one that was ≤ 30 g kg^{-1} of OM.

Potato yields at different N application rates are shown in Figure 3.1, which represents the relationship between N rates and potato yields for the sites that had ≤ 30 g kg^{-1}of soil OM, ≥ 30 g kg^{-1} of soil OM, and an average of all sites combined. The potato yield improved significantly with N fertilizer applications at all sites ($P< 0.05$). Compared with the control treatment (0 kg ha^{-1} of N), yields under 56, 112, and 168 kg ha^{-1} treatments were increased by 10.8%, 20.7%, and 18.5% respectively for 56 kg ha^{-1} of N; 13.3%, 28.8%, and 25.4%, respectively for 112 kg ha^{-1} of N, and 21.7%, 42.7%, and 37.7% respectively for 168 kg ha^{-1} of N. For all sites, potato yields increased as N rate increased from 0 kg ha^{-1} to 168 kg ha^{-1}. However, there was no significant increase witnessed by applying 224 kg ha^{-1} of N ($P> 0.05$), which implied that the 168 kg ha^{-1} of N was the maximum economic rate for potato production.

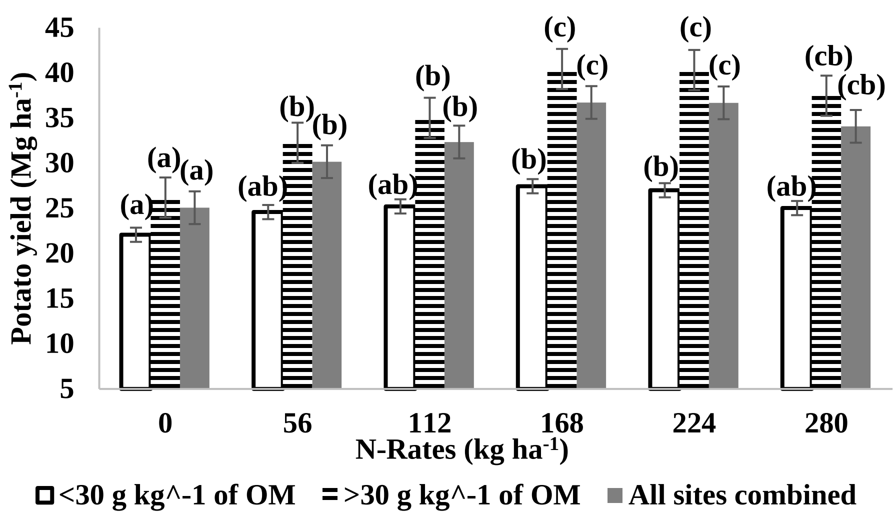


Figure 3.1. The response of potato yield to different applications of N fertilizer rates, P< 0.05. Adopted from (Ahmed et al., 2020).

3.4.2 Relationships between Normalized Difference Vegetation Index Measurements and Potato Yields

The Pearson correlation analysis results of INSEY measurements and yield of potatoes are shown in (Table 3.1). The correlation coefficient (*r*) values exhibited that INSEY measurements had a significant relationship with the potato yield in all sites only after the mid growing season, 16^{th} and 20^{th} leaf growth stage ($P< 0.01$). However, correlation coefficient values were relatively low at the early growth stages (data not shown). The highest value of correlation coefficient in the sites with ≤ 30 g kg^{-1} of soil OM content was achieved at the 16^{th} leaf stage, while the sites that had ≥ 30 g kg^{-1} of soil OM content and all sites combined exhibited the highest value at the 20^{th} leaf stage. As a comparison between data obtained from different sensors, the INSEY data derived from the red-edge band exhibited the highest correlation with potato yield data in all sites. However, INSEY derived from the GS and CC sensors using the red band showed a relatively similar association with the tuber yield. Still, the correlation was relatively low in comparison to the red-edge band.

Table 3.1. Pearson correlation and regression analysis between the sensors measurements and potato yield.

	Time of sensing	Leaf stage	Sensor type	*r*	R^2
≤ 30 g kg^{-1} of OM	July 25^{th}	16	GS-red-INSEY	0.67^{**}	0.45^{**L}
			CC-red-INSEY	0.61^{**}	$0.38^{**\ Exp}$
			CC-red-edge-INSEY	0.69^{**}	0.48^{**L}
	Aug 1^{st}	20	GS-red-INSEY	0.61^{**}	0.38^{**L}
			CC-red-INSEY	0.57^{**}	0.32^{**L}
			CC-red-edge-INSEY	0.64^{**}	0.41^{**L}
≥ 30 g kg^{-1} of OM	July 25^{th}	16	GS-red-INSEY	0.51^{**}	$0.26^{**\ P}$
			CC-red-INSEY	0.47^{**}	$0.22^{**\ Exp}$
			CC-red-edge-INSEY	0.60^{**}	$0.36^{**\ Exp}$
	Aug 1^{st}	20	GS-red-INSEY	0.44^{**}	0.25^{**Exp}
			CC-red-INSEY	0.49^{**}	$0.27^{**\ Exp}$
			CC-red-edge-INSEY	0.60^{**}	$0.38^{**\ Exp}$
All sites combined	July 25^{th}	16	GS-red-INSEY	0.31^{**}	$0.12^{**\ Exp}$
			CC-red-INSEY	0.35^{**}	$0.15^{**\ Exp}$
			CC-red-edge-INSEY	0.48^{**}	$0.28^{**\ Exp}$
	Aug 1^{st}	20	GS-red-INSEY	0.53^{**}	$0.28^{**\ Exp}$
			CC-red-INSEY	0.50^{**}	$0.25^{**\ Exp}$
			CC-red-edge-INSEY	0.62^{**}	$0.38^{**\ Exp}$

GS: GreenSeeker active sensor, CC: Crop circle active sensor, red: red wavelength, red-edge: red-edge wavelength, INSEY: (NDVI/growing degree days from planting date), *r*: correlation coefficient, R^2: coefficient of determination, **: significant correlation at 0.01 probability level, Exp: exponential model, P: power model, L: linear model for the best fit.

Regression analysis revealed that each of the 16th and 20th leaf growth stage showed the highest values of determination coefficient, R^2, to explain the relationship between potato yield and sensor data (Table 3.2). The exponential model showed the best fit for the relationship between potato yield and sensor data (INSEY), especially for the sites characterized by ≥ 30 g kg^{-1} of soil OM content and the combined sites. However, the linear model showed the best fit for the relationship in the sites characterized by ≤ 30 g kg^{-1} of soil OM content. The model showed that INSEY data before July 25th, 16th leaf growth stage, exhibited a very low R^2 with potato yield. Therefore, the regression analysis could not make an adequate forecast of in-season yield with NDVI readings of potato yield before July 25th. The sites of ≥ 30 g kg^{-1} of soil OM and all sites combined showed the highest R^2 during the 20th leaf growth stage, while the 16th leaf growth stage was the best for sites with ≤ 30 g kg^{-1} of soil OM. In all the sites, the highest R^2 was achieved using the red-edge band at the 16th and 20th leaf growth stage in comparison with INSEY values derived from the red band.

3.4.3 Predicting Potato Yields Using Measured Normalized Difference Vegetation Index at the Optimum Time

The results summarized in the regression analyses exhibited that the 16th and 20th leaf growth stages were the most appropriate times for yield prediction of potatoes. The fitting curves of measured INSEY values and potato yield at these stages were most significantly associated using the exponential and linear function.

3.4.3.1 Sites with ≤ 30 g kg^{-1} of Organic Matter

The measured INSEY values could explain the yield variation and predict the in-season yield of potatoes with R^2 values 0.38, 0.45, and 0.48 at $p < 0.01$ for INSEY that were derived from CC-red, GS-red, and CC-red-edge bands, respectively. The INSEY values at the 16th leaf growth stage exhibited the highest values of R^2, and were approximately 15.7%, 16.9%, and 17.1% higher than what was obtained at the 20th leaf growth stage using CC-red-edge, GS-red, and CC-red, respectively (Figure 3.2 a, b, and c).

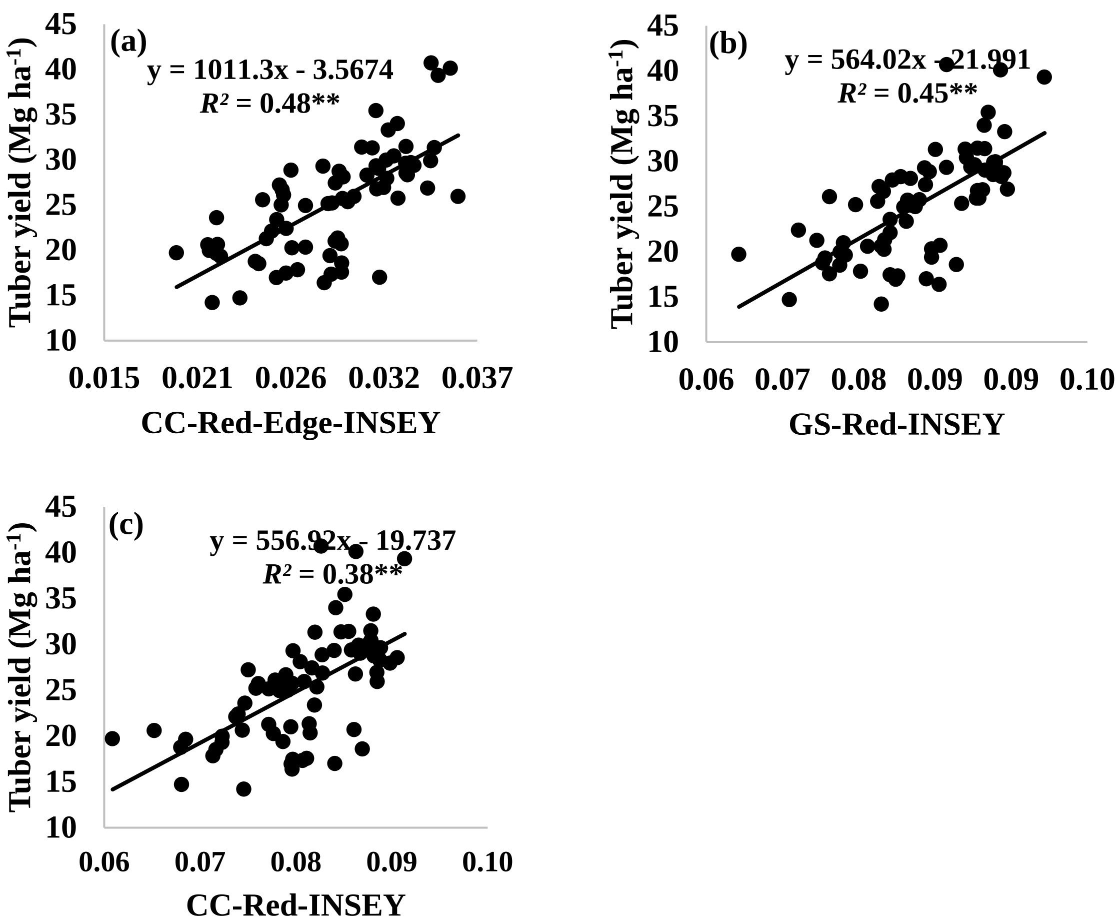


Figure 3.2. The relationship between potato yield in the sites with OM content ≤ 30 g kg^{-1} and sensors data, INSEY, that (a) derived from CC-red-edge band at 16th leaf growth stage,

(b) obtained from GS-red band at 16th leaf growth stage, and (c) obtained from CC-red band at 16th leaf stage. ** denotes P<0.01 level.

