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**Final Report**

PROJECT TITLE: **Carbon, Nitrogen, Phosphorus, and Sulfur Interactions Effects on Soil Biochemical Processes and Corn Grain Yield**

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**ABSTRACT**

This research was designed to investigate how the addition of nutrients at different levels interacted with residue management and their impact on the parameters controlling corn grain yield. Our primary interest was to understand how different levels of N, P, and S affected nutrient availability during the growing season in addition to how those levels affected microbial activity. Furthermore, we were also interested in investigating if residue management would interfere with nutrient availability and microbial activity. The study was set up in small plots located in a farmers field that had initial test levels for P and K that were considered low. The area of the study was just over 13 acres, which should provide enough data to answer our research questions. The study was carried out from 2012, the initial year when a detail characterization of the site was done, until the end of the 2015 growing season. The cropping systems used was a continuous corn rotation. The results of the study showed that corn grain was significantly affected in some level by all parameters being studied. The most dramatic effect, however, was residue management. It was determined that residue incorporation, in general, provided the best conditions for corn grain yield to be maximized when higher levels of P, N and S were applied. It was observed that plots were the residue was incorporated kept microbial activity higher than in the plots were the residue was removed, which in combination with higher moisture levels, led to a higher nutrient availability to the growing crop. Although, the in-season measurements seem to indicate that nutrient uptake and biomass yield would be greater in plots where residue was removed, final grain yield and nutrient uptake showed a contradictory result. It was observed that a change in fertilizer and residue management will likely be need to maintain or improve corn grain yield in continuous corn cropping system in soils that are similar in properties to those used in this study.

**INTRODUCTION**

Over the past few decades, increases in crop production, especially corn grain yields, have been mainly a result of genetic improvements. This can easily be observed in yields of control plots from long-term trials where yields have steadily increased over the time even though no fertilizer has been applied to those plots (Personal communications). Among the essential macronutrients required for plant growth, nitrogen (N) and phosphorus (P) are the most limiting nutrients for optimum grain yield in the Midwest. Grain yield response to N shows a rapid increase at lower application rates (e.g. 10 to 60 lbs N acre-1) when compared with a non fertilized field; with greater N rates there is a decrease in the rate of grain yield gains per lb of N applied (e.g. 80 to 120 lbs N acre-1); and grain yield reaches a plateau (approximately 200 bu acre-1 at high yielding sites) with greater N rates (e.g. 160 to 200 lbs N acre-1). Although this process is well understood, there has been no information in the literature that provides an explanation as to why grain yield levels off at a plateau at a given N rate, both which vary by location. This result could be interpreted as the crop has reached its maximum yield potential, and further increases in N rates will not improve yields. However, the fact that grain yield can be much greater at localized, apparently random locations within a field, suggests that possibly other factors including nutrient availability, soil moisture, temperature, microbial activity, among others could be limiting crop yields. It is apparent that nitrogen will only increase crop yield until it is not a limiting factor, or until another factor becomes limiting, and therefore prevents further yield increases (Liebig’s Law of the Minimum).

Current research being conducted to provide information on how to increase yield beyond the current average reported (a given plateau) usually focuses on the interactions between tillage systems, crop rotation, and often a single nutrient. However, the number of interactions between multiple nutrients studied at the same time is limited. This is perhaps a reflection of the difficulty in interpreting higher-order interactions and logistic problems related to the number of plots required as the number of interactions increase. For example, in a given study a researcher will test the effects of different tillage systems, in combination with five or six increasing N rates, and also with or without sulfur (S). Although this is an important study to be conducted, it could be improved by adding a few increasing S rates instead of only two (with or without). Better results could be achieved if the researcher would add increasing rates of yet another limiting nutrient, for example P.

Carbon (C), N, P, and S have been reported to interact with each other in the soil, and as a result, affect mineralization and immobilization rates of nutrients under forest system (Vitousek et al., 1988). Very few, if any, similar studies have been conducted for agronomic crops, where the interaction of all four nutrients is evaluated. Crop rotation can play a major role in nutrient cycling, availability and mobility and how subsequent crops will perform. Multicropping systems has been reported to provide better conditions for microbial growth in the soil than continuous cropping (Moore et al., 2000), which will have an effect on nutrient mineralization and immobilization rates.

From a nutrient mineralization standpoint, the release of C and N from the soil organic matter is a process strictly driven to obtain energy, which is known as biological mineralization; whereas the release of P and S from soil organic matter might come from either biological mineralization, or from biochemical mineralization (McGill and Cole, 1981). Biochemical mineralization is a process catalyzed by enzymes released by microorganisms and roots of higher plant in the soil solution, which promote the hydrolysis of organic P and S into their inorganic forms PO42- and SO42-. Biochemical mineralization of P and S is regulated by the concentration of inorganic P and S in the soil solution (Maynard et al., 1985, Stevenson and Cole, 1999); therefore, fertilizer application can affect biochemical mineralization rates and as a result affect nutrient availability to plants and microbes. It is important to understand what the effects of nutrient application are on microbial activity because they are responsible for almost all of the biological mineralization that increases soil fertility.

To maintain soil sustainability, a dynamic equilibrium between nutrient mineralization and immobilization in the soil must be achieved so nutrient depletion can be avoided. Increasing grain yield beyond current yield potential might develop or aggravate the effects of nutrient deficiency on crop growth, unless a balance between nutrient inputs and export is implemented. The potential for environmental pollution (ground water contamination with N, S, and P) must also be evaluated to assure that new methodologies are not detrimental. For example, if S application in combination with P can increase yields at a given N rate, then there is a potential for the decrease in N leaching, as greater amounts of N will be taken up by the crop and assimilated into biomass. On the other hand, if S and P increases N mineralization rates during a period of high soil moisture and low plant requirement, then greater amount of NO3- could leach out of the system. Because C, N, P, and S are in a dynamic interaction state within the soil matrix, it would be of interest to try and understand how the manipulation of any one the four elements would affect corn production.

**OBJECTIVE AND GOAL STATEMENTS**

The overall objective of this research was to determine if corn grain yield could be increased beyond current averages by evaluating the interactions between C, N, P, and S. This study looked at how the addition of these nutrients at several rates affects microbial activity in the soil and the rate of nutrient mineralization, by using enzymatic activity as surrogates. Understanding how the addition of C, N, P, and S affects these nutrients reactions, transformations, and availabilities during the growing season and understanding their interactions might help improve nutrient management, increase crop performance, and therefore, lead to potential increased grain yield and potentially reduced nutrient losses.

Carbon, N, P, and S were selected because they are the only macronutrients required for plant growth that are present in the organic and also inorganic forms in the soil. It was hypothesized that application of N, P, and S could potentially decrease biochemical mineralization by maintaining sufficient levels of available P and S for plant uptake. In addition, N immobilization by microbial activity was expected to be lower in plots where the previous crop residue was removed compared with plots where the previous crop residue was incorporated.

In this study soil enzyme activity was monitored in plots with and without plants to assess how the rhizosphere around the plant roots can change microbial activity, and as result, biological and biochemical mineralization rates. The hypothesis was that plants would exude enzymes that promote higher rates of N, P, and S mineralization compared to mineralization rates in plots without growing plants. In addition, the decrease in nutrient availability in soil due to crop uptake might also increase enzymatic activity in plots with growing plants compared with plots that are kept without growing plants.

Soil temperature and moisture content play a significant role in biological and biochemical mineralization, as microbes have ideal moisture content and temperature for maximum growth rates. Enzyme activity is also highly dependent on temperature. Therefore, it was hypothesized that rates of biological and biochemical mineralization would be different throughout the growing season.

**MATERIALS AND METHODS**

Corn-following-corn was the crop rotation tested and the plot size was 10 feet long by 40 feet wide (4 corn rows per plot). The fertility treatments selected for this research were applied in the spring and were:

1. Nitrogen applied as urea at six rates from 0 to 200 lb N acre-1 increasing incrementally by 40 lb acre-1;
2. Phosphorus as triple super phosphate at five rates from 0 to 100 lb P2O5 acre-1 increasing incrementally by 25 lb acre-1;
3. Sulfur as potassium sulfate at four rates from 0 to 15 lb S acre-1 increasing incrementally by 5 lb acre-1;
4. Residue management will be whole plot treatments with residue removed every year in one treatment and never removed in the other treatment.

The experiment was set up in a full factorial design, replicated four times in a randomized complete block design. Fertilizer was always hand broadcasted and machine incorporated as soon as hand fertilization was completed. In addition, potassium was applied at recommended levels such that it was a non-limiting nutrient. The tillage system was fall disk-ripped. Weed and insect control in the plots kept without plants will be same as in the plots with growing plants.

In 2013, assessment of treatment effects on the baseline soil chemical and biological properties was monitored in all plots at two periods during the growing season that coincided with two crop physiological stages (V6 and R1). Biomass yield and nutrient uptake was measured in all plots at two predetermined crop physiological stages (V6 and R1) and grain yield was measured in all plots at harvest. In 2014 and 2015, assessment of treatment effects on the baseline soil chemical and biological properties was monitored in selected plots at two periods during the growing season that coincided with crop physiological stages V6 and R1. Biomass yield and nutrient uptake was measured at two predetermined crop physiological stages V6 and R1 and grain yield was measured in all plots at harvest.

Volumetric soil water content was measured on selected plots between 2013 and 2015. Decagon 5TM sensors were buried in the soil at two depths 0-10 cm (0-4 inch) and 10-20 cm (4-8 inch). These sensors were continuously monitored throughout the growing season. Daily precipitation was measured either at the site or at the nearest weather station located in Redwood Falls, MN. Complete data sets were obtained for 2014 and 2015 and were used for interpretation of the impacts of residue management and fertilizer management on volumetric soil water content. Two nutrient management regimes: a) control with No Fertilizers (NF) and b) fully fertilized (FF) as; N (urea) 224 kg N ha-1, 112 kg P2O5 ha-1, 16.8 kg S ha-1 and potassium (K) fertilizers applied at the recommended rates for optimum corn yield.

Statistical analysis was used to assess treatment effects and evaluate interactions between nutrient application rates on plant development, biomass yield, grain yield, and also their effects on chemical and biological soil properties using the most up to date statistical methodologies. The SAS Proc Glimmix and Proc Nlmixed (because grain yield response to fertilizer addition need not necessarily be linear) programs were used (SAS Institute, 2010); in addition the open source statistical software, R, was also used for statistical analysis and data interpretation (R, 2007).

**RESULTS**

*Soil background levels*

Figure 1 shows the experimental site as in the mid-season in 2014. Figure 2 shows the soil test P (Olsen) distribution throughout the experimental site. It can be seen that in general the location can be categorized as low soil testing P and responses to P would be expected. Figure 3 to 5 shows the enzyme activity for the experimental site for glucosidase (carbon turnover), phosphatase (organic P mineralization potential), and sulfatase (organic sulfur mineralization potential). From the enzyme background levels, the most interesting results is the negative relationship between phosphatase and sulfatase activities as when one increases the other decreases (Figures 4 and 5).

*Soil moisture and water use efficiency*

The soil moisture data showed that, in general, 2014 had more available water in the 0-20 cm (8 inch) soil profile throughout the growing season than 2015 (Fig. 6A and B). Frequent, plentiful precipitation early in 2014 greatly influenced the amount of soil water during the entire season. The trend of decreasing soil water content beginning in mid to late June is evidence of the period of rapid crop growth coupled with intense water and nutrient uptake by the growing crop. The residue incorporated treatment showed greater available water for the fully fertilized treatments in both years (Fig. 6A and B). This can be partially explained by the increased soil water conservation due to the presence of residue and possible great water retention due to the decomposing carbon. This trend continued into 2015, despite the evenly spaced rain events, until August (Fig. 6B).