3.4.3.2 Sites with ≥ 30 g kg^{-1} of Organic Matter

The measured INSEY values could explain the yield variation and predict the in-season yield of potatoes with R^2 values of 0.25, 0.27, and 0.36 at $p < 0.01$ for INSEY that were derived from GS-red, CC-red, and CC-red-edge bands respectively. The INSEY values at the 20th leaf growth stage exhibited the highest value of R^2, and were approximately 3.9%, 20.4%, and 5.4% higher than what was obtained at the 16th leaf growth stage using GS-red, CC-red, and CC-red-edge, respectively (Figure 3.3 a, b, and c)

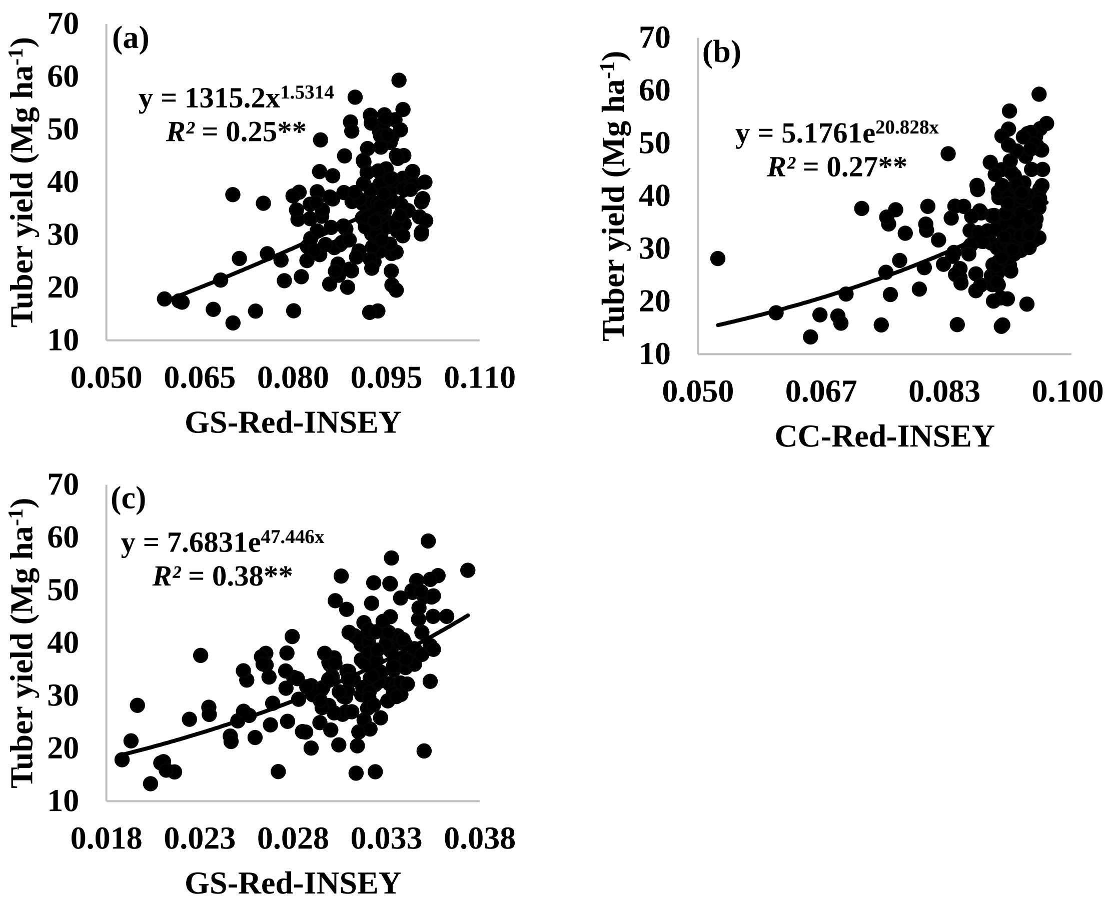


Figure 3.3. The relationship between potato yield in the sites with OM content ≥ 30 g kg^{-1} and sensors data, INSEY, that (a) derived from GS-red band at 20th leaf growth stage, (b) obtained from CC-red band at 20th leaf growth stage, and (c) obtained from CC-red-edge band at 20th leaf growth stage. ** denotes P<0.01 level.

3.4.3.3 All Sites Combined

The results of the regression analysis between potato yield and sensor data for all sites combined showed there was a significant association that could be utilized to predict the in-season potato yield. The R^2 values were 0.25, 0.28, and 0.38 at $p < 0.01$ for INSEY values that were derived from CC-red, GS-red, and CC-red-edge bands, respectively. The INSEY values at the 20th leaf growth stage exhibited the highest values of R^2 and were approximately 50%, 80%, and 30% higher than what was obtained at the 16th leaf growth stage using CC-red, GS-red, and CC-red-edge, respectively (Figure 3.4 a, b, and c).

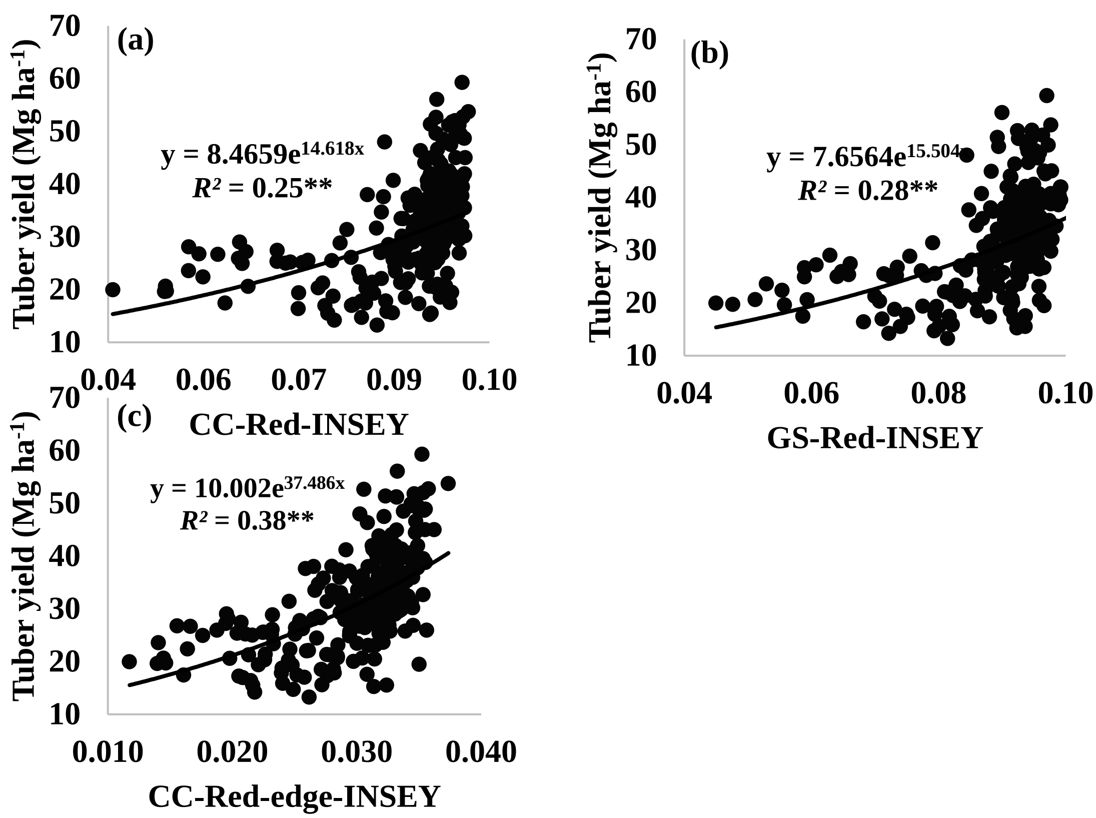


Figure 3.4. The relationship between potato yield in the sites with all sites combined and sensors data derived from (a) CC-red band at 20th leaf growth stage, (b) GS-red band at 20th leaf growth stage, and (c) CC-red-edge band at 20th leaf growth stage. ** denotes P<0.01 level.

3.4.4 Chlorophyll Measurements to Predict Yield

Pearson correlation analysis showed that CI measurements had a significant relationship with the potato yield in all sites at the 16th and 20th leaf growth stage ($P < 0.01$). However, the *r* values were relatively lower in the early growth stages. The highest *r* value (0.48) at the sites with ≤ 30 g kg^{-1} of soil OM content was achieved at the 16th leaf growth stage (Figure 3.5 a) while the sites that had ≥ 30 g kg^{-1} of soil OM content showed the highest *r* value (0.38) at the 20th leaf growth stage (Figure 3.5 b). In the case of all sites combined, a significant correlation was observed at the 20th leaf growth stage ($r = 0.41$) (Figure 3.5 c).

The regression analysis between potato yield as a dependent variable and CI as an independent variable showed that there was an applicable relationship that could be utilized for in-season yield prediction measurements. The significant linear relationship between potato yield and CI was more significant than the yield prediction model based on NDVI measurements. The exponential model showed the best fit for the relationship between potato yield and CI, especially for the sites characterized by ≥ 30 g kg^{-1} of soil OM content and also the combined sites. However, the linear model showed the best fit for the relationship in the sites characterized by ≤ 30 g kg^{-1} of soil OM content.

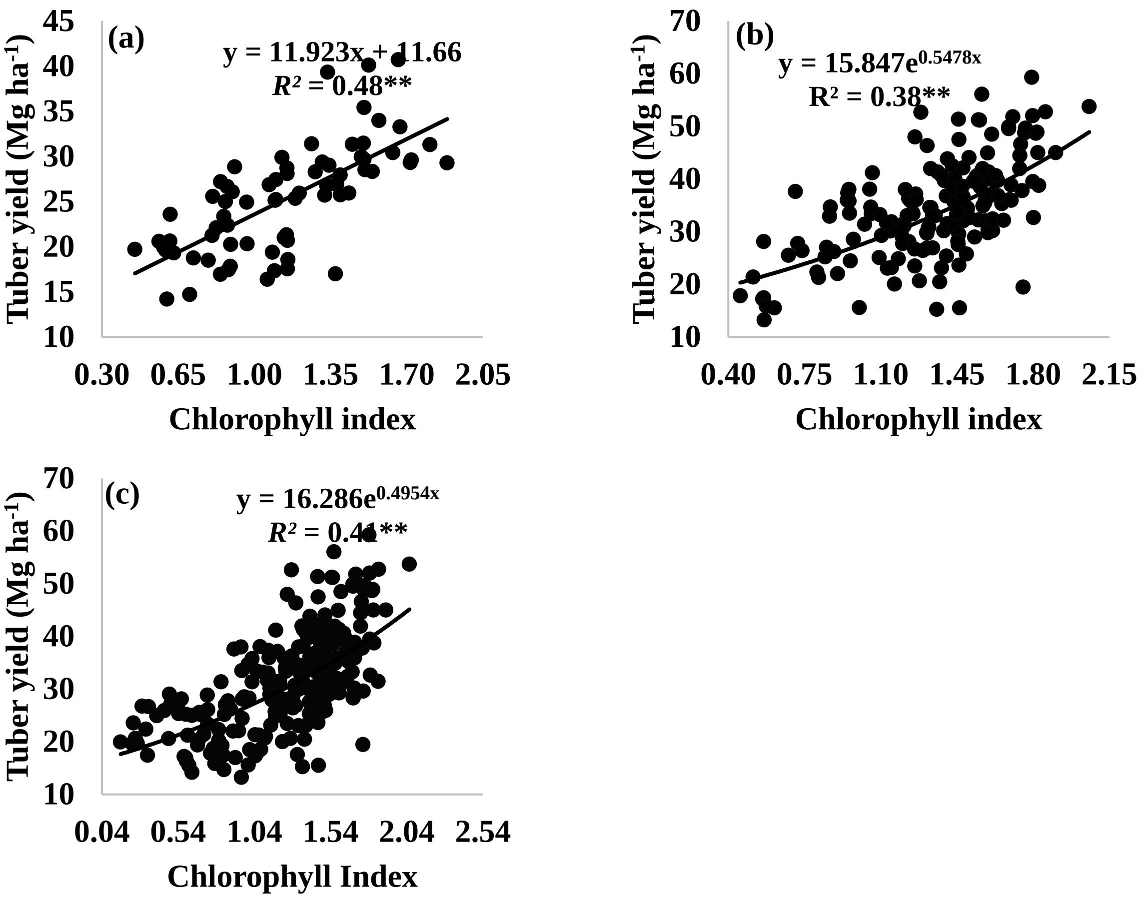
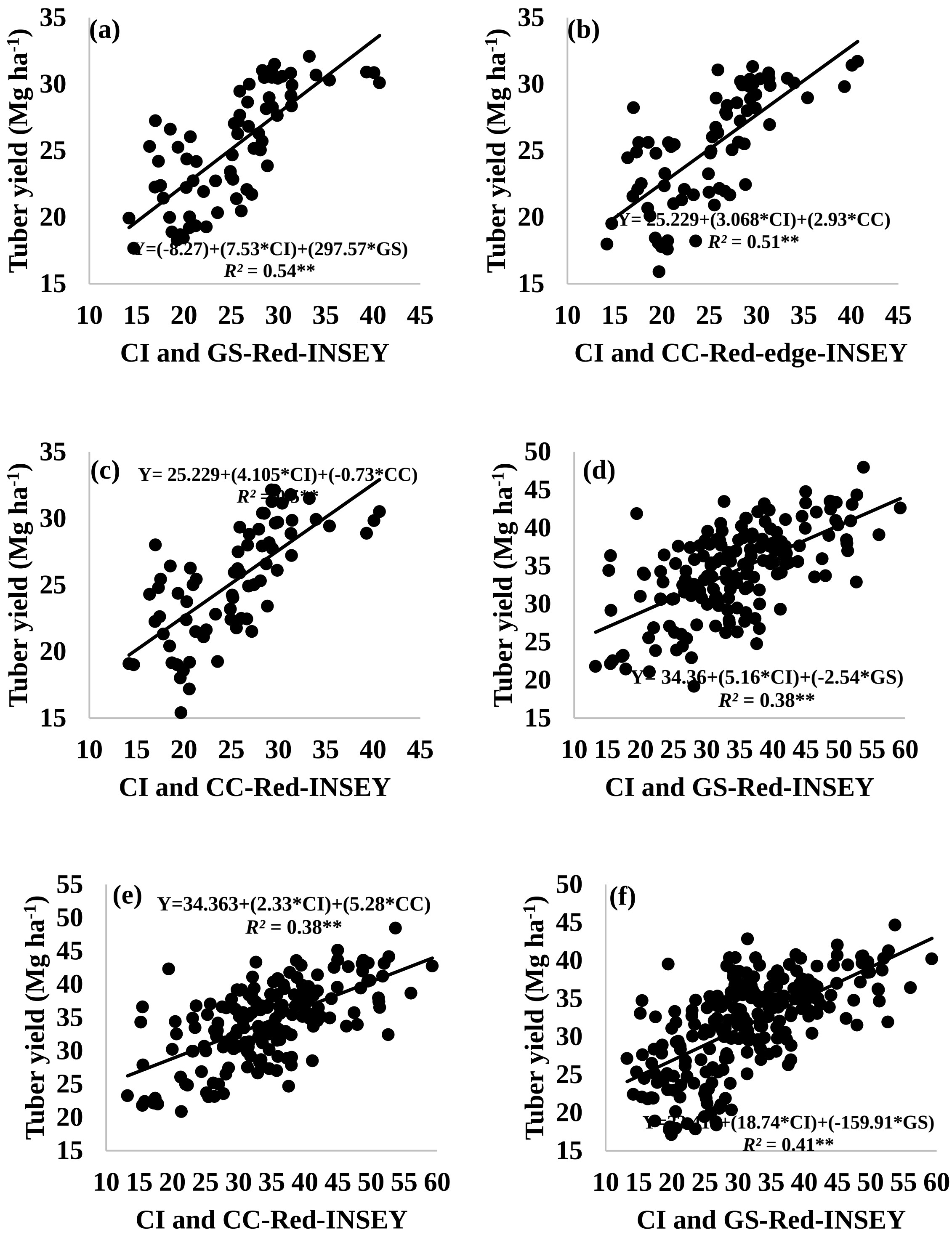


Figure 3.5. The relationship between potato yield and chlorophyll index in the site (a) with ≤ 30 g kg^{-1} of soil OM at 16th leaf stage, (b) with OM content ≥ 30 g kg^{-1} of soil OM at 20th leaf stage, (c) all sites combined at 20th leaf stage. ** denotes P<0.01 level.

3.4.5 Chlorophyll Measurements to Enhance Yield Prediction Efficiency

The CI and NDVI measurements as independent variables enhanced the algorithm of potato yield prediction. Multiple regression analysis results showed that at the 16th and 20th leaf growth stages, there were improvements in the R^2, whether at the classified (≥ 30 g kg^{-1}, ≤ 30 g kg^{-1} of soil OM) or combined sites. However, the sites with ≤ 30 g kg^{-1} of OM were the only sites that did not show a significant relationship at the 20th of leaf growth stage, where R^2 improved up to 0.54**, 0.52**, and 0.50** when using GS-red, CC-red-edge, and CC-red, respectively, and VIF 2.0, 1.0, and 1.0 respectively (Figure 3.6 a, b, and c).

In the sites with ≥ 30 g kg^{-1} of OM, CI improved the R^2 up to 0.38** and 0.38** and VIF up to 1.0 and 1.0 when using GS-red and CC-red, respectively, but there was no improvement with CC-red-edge (Figure 3.6 d and e). At the all combined sites, CI improved the R^2 for GS-red, CC-red, and C-red-edge by 0.41**, 0.41**, and 0.43** respectively; VIF values were 4.0, 1.0, and 1.0, respectively (Figure 3.6 f, g, and h).


(a)
Y=(-8.27)+(7.53*CI)+(297.57*GS)
R^2 = 0.54**
Tuber yield (Mg ha-1)
CI and GS-Red-INSEY
(b)
Y= 25.229+(3.068*CI)+(2.93*CC)
R^2 = 0.51**
Tuber yield (Mg ha-1)
CI and CC-Red-edge-INSEY
(c)
Y= 25.229+(4.105*CI)+(-0.73*CC)
Tuber yield (Mg ha-1)
CI and CC-Red-INSEY
(d)
Y= 34.36+(5.16*CI)+(-2.54*GS)
R^2 = 0.38**
Tuber yield (Mg ha-1)
CI and GS-Red-INSEY
(e)
Y=34.363+(2.33*CI)+(5.28*CC)
R^2 = 0.38**
Tuber yield (Mg ha-1)
CI and CC-Red-INSEY
(f)
+(18.74*CI)+(-159.91*GS)
R^2 = 0.41**
Tuber yield (Mg ha-1)
CI and GS-Red-INSEY

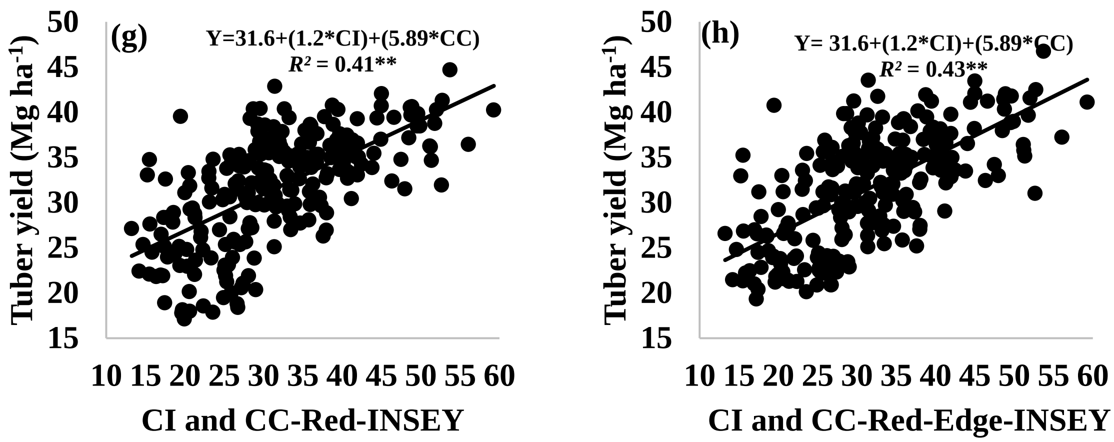


Figure 3.6. The multiple regression relationship between potato yield as the dependent variable with CI and INSEY as independent variables in the (a) sites ≤ 30 g kg^{-1} of OM using GS-red, (b) sites ≤ 30 g kg^{-1} of OM using CC-red-edge, (c) sites ≤ 30 g kg^{-1} of OM using CC-red, (d) sites ≥ 30 g kg^{-1} of OM using GS-red, (E) sites ≥ 30 g kg^{-1} of OM using CC-red, (f) combined sites using GS-red, (g) combined sites using CC-red, and (h) combined sites using CC-red-edge. ** denotes P<0.01 level.

3.4.6 Model Validation

To validate the yield prediction models, a correlation analysis was conducted between actual tuber yield and predicted yield for each sensor used (CC and GS). The results of the correlation analysis were positive and significant, implying that the relationship between the actual yield and predicted yield for all the models was strong (Table 3.2). Each model predicted the yield under field conditions despite uncertain environmental conditions such as pest damage, high temperature, and water stress. The correlation values confirm that the capability of the sensor was strong with regard to potato yield prediction, particularly red-edge wavelength that excelled over all the wavelengths in comparison to red wavelength. In general, the correlation coefficient showed higher values with lower values of root mean square error (RMSE) when using the CC sensor with each wavelength band (red and red-edge) in comparison with the GS sensor, which showed lower values of the correlation coefficient. However, multiple regression was different from simple regression, where the correlation coefficient values were high when using all sensors with insignificant differences between them.

Table 3.2. Coefficient of correlation and root mean square error for the model validation, the relation between actual and predicted potato yield.

Sites	Plant Index	Monitoring Stage	*R*	RMSE
≤ 30 g kg^{-1} OM	GS-red-INSEY	16^{th}	0.67^{**}	4.35
≤ 30 g kg^{-1} OM	CC-red-INSEY	16^{th}	0.61^{**}	4.64
≤ 30 g kg^{-1} OM	CC-red-edge-INSEY	16^{th}	0.69^{**}	4.23
≤ 30 g kg^{-1} OM	GS-red+CI-INSEY	16^{th}	0.74^{**}	3.88
≤ 30 g kg^{-1} OM	CC-red+CI-INSEY	16^{th}	0.71^{**}	4.07
≤ 30 g kg^{-1} OM	CC-red-edge-INSEY+CI	16^{th}	0.72^{**}	3.99
≥ 30 g kg^{-1} OM	GS-red-INSEY	20^{th}	0.44^{**}	8.32
≥ 30 g kg^{-1} OM	CC-red-INSEY	20^{th}	0.49^{**}	8.11
≥ 30 g kg^{-1} OM	CC-red-edge-INSEY	20^{th}	0.60^{**}	7.43
≥ 30 g kg^{-1} OM	GS-red+CI-INSEY	20^{th}	0.62^{**}	4.72
≥ 30 g kg^{-1} OM	CC-red+CI-INSEY	20^{th}	0.62^{**}	4.67
≥ 30 g kg^{-1} OM	CC-red-edge-INSEY+CI	20^{th}	0.61^{**}	4.66
All-combined	CC-red-INSEY	20^{th}	0.49^{**}	8.20
All-combined	CC-red-edge-INSEY	20^{th}	0.61^{**}	7.46
All-combined	GS-red-INSEY+CI	20^{th}	0.64^{**}	3.33
All-combined	CC-red-INSEY+CI	20^{th}	0.66^{**}	3.22
All-combined	CC-red-edge-INSEY+CI	20^{th}	0.64^{**}	3.31

GS: GreenSeeker active sensor, CC: Crop circle active sensor, red: red wavelength, red-edge: red-edge wavelength, CI: chlorophyll index, INSEY: (NDVI/growing degree days from planting date), r: correlation coefficienet, **: denotes significance at 0.01 probability level, RMSE: root mean square error.

3.5 DISCUSSION

Potato yield responded to the different N rates significantly. There was a clear difference between the treatments of 0 kg ha^{-1} of N and the series of N rates at all sites. Nitrogen treatments of 0 kg ha^{-1} showed the lowest yield in comparison with other N rates. Potato yield increased with increasing N rates up to 168 kg ha^{-1}, after which potato productivity decreased gradually regardless of a continual supply of N. This is consistent with the findings of other studies which suggested that the over-application of N fertilizer would not incearese yield, but that it couldlead to high N losses (Ju et al., 2009; Ju et al., 2011). A reduction in yield observed in all groups (≤ 30 g kg^{-1} of soil OM, ≥ 30 g kg^{-1} of soil OM, and all combined sites) could be a result of delayed tuber growth and increased vegetative growth (leaves and stems) in comparison to tuber growth.

The excessive amount of N applied encouraged a dense vegetative growth, which in turn reduced the amount of carbohydrates that were expected to be available for uptake by the tubers. As a result, photosynthesis supported the leaves of the plant more than the tubers leading to reduced tuber quality (Porter and Sisson, 1989; Ahmed et al., 2009). Therefore, timely prediction of yield in the growing season would help to manage the accurate application of N fertilizer and achieve maximum economic yields.

In this study, Pearson correlation analysis showed that NDVI measurements had a significant positive relationship with the potato yield (Table 3.2) at the 16^{th} and 20^{th} leaf growth stages, indicating that the active sensors had great potential to be utilized for potato yield prediction. At the early stage (before July), the temperature was relatively low, and the growth rate was minimal. Consequently, nutrient uptake was relatively low, and this stage did not fully develop potato biomass. After the middle stage of growth (late July), the growth of potatoes accelerated significantly, and it was the appropriate stage for the collection of reliable sensing data. However, at a later stage (mid to late August) close to maturity, the relationship seemed stable but weak, and the potato plant started wilting and turneda yellowish color. Thus, sensing time is crucial for predicting potato yield.

Linear and non-linear regression analyses were utilized in past studies to predict crop yields in-season (Raun et al., 2005; Cao et al., 2015). In this study, the best fit of the curves was observed with the linear and exponential equations. The linear model represented the curves in the data generated from sites with ≤ 30 g kg^{-1} of soil OM, while sites with ≥ 30 g kg^{-1} of OM were represented by the exponential model, Xu et al. (2012) mathematically defined the linear function as one that is increasing at a constant rate as x increases, while the exponential function is one that increases at a rate that is always proportional to the rate of the function. Therefore, soils with low OM content depend totally on N fertilizer applications and, any N deficiency might have an innediate effect on plant growth . Soils with high OM content can support plant growth even if there is a deficiency or short stress in the soil nutrients. Besides, a similar change pattern was observed with the R^2 values during the growing seasons. The difference in the trend of leaf chlorophyll index as a function of sampling date during the growing season agrees with the observations of (Botha et al., 2006). This difference is due to canopy enlargement and the partitioning of N between the canopy and the tubers (Millard and Marshall, 1986).

The apparent decrease in the canopy N content, accompanying the rapid onset of tuber bulking, may describe the low chlorophyll content of the leaves. This decrease was not observed in the sites ≥ 30 g kg^{-1} of OM at the 20^{th} leaf stage, possibly because the high content of OM supplied more nutrients which extended the growing season compared to ≤ 30 g kg^{-1} of OM which exhibited an association at the 16^{th} leaf growth stage more than 20^{th} leaf growth stage.

The association between potato yield and each of INSEY and CI that derived from NDVI red-edge wavelength is more than INSEY derived from NDVI-red wavelength, which attributed to the chlorophyll saturation condition at that growth stage. The sensor light penetrates the leaf deeply when using the red-edge wavelength compared to the red wavelength. During the photosynthesis process, approximately 80% of incident light absorption was observed between 400 and 700 nm (Moss and Loomis, 1952). Thus, light in the red-edge spectra is more sensitive to changes in chlorophyll content than other wavelength bands (A. Gitelson et al., 2003). The red band can measure plant biomass, but it is sensitive to a low range of chlorophyll content (3-5 µg cm^{-2}), while the red-edge band is sensitive to a wide range of chlorophyll (0.3-45 µg cm^{-2}) (Gitelson and Merzlyak, 1997). This property helped to overcome a saturation problem that happens at the end of the growing season, where there is a considerable density of plant biomass.

3.6 CONCLUSION

Nitrogen treatments of 168 kg ha^{-1} increased the average fresh tuber production to maximum yield. Excessive N (more than 168 kg ha^{-1}), did not significantly increase tuber yield. Soil OM played a significant role in improving potato yield due to valuable benefits that support soil chemical, physical, and biological characteristics.