These data showed a similar trend with respect to available water in the soil profile between 2014 and 2015 as did the full fertilizer treatments for the 0-20 cm (8 inch) soil profile depth. For 2014, the available water trend between residue treatments was not as obvious (Fig. 7A) as observed in the fully fertilized treatments (Fig. 6A and B). The lack of distinct separation between the residue treatments in 2014 suggests that water was not a limiting factor for this set of comparisons. In contrast, during 2015, the residue incorporated treatment showed higher available water content throughout the entire growing season (Fig. 7B). As explained previously, this can be partially explained by the increased soil water conservation due to the presence of residue and possible great water retention due to the decomposing carbon.

*Grain and biomass yield results*

*2013*

A summary of the statistical analysis for corn grain yield can be found in Table 1. Corn grain yield in 2013 was primarily affect by nitrogen and residue management and their interaction as well as by phosphorus application; there was no significant effects due to sulfur application (Table 1). The reason for the significant interaction between nitrogen and residue management was likely due to random variation (Table 2). From an agronomic point of view, the most significant results that can be taken from the interaction is that the areas where residue was removed showed a decrease of 16 bushels per acre compared with where the residue was incorporated and also the significant response to nitrogen application (Table 2). The significantly greater yields observed when the residue was incorporated is likely due to the higher moisture content of the soils as less evaporation is observed when residue is left on the field. Although, there was tillage operation in the field to incorporate the residue, the amount of residue incorporated helped retain available water for the growing crop. As for the nitrogen application rate, the best rate regardless of residue management was between 120 and 160 lbs per acre (Table 2). The grain yield response to phosphorus application rate was quiet interesting (Table 3). It was observed that no significant increase in yield were found for the 25 and 50 lbs of P per acre; however, yields increased with the 75 and 100 lbs P per acre (Table 3). As indicated previously, the location chosen for the study had initial low test P and responses to P would be expected.

The 2013 biomass yield at the V6 was affected by P and N rate, as well by residue management and its interaction with N rate (Table 8). Biomass uptake at the R1 stage in 2013 was affected by N and S rates and residue management as well as by their interactions (Table 9). Biomass at the V6 stage increased with P rate, however, 75 lbs of P per acre was enough to assure maximum plant development (Table 11). Biomass yield at the V6 stage responded positively to N application when residue was removed or incorporated with the main difference being the amount of biomass produced for each incremental N rate (Table 13). When the residue was removed as little as 40 lbs of N was enough to assure maximum growth, in contrast, when the residue was incorporated 80 lbs of N per acre was needed (Table 13). At the R1 stage biomass yield responded more significantly to N rate and biomass production increased as N application increased specially where the residue was incorporated (Table 13). In addition, corn biomass in 2013 was also affected by the interaction of N rate by S rate (Table 9), suggesting that the biomass response to N was limited based on S availability. The higher the amount of S applied the greater the need for N (Table 14).

*2014*

In 2014, corn grain yield was affected by all four parameters being tested (Table 1). Most of the influence on grain yield was due to N and P, with S and residue management also playing smaller role on grain yield (Table 4 and Fig. 8). Figure 8 shows the interaction between N, P and S. The reason for the three-way interaction is likely due to the random response to S addition for the N rates 80, 120 and 160 lbs per acre (Fig. 8). Although, not yet well understood, it is likely that at those rates of N, there was higher microbial activity in the soil which could have limited S availability for the crop. The response to P was only significant at the higher N rates (160 and 200 lbs per acre) and in most cases 75 lbs of P per acre was enough to assure maximum yield (Fig. 8).

A summary of biomass yield at the V6 and R1 stage is reported on Table 15. For both sampling times, biomass yield was only affected by N application rate and residue management. Biomass uptake increased with each addition of N up to the 80 lbs N (Table 16) and further increases in N rate did not lead to higher biomass production. In addition, biomass yield was higher when the residue was removed compared with when the residue was incorporated.

*2015*

In 2015, most of the corn response was linked to P management with interactions with N and residue management (Table 1). For the two lower P rates, grain yield increased as N rate increased; whereas, for the 75 lbs of P per acre, corn grain yield increased as N rate increased but tended to level off after 160 lbs of N per acre; and for the highest P rate, grain yield tended to decrease when N rates reached 120 lbs per acre (Table 5). The effects of residue management and P application rates can be observed in Table 6. It can be seen that when the residue was removed grain yield tended to increase as P rate increased and was highest for the highest P application rate; in contrast, when the residue was incorporated, there was no clear P rate effect on grain yield, and as little as 25 lbs of P per acre was enough to assure maximum yield (Table 6).

Biomass yield in 2015 at the V6 stage was not affected by any factor being studied, while at R1 only residue management caused a change in biomass yield where yield was higher when residue was removed (Table 24).

*Grain and tissue nutrient uptake*

*2013*

A summary of the statistical analysis for the 2013 grain and tissue nutrient uptake can be found in Tables 7, 8, and 9. Grain nutrient uptake in 2013 differed for all of the nutrients measured (Table 7). Responses to N application was observed only for N and S, response to P application was observed only for S, P and Mn; however, uptake for most nutrients was affected by the N rate x residue management interaction (Table 7). At the V6 stage the uptake of all nutrients were affected by residue management and N rate, with exception of Fe and Zn (Table 8). Nitrogen, S, and P uptake was affected by the N rate by residue management interaction; and S uptake was also affected by P and S application rate (Table 8). Nutrient uptake at the R1 stage was also different for each nutrient and in most cases more responses were observed for N rate and residue management (Table 9). A more comprehensive description of the results observed for nutrient uptake in the grain and also by tissue will be given below.

Nitrogen uptake in the grain increased as N application rate increased (Table 10) but reached an equilibrium between 160 and 200 lbs of N. Sulfur uptake in the grain also increased with N application rate up to 120 lbs of N (Table 10). Phosphorus uptake in the grain responded positively with increasing P application rate up to 75 lbs of P (Table 11). Sulfur uptake as a function of P application rate varied and tended to decrease with initial P application rates and then increased as P rate increased over 50 lbs of P. Phosphorus, K, Ca, Mg, Fe, Mn, and Zn uptake in the grain were affected by the interaction between N application rate and residue management (Table 7 and 12). When the residue was removed, no differences in nutrient uptake was observed due to N application rate, with exception of Fe and Mn (Table 12). For Fe and Mn there was an increase in the amount of nutrient taken up as N application rate increased. In contrast, when the residue was incorporated for all nutrients there was an increase in nutrient uptake up to the 160 lbs of N and with additional N application there was a decrease in nutrient uptake. This could be due to a dilution effect as the uptake is a function of nutrient concentration and total yield.

At the V6 stage only S uptake was affected by S and P application rate (Table 8 and 11). In general, S uptake tended to increase when P and S application rate increased (Table 11). Nitrogen, P, and S uptake was also affected by the interaction between N application rate and residue management (Table 8 and 13). In general N, P and S uptake increased as N application rate increase and the uptake was greater when the residue was removed. For K, Ca, Mg, and Mn there was a significant response to N application rate and the uptake of those nutrient tended to increase as the N application increased (Table 10). During the R1 stage, P uptake increased as P and N application rate increased (Table 10 and 11). Calcium and Mg uptake was affected by the N application rate by residue management interaction (Table 13). For Ca and Mg uptake there was an initial increase in uptake with the first N rate but no increase with subsequent N rates; while the removal of residue resulted in a higher level of nutrient uptake as well. Nitrogen and S uptake was affected by the N and S application rate interaction (Table 14). Nitrogen uptake tended to increase with N application rate but it seemed to decrease, or be more variable as S rates changed without a clear-cut trend. Sulfur uptake was even more complicated than N uptake, and it appeared to be higher for the intermediate N rates and at the 0 or 15 lbs S rates (Table 14).

*2014*

A summary of the statistical analysis for the 2014 grain and tissue nutrient uptake can be found in Table 15. Grain nutrient uptake was affected by N and P application rate, and in some cases by their interaction as well as by the residue management (Table 15). Phosphorus, Mg, Mn, and Zn were the nutrients that were affected by the interaction P application rate by N application rate (Tables 15, 17, 18, 19 and 20). The uptake of all four nutrients followed the same general trends and increased as P application rate increased, however, when N application rate increased there was a tendency for P uptake to decrease particularly at the high N rates and P rates (Tables 17, 18, 19, and 20). Nitrogen, S, K, Ca, and Fe were affected by the main effect of N application rate (Table 15 and 21). Nitrogen, S, Ca, and Fe showed a similar pattern where nutrient uptake increased as N application rate increased up to 120 lbs N, but higher N rates did not significantly increase nutrient uptake (Table 21). In contrast, K uptake increased as N application rate increased up to 120 lbs and then started to decrease with higher rates (Table 21). Potassium, Ca, and Fe were affected by the main effect of P application rate (Table 23). For K and Ca, there was an initial increase in uptake for the first P rate with no increases after that, while Fe uptake increased with each increment in P application rate (Table 23). For the response to residue management, nutrient uptake in the grain was always greater when the residue was incorporated than when the residue was removed (Table 22).

In 2014, nutrient uptake at the V6 stage was in most cases affected by N application rate and residue management, with Ca and Mg uptake also being significantly affected by the interaction of N rate by residue management (Table 15). At the R1 stage, N, S, K, Ca, Mg, Fe, Mn, and Zn uptake were affected by the N application rate by residue management interaction, while P uptake was affected by the main effects of N application rate and residue management (Table 15). In all cases, residue removal led to higher nutrient uptake than plots where residue was incorporated (Table 16). At the V6, N, S, K, Fe, Mn, and Zn nutrient uptake; and at the R1, P uptake increased as N application rate increased up to 80 lbs and then tended to level off with no differences between the 120 and 160 lbs of N per acre (Table 16). Calcium and Mg uptake at the V6 stage was significantly greater where the residue was removed and responses to N application rate was also greater where the residue was removed (Table 16). For nutrient uptake at the R1 stage there was primarily a response to N application rate in the plots where the residue was removed, while little to no response to N application rate was observed where residue was incorporated (Table 16).

*2015*

A summary of the statistical analysis for the 2015 grain and tissue nutrient uptake can be found in Table 24. Grain nutrient uptake for P, Ca, Mg, Mn and Zn was affected by the interaction between N and P application rate, while all other nutrients were affected by N application rate and residue management (Table 24). Phosphorus, Ca, Mg, Mn and Zn uptake in the grain increase as P application rate increased; however, within each P rate the response to N application rate varied for the different nutrients (Table 25). For P, at the lower P rated, there was primarily a response to 40 lbs of N with no increases in P uptake as N rate increased, in contrast, for the highest P application rate, P uptake tended to increase with medium rates of N and decreased at the higher N rates (Table 25). Ca and Mg uptake was highly variable and the response to P and N application did not follow any clear trend (Table 25). Manganese and Zn uptake tended to be lower at the lower P and N rate, then it increased at intermediate P and N rate, and tended to decrease with the higher P and N rates (Table 25). Residue removal led to lower uptake of nutrients in the grain than residue incorporation (Table 26). Nitrogen, S, and Fe uptake in the grain increase with N application rate up to 120 lbs N and higher N rates did not increase the uptake of these nutrients (Table 27). For K uptake in the grain, only the rates 120 and 160 had higher uptake than the other rates (Table 27).

In 2015, only a few significant differences were observed for nutrient uptake at the V6 stage (Table 24). There was a significant P application rate by residue management interaction for K and Ca (Tables 24 and 28). For K, there was no differences when the residue was removed; while the application of 25 lbs of P had the lowest K uptake when the residue was incorporated (Table 28). For Ca, the 25 lbs of P rate had the highest uptake when the residue was removed, but the lowest Ca uptake when the residue was incorporated (Table 28). For N, Mg, Fe, Mn, Zn, there was mainly a residue management effect during the V6 stage where the removal of residue led to higher nutrient uptake compared with the residue incorporation management (Table 29). Significant interaction between N application rate and residue management was observed at the R1 stage for N, S, P, Ca, and Zn in 2015 (Tables 24 and 30). Although there was a significant interaction between N rate and residue management, there was no clear-cut trends for N and S uptake. In contrast, P, Ca, and Zn uptake tended to decrease with increasing N application rate, with uptake being higher where residue was incorporated (Table 30). In addition, there was a significant effect of P application rate for P uptake at the R1 stage in 2015 (Tables 24 and 31). In general P uptake increased with P application rate (Table 31).

*Soil Nutrient Status and Enzyme Activity*

*2013*

A summary of the statistical analysis for the selected soil properties measured in the study is presented in Tables 32, 33, and 34 for 2013, 2014 and 2015, respectively. In 2013, soil samples were collected from every plot twice, while in 2014 and 2015 only the plots receiving the highest sulfur application were sampled. Soil Available N (nitrate and ammonium) and P showed the most variability in the first sampling in 2013 (Table 32). Nitrate and ammonium were primarily affected by N application rate and residue management interaction in the first sampling, as well as by N and S application rate (nitrate only first sampling) (Table 32). In the second sampling nitrate levels were also affected by the interaction between N and P application rate (Table 32). In the first sampling, P levels were affected by the four-way interaction between N, P, and S application rate and residue management (Table 32); while in the second sampling soil available P was affected by P rate only. The enzyme activity for the enzymes monitored in this study were in most cases only affected by residue management (Table 32). The only exceptions were glucosidase in the second sampling which was affected only by N application rate; and FDA second sampling which was affected by N and P application rate in addition to residue management (Table 32).

Soil available nitrate levels in 2013 increased as N application rate increased (Table 35); however, the level of increase varied by residue management. When residue was removed, application of low N rates increase nitrate levels more than in the plots where the residue was incorporated (Table 35). However, at the highest N application, nitrate concentration was greater in the plots where residue was incorporated (Table 35). For ammonium, available ammonium also increased with increasing N application rate; in contrast to nitrate, ammonium concentration was greater in plots where residue was incorporated compared with plots where residue was removed (Table 35). Soil available nitrate levels were also affected by the interaction of N and S application rate and N application rate by P application rate (Tables 36 and 37). The main reason for this significant interaction was that at the highest N application rate nitrate levels increased as S application rate increased (Table 36). In contrast, no significant differences between nitrate levels for the lowers N application rates were observed among the different S rates (Table 36). Nitrate levels on the second sampling were higher as N application rate increased but levels varied by P application rate specially at the two highest N application rates (Table 37).

Soil available P was affected by the four-way interaction in the first sampling, suggesting that fertilizer P takes several weeks to dissolve and reach equilibrium. At the second sampling in 2013, however, there was only an effect of P application rate (Table 32). At the second sampling, soil extractable P increased as P application rate increased (Table 38).

Enzyme activity in 2013 was in most cases only affected by residue management with exception of glucosidase and FDA which were also affected by N application rate and N and P application rate, respectively (Table 32). Glucosidase and FDA activity also increased as N application rate increased (Table 40); in addition, FDA activity tended to increase with increasing P application rate (Table 41). In general, phosphatase and FDA activity was greater in plots where the residue was incorporated, while sulfatase and glucosidase activity was generally greater where residue was removed (Table 42).

*2014*

For the samples collected in 2014, nitrate was found to be the most variable of all parameters measured as indicated by the number of two-way significant interactions; while ammonium was only affected by the N application; available P was only affected by the P application rate; and most of the enzymes were only affected by the residue management (Table 33).

Nitrate levels varied by N application rate as well as by P application rate and the response changed between the two sampling times, V6 and R1 (Table 37). For samples collected at the V6 stage, nitrate levels increased as N rate increased and there was response to P application rate only at the highest P application rate and N application rate, where nitrate levels were the highest measured (Table 37). A similar result was observed for nitrate levels at the second sampling where the highest levels were observed for the highest N and P application rates (Table 37). The effect of residue was only present in the plots where residue was removed, where there was increase in nitrate levels with increasing N application rate (Table 35). Ammonium levels increased with increasing N application rate at the V6 sampling; while the application of any N rate at the second sampling showed the same levels of ammonium in the soil, which were always greater than the control (Table 39).

Soil available P behaved similarly at both sampling times where it was observed that available P increased as P application increased (Table 38).

Contrasting results were observed for enzyme activity as compared with those of 2013. In 2014, phosphatase activity was greater in plots where the residue was incorporated at the V6 sampling, but higher where the residue was removed at the R1 sampling (Table 43). Sulfatase activity at the R1 sampling was greater when residue was removed; and for glucosidase and FDA, activities were always greater where residue was incorporated (Table 43).

*2015*

In 2015, much less significant effects were observed for the soil samples collected at V6 and also at R1 (Table 34). Soil nitrate levels were affected by N application rate and residue management; ammonium was affected by the two-way interaction between N and P application rate, available soil P was affected by P application rate, and only phosphatase and glucosidase sampled at R1 showed a significant response to residue management (Table 34).

Soil nitrate increased with N application rate at both sampling times, however, the nitrate levels were much higher at the V6 sampling than at the R1 sampling (Table 39). In addition, nitrate levels were greater in plots were the residue was incorporated compared with the plots where the residue was removed (Table 44). Soil extractable ammonium at the V6 stage was significantly increased only at the 2 highest N and P application rates; while ammonium levels in all other N and P application rates were similar to levels observed in the control plots (Table 37). Available P was significant affect by P application rate only in samples collected at the R1 stage, where soil P levels increased with increasing P application rate (Table 38). As observed in the previous sampling, phosphatase and glucosidase activity was greater in plots where the residue was incorporated compared with plots where the residue was removed.

**DISCUSSION**

This study was designed to help us create an understanding of how different levels of fertilizer added to a field would impact soil nutrient availability and microbial activity, plant nutrient uptake and biomass yield, and also corn grain yield and total nutrient export. During the three years of the study, it was observed that grain yield response to fertility and residue management changed, perhaps due to changes in weather as well as to residual effects of treatments and its effects on soil available water. In 2013, there was primarily a response to N application rate which was more evident in the plots where the residue was incorporated, which showed an increased yield of as much as 16 bushels per acre compared with plots where the residue was removed. Others have also reported grain yield to not be affected by residue removal or incorporation (Coulter and Nafziger, 2008)). This result contradicts some of the results reported in the literature. For example, Sindelar et al. (2013) reported that residue removal increased grain yield by 7 to 24% compared with no residue removal at Lamberton and Waseca. Phosphorus application also seemed to improve yield in 2013 though only at very high application rates, reflecting the need for P application in soils with soil test P levels in the low to very low categories. Schlegel and Havlin 2017, reported that N and P can account for more than 50% of the variability in corn yield from long-term experiments that have been going on for over 75 years. The application of high rates of N with low rates of P, or high rates of P with low rates of N undermines the additive effect of applying high rates of both fertilizers. For example, Schlegel and Havlin (2017) reported that in addition of high P rates with low N rates increased grain yield about 20% compared with unfertilized control; while the application of high N rates with low P rates increased grain yields about 100% compared with the unfertilized control; lastly, applying high N and P rates increase grain yield well over 200% in comparison with the control.

In 2014 however, there was also a S effect on grain yield, but it was as a three-way interaction with N and P application rate. The response to S, nonetheless, was not clear as there was only a response to S for the 80 and 120 lbs of N and also at the lower P rates of 25 and 50 lbs of P (Fig. 6). This S effect was observed as a reduction in grain yield when S rates were either 5 or 10 lbs of S per acre (Fig. 6). Corn grain yield responses to S fertilization is more common in sandy soils than in loam type soils (O’Leary and Rehm, 1989). In most cases, when a response to S happens, about 10 lbs per acre seems to be enough (O’Leary and Rehm, 1989). In more recent years, other researchers have reported some response to S to rates as high as 15 lbs per acre (Rehm, 2005). The significant interaction including S observed in this study suggests that S deficiency is starting to become more common in fine textured soils and more work is needed to better understand the role of S in grain yield in southwest MN.

In 2015, the grain yields were again primarily affected by N and P rates and residue management (Tables 5 and 6). Like in 2013, plots where the residue was incorporated were found to have higher grain yields than plots where the residue was removed (Table 6). However, there was only a N response in plots where the residue was removed (Table 6). There was also a N by P application rate interaction where the higher grain yield was observed for the highest N and P application rates (Table 5).

Overall, continuous corn production in southwest MN is likely to rely on high rates of N, P, and S fertilizer and also residue management is likely to be an important driver for yield. Residue has been known to keep soils cooled and wetter in the spring, which has been reported to in some cases lead to a decrease in yield. However, when the need for moisture is high in the later summer months during grain filling, residue cover can provide more available water than when residue is removed. In addition, it was observed that residue management also changed how microbes behaved in the soil. Residue management was the parameter that had the most effect on enzyme activity of all parameters measured in this study. Higher enzyme activity could be related to higher microbial turn-over of organic matter with higher amounts of nutrients being available to the crop. Therefore, it is possible that the higher amount of residue left in the plots had an additive effect where the higher moisture available and higher mineralization lead to higher nutrient availability to the corn. Grain nutrient uptake can also be used to try and understand how the nutrient availability and uptake affected grain yield. Grain nutrient uptake was primarily affected by residue management but also by P and N application rate. In all cases, nutrient uptake was greater when residue was incorporated also collaborating the results observed for grain yield.

Biomass yield at V6 has little to no relation to final biomass yield or corn grain and in most cases, there was only an initial response to N application rate, where as much as 40 lbs of N was enough to provide the plant with enough N at this growth stage. Biomass at R1 although not related to final grain yield either, has its importance when considering silage production. In 2013, biomass yield at R1 was affected by the interaction between N application rate and residue management as well as by the interaction between N and S application rate. In all cases, however, biomass yield was always greater for the highest N rate. The addition of S tended to decrease biomass yield at the lower and mid N application rates, suggesting that N was being used elsewhere in the system and not available for plant uptake. In 2014 and 2015 biomass yield was reduced in plots where residue was incorporated. These results for biomass suggests that residue and sulfur are likely interacting with N and limiting corn biomass yield. Although no clear mechanisms can be derived from our results, it is likely that as residue is incorporated microbial communities use the S added to help in the breakdown of the residue added. In the breakdown process it is likely that some N is also needed, but the amount of N needed is likely to be related to the amount of N currently present in the soil. This is more evident by analyzing the amount of available N present in the soil. Soil available nitrate and ammonium was found to be significantly affect by residue management and sulfur application rate. In addition, as mentioned previously enzyme activity was also found to be affected primarily by residue management. In most cases enzyme activities were higher when residue was incorporated showing a higher rate of microbial activity which could be using more of the available nutrients and interfering with biomass yield. The fact that biomass yield at R1 is not related to grain yield, indicates that the lower nutrient availability can at R1 is easily overcome when there is adequate moisture and nutrient available in the later season. Recent research has shown that P, S, and Zn uptake happens much later in the growing season compared with N and K (Bender et al., 2012).