Soil OM content did not influence prediction calculations and the N rate required for maximum potato yield. Still, there was a considerable difference in potato yield in comparison to sites with $\leq$ 30 g kg^{-1} of OM. The results of the correlation analysis between potato yield and remote sensing data during the growing season indicated that the 16th and 20th leaf growth stages are the optimum time to use these indices for yield prediction. Chlorophyll index either individually, or jointly with other spectral vegetation indices (INSEY) enhanced the determination coefficient of the prediction model better than using the INSEY data separately. The INSEY obtained from the red-edge wavelength, compared to the INSEY that was obtained from the red band, was shown to be the most effective method to overcome the saturation condition caused by heavy canopy density. Further research is required to generalize the results for other varieties of potato. Additionally, furture research should be conducte under irrigated systems to study the effect of soil moisture on yield and chlorophyll content.

CHAPTER 4

DEVELOPING NITROGEN FERTILIZER RECOMMENDATIONS FOR POTATO CROP USING ACTIVE OPTICAL SENSORS

4.1. ABSTRACT

The use of active optical sensors to measure nitrogen (N) application rates in crop production has received increasing acceptance by growers in the past decade; nevertheless, the technology has yet to adopt for the potato crop (*Solanum tuberosum* L.) production. This research was conducted in Maine to determine whether active optical sensors can be utilized to generate an algorithm for N recommendation for the potato crop. Three potato cultivars, Russet Burbank, Superior, and Shepody, were planted, and six rates of N (0, 56, 112, 168, 224, and 280 kg ha^{-1}), ammonium sulfate, which replaced by ammonium nitrate in the second year, were applied on eleven sites in a randomized complete block design with four replications. All sites depend on the rainfed system. Normalized difference vegetation index (NDVI) measurements were obtained weekly from the active optical sensors, GreenSeeker (GS) and Crop Circe (CC). Sensors measurements obtained at the 20^{th} of the leaf growth stage were significantly correlated (exponential model) with tuber yield. Conventionally, the rate of 168 kg ha^{-1} produced the maximum potato tuber yield. Sites with ≥ 30 g kg^{-1} of soil organic matter (OM) content produced yield 39.45% higher than the sites with ≤ 30 g kg^{-1} of OM. Nitrogen rate calculated based on in-season sensors reading is saving approximately 12-14% from the total N rate that growers used to apply, the conventional procedure. Studying cultivars separately in soils ≥ 30 g kg^{-1} and ≤ 30 g kg^{-1} of OM can improve the algorithm accurately with considering to potato cultivar and soil OM content.

4.2 INTRODUCTION

It has been an established fact that excessive application of N fertilizer to the potato crop causes low tuber production due to excessive vegetative growth, lower tuber quality (low specific gravity, large size with hollow heart, delay in maturity, etc.), and lower N use efficiency (NUE) that causes the leaching of a large part of N to groundwater and leads to a high risk of environmental contamination of the atmosphere by nitrous oxides and water by nitrate, etc. (Errebhi et al., 1998; Alva, 2004). An N deficiency, in contrast, can considerably decrease crop yield. Furthermore, the potato production system is well known for low NUE, varying between 50 and 60% (Tyler et al., 1983; Dilz, 1988), and this could be due to shallow and poorly developed root systems. Typically, loss of N occurs when mineral N (NH_4^+ and NO_3^-) is present in the soil, in amounts higher than plant requirements (Johnson and Raun, 1995). Consequently, inadequate synchronization between soil N supply and crop demand is one of the main reasons for low N fertilizer use efficiency (Raun and Johnson, 1999; Cassman et al., 2002; Thind et al., 2011; Ali et al., 2015).

Potato growers in developed countries are under immense pressure to keep profitability against new environmental restrictions, such as the commitment to the EU nitrate directive (91/676/EEC) and a recent increment in N fertilizer prices, to motivate them for precise input management. Nevertheless, having adequate food supplies at a global level is a challenge that cannot be achieved without fertilizer application (Tilman et al., 2002). In such a context, it is a necessity to develop instruments and strategies for potato growers that could help them to determine “the right N fertilizer rate at the right time and place.” It is generally acknowledged that a temporary field-specific N recommendation for potato at planting time can never be accurate. Furthermore, it is difficult to predict crop N requirements during the growing season (Vos and

MacKerron, 2000) due to numerous predictable or unpredictable factors, such as chemical, physical and biological soil characteristics, soil organic matter, cultural practices, crop maturity time, and weather conditions.

Nitrogen fertilization recommendation with estimated requirements during crop growing seasons can largely aid in matching crop N requirement times and rates with supplies. Accordingly, N fertilizer efficiency can be improved (Vos and MacKerron, 2000; Alva, 2004). Precision agriculture technology allows growers to apply the right quantity of fertilizer in real-time based on the crop's current growth status without negatively affecting the final yield. A modeling strategy (N recommendation at field-specific scale) of crop N status monitoring can lead to helpful decision-support methods to enhance N fertilizer use efficiency. It has been found that the approach of using crop N status assessment to determine crop demands is more reliable than predicting the available soil N supply (Sharma, 2014). Plants are often considered a good indicator (mirror) of growing conditions (Sharma and Bali, 2017).

Most of the available crop monitoring techniques depend on the magnitudes of reflected light above the crop canopy (Sharma et al., 2015). A remote sensing approach can be performed at several spatial scales: ground-based, airborne, or space-borne (Tremblay, 2004b; Jongschaap, 2006). All these scales focus on measuring plant canopy formation factors, such as the leaf area index (LAI) and leaf chlorophyll, among others, with well-established science that these factors are strongly related to each other as well as plant N status (Lakesh Sharma et al., 2017). The most common precision agriculture tools used for grain crops, such as corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and sunflower (*Helianthus annuus* L.), among others, are ground-based active optical sensors such as GS, Cropscan, N-sensor, and Holland CC (Bu et al., 2016). The GS and CC are the most prevalent ground-based sensors in North America for research and commercial use.

GreenSeeker (GS) has been widely used for developing N recommendations (Lakesh Sharma et al., 2017), and with which an algorithm for wheat crop increased nitrogen use efficiency by more than 15% (Govender et al., 2007). In another study in Oklahoma, the coefficient of variation (CV) from NDVI data was used to evaluate plant density in wheat (Bronson et al., 2003). Similar techniques used in wheat and rice (*Oryza sativa* L.) grown in Northwest India and attained higher NUE compared with the conventional methods (Franzen et al., 2014; Lakesh Sharma et al., 2017). The CV was further used to adjust the algorithm in wheat (Felton et al., 2002). Another algorithm was developed for rice using in-season N uptake, which not only increased the NUE but yields as well (Blackmer et al., 1996).

Crop characteristics have been used in various methods to calculate optimum N requirements (Franzen et al., 2014). Several other research studies have used plant biomass (Felton et al., 2002; Bronson et al., 2003) and plant N content (Blackmer and Schepers, 1996; Bronson et al., 2003) to determine N requirements. Spectral measurements have also been used to determine yield potential (YP0) (Raun et al., 2001; Teal et al., 2006). Yield potential is a function of the growing environment (Johnson, 1991) and is an important part of fertilizer N calculation methods. The YP0 has been predicted in-season utilizing optical sensors (Sharma et al., 2016). In addition, the NDVI has been used to determine in-season estimated yield (INSEY) (Sharma et al., 2016), which is a measurement of biomass produced per day as NDVI; (Large, 1954) divided by number of growing degree days (GDD), as show in equation (1)

$$GDD = \left[\frac{T_{max} + T_{min}}{2} - 4.4^{\circ}C\right] \quad (1)$$

A few studies have utilized active optical sensors to predict leaf N content (Herrmann et al., 2010; Basyouni and Dunn, 2013) and yield (Lakesh Sharma et al., 2017); however, none of those studies developed an algorithm for N recommendations for potato crops. Therefore, the purpose of this study was to use the data of active optical sensors (NDVI) to develop N recommendation and compare it with what potato growers commonly applied in Maine, USA.

4.3 METHODS

4.3.1 Measurements

4.3.1.1 Active Sensors and Data Collection

Active optical sensors (GS and CC) were used to collect NDVI data weekly, where sensing started once plants completed the fourth leaf. The NDVI data has been normalized by calculating in-season yield estimation (INSEY) and then combined according to leaves number as growth stage, which has counted during each date of sensing. Data collection was continued until completing the twentieth leaf stage. After that, plants start laying down, and greenness declines, preparing to enter the maturing stage. Table 4.1 shows how sensors provided NDVI data during walk-throughs of plant rows; due to the long Excel columns, the table has been truncated to show the beginning and end of the data series. Table 4.1 a shows the beginning of collecting data, while (Table 4.1 b) with a marked row represents a new data collection for the next plot in the RCBD.

Table 4.1. Data (NDVI) collected from active optical sensor GS, a) when starting a new plot, b) copleting the first plot and begingning the next one, Column C shows that there are 62 readings for the first plot.

(a) A	B	C	D
Time	Plot	Count	NDVI
437010	27	1	0.689
437110	27	2	0.798
437210	27	3	0.829
437310	27	4	0.832
437410	27	5	0.852
437510	27	6	0.722
437610	27	7	0.828
437710	27	8	0.847
437810	27	9	0.851
437910	27	10	0.871
438010	27	11	0.855
438110	27	12	0.871
438210	27	13	0.864
438310	27	14	0.842
438410	27	15	0.838
438510	27	16	0.856
438610	27	17	0.866
438710	27	18	0.865
438810	27	19	0.881
438910	27	20	0.878
439010	27	21	0.856
439110	27	22	0.878
439210	27	23	0.872
439310	27	24	0.876
439410	27	25	0.861
439510	27	26	0.811
439610	27	27	0.874
439710	27	28	0.845
439810	27	29	0.828
439910	27	30	0.809
440010	27	31	0.815
440110	27	32	0.854
440210	27	33	0.828
440310	27	34	0.809
440410	27	35	0.815

(b) A	B	C	D
440510	27	32	0.854
440610	27	33	0.828
440710	27	34	0.815
440810	27	35	0.864
440910	27	36	0.847
441010	27	37	0.856
441110	27	38	0.868
441210	27	39	0.875
441310	27	40	0.837
441410	27	41	0.839
441510	27	42	0.853
441610	27	43	0.842
441710	27	44	0.795
441810	27	45	0.836
441910	27	46	0.769
442010	27	47	0.43
442110	27	48	0.256
442210	27	49	0.258
442310	27	50	0.256
442410	27	51	0.456
442510	27	52	0.514
442610	27	53	0.589
442710	27	54	0.682
442810	27	55	0.764
442910	27	56	0.668
443010	27	57	0.767
443110	27	58	0.689
444610	27	59	0.874
444710	28	60	0.821
444810	28	61	0.878
444910	28	62	0.787
445010	28	1	0.846
445110	28	2	0.847
445210	28	3	0.846
445310	28	4	0.835
445410	28	5	0.819

4.3.1.2 Sensor Description and Sensing Procedure

Two handheld active optical sensors, GS (Trimble Navigation Limited, Sunnyvale, CA, USA) and CC (A-470 sensor Holland Scientific, Inc., Lincoln, NE, USA) were utilized for this research. The GS sensor measures incident and reflected beams from the plant canopy at a wavelength in the ranges of 660 ± 15 nm (R) and 770 ± 15 nm (NIR), respectively (Sharma et al., 2015).

In GreenSeeker, a beam is transmitted from electric diodes at different times, such that the visible source pulses for 1.0 ms, and then the NIR diode source pulses for 1.0 ms at 40,000 Hz. The light covered area is about 60 cm in width by 1.0 cm in length, with a long dimension positioned vertically to the direction of running.

The CC sensor emits three bands; R 650 nm, red-edge 730 nm, and NIR 760 nm. The sensor collects about 2–20 readings per second, so with each recorded value in a 6.0 m plot length, while walking about 5.0 km·hr-1, there is an average of about 4000 readings. Sensor outputs are reflectance values that allow the calculation of vegetation indices The NDVI involves R and red-edge bands, which is different from the G(Sharma et al., 2015).

The equation for red-NDVI and red-edge NDVI are as follows:

$$\text{Red NDVI} = \frac{NIR - Red}{NIR + Red} \qquad (2)$$

$$\text{Red Edge NDVI} = \frac{NIR - Red\ Edge}{NIR + Red\ Edge} \qquad (3)$$

The GS emits two bands: red (660 nm) and NIR (774 nm), with the equation as follows:

$$\text{NDVI} = \frac{(774\ nm - 660\ nm)}{(774\ nm + 660\ nm)} \qquad (4)$$

CC emits three bands: R (670 nm), red-edge (730 nm), and NIR (760 nm):

$$\text{NDVI} = \frac{(760\ nm - 670\ nm)}{(760\ nm - 670\ nm)} \qquad (5)$$

or red edge NDVI

$$\text{NDVI} = \frac{(760\ nm - 730\ nm)}{(760\ nm + 730\ nm)} \tag{6}$$

Both sensors, GS and CC, were used weekly during the growing season, which started immediately once plants completed the fourth leaf, (4, 8, 10, 12, 16, and 20). Readings were obtained 60 cm over the top of a potato plant from the middle row of each plot. About 40–60 readings were obtained from every single experimental unit. In-house macro programs for Visual Basic and Excel were used to calculate the means of sensing-data(Franzen, 2012).