Although there were several cases of a significant effect for the parameters studied, nutrient uptake was mostly affected by residue management. It was observed, however, that nutrient uptake in tissue during the growing season has little to no relationship with grain nutrient uptake and yield. In the majority of the cases, nutrient uptake during the growing season was higher for the plots where residue was removed, and in contrast, nutrient uptake in the grain was higher for the plots where the residue was incorporated. As mentioned earlier, several nutrients are needed most after flowering and if the availability of nutrients is higher at that moment than chances for increases in yield will also be higher. The fact that there is a change in nutrient uptake during the growing season where the uptake is reversed and becomes higher in plots where residue was incorporated shows the important role that residue management plays in continuous corn systems. More research should be conducted to better understand how residue management can help maintaining high yields in continuous corn production in southwest MN, with a primary focus on nutrient uptake in the late season.

**CONCLUSIONS**

The results of this research showed that in the three years of research several interactions were observed, where different levels of nutrients and residue management were affecting corn development and yield. It has been reported in recent literature that nutrient requirement by corn in a continuous cropping system is different based on the different nutrients. Residue management has been found to play a key role in microbial activity and in turn also affected nutrient mineralization and availability to corn. We hypothesized that plots that had residue incorporated had higher moisture content in the later season and also higher nutrient mineralization which led to a higher nutrient availability of key nutrients which led to higher corn yields in plots that had the residue incorporated. The results of this work suggest that nutrient availability in continuous corn should managed differently than it currently is. For example, P and S, when needed, application takes place in the fall prior to planting of corn or in the spring just before planting. The literature and also our results shows that these nutrients are needed much later in the season. Applying those nutrients too early in the season seems to lead to lower availability when the corn needs it most which limits grain yield and nutrient uptake. Therefore, it is likely that to maintain or perhaps increase potential grain yield on a continuous corn system will require a new strategy for residue management and also fertilizer application.

**EDUCATION, OUTREACH, AND PUBLICATIONS**

*Identify conferences, workshops, field days etc. at which project results were presented. Include number of farmers estimated to be present. List articles and/or manuscripts in which project results were published.*

Timing and rate of fertilizer N influence 2014 corn yield and N uptake. Talk given at the annual winter crops and soils day presented at 4 locations in southwest Minnesota Feb 2 - 4th, 2016.

J.S. Strock, T. Varga, P.H. Pagliari, and A. Garcia y Garcia. Effect of Nitrogen Rate and Residue Management on Soil Water Status and Yield. In proceedings of 2016 Annual Meetings of the Soil Science Society of America. Nov. 6-9, 2016. Phoenix, AZ

P.H. Pagliari, J.S. Strock, L. Klossner, M. Coulter, and E.E. Evans. Enzyme Activity in Response to Fertilizer Application. In proceedings of 2016 Annual Meetings of the Soil Science Society of America. Nov. 6-9, 2016. Phoenix, AZ

Importance of soil health and best management practices on crop sustainability. Talk given at the 2015 CTIC tour in Southeast Minnesota on August 12, 2015.

Soil fertility and biology effects on corn grain yield. SWROC Winter Crops and Soil field day, February 3, 4, and 5, 2015, presented at Luverne, Lamberton, and Granite Falls.

P.H. Pagliari, J.S. Strock, L. Klossner, E.E. Evans, and M. Coulter. Carbon, Nitrogen, Phosphorus, and Sulfur Interactions Effects on Soil Biochemical Processes and Corn Grain Yield. In proceedings of 2014 Annual Meetings of the Soil Science Society of America. Nov. 2-5, 2014. Long Beach, CA.

Effects of carbon, nitrogen, phosphorus and sulfur interaction on soil biochemical processes and corn grain yield. SWROC Winter Crops and Soil field day, February 4, 5, and 6, 2014, presented at Luverne, Lamberton, and Granite Falls.

Carbon, nitrogen, phosphorus and sulfur interactions effects on soil biochemical processes and corn grain yield. Jan 28, 2013. Minnesota Ag. Expo. Mankato, MN.

**REFERENCES**

Bender, R. R.; Haegele, J. W.; Ruffo, M.; Below, F. E., Nutrient uptake and partitioning in high-yielding corn. MS Thesis, University of Illinois. Urbana, Illinois: 2012.

Coulter, J. A.; Nafziger, E. D., Continuous corn response to residue management and nitrogen fertilization. Agronomy journal **2008,** 100 (6), 1774-1780.

Maynard, D.G., J.W.B. Stewart, and J.R. Bettany. 1985. The effects of plants on soil sulfur transformations. Soil Biol. Biochem. 17:127-134.

Moore, J.M., S. Klose, and M.A. Tabatabai. 2000. Soil microbial biomass carbon and nitrogen as affected by cropping systems. Biol. Fertility Soils 31:200-210.

O'Leary, M. J.; Rehm, G. W., Nitrogen and Sulfur Effects on the Yield and Quality of Corn Grown for Grain and Silage. Journal of Production Agriculture **1990,** 3 (1), 135-140.

R Development Core Team. 2007. R: A language and environment for statistical computing. R Foundation for Statistical Computing Vienna, Austria.

Rehm, G. W., Sulfur Management for Corn Growth with Conservation Tillage. Soil Science Society of America Journal **2005,** 69 (3), 709-717.

SAS Institute, 2010. SAS 9.2. SAS Inst., Cary, NC.

Schlegel, A. J.; Havlin, J. L., Corn Yield and Grain Nutrient Uptake from 50 Years of Nitrogen and Phosphorus Fertilization. Agronomy Journal **2017,**109 (1), 335-342.

Scherer, H.W. 2001. Sulphur in crop production — invited paper. Eur. J. Agron. 14:81-111.

Sindelar, A.; Coulter, J.; Lamb, J.; Vetsch, J., Agronomic responses of continuous corn to stover, tillage, and nitrogen management. Agronomy Journal **2013,** 105 (6), 1498-1506.

Stevenson, F.J. and M.A. Cole. 1999. Cycles of soil. 2nd Edition. John Wiley & Sons, New York.

Vitousek, P., T. Fahey, D. Johnson, M. Swift. 1988. Element interactions in forest ecosystems: Succession, allometry and input-output budgets. Biogeochem 5:7-34.

Table 1. Summary of statistical analysis for corn grain yield from 2013 to 2015 during the study years.

|  |  |  |  |
| --- | --- | --- | --- |
| **Main Effects and Interactions** | **2013** | **2014** | **2015** |
| Probability level | | |
| **Crate** | **<.0001 †** | **<.0001** | 0.0759 |
| **Nrate** | **<.0001** | **<.0001** | **<.0001** |
| **Crate\*Nrate** | **0.0313** | **0.0054** | 0.8208 |
| **Prate** | **0.0035** | **<.0001** | **<.0001** |
| **Crate\*Prate** | 0.8320 | 0.2331 | **0.0030** |
| **Nrate\*Prate** | 0.8896 | **<.0001** | **<.0001** |
| **Crate\*Nrate\*Prate** | 0.8744 | 0.5182 | 0.4011 |
| **Srate** | 0.8274 | 0.1860 | 0.1880 |
| **Crate\*Srate** | 0.8369 | 0.4984 | 0.3225 |
| **Nrate\*Srate** | 0.1541 | **<.0001** | 0.6502 |
| **Crate\*Nrate\*Srate** | 0.4037 | 0.8326 | 0.1953 |
| **Prate\*Srate** | 0.5674 | **<.0001** | 0.5320 |
| **Crate\*Prate\*Srate** | 0.8763 | 0.4723 | 0.6358 |
| **Nrate\*Prate\*Srate** | 0.6113 | **<.0001** | 0.2491 |
| **Crate\*Nrate\*Prate\*Srate** | 0.4348 | 0.9913 | 0.7313 |

† Significant effects are those with probability levels <0.05 and are indicated in bold numbers.

Table 2. 2013 Grain yield as affected by nitrogen rate and residue management.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **2013 Corn Grain Yield (bu acre-1)** | | | | | |
| Removed | | | Incorporated | | |
| 0 | 114 | | f † | 124 | | ef |
| 40 | 130 | | de | 138 | | cd |
| 80 | 138 | | cd | 158 | | ab |
| 120 | 139 | | c | 156 | | b |
| 160 | 139 | | c | 165 | | a |
| 200 | 145 | | c | 159 | | ab |
| Average | | 134 B | | | 150 A | |
| LSD: 7 bushels acre-1 | | | | | | |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 3. 2013 grain yield as affected by phosphorus rate.

|  |  |  |
| --- | --- | --- |
| **Phosphorus Rate**  **(lbs acre-1)** | **2013 Corn Grain Yield**  **(bu acre-1)** | |
| 0 | 139 | b † |
| 25 | 140 | b |
| 50 | 139 | b |
| 75 | 147 | a |
| 100 | 146 | a |
| LSD: 4 bushels acre-1 | | |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 4. 2014 corn grain yield as affected by nitrogen rate and residue management.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **2014 Corn Grain Yield (bu acre-1)** | | | | | |
| Removed | | | Incorporated | | |
| 0 | 93 | | h† | 68 | | i |
| 40 | 114 | | f | 86 | | h |
| 80 | 140 | | d | 105 | | g |
| 120 | 160 | | bc | 123 | | e |
| 160 | 164 | | b | 138 | | d |
| 200 | 175 | | a | 154 | | c |
| Average | | 141 A | | | 112 B | |
| LSD: 5 bushels acre-1 | | | | | | |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 5. 2015 Corn grain yield as affected by nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | | | | |
| **0** | | **25** | | | **50** | | | **75** | | | **100** | | |
| **2015 Corn Grain Yield (bu acre-1)** | | | | | | | | | | | | | |
| 0 | 111 | m† | 106 | m | 101 | | m | 105 | | m | 107 | | m |
| 40 | 136 | l | 140 | kl | 145 | | jkl | 139 | | kl | 142 | | kl |
| 80 | 145 | jkl | 170 | hi | 173 | | gh | 175 | | fgh | 184 | | defg |
| 120 | 150 | jk | 177 | efgh | 192 | | bcd | 189 | | bcde | 205 | | a |
| 160 | 148 | jkl | 176 | efgh | 186 | | cdef | 199 | | abc | 193 | | abcd |
| 200 | 158 | ij | 175 | fgh | 195 | | abcd | 200 | | ab | 199 | | abc |
| Average | 141 | C | 157 | B | 165 | | AB | 168 | | A | 172 | | A |
| LSD: 9 bushels acre-1 | | | | | | | | | | |  | |  |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 6. 2015 corn grain yield as affected by phosphorus rate and residue management.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Phosphorus Rate**  **(lbs acre-1)** | **2015 Corn Grain Yield (bu acre-1)** | | | | | |
| Removed | | | Incorporated | | |
| 0 | 132 | | d | 150 | | c |
| 25 | 152 | | c | 163 | | ab |
| 50 | 161 | | b | 170 | | ab |
| 75 | 168 | | ab | 167 | | ab |
| 100 | 173 | | a | 171 | | ab |
| Average | | 157 B | | | 164 A | | |
| LSD: 6 bushels acre-1 | | | | | | | |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 7. Summary of statistical analysis for 2013 corn grain nutrient uptake.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | N | S | P | K | Ca | Mg | Fe | Mn | Zn |
| Probability level | | | | | | | | |
| **Crate** | 0.29† | **0.01** | **0.01** | **0.01** | 0.22 | **0.01** | **0.01** | **0.01** | **0.01** |
| **Nrate** | **0.01** | **0.01** | **0.01** | **0.00** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Crate\*Nrate** | 0.23 | 0.55 | **0.01** | **0.01** | **0.01** | **0.01** | **0.04** | **0.02** | **0.01** |
| **Prate** | 0.14 | **0.04** | **0.01** | 0.18 | 0.17 | 0.11 | 0.21 | **0.02** | 0.33 |
| **Crate\*Prate** | 0.52 | 0.26 | 0.49 | 0.89 | 0.55 | 0.32 | 0.35 | 0.47 | 0.37 |
| **Nrate\*Prate** | 0.99 | 0.89 | 0.24 | 0.40 | 0.21 | 0.19 | 0.36 | 0.13 | 0.13 |
| **Crate\*Nrate\*Prate** | 0.73 | 0.41 | 0.15 | 0.37 | 0.61 | 0.23 | 0.10 | 0.37 | 0.26 |
| **Srate** | 0.44 | 0.28 | 0.62 | 0.27 | 0.19 | 0.62 | 0.94 | 0.21 | 0.67 |
| **Crate\*Srate** | 0.42 | 0.33 | 0.62 | 0.52 | 0.38 | 0.75 | 0.65 | 0.90 | 0.76 |
| **Nrate\*Srate** | 0.16 | 0.33 | 0.71 | 0.98 | 0.26 | 0.81 | 0.56 | 0.47 | 0.54 |
| **Crate\*Nrate\*Srate** | 0.40 | 0.29 | 0.68 | 0.77 | 0.09 | 0.73 | 1.00 | 0.98 | 0.80 |
| **Prate\*Srate** | 0.65 | 0.48 | 0.61 | 0.69 | 0.41 | 0.68 | 0.57 | 0.39 | 0.61 |
| **Crate\*Prate\*Srate** | 0.71 | 0.26 | 0.83 | 0.44 | 0.38 | 0.82 | 0.68 | 0.49 | 0.91 |
| **Nrate\*Prate\*Srate** | 0.86 | 0.50 | 0.85 | 0.98 | 0.75 | 0.90 | 0.79 | 0.60 | 0.85 |
| **Crate\*Nrate\*Prate\*Srate** | 0.76 | 0.74 | 0.37 | 0.99 | 0.92 | 0.55 | 0.60 | 0.30 | 0.69 |

† Significant effects are those with probability levels <0.05 and are indicated in bold numbers.

Table 8. Summary of statistical analysis for 2013 corn biomass yield and nutrient uptake at V6.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | Biomass | N | S | P | K | Ca | Mg | Fe | Mn | Zn |
| Probability level | | | | | | | | | |
| **Crate** | **0.01†** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Nrate** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | 0.39 | **0.01** | 0.07 |
| **Crate\*Nrate** | **0.01** | **0.01** | **0.01** | **0.04** | 0.07 | 0.49 | 0.06 | 0.20 | 0.19 | 0.05 |
| **Prate** | **0.05** | 0.41 | **0.01** | 0.20 | 0.99 | 0.34 | 0.84 | 0.76 | 0.33 | 0.17 |
| **Crate\*Prate** | 0.37 | 0.24 | 0.18 | 0.31 | 0.50 | 0.44 | 0.23 | 0.89 | 0.33 | 0.24 |
| **Nrate\*Prate** | 0.58 | 0.18 | 0.60 | 0.28 | 0.98 | 0.22 | 0.34 | 0.44 | 0.28 | 0.64 |
| **Crate\*Nrate\*Prate** | 0.82 | 0.36 | 0.87 | 0.76 | 0.39 | 0.64 | 0.75 | 0.40 | 0.48 | 0.25 |
| **Srate** | 0.29 | 0.24 | **0.01** | 0.20 | 0.08 | 0.19 | 0.06 | 0.71 | 0.93 | 0.98 |
| **Crate\*Srate** | 0.56 | 0.25 | 0.16 | 0.98 | 0.42 | 0.19 | 0.26 | 0.10 | 0.07 | 0.68 |
| **Nrate\*Srate** | 0.99 | 0.87 | 0.89 | 0.92 | 0.54 | 0.98 | 0.69 | 0.33 | 0.70 | 0.30 |
| **Crate\*Nrate\*Srate** | 0.76 | 0.65 | 0.98 | 0.53 | 0.88 | 0.80 | 0.72 | 0.31 | 0.27 | 0.90 |
| **Prate\*Srate** | 0.88 | 0.58 | 0.74 | 0.31 | 0.98 | 0.49 | 0.27 | 0.65 | 0.35 | 0.71 |
| **Crate\*Prate\*Srate** | 0.73 | 0.93 | 1.00 | 0.06 | 0.52 | 0.85 | 0.17 | 0.40 | 0.11 | 0.64 |
| **Nrate\*Prate\*Srate** | 0.43 | 0.62 | 0.50 | 0.98 | 0.19 | 0.25 | 0.30 | 0.34 | 0.16 | 0.06 |
| **Crate\*Nrate\*Prate\*Srate** | 0.57 | 0.24 | 0.05 | 0.96 | 0.28 | 0.86 | 0.15 | 0.11 | 0.41 | 0.16 |

† Significant effects are those with probability levels <0.05 and are indicated in bold numbers.

Table 9. Summary of statistical analysis for 2013 corn biomass yield and nutrient uptake at R1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | Biomass | N | S | P | K | Ca | Mg | Fe | Mn | Zn |
| Probability level | | | | | | | | | |
| **Crate** | 0.22† | 0.91 | 0.57 | **0.03** | **0.01** | **0.01** | **0.01** | **0.01** | 0.09 | 0.25 |
| **Nrate** | **0.01** | **0.01** | **0.01** | **0.01** | 0.05 | **0.01** | **0.01** | 0.15 | 0.10 | 0.49 |
| **Crate\*Nrate** | **0.01** | 0.23 | 0.56 | 0.88 | 0.10 | **0.03** | **0.04** | 0.40 | 0.21 | 0.43 |
| **Prate** | 0.13 | 0.27 | 0.85 | **0.01** | 0.61 | 0.47 | 0.53 | 0.98 | 0.65 | 0.53 |
| **Crate\*Prate** | 0.90 | 0.78 | 0.36 | 0.60 | 0.50 | 0.50 | 0.47 | 0.95 | 0.99 | 0.08 |
| **Nrate\*Prate** | 0.38 | 0.06 | 0.94 | 0.70 | 1.00 | 0.69 | 0.34 | 0.99 | 0.78 | 0.17 |
| **Crate\*Nrate\*Prate** | 0.28 | 0.82 | 0.32 | 0.31 | 0.64 | 0.20 | 0.50 | 0.93 | 1.00 | 0.48 |
| **Srate** | **0.01** | **0.01** | 0.15 | **0.01** | 0.13 | **0.02** | **0.02** | 0.77 | 0.91 | 0.54 |
| **Crate\*Srate** | 0.25 | 0.16 | 0.19 | 0.37 | 0.59 | 0.34 | 0.16 | 0.75 | 0.42 | 0.31 |
| **Nrate\*Srate** | **0.04** | **0.02** | **0.04** | 0.44 | 0.19 | 0.54 | 0.79 | 1.00 | 0.11 | 0.49 |
| **Crate\*Nrate\*Srate** | 0.95 | 0.79 | 0.86 | 0.49 | 0.35 | 0.86 | 0.80 | 0.75 | 0.37 | 0.58 |
| **Prate\*Srate** | 0.15 | 0.29 | 0.29 | 0.97 | 0.91 | 0.99 | 1.00 | 0.94 | 0.83 | 0.08 |
| **Crate\*Prate\*Srate** | 0.68 | 0.83 | 0.36 | 0.75 | 0.79 | 0.74 | 0.65 | 0.91 | 0.92 | 0.24 |
| **Nrate\*Prate\*Srate** | 0.26 | 0.28 | 0.76 | 0.81 | 0.78 | 0.53 | 0.68 | 0.95 | 0.52 | 0.66 |
| **Crate\*Nrate\*Prate\*Srate** | 0.61 | 0.57 | 0.48 | 0.40 | 0.93 | 0.85 | 0.92 | 1.00 | 0.97 | 0.14 |

† Significant effects are those with probability levels <0.05 and are indicated in bold numbers.