Due to the small differences in the growth stages between sites, NDVI data were normalized using the INSEY approach. The in-season estimate of yield (INSEY) could be particularly useful when combining NDVI data from different site-years. The in-season estimate of yield (INSEY) (Raun et al., 2001) was computed by dividing NDVI data with the GDD that started from the planting date to the date of taking sensor readings (United States Climate Data, 2018) to calculate weather data, as shown in equation (7).

$$\text{GDD} = \left[\frac{T_{max} + T_{min}}{2} \right] - \text{C} \tag{7}$$

where Tmax and Tmin represent the daily maximum and minimum temperature and C represents the base growing temperature for potato, which is 10°C. Sensing was conducted by placing the GS and CC at an approximate distance of 60 cm above the plant canopy, resulting in a similar magnitude of reflectance at all sites and each growth stage (Franzen, 2012).

4.3.2 Data Analysis

Analysis of variance (ANOVA) was conducted to evaluate the effect of nitrogen rates on potato tuber yield by using SPSS software. Microsoft Excel was used to plot the relationships between potato tuber yields and a series of nitrogen rates. The bar graph (Figure 1) shows the difference between the control treatment (0 N kg ha^{-1}) and other treatments in addition to the N rate that maximized the potato yield and the rate after which potato yield did not respond significantly. Regression analysis was conducted between potato yield and sensors data (INSEY) to generate models for yield prediction.

4.4 RESULTS AND DISCUSSION

Large differences were noticed among yield data from the 11 sites. Therefore, a multiple regression analysis was conducted (data not shown) between soil properties and yield, where OM was found to be the main factor that had a high correlation with crop yield (Figure 2.1) (R^2= 0.78**) at P <0.01. Therefore, all sites were divided into ≤30 g kg^{-1} and ≥30 g kg^{-1} of soil OM. The sites NS-1, NS-2, FV, CA1, CA2, CA3, LM, and WD were classified as ≥30 g kg^{-1} OM, while AF1, AF2, and AF3 were classified as ≤30 g kg^{-1} OM. It is important to note that the ‘Shepody’ and ‘Superior’ potato cultivars had only one site each that came under ≤30 g kg^{-1} OM.

4.4.1 Yield Responses to Nitrogen Rates

Potato yields at different N rates are shown in (Figure 3.2), which shows the ANOVA results between N rates and potato yields for sites that have ≤ 30 g kg^{-1} of OM, ≥ 30 g kg^{-1} of soil OM, and an average of all sites combined. The yield of potato significantly improved with N fertilizer applications in all abovementioned sites. Compared with the control treatment, 0 kg N ha^{-1}, the yields under 56, 112, 168 kg ha^{-1} treatments were increased by 10.8%, 20.7%, and 18.46%, respectively, for 56 kg N ha^{-1}; 13.3%, 28.8%, and 25.4% respectively for 112 kg N ha^{-1}, 21.7%, 42.7%, and 37.7% respectively for 168 kg N ha^{-1}. For all sites, potato yields increased as N rate increased from 0 kg N ha^{-1} to 168 kg N ha^{-1}. Still, no significant increase was witnessed for 224 kg N ha^{-1}, implying that 168 kg N ha^{-1} was the maximum economic rate for potato production.

4.4.2 Procedure #1 For Nitrogen Recommendation

4.4.2.1 Generating The "Nitrogen Fertilizer Optimization Algorithm" (NFOA)

Algorithms for managing N rates for numerous crops and regions have been established (Holzapfel et al., 2009). They can be practiced in a sensor-based N rate calculator produced by agronomists at Oklahoma State University to feed in zone-specific sensor data for determining the in-season crop yield and N response index (RI). The algorithm of N rate recommendation for sensor-based information is (Raun et al., 2002), equation (4.10);

$$N_{rate} = \frac{[(YP0 \times RI) - YP0] \times N\%}{\mathrm{NUE}} \qquad \text{(Eq. 4.10)}$$

where YP0 is the maximum achievable crop yield with no applied N.

RI is the response index

N% is the percentage of N in the yield, 0.026 (2.6%)(Ahmed et al., 2009)

NUE: nitrogen use efficiency

4.4.2.2 Yield potential (YP0)

YP0 is defined as the maximum achievable crop yield with no applied N. Considered the backbone of any N fertilizer rate measurements, YP0 can be predicted from the relationship between crop yield and INSEY(Lukina et al., 2001; Raun et al., 2002). The yield potential (YP0) is presented by equation (4.11).

$$YP0 = Ae^{b \frac{\mathrm{NDVI}}{\mathrm{GDD}}} \qquad \text{(Eq. 4.11)}$$

where, A and b represent the intercept and slope, respectively, of the exponential function as a result of the regression analysis between potential yield and INSEY (Raun et al., 2002; Teal et al., 2006). The regression analysis between tuber yield data (kg ha^{-1}) and INSEY reading generated the prediction equation for the YP0, where the coefficient of determination at $p < 0.05$ level was

0.24, and INSEY derived from GS-red data showed a higher significant relationship ($p < 0.05$) than the CC-red and CC-red-edge data, (Figure 4.1).

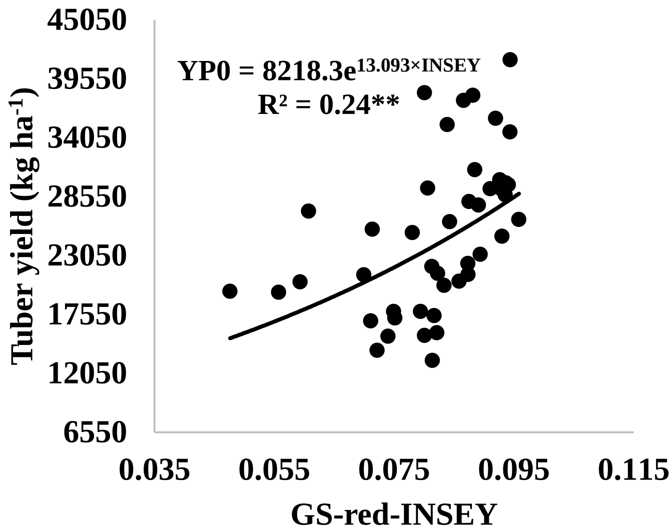


Figure 4.1. **The relationship between potato tuber yield and the sensor reading, INSEY. at p< 0.01.**

4.4.2.3 Response Index

The normalized difference vegetation index (NDVI) readings from the N-rich plot divided by NDVI of the test plot is described as response index (RI) to fertilizer N (Johnson and Raun, 2003). The in-season response index based on NDVI readings from a N-rich reference plot was confirmed to be a viable method in managing N fertilizer for crops (Mullen et al., 2003; Ali and Thind, 2015). Raun et al. (2002) defined the response index (RI) as the ratio of crop yield measured from a non-N limiting plot, which in our case was the plot treated by 280 kg N ha^{-1}, to that of a non-N treated plot, which is the plot that treated by 0 kg N ha^{-1}.

The response index (RI) value indicates the possibility and quantity of increment in crop growth with added N. It is based on the theory that the amount of N to add at a given area can be measured by examining spatial crop growth differences of an N-reference plot (N-rich plot, 280 kg ha^{-1}) to variations of the untreated plot. The nitrogen reference plot is a typical section of an entire field that is sufficiently fertilized to accomplish maximum yield potential. Comparing N-sufficient plot with the non-N treated plot is also essential because the output (crop yield) requires to be normalized (adjusted) to the N-reference plot to consider any color development not related to N stress. Consequently, within the growing season, the magnitude of response to N input can be measured, and the N rate calculated based on potential yield. Also, RI is a remarkable cost-saving information guide to reduce Type II errors by recommending a need to apply N only when crops undoubtedly need it (Johnson and Raun, 2003; Mullen et al., 2003). Hodgen et al. (2005) concluded that when,

$1 < RI < 1.1$, N application will likely be non-responsive

$1.1 < RI < 1.25$, N application will likely be marginally responsive

$RI > 1.25$, N application will be responsive

Where marginal yield response to additional N application means the cost-benefit proportion of yield to added fertilizer is likely expensive, mainly because the market prices of the crop may be meager to yield significant earnings from the 25% yield increment. Whereas most growers are believed to have a good understanding of spatial yield variability in their areas, they are often less knowledgeable to decide how much fertilizer to add or reduce to high or low yielding regions, respectively. RI and INSEY provide this information.

Raun et al. (2002) first defined yield response to applied N as the proportion of crop yield of an N-reference plot to that of a non-N treated plot given by equation (4.12),

$$RI_{\text{Harvest}} = \frac{\text{Yield}_{\text{N-Reference strip}}}{\text{Yield}_{\text{non-treated strip}}} \qquad \text{(Eq. 4.12)}$$

The mean tuber yield produced from N-rich plot (280 kg N ha^{-1}) was 34080.91 kg ha^{-1}, while untreated plots (0 kg N ha^{-1}) produced a mean of 25071.85 kg ha^{-1}. As a result, the response index (RI) was equal to 1.36, which is more than 1.25; this means the N application will result in a response. Raun et al. (2002) stated that the combined advantage of the RI concept and INSEY allowed an accurate top-dressed N rate for wheat. Total grain (yield) N removed from each area is measured, and the difference between the N-rich and farmer's practice values were divided by a calculated NUE factor.

$$RI_{NDVI} = \frac{NDVI_{-Reference\ strip}}{NDVI_{non-treated\ strip}} \qquad \text{(Eq. 4.12)}$$

4.4.2.4 Nitrogen Use Efficiency

The most basic definition of nutrient use efficiency is a crop yield per unit of available nutrients (Swain et al., 2014), while Teboh et al. (2012) defined it as the amount of N input, suggesting that it corresponds to the portion of N taken up to satisfy further yield demands. This information can be used to evaluate the efficiency of nutrient use of a given cropping operation on an annual or multi-year basis. Nitrogen use efficiency (NUE) can be calculated as described by Baligar et al. (2001) as follows, equation (4.13):

$$NUE = \frac{(\text{Crop yield in N fertilized plot} - \text{Crop yield in no N plot})}{(\text{Quantity of N fertilizer applied in N fertilized plot})} \qquad \text{(Eq. 4.13)}$$

Thus, applying the data of potato yield and sensors in equation (4.10) resulted in 195 kg ha^{-1} being the N recommendation for the potato crop, which is about 14% lower than the amount that potato growers have previously applied, 224 kg N ha^{-1}.

4.4.3 Procedure #2 for Nitrogen Recommendation

This procedure differs from procedure number (1) mathematically; however, the materials (yield and sensor data) are still the same. Sharma (2014) used procedure number (2) to generate a N recommendation for corn crop, as in equation (4.14).

$$\text{N rate in kg ha}^{-1} = \frac{[(Yp1 - Yp2) \times N\%]}{NUE} \qquad \text{(Eq. 4.14)}$$

Where:

Y1 is the predicted yield from the N-rich plot in kg ha^{-1}

Y2 is the predicted yield from farmer practice plot in kg ha^{-1}

N% is nitrogen percent in potato tuber, 0.026 (2.6%) (Ahmed et al., 2009)

NUE is the nitrogen use efficiency

As mentioned before, the N-rich plot is the plot that has been provided with full fertilizer in order to be an unlimited N area. Nitrogen (N) at a rate of 280 kg N ha^{-1} was applied to fulfill the N-rich plot, while 224 kg N ha^{-1} was the rate practiced by potato growers in Maine.

A regression analysis between potato tuber yield and sensor data (INSEY) was conducted to generate an algorithm for potato yield prediction at $p < 0.05$. The exponential model was the best to fit that curve for both Y1 and Y2, respectively. The twentieth leaf stage was the time most likely to have a significant relationship between yield data and INSEY. The GS and CC sensors showed a significant relationship with yield data, but the determination coefficient for the CC-red-edge was higher than those for other wavelengths (Figure 4.2 a and b). At the twentieth leaf stage, the plant vegetation density is at the maximum, which is called the NDVI saturation condition.

The red (R) wavelength from GS and CC is sensitive only for a low range of chlorophyll (3–5 µg cm^{-2}) in comparison to the CC red-edge wavelength that is sensitive to a wider range (0.3–45 µg cm^{-2}) (A. Gitelson et al., 2003). As a result, applying the potato yield data of and sensor data in equation (14) resulted in 199 kg ha^{-1} being the N recommendation for potato crops, which is about 12% lower than the amount that potato growers used to apply, 224 kg N ha^{-1}.

Although the coefficient of determination (R^2) was statistically significant but not very strong (0.24, 0.27, and 0.38), it could still be considered as a step toward utilizing active optical sensors for the N recommendation calculation for potato crop. Conducting an experiment at sites with different soil properties is a reason to have representative samples from multiple locations.

However, having a massive gap among sites could be a problem, especially for statistical analysis. That was our problem; there was a considerable gap in the yield data between sites. Classifying or grouping sites is an excellent idea to overcome this issue, but running a regression analysis for a single N rate (0, 224, 280 kg N ha^{-1}) using a few points are considered insufficient. Therefore, conducting the experiment with enough numbers of sites would be the solution to this issue.