Table 10. 2013 grain and tissue nutrient uptake as a function of nitrogen application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **—— Grain Uptake——** | | | | **———————— Tissue V6 ————————** | | | | | | | | **— R1 —** | |
| **N** | | **S** | | **K** | | **Ca** | | **Mg** | | **Mn** | | **P** | |
|  | **(lbs acre-1)** | | | | | | | | | | | | | |
| 0 | 73 | d † | 8.1 | d | 99 | b | 7.1 | b | 7.9 | d | 0.24 | b | 8.3 | d | |
| 40 | 84 | c | 9.0 | c | 110 | a | 8.6 | a | 9.5 | c | 0.29 | a | 8.9 | cd | |
| 80 | 103 | b | 10.0 | b | 111 | a | 8.8 | a | 9.8 | bc | 0.28 | a | 9.9 | ab | |
| 120 | 107 | b | 10.8 | a | 113 | a | 9.1 | a | 10.4 | a | 0.28 | a | 9.6 | bc | |
| 160 | 112 | a | 10.9 | a | 109 | a | 9.1 | a | 10.4 | a | 0.28 | a | 9.7 | bc | |
| 200 | 114 | a | 10.8 | a | 112 | a | 9.0 | a | 10.3 | ab | 0.29 | a | 10.6 | a | |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 11. 2013 grain and tissue nutrient uptake as a function of phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Phosphorus Rate**  **(lbs acre-1)** | **———— Grain Uptake ————** | | | | | | **———— V6 ————** | | | | **— R1 —** | |
| **S** | | **P** | | **Mn** | | **Biomass** | | **S** | | **P** | |
|  | **(lbs acre-1)** | | | | | | | | | | | |
| 0 | 9.9 | abc† | 47 | b | 0.18 | b | 2,115 | b | 5.3 | c | 9.2 | bc |
| 25 | 9.7 | bc | 51 | b | 0.18 | b | 2,108 | b | 5.4 | bc | 8.9 | c |
| 50 | 9.6 | c | 50 | b | 0.18 | b | 2,148 | ab | 5.5 | ab | 9.5 | abc |
| 75 | 10.3 | a | 57 | a | 0.20 | a | 2,149 | a | 5.7 | a | 9.8 | ab |
| 100 | 10.2 | ab | 56 | a | 0.20 | a | 2,179 | a | 5.7 | a | 10.1 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 12. 2013 corn grain nutrient uptake as affected by nitrogen rate and residue management.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **P** | | **K** | | **Ca** | | **Mg** | | **Fe** | | **Mn** | | **Zn** | |
| **Residue Removed** | | | | | | | | | | | | | |
|  | **(lbs acre-1)** | | | | | | | | | | | | | |
| 0 | 58 | a† | 83 | ab | 49 | ab | 64 | abc | 0.61 | ef | 0.18 | cde | 0.33 | abc |
| 40 | 61 | a | 89 | a | 51 | ab | 69 | abc | 0.72 | de | 0.20 | bcd | 0.36 | a |
| 80 | 60 | a | 89 | a | 53 | ab | 70 | a | 0.82 | bc | 0.21 | ab | 0.35 | ab |
| 120 | 54 | ab | 84 | ab | 52 | ab | 66 | abc | 0.83 | bc | 0.21 | bc | 0.32 | abc |
| 160 | 54 | ab | 84 | ab | 51 | ab | 69 | abc | 0.89 | ab | 0.21 | bc | 0.32 | abc |
| 200 | 54 | ab | 83 | ab | 52 | ab | 70 | ab | 0.96 | a | 0.24 | a | 0.33 | ab |
|  | **Residue Incorporated** | | | | | | | | | | | | | |
| 0 | 34 | d | 44 | e | 32 | c | 39 | f | 0.36 | g | 0.12 | f | 0.21 | e |
| 40 | 46 | bc | 66 | cd | 46 | b | 52 | de | 0.51 | f | 0.15 | e | 0.28 | cd |
| 80 | 54 | ab | 67 | cd | 55 | a | 58 | cde | 0.64 | e | 0.18 | bcd | 0.31 | abc |
| 120 | 52 | ab | 71 | bc | 51 | ab | 59 | bcd | 0.65 | e | 0.18 | bcd | 0.30 | bc |
| 160 | 53 | ab | 74 | abc | 55 | a | 64 | abc | 0.76 | cd | 0.20 | bcd | 0.32 | abc |
| 200 | 40 | cd | 59 | d | 45 | b | 50 | e | 0.61 | e | 0.17 | de | 0.25 | de |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 13. 2013 corn tissue nutrient uptake as affected by nitrogen rate and residue management.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **—————————— V6 ——————————** | | | | | | | | **——————— R1 ———————** | | | | | |
| **Biomass** | | **N** | | **S** | | **P** | | **Biomass** | | **Ca** | | **Mg** | |
| **Residue Removed** | | | | | | | | | | | | | |
|  | **(lbs acre-1)** | | | | | | | | | | | | | |
| 0 | 1981 | b† | 58 | d | 5.1 | b | 9.1 | ab | 6722 | e | 13 | def | 28 | d |
| 40 | 2229 | a | 72 | c | 5.7 | a | 9.2 | ab | 8078 | d | 16 | bc | 34 | c |
| 80 | 2252 | a | 81 | b | 5.9 | a | 9.1 | abc | 8842 | bc | 21 | a | 41 | ab |
| 120 | 2246 | a | 85 | ab | 6.0 | a | 9.3 | a | 8938 | bc | 20 | a | 42 | ab |
| 160 | 2233 | a | 84 | ab | 5.9 | a | 9.5 | a | 8912 | bc | 18 | b | 38 | b |
| 200 | 2230 | a | 88 | a | 5.9 | a | 9.2 | ab | 9090 | ab | 21 | a | 43 | a |
|  | **Residue Incorporated** | | | | | | | | | | | | | |
| 0 | 1669 | c | 42 | e | 4.0 | c | 6.5 | e | 5746 | f | 10 | g | 16 | g |
| 40 | 2025 | b | 59 | d | 4.9 | b | 7.8 | d | 7164 | e | 12 | fg | 21 | f |
| 80 | 2196 | a | 71 | c | 5.6 | a | 8.0 | d | 8305 | cd | 12 | ef | 22 | f |
| 120 | 2205 | a | 80 | b | 5.8 | a | 8.1 | cd | 9034 | b | 14 | cde | 24 | def |
| 160 | 2201 | a | 80 | b | 5.6 | a | 8.3 | bcd | 8855 | bc | 13 | def | 24 | def |
| 200 | 2213 | a | 83 | ab | 5.8 | a | 8.1 | d | 9682 | a | 15 | cd | 25 | de |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 14. 2013 corn biomass yield at R1 and tissue nutrient uptake at R1 as affected by nitrogen and sulfur application rate

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Sulfur Rate**  **(lbs acre-1)** | **Biomass** | | **Nitrogen** | | **Sulfur** | |
| **(lbs acre-1)** | | | | | |
| 0 | 0 | 6,466 | jkl† | 77 | hi | 7.2 | hij |
| 40 | 0 | 7,752 | gh | 86 | gh | 8.3 | fghi |
| 80 | 0 | 9,078 | abcd | 114 | bc | 10.1 | bcdef |
| 120 | 0 | 9,373 | ab | 124 | ab | 13.5 | a |
| 160 | 0 | 8,670 | bcdef | 115 | bc | 10.1 | bcdef |
| 200 | 0 | 9,574 | a | 132 | a | 11.1 | bc |
| 0 | 5 | 6,661 | jk | 77 | hi | 7.3 | hij |
| 40 | 5 | 8,329 | efg | 95 | efg | 9.4 | cdefg |
| 80 | 5 | 8,412 | defg | 102 | def | 9.3 | defg |
| 120 | 5 | 8,856 | abcdef | 107 | cde | 9.7 | bcdefg |
| 160 | 5 | 9,507 | a | 127 | a | 10.9 | bcd |
| 200 | 5 | 9,150 | abc | 127 | a | 10.4 | bcde |
| 0 | 10 | 5,845 | l | 66 | i | 6.5 | j |
| 40 | 10 | 7,549 | hi | 83 | gh | 8.1 | hij |
| 80 | 10 | 8,220 | fgh | 93 | fg | 8.8 | efgh |
| 120 | 10 | 9,032 | abcde | 109 | cd | 9.9 | bcdefg |
| 160 | 10 | 8,684 | bcdef | 113 | bcd | 10.5 | bcde |
| 200 | 10 | 9,573 | a | 133 | a | 11.5 | b |
| 0 | 15 | 5,964 | kl | 66 | i | 6.6 | ij |
| 40 | 15 | 6,855 | ij | 78 | hi | 8.1 | ghij |
| 80 | 15 | 8,585 | cdef | 105 | cdef | 10.0 | bcdef |
| 120 | 15 | 8,682 | bcdef | 112 | bcd | 10.4 | bcde |
| 160 | 15 | 8,673 | bcdef | 113 | bcd | 10.3 | bcde |
| 200 | 15 | 9,247 | abc | 131 | A | 11.4 | b |

† Means followed by different letters are within a column significantly different (P<0.05).

Table 15. Summary of statistical analysis for 2014 corn grain nutrient uptake, biomass yield and nutrient uptake at V6 and R1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | **Biomass** | **N** | **S** | **P** | **K** | **Ca** | **Mg** | **Fe** | **Mn** | **Zn** |
| **V6** | | | | | | | | | |
|  | **Probability level** | | | | | | | | | |
| **Nrate** | **0.01†** | **0.01** | **0.01** | 0.12 | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Prate** | 0.75 | 0.91 | 0.79 | 0.75 | 0.69 | 0.63 | 0.91 | 0.32 | 0.82 | 0.91 |
| **Nrate\*Prate** | 0.91 | 0.95 | 0.91 | 0.99 | 0.91 | 0.96 | 0.99 | 0.99 | 0.99 | 0.94 |
| **Crate** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Crate\*Nrate** | 0.16 | 0.15 | 0.11 | 0.45 | 0.07 | **0.03** | **0.04** | 0.49 | 0.16 | 0.14 |
| **Crate\*Prate** | 0.47 | 0.59 | 0.58 | 0.57 | 0.39 | 0.48 | 0.60 | 0.46 | 0.42 | 0.42 |
| **Crate\*Nrate\*Prate** | 0.07 | 0.35 | 0.17 | 0.22 | 0.06 | 0.24 | 0.32 | 0.13 | 0.15 | 0.25 |
|  | **R1** | | | | | | | | | |
| **Nrate** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Prate** | 0.98 | 0.73 | 0.59 | 0.31 | 0.52 | 0.72 | 0.98 | 0.88 | 0.91 | 0.97 |
| **Nrate\*Prate** | 0.89 | 0.90 | 0.80 | 0.37 | 0.24 | 0.68 | 0.82 | 0.36 | 0.65 | 0.39 |
| **Crate** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Crate\*Nrate** | 0.11 | **0.01** | **0.03** | 0.07 | **0.04** | **0.01** | **0.03** | **0.02** | **0.03** | **0.01** |
| **Crate\*Prate** | 0.53 | 0.75 | 0.35 | 0.59 | 0.64 | 0.56 | 0.76 | 0.67 | 0.74 | 0.89 |
| **Crate\*Nrate\*Prate** | 0.36 | 0.58 | 0.59 | 0.16 | 0.33 | 0.58 | 0.73 | 0.09 | 0.68 | 0.38 |
|  | **Grain** | | | | | | | | | |
| **Nrate** | **---** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Prate** | **---** | 0.18 | 0.11 | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Nrate\*Prate** | **---** | 0.77 | 0.67 | **0.01** | 0.07 | 0.31 | **0.02** | 0.28 | **0.02** | **0.03** |
| **Crate** | **---** | **0.01** | 0.97 | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Crate\*Nrate** | **---** | 0.12 | 0.19 | 0.92 | 0.91 | 0.34 | 0.79 | 0.98 | 0.94 | 0.89 |
| **Crate\*Prate** | **---** | 0.13 | 0.14 | 0.73 | 0.85 | 0.96 | 0.74 | 0.80 | 0.72 | 0.74 |
| **Crate\*Nrate\*Prate** | **---** | 0.29 | 0.45 | 0.09 | 0.38 | 0.12 | 0.12 | 0.24 | 0.24 | 0.41 |

† Significant effects are those with probability levels <0.05 and are indicated in bold numbers.

Table 16. Summary of statistical analysis for 2014 corn biomass yield and nutrient uptake at V6 and R1.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **———V6 ———** | | | | **———————————————— R1 ————————————————** | | | | | | | | | | | | | |
| **Ca** | | **Mg** | | **N** | | **S** | | **K** | | **Mg** | | **Fe** | | **Mn** | | **Zn** | |
| **Residue Removed (lbs of nutrient acre-1)** | | | | | | | | | | | | | | | | | |
| 0 | 13 | cd† | 7 | d | 40 | de | 2.9 | e | 47 | d | 12 | efg | 1.6 | e | 1.0 | de | 0.5 | c |
| 40 | 25 | b | 15 | bc | 67 | c | 4.6 | cde | 67 | bc | 20 | cd | 3.1 | cd | 1.7 | c | 0.8 | b |
| 80 | 25 | b | 15 | bc | 101 | b | 6.5 | bc | 78 | ab | 25 | bc | 3.8 | bc | 2.4 | b | 0.8 | b |
| 120 | 38 | a | 21 | ab | 110 | b | 8.5 | ab | 90 | a | 29 | ab | 4.3 | ab | 2.7 | ab | 1.0 | a |
| 160 | 45 | a | 27 | a | 135 | a | 8.7 | a | 92 | a | 33 | a | 4.8 | a | 3.1 | a | 0.9 | ab |
|  | **Residue Incorporated (lbs of nutrient acre-1)** | | | | | | | | | | | | | | | | | |
| 0 | 7 | d | 4 | d | 37 | e | 3.3 | de | 47 | d | 9 | g | 1.3 | e | 0.9 | e | 0.5 | c |
| 40 | 8 | cd | 4 | d | 37 | e | 3.4 | de | 47 | d | 10 | fg | 1.3 | e | 1.0 | de | 0.5 | c |
| 80 | 16 | bcd | 8 | cd | 52 | cde | 4.1 | de | 59 | cd | 14 | efg | 2.3 | de | 1.5 | de | 0.5 | c |
| 120 | 18 | bc | 9 | cd | 62 | cd | 4.5 | cde | 58 | cd | 16 | def | 2.2 | de | 1.6 | cde | 0.6 | c |
| 160 | 15 | bcd | 7 | d | 68 | c | 5.1 | cd | 66 | bc | 16 | de | 2.2 | de | 1.6 | cd | 0.6 | c |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **———————————————V6———————————————** | | | | | | | | | | | | | | | | **————R1————** | | | | | |
| **Biomass** | | **N** | | **S** | | **K** | | | **Fe** | | | **Mn** | | **Zn** | | **Biomass** | | | **P** | | |
| lbs acre-1 | | | | | | | | | | | | | | | | | | | | | |
| 0 | 222 | c† | 5 | d | 0.5 | d | 7 | | c | 0.6 | | b | 0.1 | c | 0.04 | c | 2,651 | | b | 58 | | b |
| 40 | 373 | bc | 7 | cd | 0.7 | cd | 12 | | bc | 0.9 | | a | 0.2 | bc | 0.06 | bc | 3,530 | | b | 66 | | ab |
| 80 | 492 | ab | 10 | bc | 0.9 | bc | 14 | | ab | 1.0 | | a | 0.3 | ab | 0.07 | bc | 5,016 | | a | 79 | | a |
| 120 | 576 | a | 13 | ab | 1.1 | ab | 17 | | ab | 1.2 | | a | 0.4 | ab | 0.08 | ab | 5,581 | | a | 81 | | a |
| 160 | 628 | a | 15 | a | 1.2 | a | 19 | | a | 1.2 | | a | 0.4 | a | 0.10 | a | 5,972 | | a | 82 | | a |
| **Residue Management** | **———————————————V6———————————————** | | | | | | | | | | | | | | | | | **————R1————** | | | | |
| **Biomass** | | **N** | | **S** | | | **K** | | | **Fe** | | **Mn** | | **Zn** | | | **Biomass** | | | **P** | |
| Removed | 599 | a | 14 | a | 1.2 | a | 18 | | a | 1.1 | | a | 0.4 | a | 0.10 | a | 5,483 | | a | 86 | | a |
| Incorporate | 318 | b | 6 | b | 0.6 | b | 9 | | b | 0.8 | | b | 0.2 | b | 0.04 | b | 3,616 | | b | 61 | | b |

† Means followed by different letters within the column are significantly different (P<0.05).

Table 17. 2014 corn grain phosphorus uptake as a function of nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | | | | |
| **0** | | **25** | | | **50** | | | **75** | | | **100** | | |
| **P uptake lbs acre-1** | | | | | | | | | | | | | |
| 0 | 29 | b† | 32 | b | 26 | | c | 31 | | b | 35 | | c |
| 40 | 34 | ab | 43 | ab | 40 | | b | 44 | | a | 43 | | bc |
| 80 | 40 | a | 48 | a | 42 | | b | 51 | | a | 61 | | a |
| 120 | 34 | ab | 45 | a | 55 | | a | 54 | | a | 60 | | a |
| 160 | 33 | ab | 42 | ab | 59 | | a | 55 | | a | 51 | | ab |
| 200 | 36 | ab | 40 | ab | 38 | | b | 47 | | a | 45 | | bc |

† Means followed by different letters within each P rate are significantly different (P<0.05).

Table 18. 2014 corn grain magnesium uptake as a function of nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | | | | |
| **0** | | **25** | | | **50** | | | **75** | | | **100** | | |
| **Mg uptake lbs acre-1** | | | | | | | | | | | | | |
| 0 | 22 | b† | 24 | b | 19 | | c | 23 | | c | 25 | | c |
| 40 | 27 | ab | 32 | a | 30 | | b | 34 | | b | 31 | | bc |
| 80 | 30 | a | 36 | a | 32 | | b | 37 | | ab | 43 | | a |
| 120 | 29 | a | 36 | a | 43 | | a | 40 | | ab | 43 | | a |
| 160 | 31 | a | 36 | a | 47 | | a | 43 | | a | 40 | | a |
| 200 | 32 | a | 33 | a | 32 | | b | 38 | | ab | 37 | | ab |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 19. 2014 corn grain manganese uptake as a function of nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | | | | |
| **0** | | **25** | | | **50** | | | **75** | | | **100** | | |
| **Mn uptake lbs acre-1** | | | | | | | | | | | | | |
| 0 | 0.13 | c† | 0.14 | b | 0.11 | | c | 0.14 | | b | 0.14 | | d |
| 40 | 0.14 | c | 0.17 | ab | 0.16 | | bc | 0.17 | | b | 0.19 | | bc |
| 80 | 0.19 | ab | 0.20 | a | 0.19 | | b | 0.24 | | a | 0.26 | | ab |
| 120 | 0.15 | bc | 0.21 | a | 0.26 | | a | 0.26 | | a | 0.28 | | a |
| 160 | 0.16 | bc | 0.21 | a | 0.27 | | a | 0.26 | | a | 0.24 | | ab |
| 200 | 0.22 | a | 0.21 | a | 0.22 | | ab | 0.26 | | a | 0.21 | | b |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 20. 2014 corn grain zinc uptake as a function of nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | | | | |
| **0** | | **25** | | | **50** | | | **75** | | | **100** | | |
| **Zn uptake lbs acre-1** | | | | | | | | | | | | | |
| 0 | 0.71 | b† | 0.76 | b | 0.62 | | c | 0.72 | | c | 0.77 | | c |
| 40 | 0.82 | ab | 1.02 | a | 0.94 | | b | 0.99 | | b | 1.03 | | b |
| 80 | 0.97 | a | 1.11 | a | 0.98 | | b | 1.17 | | a | 1.32 | | a |
| 120 | 0.91 | a | 1.02 | a | 1.28 | | a | 1.17 | | a | 1.29 | | a |
| 160 | 0.92 | a | 1.09 | a | 1.34 | | a | 1.21 | | a | 1.13 | | ab |
| 200 | 0.98 | a | 1.04 | a | 0.93 | | b | 1.07 | | ab | 1.01 | | b |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 21. 2014 corn grain nutrient uptake as a function of nitrogen application rate.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **N** | | **S** | | **K** | | **Ca** | | **Fe** | |
|  | **Grain nutrient uptake lbs acre-1** | | | | | | | | |  |
| 0 | 17 | C† | 1.3 | b | 59 | c | 38 | c | 0.42 | d |
| 40 | 18 | c | 1.4 | b | 81 | b | 54 | b | 0.59 | c |
| 80 | 28 | b | 2.0 | a | 88 | ab | 63 | a | 0.78 | b |
| 120 | 33 | ab | 2.3 | a | 97 | a | 67 | a | 0.86 | ab |
| 160 | 33 | ab | 2.2 | a | 95 | a | 65 | a | 0.93 | ab |
| 200 | 34 | a | 2.2 | a | 85 | b | 60 | ab | 0.98 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 22. 2014 corn grain nutrient uptake as a function of residue management

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Residue Management** | **N** | | **P** | | **K** | | **Ca** | | **Mg** | | **Fe** | | **Mn** | | **Zn** | |
|  | **Grain nutrient uptake lbs acre-1** | | | | | | | | | | | | | | | |
| Removed | 25 | b | 38 | b | 73 | b | 49 | b | 60 | b | 0.69 | b | 0.19 | b | 0.91 | b |
| Incorporate | 30 | a | 48 | a | 96 | a | 67 | a | 74 | a | 0.83 | a | 0.21 | a | 1.11 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 23. 2014 corn grain nutrient uptake as a function of phosphorus application rate.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Phosphorus Rate**  **(lbs acre-1)** | **K** | | **Ca** | | **Fe** | |
| **(lbs acre-1)** | | | | | |
| 0 | 71 | b† | 50 | b | 0.63 | c |
| 25 | 84 | a | 56 | a | 0.71 | bc |
| 50 | 86 | a | 58 | a | 0.74 | bc |
| 75 | 89 | a | 62 | a | 0.81 | ab |
| 100 | 92 | a | 62 | a | 0.92 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 24. Summary of statistical analysis for 2015 corn grain nutrient uptake, biomass yield and nutrient uptake at V6 and R1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | **Biomass** | **N** | **S** | **P** | **K** | **Ca** | **Mg** | **Fe** | **Mn** | **Zn** |
| **V6** | | | | | | | | | |
|  | **Probability level** | | | | | | | | | |
| **Nrate** | 0.48† | 0.15 | 0.36 | 0.51 | 0.45 | 0.58 | 0.76 | 0.21 | 0.11 | 0.18 |
| **Prate** | 0.94 | 0.71 | 0.96 | 0.75 | 0.95 | 0.51 | 0.94 | 0.31 | 0.64 | 0.65 |
| **Nrate\*Prate** | 0.53 | 0.83 | 0.55 | 0.89 | 0.28 | 0.42 | 0.92 | 0.57 | 0.80 | 0.89 |
| **Crate** | 0.97 | **0.03** | 0.06 | 0.61 | 0.11 | 0.78 | **0.01** | **0.01** | **0.04** | **0.01** |
| **Crate\*Nrate** | 0.55 | 0.48 | 0.49 | 0.64 | 0.49 | 0.71 | 0.49 | 0.15 | 0.30 | 0.79 |
| **Crate\*Prate** | 0.19 | 0.34 | 0.16 | 0.17 | **0.04** | **0.04** | 0.21 | 0.33 | 0.18 | 0.26 |
| **Crate\*Nrate\*Prate** | 0.50 | 0.17 | 0.28 | 0.46 | 0.19 | 0.88 | 0.39 | 0.55 | 0.49 | 0.56 |
|  | **R1** | | | | | | | | | |
| **Nrate** | 0.27 | 0.27 | 0.31 | **0.01** | 0.08 | **0.01** | 0.68 | 0.58 | 0.50 | **0.01** |
| **Prate** | 0.23 | 0.93 | 0.29 | **0.01** | 0.10 | 0.13 | 0.76 | 0.13 | 0.33 | 0.56 |
| **Nrate\*Prate** | 0.40 | 0.51 | 0.96 | 0.45 | 0.39 | 0.66 | 0.68 | 0.46 | 0.64 | 0.94 |
| **Crate** | **0.01** | **0.04** | 0.09 | **0.01** | **0.01** | **0.01** | **0.02** | **0.01** | 0.68 | 0.07 |
| **Crate\*Nrate** | 0.39 | **0.01** | **0.01** | **0.01** | 0.35 | **0.03** | 0.19 | 0.86 | 0.41 | **0.01** |
| **Crate\*Prate** | 0.17 | 0.71 | 0.49 | 0.44 | 0.57 | 0.26 | 0.79 | 0.53 | 0.42 | 0.76 |
| **Crate\*Nrate\*Prate** | 0.81 | 0.15 | 0.37 | 0.16 | 0.21 | 0.37 | 0.31 | 0.06 | 0.09 | 0.30 |
|  | **Grain** | | | | | | | | | |
| **Nrate** | **---** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Prate** | **---** | 0.19 | 0.13 | **0.01** | 0.81 | **0.01** | **0.01** | 0.61 | **0.01** | **0.01** |
| **Nrate\*Prate** | --- | 0.75 | 0.65 | **0.01** | 0.05 | **0.01** | **0.02** | 0.25 | **0.02** | **0.03** |
| **Crate** | **---** | **0.01** | 0.96 | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** |
| **Crate\*Nrate** | --- | 0.13 | 0.19 | 0.91 | 0.93 | 0.31 | 0.81 | 0.98 | 0.95 | 0.89 |
| **Crate\*Prate** | --- | 0.15 | 0.15 | 0.76 | 0.85 | 0.96 | 0.76 | 0.82 | 0.72 | 0.83 |
| **Crate\*Nrate\*Prate** | --- | 0.28 | 0.44 | 0.10 | 0.39 | 0.11 | 0.14 | 0.24 | 0.32 | 0.15 |

† Significant effects are those with probability levels <0.05 and are indicated in bold numbers.