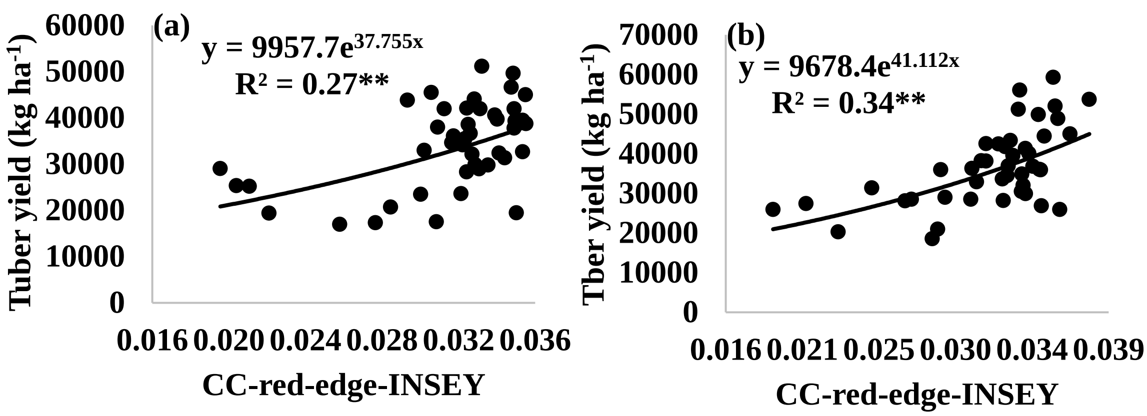


Figure 4.2. Relationship between potato yield and sensor data (INSEY) that used to predict yield potential from the treatments a,) N-rich plot, b) farmer-practicing plot, at p< 0.01.

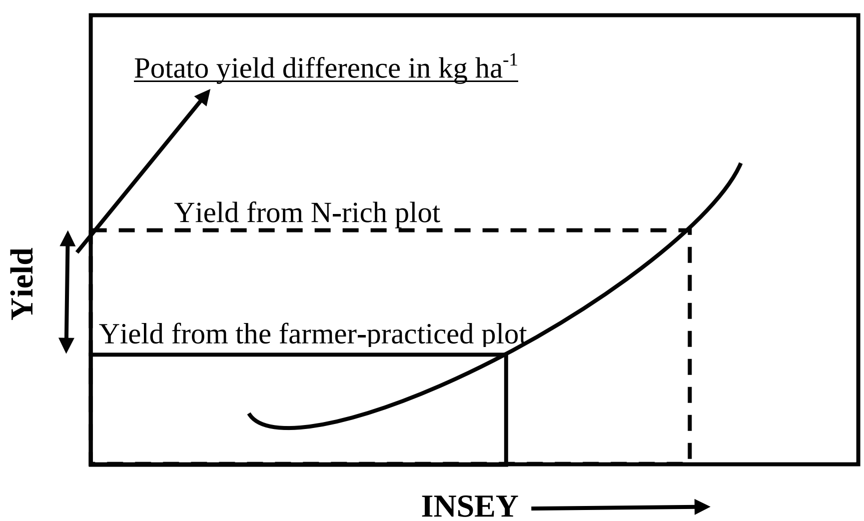


Figure 4.3 The schematic demonstrates how the algorithm of N recommendation works.

4.5 CONCLUSIONS

The calculations from both procedures (1 and 2) proved that the N-recommendation algorithm for potato crop could be generated based on active optical sensors. The sensing time at the twentieth leaf stage has been observed to give a significant estimation of yield. In procedure number (1), the calculation depended totally on the predicted yield from the control treatment (0 kg N ha^{-1}), where there was no chlorophyll saturation issue, so the R wavelength showed a significant relationship with yield data.

In contrast, procedure number (2) calculations depended on the N-rich and farmer-practice plots (280 and 224 kg N ha^{-1}), respectively, where the chlorophyll saturation issue happens commonly, so the red-edge wavelength was the best to overcome this issue, and showed a significant relationship with yield data.

The N-recommendation rates from both procedures (1 and 2) (195 and 199 kg N ha^{-1}), respectively, were lower than the average rate that potato growers in Maine have previously applied annually. Procedure number (1) can save about 14% of the rate that potato growers previously applied, while procedure number (2) can save about 12%. So far, these were useful results and a good step toward utilizing active optical sensors to generate N recommendations. However, to be more accurate, the sites had to be classified into two classes, soil with high organic matter content (>30 g kg^{-1}) and soils with low organic matter content (<30 g kg^{-1}). Conducting the experiment in separate soil types (>30 g kg^{-1} of OM and <30 g kg^{-1} of OM) can help determine whether soil properties have a significant effect on the N-recommendation outcome or not. The same issue holds true for potato cultivars when planting specific cultivars in a particular type of soil, differences can expose whether potato cultivars have significant effects on the N-recommendation outcome.

CHAPTER 5

ECONOMIC AND FERTILITY CONSIDERATIONS OF NITROGEN APPLICATIONS IN POTATO-MAINE

5.1 ABSTRACT

Nitrogen (N) fertilizer rates are commonly selected to maximize yield and therefore economic profit. The most commonly practiced process of estimating N fertilizer requirements, however, does not directly correlate application rates to profits. To determine the optimum N application rates for maximum profit, potato experiments were conducted in Maine on soils with different organic matter (OM) content. Three potato cultivars, Russet Burbank, Superior, and Shepody, were planted, and six N rates (0-280 kg ha^{-1}) (ammonium sulfate and ammonium nitrate) were applied on 11 sites in a randomized complete block design, with four replications. A quadratic model was used to fit the relationship between N rates and tuber yield (R^2=0.96**). Soil organic matter (OM) content supported the total yield but did not reduce the N rate required for production. An N rate of 168 kg ha^{-1} produced the maximum potato yield at all sites. Sites that had high soil OM content (>30 g kg^{-1}) produced a higher tuber yield (47%) than sites with <30 g kg^{-1}. Economic optimum N rate (EONR) calculations showed that 198.2 kg ha^{-1} is the best N rate for economic production for all sites combined, but particularly, 202.9 and 166.9 kg ha^{-1} are the EONR for the sites with >30 g kg^{-1} and <30 g kg^{-1} of soil OM respectively. The maximum return to N (MRTN) was \$14,051 ha^{-1} and \$8,432 ha^{-1} from sites with > 30 g kg^{-1} and <30 g kg^{-1}, respectively. Planting of more sites of each cultivar under different contents of soil OM to study their response to be more specific and accurate regarding EONR is being considered.

5.2 INTRODUCTION

Nitrogen is an essential nutrient that requires precise management in intensive cropping practices because of its various advantageous and deleterious effects (Ju and Christie, 2011). Globally, N has contributed to higher crop yields and economic profits to growers, but it has also been determined that more than 50% of the amount of applied N is still unutilized, leading to losses of billions of US dollars (Raun and Johnson, 1999). Meanwhile, the extensive amounts of N that have drained into the groundwater, or that have been lost into the air (atmosphere) by ammonia volatilization or denitrification (Zhu and Chen, 2002), have contributed negatively to the environment.

In the future, the global application of N fertilizer will have to rise by 110–130%. Accordingly, it is essential to resolve the inconsistencies among yield production, economic profit, and environmental damage, and to devise solutions to develop N management policies agronomically, economically, and environmentally (Cassman and Pingali, 1995; Tilman et al., 2001; Galloway et al., 2004). There is a definite need to improve N fertilizer management for all crops in general for economic and environmental reasons (Morris et al., 2018). Lasting economic feasibility of crop production demands the adoption of proper rates, types, and sources of fertilizers. Crop N demand and soil N supply fluctuate spatially and temporally over the field , making it challenging to predict N application concentrations (Lory and Scharf, 2003; Mamo et al., 2003). Given this ambiguity, growers in North America typically over apply N fertilizer as protection against yield decline, because the price of N fertilizer is low compared to the potential cost of yield decline (Rajsic et al., 2009; Sadeghpour et al., 2017). This creates greater opportunities for N loss, which consequently influences the environment and reduces profitability comparatively to the optimal rate (Scharf et al., 2005).

Substantial experimentation effort has been concentrated on the improvement of recommendation policies to predict variation between indigenous soil N supply and crop N demands, and determine the economically optimal N rate (EONR) (Morris et al., 2018; Puntel et al., 2018). The EONR is described as the N rate at which the last increase of applied N exhibits a yield response of similar monetary profit. Nevertheless, mechanistically, the response model that represents the relationship between the applied N rate and yield is controlled by the gap between crop N demand and soil N supply. While Camberato et al. (2017) defined the EONR as the rate that maximizes dollar profit from the N fertilizer application, because the yield gains from additional N decrease as N rates reach the agronomic optimum N rate (AONR), the EONR will nearly constantly be less than the AONR. The AONR denotes the total amount of N required to maximize crop yield, yet not necessarily maximize profit.

Fontes et al. (2010) applied different rates of N (0- 300 kg ha^{-1}) to four potato cultivars, Ágata, Asterix, Atlantic, and Monalisa. The results showed the highest tuber yields with rates of 180, 201, 175, and 176 kg ha^{-1} of N. However, the economic optimum N fertilization rates ranged from 147 to 201 kg ha^{-1}, depending upon cultivar and corresponding prices of N and potato. Teklu and Hailemariam (2009) experimented with studying the effect of different rates of manure (M) and N on, wheat (*Triticum durum*) and tef (*Eragrostis tef*). The application of 6 t M ha^{-1} and 30 kg ha^{-1} of N produced the highest yield. However, the EONR showed that the optimum economic rates were 6.85 t M ha^{-1} and 44 kg ha^{-1} of N for wheat and 4.53 t M ha^{-1} and 37 kg ha^{-1} of N for tef.

The purpose of this study was to evaluate the response of potato crops to different N rates under different soil organic content, determine the economic optimum N fertilization rates, and study the impact of soil OM content on the maximum return to N.

5.3 METHODS

Total tuber yield was evaluated statistically by utilizing the analysis of variance (ANOVA) and regression. To describe the relationship of potato yield response to N fertilizer rate, statistical models (linear, exponential quadratic, and cubic) were tested and applied to the data using statistical software SPSS V-25 (SPSS-IBM-Corp., 2017) at $P \leq 0.05$. Statistical parameters such as regression coefficient, $P \leq 0.05$, and Durbin Watson (DW) were used to test the accuracy of the models, where the calculated value of DW (2.5) was compared with the estimated one from the Savin and White table (Savin and White, 1977), The calculated DW is higher than 4-dU and lower than 4-dL (2.4) and (2.7), respectively. DW was tested if there was autocorrelation in the residuals from the regression analysis, or in other words, that the residuals were independent (Montgomery et al., 2001).

The quadratic model was the best fit to represent the response of potato yield to N fertilizer rate and to calculate the economic optimum N rates (Table 5.1). Similarly, studies conducted by (Bélanger et al., 2000; de C Silva et al., 2007) showed that the quadratic pattern fitted data with less bias than other patterns (exponential and square root). Colwell (1994) defined the EONR (kg ha^{-1} of N) as the rate of N application where \$1.00 of supplementary N fertilizer yielded \$1.00 of potatoes, and it represents the minimum rate of N application needed to maximize economic profit.

The EONR was calculated by setting the first derivative of the N response curve equal to the ratio between the cost of fertilizer (\$ cost kg^{-1}) and the price of potatoes (\$ kg^{-1}), (\$c/\$p). The price ratio was the ratio of N fertilizer price to potato tuber price (\$ kg^{-1} / \$ kg^{-1}) in two years (2018 to 2019). The resulting formula was resolved for the EONR. The EONR was the point at the curve where the last increment of N produced a yield considerable enough to pay for the additional N applied. The selected model (quadratic) was outlined in Cerrato and Blackmer (1990), and is explained briefly below:

$Y = a + bx - cx^2$……………………………………………………………………….(Eq. 5.2)

Where,

Y is the potato yield (kg ha^{-1})

x is the rate of N fertilizer (kg ha^{-1})

a, *b*, and *c* are parameters of the model

The agronomic optimal N rate (kg ha^{-1} of N) was measured by determining the first derivative of the N-derived potato yield response model to the N application rate (Eq. 5.3) (Bullock and Bullock, 1994).

$Y (dy/dx) = 0 + x - 2cx$……………………………………………………………………(Eq. 5.3)

where:

Y is the potato yield (kg ha^{-1})

x is the AONR (kg ha^{-1})

c is parameter of the model

The same relationship (yield and N rates) were used to calculate the maximum return to N (MRTN), which is the N fertilizer rate where the economic net profit to N use is greatest (Nafziger et al., 2004; Sawyer et al., 2006). The following equations summarize the MRTN calculation steps, and Table 5.2 shows the calculation steps:

Gross \$ return at the yield increase= yiled (kg) × yield price (\$)………………………….(Eq. 5.4)

Nitrogen cost= N rate (kg) × N cost (\$)……………………………………………………(Eq. 5.5)

Net return to N= Gross \$ return at the yield increase- Nitrogen cost…………….…...….……(Eq. 5.6)

Table 5.1. Models of the relationship between potato yield and nitrogen fertilizer for all sites.

Model	Formula	R^2	P	DW
Linear	$Y=24520e^{0.0011\ X}$	0.69	0.04	1.32
Exponential	Y=31.425X ×24635	0.67	0.028	1.32
Quadratic	$Y=-0.2701X^2 + 110.82X + 24764$	0.96	0.007	2.5
Cubic	$Y=-0.0009X^3 + 0.1167\ X^2 + 62.316\ X + 22564$	0.97	0.03	3.5

R^2 is the regression coefficient, P-value is the probability that was employed to distinguish the treatments from each other in terms of statistical differences, and DW is the Durbin Watson to test if there is autocorrelation in the residuals from a regression analysis.

Table 5.2. Calculations of the maximum nitrogen rate to nitrogen for all sites.

N-rates (kg ha^{-1})	Potato yield (kg ha^{-1})	Gross $ return at the yield increase	N-cost	Net return to N
0	22389	7903.2	0.0	7903.2
56	26941	9510.2	74.1	9436.1
112	28887	10197.1	148.2	10048.9
168	32795	11576.7	222.3	11354.5
224	32761	11564.8	296.4	11268.4
280	30434	10743.0	370.4	10372.6

5.4 RESULTS

5.4.1. Yield Responses to Nitrogen Rates

Potato yields under different N rates are shown in (Figure 5.1), which represents the relationship between N rates and potato yields for sites that had ≤ 30 g kg^{-1} of soil OM, ≥ 30 g kg^{-1} of soil OM, and an average of all sites combined. The potato yield was significantly improved by N fertilizer applications in the experimental sites, classified and combined, where the highest tuber yields were 36725.8, 40434.5, and 27453.9 kg ha^{-1} in the all combined sites, ≥ 30 g kg^{-1} of soil OM, and ≤ 30 g kg^{-1} of soil OM by applying the N rate 168 kg ha^{-1}. In comparison with the control treatment, (0 kg ha^{-1} of N, potato yields under 56, 112, and 168 kg ha^{-1} treatments were increased by 10.8%, 20.7%, and 18.46% respectively when applying 56 kg ha^{-1} of N were increased by 13.3%, 28.8%, and 25.4% respectively when applying 112 kg ha^{-1} of N and were increased by 21.7%, 42.7%, and 37.7% respectively when applying 168 kg ha^{-1}of N. For all sites, potato yields increased significantly as N rate increased from 0 kg ha^{-1} up to 168 kg ha^{-1} ($P< 0.05$). However, there was no significant increase achieved by applying 224 kg ha^{-1}of N ($P> 0.05$).

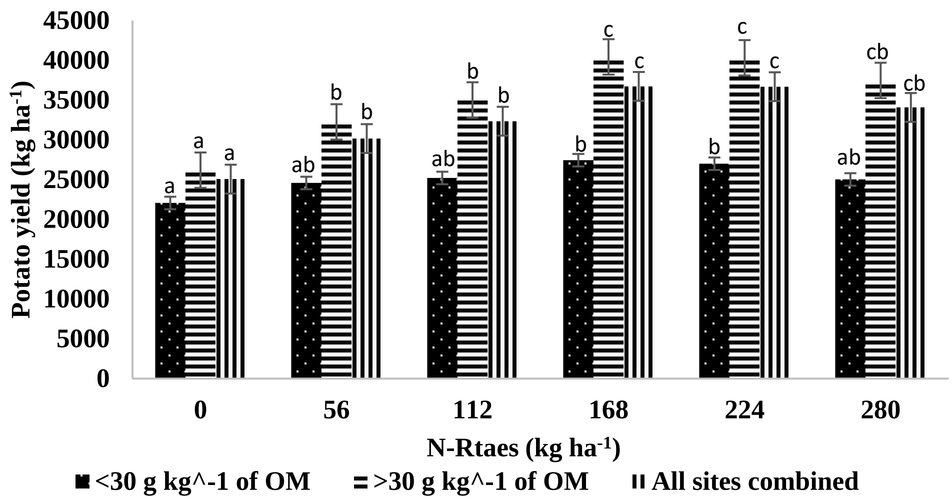


Figure 5.1. The response of potato yield to different applications of N fertilizer rates, ANOVA at P< 0.05. Adopted from (Ahmed et al., 2020).

5.4.2. Agronomic Optimum Nitrogen Rate, Economic Optimum Nitrogen Rate, and Maximum Return to Nitrogen

5.4.2.1. All sites combined

Deriving the quadratic equation (Eq. 5.7) for the relationship between potato yield and N rates, (Figure 5.2) produced the X value, which represents the AONR. Across all 11 experimental sites, the AONR value was 205.6 kg ha^{-1} of N, which is higher than the conventional method (Figure 5.1) that depends only on selecting the rate that produced the highest yield among the applied series of rates (168 kg N ha^{-1}).

$Y= -0.2701X^2 + 110.82X + 24764$………………………………..…………………….…(Eq. 5.7)

$Y (dy/dx) = -0.5402X + 110.82 + 0$…………………………..….…..…………………(Eq. 5.8)

Where,

X= 205.1 kg ha^{-1} of N, which represents the AONR.

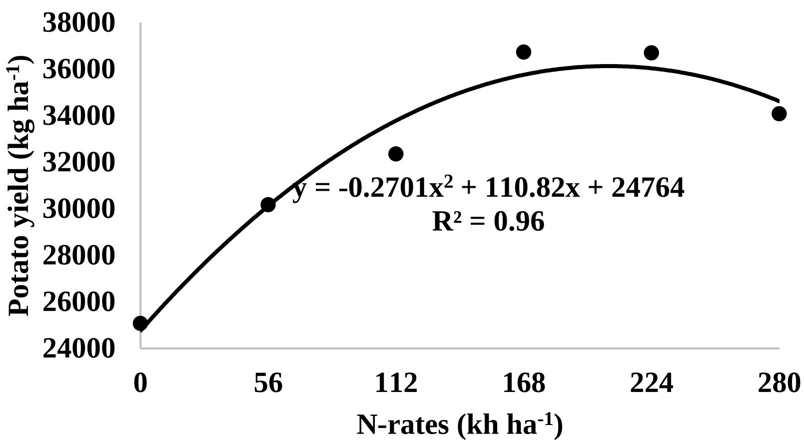


Figure 5.2. Relationship between potato yield and nitrogen rates from all sites during two growing seasons, 2018-2019, P< 0.05.

By including the ratio of N cost to potato yield price and subtracting it from the same derived quadratic equation (Eq. 5.9), a value of the EONR was obtained (Eq.5.10).

$Y (dy/dx) = -0.5402X + 110.82 - (\$c/\$p)$…………………………………………… (Eq. 5.9)

Where,

($c/$p) is the ratio of N cost to potato price (which is \$1.323 kg^{-1}/\$0.355 kg^{-1})

$Y (dy/dx) = -0.5402X + 110.82 - 3.73$………………………………………………(Eq. 5.10)

Where,

X= EONR= 198.2 kg ha^{-1}, which could produce 36114.2 kg ha^{-1} of potato tuber

The price of potatoes from such a N rate minus the cost of N applied for that rate gives the net MRTN, where equation (5.11) explains the calculations steps (Figure 5.3).

[(Potato yield (kg ha^{-1}) × potato price (\$)) - (N rate (kg ha^{-1}) × N cost (\$))] ………..…(Eq. 5.11)

The highest MRTN was \$12,743.4 at 168 kg $ha^{-1}$of N; applying the EONR value (198.2 kg ha^{-1}) in the calculation, provided an estimation about the highest return to N from that rate, (\$12,486.1 ha^{-1}). Table 5.3 shows MRTN values for each N rate and EONR.

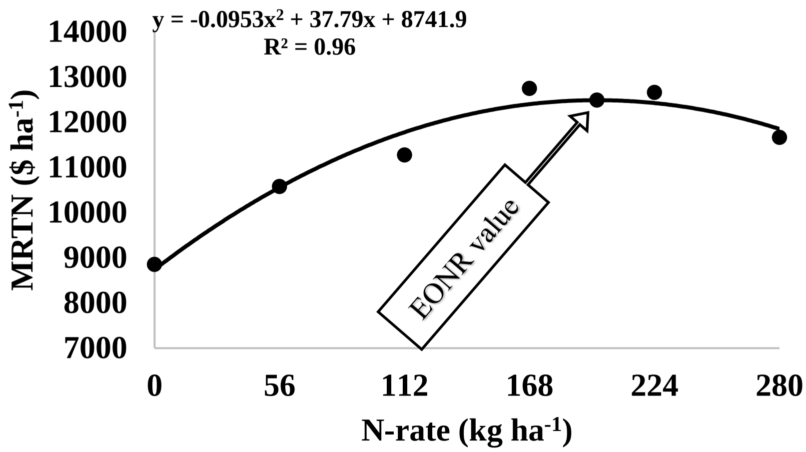


Figure 5.3. The returns to N (MRTN) at a series of N rates based on averages from 11 sites during two growing seasons 2018-2019, P< 0.01.

Table 5.3. Gross return, N-cost and MRTN values for each N rate when all sites (11 sites) combined, including the EONR value.

N-rate (kg ha^{-1})	Yield (kg ha^{-1})	Gross return at the yield increase (\$)	N-Cost (\$ ha^{-1})	MRTN (\$)
0	25070	8849.7	0.0	8849.7
56	30170	10650.0	74.1	10575.9
112	32350	11419.6	148.2	11271.4
168	36730	12965.7	222.3	12743.4
198.2	36114	12748.3	262.2	12486.1
205	36131	12754.3	271.2	12483.1
224	36690	12951.6	296.4	12655.2
280	34080	12030.2	370.4	11659.8

5.4.2.2. Sites with > 30 g kg^{-1} of Soil Organic Matter Content

Deriving the quadratic equation (Eq. 5.12) for the relationship between potato yield and N rate, (Figure 5.4) produced the X value (Eq. 5.13), which represents the AONR. In sites with > 30 g kg^{-1} of OM, the AONR value was 208.7 kg ha^{-1} of N, which is higher than the conventional method (Figure 5.2) which depends only on selecting the N rate that produced the highest yield among the applied series of rates (168 kg N ha^{-1}).

Y= -0.3192X^2 + 133.25X + 25807……………………………………………………..…(Eq. 5.12)

Y (dy/dx) = -0.6384X + 133.25 + 0……………………………..……..…………………(Eq. 5.13)

Where,

X= 208.7 kg N ha^{-1}, which represents the AONR.

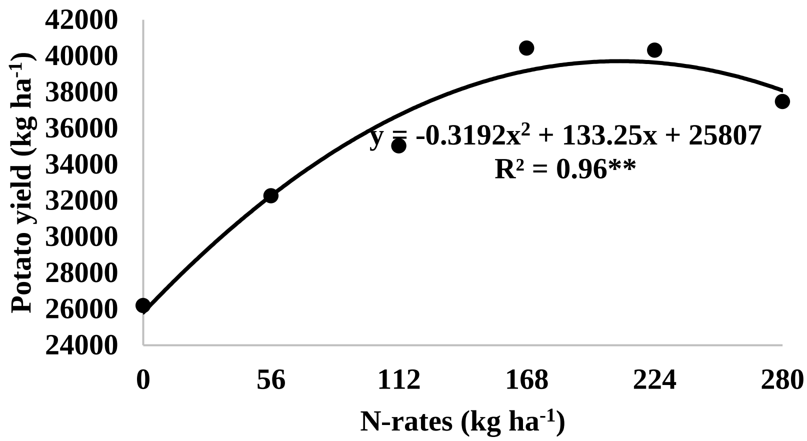


Figure 5.4. Relationship between potato yield and nitrogen rates from sites (>30 g kg^{-1} of OM) during two growing seasons, 2018-2019, P< 0.01.

Involving the ratio of N cost to potato yield price and subtracting it from the same derived quadratic equation (Eq. 5.14), will result in a value of the EONR (Eq. 5.15).

Y (dy/dx) = -0.6384X + 133.25 - (\$c/\$p)…………………………………………….…… (Eq. 5.14)

Where,

(\$c/\$p) is the ratio of N cost to potato price (which is \$1.323 kg^{-1}/\$0.355 kg^{-1})

Y (dy/dx) = -0.6384X + 133.25- 3.73…………………………………………………(Eq. 5.15)

Where,

X= EONR= 202.9 kg ha^{-1}, which could produce 35448.1 kg ha^{-1} of potato tuber.

The price of potato from such a N rate minus the cost of N applied for that rate gives the net MRTN, where equation (5.16) explains the calculations steps (Figure 5.5).

[(Potato yield (kg ha^{-1}) × potato price ($)) - (N rate (kg ha^{-1}) × N cost ($))] …………(Eq. 5.16)

The highest MRTN was $14051.1 at 168 kg ha^{-1}of N; applying the EONR value (202.9 kg ha^{-1}) in the calculation, provided an estimation about the highest return to N from that rate ($13746.5 ha^{-1}). Table 5.4, shows MRTN values for each N rate and EONR.

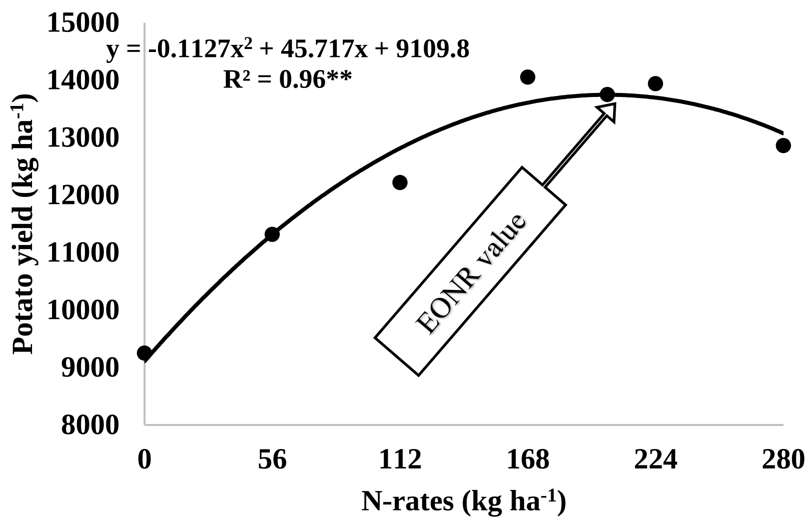


Figure 5.5. Returns to N (MRTN) at a series of N rates based on averages from sites with > 30 g kg^{-1} of OM during two growing seasons 2018-2019, P< 0.01.

Table 5.4. Gross return, N-cost and MRTN values for each N rate for sites with > 30 g kg^{-1} of SOM, including the EONR value.

N-rate (kg ha^{-1})	Yield (kg ha^{-1})	Gross return at the yield increase ($)	N-Cost ($ ha^{-1})	MRTN ($)
0	23392.2	8257.4	0.0	8257.4
56	28810.2	10170.0	74.1	10095.9
112	31275.0	11040.1	148.2	10891.9
168	36107.2	12745.8	222.3	12523.6
202	35448.1	12513.2	267.4	12245.8
224	36003.7	12709.3	296.4	12413.0
280	33463.6	11812.6	370.4	11442.2

5.4.2.3. Sites with < 30 g kg^{-1} of Soil Organic Matter Content

Deriving the quadratic equation (Eq. 5.17) for the relationship between potato yield and Nrates (Figure 5.6) produced the X value, which represents the AONR. In sites with < 30 g kg^{-1} of OM, the AONR value was 180.6 kg ha^{-1} of N, which is higher than the conventional method (Figure 5.2) that depends only on selecting the rate that produced the highest yield among the applied series of rates (168 kg N ha^{-1}).

$Y= -0.136X^2 + 49.135X + 19559$……………………………………………………..…(Eq. 5.17)

$Y (dy/dx) = -0.272X + 49.135 + 0$…………………………..……..…………………(Eq. 5.18)

Where,

X= 180.6 kg N ha^{-1}, which represents the AONR.

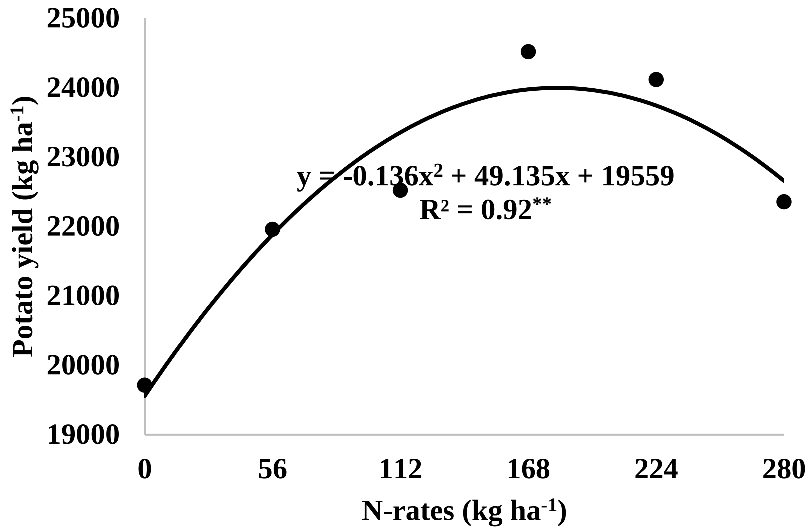


Figure 5.6. Relationship between potato yield and nitrogen rates from sites (< 30 g kg^{-1} of OM) during two growing seasons, 2018-2019, P< 0.01.

Involving the ratio of N cost to potato yield price and subtracting it from the same derived quadratic equation (Eq.5.18), will result in a value of the EONR (Eq.5.19).

Y (dy/dx) = -0.271X + 49.135 - ($c/$p)……………………………………………… (Eq. 5.18)

Where,

($c/$p) is the ratio of N cost to potato price, which is ($1.323 kg^{-1}/$0.355 kg^{-1})

Y (dy/dx) = -0.271X + 49.135 - 3.73…………………………………………………(Eq. 5.19)

Where,

X= EONR= 166.9 kg ha^{-1}, which could produce 23971.3 kg ha^{-1} of potato tuber.

The price of potatoes from such a rate of N minus the cost of N applied for that rate provides the net MRTN, where equation 5.20 explains the calculations steps (Figure 5.7).

[(Potato yield (kg ha^{-1}) × potato price ($)) - (N rate (kg ha^{-1}) × N cost ($))] ……..……(Eq. 5.20)

The highest MRTN was \$8431.8 at 168 kg ha^{-1}of N; applying the EONR value (166.9 kg ha^{-1}) in the calculation, provided an estimation about the highest return to N from that rate (\$8241.1 ha^{-1}). Table 5.5 shows MRTN values for each N rate and also EONR.

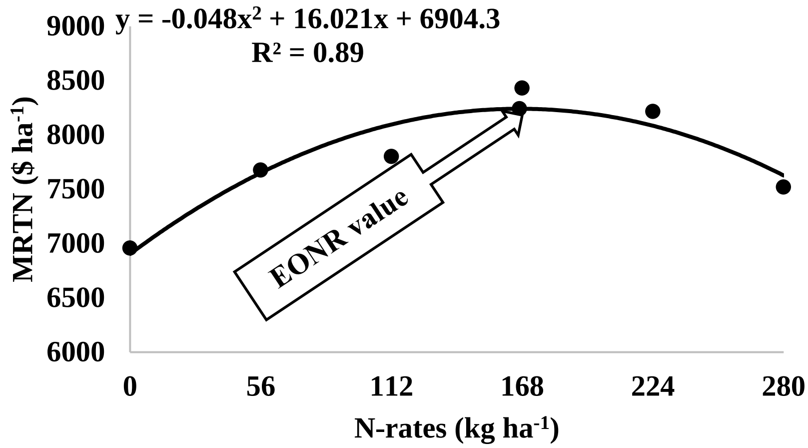


Figure 5.7. Returns to N (MRTN) at a series of N rates based on averages from sites with < 30 g kg^{-1} of OM during two growing seasons 2018-2019, P< 0.01.

Table 5.5. Gross return, N-cost and MRTN values for each N rate for sites with < 30 g kg^{-1} of SOM, including the EONR value.

N-rate (kg ha^{-1})	Yield (kg ha^{-1})	Gross return at the yield increase (\$)	N-Cost (\$ ha^{-1})	MRTN (\$)
0	19712	6958.5	0.0	6958.5
56	21957	7750.8	74.1	7676.7
112	22519	7949.1	148.2	7800.9
167	23971	8461.9	220.8	8241.1
168	24516	8654.1	222.3	8431.8
224	24115	8512.7	296.4	8216.4
280	22353	7890.7	370.4	7520.3

5.5. Some Consideration Related to Maine State Agriculture

The total area of Maine is approximately 8602645.5 ha ("FACTS ABOUT MAINE,"), while the lands used in farming are approximately 588455 ha (USDA, 2020). Potato crop production occupies approximately 21043.7 ha (USDA, 2019). According to the (USDA., 2019), there were approximately 19020, 19425, 19830, and 21044 ha of area planted with potatoes during 2016, 2017, 2018, and 2019, respectively and potato tuber yield was 40.8, 40.2, 38.9, and 39.5 Mg ha^{-1}, respectively. The potato production project requires several points to be taken into account. Table 5.6 shows the cost to grow, harvest, and sort for Russet Burbank potatoes. The table is used as an example to clarify the expenses that farmers spent seasonally for potato production. . The approximate cost for active optical sensors is between $4,000.0 and $5,000.0 for GG and CC sensors, however, the small GS sensor is more affordable ($400) than the larger sensor and can be used by the farmers. Note: the small GS sensor can only provide NDVI data, which is enough to generate a yield prediction model and N recommendation. At the same time, the larger sensors can provide NDVI data generated from red, red-edge, and NIR bands, in addition to providing CI data and LAI. These extra indices are essential for improving R^2 values and other measurements.

Table 5.6. An example of potato budget for a conventional farm, data collected in 2004 for Maine, data adopted from (Aaron et al., 2004).

	Total Per Acre Per Cwt	Total Per Acre Per Cwt	Total Per Acre Per Cwt
Number of Acres	160	-	-
Potato Yield (cwt)	38,400	240	-
Price ($/cwt)	$6.88	-	-
Annual Revenue	$264,107	$1,650.67	$6.88
Annual Operating Expenses			
Seed	$37,368	$233.55	$0.97
Fertilizer	$22,546	$140.91	$0.59
Lime	$1,600	$10.00	$0.04
Chemicals	$26,336	$164.60	$0.69
Labor	$36,688	$229.30	$0.96
Diesel Fuel and Oil	$12,058	$75.36	$0.31
Maintenance and Upkeep	$17,754	$110.96	$0.46
Supplies	$9,215	$57.59	$0.24
Insurance	$8,865	$55.40	$0.23
Miscellaneous			
Utilities	$6,101	$38.13	$.16
Custom Hire	$0	$0	$0
Rent or Lease	$10,000	$62.50	$0.26
Freight and Trucking	$2,849	$17.81	$0.07
Storage and Warehousing	$1,879	$11.75	$0.05
Other Expenses	$960	$6.00	$0.03
Interest	$5,364	$33.52	$0.14
Total Operating Expenses	$199,581	$1,247.38	$5.20
Annual Ownership Expenses			
Depreciation and Interest	$51,305	$320.66	$1.34
Tax and Insurance	$3,133	$16.58	$0.08
Total Ownership Expenses	$54,438	$340.24	$1.42
Total Annual Cost	$254,019	$1,587.62	$6.62
Net Farm Income (NFI)	$10,088	$63.05	$0.26
Return over Variable Cost (ROVC)	$64,526	$403.29	$1.68
Performance Measures			
Breakeven Revenue		$/acre	$/cwt
Long-run to Cover All Costs		$1,587.62	$6.62
Short-run to Cover Operating Costs		$1,247.38	$5.20

5.6. DISCUSSION

The results of this study showed that potato crop responded significantly to N rates at all experimental sites. The yield reduction or insignificant increase after the rate of 168 kg ha^{-1} of N was also observed in all experimental sites, which could be due to delayed tuber growth as a result of the longer vegetative growing period in comparison to tuber growth period. Excessive N application encouraged a dense vegetative growth, which in turn reduced the amount of carbohydrates that were available to tubers. As a result, photosynthesis supported plant leaves more than tubers and reduced tuber quality (Porter and Sisson, 1989; Ahmed et al., 2009).

Sites with soil OM content > 30 g kg^{-1} produced a higher tuber yield than sites with < 30 g kg^{-1}, which is attributed to the effect of OM on soil chemical, physical, and biological properties. The most powerful impact of OM was reducing soil bulk density, which created a soft bed around tubers that allowed for flexibility in size enlargement (Lynch et al., 2008). Sites with > 30 g kg^{-1} of OM produced higher a tuber yield than sites with < 30 g kg^{-1} of OM; however, a higher N rate was required than for sites with < 30 g kg^{-1} of OM. The extra N was required to feed soil microorganisms that work on OM decomposition.

The economic optimum N rate required for sites with > 30 g kg^{-1} of soil OM (202.9 kg ha^{-1}) was 19.5% higher than sites with < 30 g kg^{-1} (166.9 kg ha^{-1}), however, tuber yield was 32.4% higher than sites with <30 g kg^{-1}. Additionally, the MRTN increased by 60% more than sites with < 30 g kg^{-1} of soil OM. In comparison with the potato growers at Aroostook County in Maine who are adding 224 kg ha^{-1} of N, by following the EONR recommendation, it allows them to save about \$28 ha^{-1} of N cost. However, the MRTN would be decreased by 1.37%.

Applying N rates according to EONR calculations is valuable and beneficial because the cost of N is stable every year. At the same time, yield could decrease unexpectedly if the potato plants are stressed (either by drought or ambient temperature) and, therefore, the extra dollars saved from yield would be equal to or lower than the EONR recommendation (Agriculture, 2015). The EONR value is typically less than the AONR. It will generally decline as N cost increases, increase as yield price raises, or remain the same as long as the proportion of N cost to yield price (c/p) does not fluctuate (Camberato et al., 2017).

5.7 CONCLUSIONS

The EONR is lower than the AONR reading regarding the N rate. However, EONR can save the growers money, protect the environment against pollution from excessive fertilization, and produce an economic bottom line comparable to the one achieved by applying 224 kg ha^{-1} of N fertilizer.

CHAPTER 6

OVERALL CONCLUSIONS

Russet Burbank cultivar produced a higher tuber yield than Shepody and Superior cultivars. To produce potato tubers of acceptable marketable quality, the N rate must be added according to the recommended amount. Increasing N to higher rate than currently recommended could negatively affect tuber yield and specific gravity. The N rate applied by potato growers in Aroostook County is approximately 224 kg ha^{-1}. However, our economic calculations suggest that an N rate of 198.2 kg ha^{-1} provides a better return on investment, and can be updated according to market fluctuations. This represents a 12% decrease in N rates currently used by growers. Sites with high OM content (> 30 g kg^{-1}) produced approximately 48% higher tuber yields than sites with low OM content (< 30 g kg^{-1}). The maximum MRTN was approximately $12,245.8 from sites with high OM content, while the maximum MRTN from sites with lower OM content was $8,241.1. Therefore, taking into account OM content can improve potato tuber yield considerably. Using active optical sensors (GreenSeeker and Crop Circle) in potato farming is an efficient method of calculating N fertilizer recommendations and of predicting in-season tuber yield that can save approximately 12-14% of the total N currently applied by growers.

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Ahmed A. Zaeen was born in Nineveh, Iraq, in 1983, but raised and lived in Baghdad. He took an early interest in agriculture; he used to follow and help his father, retired from the ministry of agriculture recently, in their little yard since he was a boy, that what encouraged him to like agriculture. He graduated from Soil Sciences and Water Resources Dept. In 2005 with a BSc, his rank was the 4^{th} of 70 students. In 2008 graduated from the same department with a master's degree. He is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences from the University of Maine in May 2020.