Table 25. 2015 corn grain nutrient uptake as a function of nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | | | | |
| **0** | | **25** | | | **50** | | | **75** | | | **100** | | |
| **Phosphorus uptake lbs acre-1** | | | | | | | | | | | | | |
| 0 | 31 | b† | 34 | b | 28 | | c | 33 | | b | 37 | | d |
| 40 | 36 | ab | 45 | a | 43 | | b | 47 | | a | 45 | | cd |
| 80 | 42 | a | 51 | a | 45 | | b | 55 | | a | 64 | | a |
| 120 | 35 | ab | 48 | a | 58 | | a | 57 | | a | 64 | | a |
| 160 | 35 | ab | 45 | a | 63 | | a | 58 | | a | 54 | | b |
| 200 | 39 | ab | 42 | ab | 40 | | b | 49 | | a | 48 | | bc |
|  | **Calcium uptake lbs acre-1** | | | | | | | | | | | | |
| 0 | 41 | c | 39 | d | 37 | | e | 38 | | c | 45 | | d |
| 40 | 51 | bc | 51 | c | 54 | | d | 70 | | ab | 61 | | c |
| 80 | 55 | ab | 75 | a | 64 | | bc | 68 | | b | 74 | | b |
| 120 | 68 | a | 69 | ab | 72 | | ab | 70 | | ab | 74 | | b |
| 160 | 53 | ab | 60 | bc | 80 | | a | 86 | | a | 64 | | c |
| 200 | 51 | bc | 68 | ab | 57 | | cd | 63 | | b | 81 | | a |
|  | **Magnesium uptake lbs acre-1** | | | | | | | | | | | | |
| 0 | 47 | d | 51 | c | 40 | | c | 49 | | d | 53 | | d |
| 40 | 57 | c | 68 | b | 63 | | b | 71 | | c | 65 | | c |
| 80 | 64 | ab | 78 | a | 67 | | b | 79 | | bc | 90 | | a |
| 120 | 61 | bc | 75 | ab | 91 | | a | 85 | | ab | 91 | | a |
| 160 | 65 | ab | 77 | a | 100 | | a | 90 | | a | 84 | | ab |
| 200 | 69 | a | 70 | ab | 67 | | b | 81 | | b | 78 | | b |
|  | **Manganese uptake lbs acre-1** | | | | | | | | | | | | |
| 0 | 0.13 | c | 0.14 | b | 0.11 | | d | 0.15 | | b | 0.14 | | d |
| 40 | 0.15 | bc | 0.18 | ab | 0.17 | | c | 0.18 | | b | 0.20 | | cd |
| 80 | 0.20 | ab | 0.22 | a | 0.20 | | bc | 0.26 | | a | 0.28 | | ab |
| 120 | 0.16 | ab | 0.22 | a | 0.28 | | a | 0.27 | | a | 0.30 | | a |
| 160 | 0.17 | ab | 0.23 | a | 0.29 | | a | 0.27 | | a | 0.26 | | ab |
| 200 | 0.23 | a | 0.22 | a | 0.24 | | ab | 0.27 | | a | 0.23 | | bc |
|  | **Zinc uptake lbs acre-1** | | | | | | | | | | | | |
| 0 | 0.76 | c | 0.80 | b | 0.66 | | c | 0.76 | | c | 0.82 | | c |
| 40 | 0.87 | bc | 1.09 | a | 0.99 | | b | 1.05 | | b | 1.08 | | b |
| 80 | 1.03 | a | 1.18 | a | 1.03 | | b | 1.24 | | ab | 1.40 | | a |
| 120 | 0.96 | ab | 1.12 | a | 1.36 | | a | 1.23 | | ab | 1.37 | | a |
| 160 | 0.97 | ab | 1.15 | a | 1.42 | | a | 1.28 | | a | 1.19 | | ab |
| 200 | 1.03 | a | 1.09 | a | 0.98 | | b | 1.14 | | b | 1.07 | | b |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 26. Summary of statistical analysis for 2015 corn grain nutrient uptake as affected by residue management.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Residue Management** | **N** | | **P** | | **K** | | **Ca** | | | **Mg** | | **Fe** | | **Mn** | | **Zn** | |
|  | **Nutrient Uptake and Biomass Yield (lbs acre-1)** | | | | | | | | | | | | | | | | |
| Removed | 26 | b | 41 | b | 77 | b | | 52 | b | 64 | b | 0.73 | b | 0.20 | b | 0.97 | b |
| Incorporate | 32 | a† | 51 | a | 101 | a | 70 | | a | 78 | a | 0.88 | a | 0.23 | a | 1.18 | a |

† Means followed by different letters within the column are significantly different (P<0.05).

Table 27. Summary of statistical analysis for 2015 corn grain nutrient uptake as affected by nitrogen rate.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **N** | | **S** | | **K** | | **Fe** | |
| **(lbs acre-1)** | | | | | | | |
| 0 | 18 | b | 1.4 | b | 62 | c | 0.44 | d |
| 40 | 19 | b | 1.5 | b | 85 | b | 0.63 | c |
| 80 | 29 | a | 2.1 | a | 94 | b | 0.83 | b |
| 120 | 35 | a | 2.4 | a | 103 | a | 0.92 | ab |
| 160 | 35 | a | 2.4 | a | 100 | a | 0.99 | ab |
| 200 | 36 | a | 2.3 | a | 90 | b | 1.04 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 28. Summary of statistical analysis for 2015 corn nutrient uptake at V6 as affected by residue management and phosphorus uptake.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Phosphorus rate**  **(lbs acre-1)** | **K** | | **Ca** | |
| **Nutrient Uptake (lbs acre-1)** | | | |
|  | **Residue Removed** | | | |
| 0 | 20 | ab† | 10 | bc |
| 25 | 22 | a | 14 | a |
| 50 | 22 | a | 13 | ab |
| 75 | 19 | ab | 10 | c |
| 100 | 18 | ab | 12 | bc |
|  | **Residue Incorporated** | | | |
| 0 | 18 | ab | 12 | bc |
| 25 | 15 | b | 10 | c |
| 50 | 18 | ab | 11 | bc |
| 75 | 20 | ab | 12 | bc |
| 100 | 22 | a | 13 | ab |

† Means followed by different letters within the column are significantly different (P<0.05).

Table 29. Summary of statistical analysis for 2015 corn biomass yield and nutrient uptake at V6 and R1 as affected by residue management.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Residue Management** | **———————————V6———————————** | | | | | | | | | | **————————R1————————** | | | | | | | |
| **N** | | **Mg** | | **Fe** | | **Mn** | | **Zn** | | **Biomass** | | **K** | | **Mg** | | **Fe** | |
| **Nutrient Uptake and Biomass Yield (lbs acre-1)** | | | | | | | | | | | | | | | | | |
| Removed | 8.3 | a† | 10.7 | a | 1.5 | a | 0.27 | a | 0.07 | a | 9,941 | a | 57 | a | 41 | a | 6.0 | a |
| Incorporate | 7.2 | b | 8.4 | b | 0.9 | b | 0.23 | b | 0.05 | b | 9,192 | b | 51 | b | 37 | b | 5.0 | b |

† Means followed by different letters within the column are significantly different (P<0.05).

Table 30. Summary of statistical analysis for 2015 corn biomass yield and nutrient uptake at R1 as affected by nitrogen rate and residue management.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **N** | | **S** | | **P** | | **Ca** | | **Zn** | |
| **Residue Removed** | | | | | | | | | |
| **(lbs acre-1)** | | | | | | | | | |
| 0 | 148 | bc† | 11 | bc | 217 | a | 182 | ab | 2.2 | a |
| 40 | 138 | bc | 10 | c | 150 | bc | 138 | cd | 1.5 | cd |
| 80 | 162 | ab | 11 | bc | 154 | bc | 137 | cd | 1.4 | cd |
| 120 | 180 | a | 13 | ab | 154 | bc | 146 | c | 1.7 | bc |
| 160 | 155 | ab | 10 | c | 121 | c | 110 | d | 1.1 | d |
|  | **Residue Incorporated** | | | | | | | | | |
| 0 | 137 | bc | 13 | ab | 229 | a | 190 | ab | 2.1 | ab |
| 40 | 158 | ab | 14 | a | 239 | a | 200 | a | 2.3 | a |
| 80 | 126 | c | 10 | c | 174 | b | 160 | bc | 1.5 | cd |
| 120 | 142 | bc | 10 | bc | 153 | bc | 146 | c | 1.4 | cd |
| 160 | 156 | ab | 12 | bc | 153 | bc | 165 | bc | 1.5 | cd |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 31. 2015 corn tissue nutrient uptake as a function of phosphorus application rate.

|  |  |  |
| --- | --- | --- |
| **Phosphorus Rate**  **(lbs acre-1)** | **P** | |
| **(lbs acre-1)** | |
| 0 | 151 | c† |
| 25 | 164 | bc |
| 50 | 178 | ab |
| 75 | 177 | ab |
| 100 | 201 | a |

† Means followed by different letters are significantly different (P<0.05).

Table 32. Summary of statistical analysis for the selected 2013 soil properties.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | **Nitrate** | | **Ammonium** | | **Bray-P** | | **P-ase†** | | **S-ase** | | **G-ase** | | **FDA** | |
| V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 |
|  | *Probability Level* | | | | | | | | | | | | | |
| **Nrate** | **0.01** | **0.01** | **0.01** | 0.70 | 0.10 | 0.73 | 1.00 | 0.99 | 0.77 | 0.92 | 0.31 | **0.01** | 0.91 | **0.01** |
| **Prate** | 0.70 | 0.74 | 0.82 | 0.14 | **0.02** | **0.01** | 0.30 | 0.43 | 0.90 | 0.57 | 0.46 | 0.80 | 0.81 | **0.02** |
| **Nrate\*Prate** | 0.25 | **0.03** | 0.95 | 0.58 | 0.02 | 0.66 | 0.21 | 0.15 | 0.29 | 0.24 | 0.97 | 0.33 | 0.86 | 0.09 |
| **Srate** | 0.86 | 0.16 | 0.64 | 0.56 | 0.16 | 0.39 | 0.52 | 0.30 | 0.58 | 0.94 | 0.13 | 0.06 | 0.65 | 0.74 |
| **Nrate\*Srate** | **0.01** | 0.09 | 0.12 | 0.26 | 0.01 | 0.51 | 0.41 | 0.30 | 0.15 | 0.13 | 0.68 | 0.27 | 0.89 | 0.41 |
| **Prate\*Srate** | 0.37 | 0.86 | 0.41 | 0.48 | 0.03 | 0.26 | 0.20 | 0.28 | 0.43 | 0.55 | 0.68 | 0.49 | 0.95 | 0.19 |
| **Nrate\*Prate\*Srate** | 0.91 | 0.55 | 0.15 | 0.83 | 0.01 | 0.97 | 0.76 | 0.44 | 0.28 | 0.68 | 0.89 | 0.47 | 0.96 | 0.11 |
| **Crate** | 0.05 | 0.52 | **0.01** | 0.81 | 0.01 | 0.52 | **0.01** | **0.01** | **0.01** | **0.01** | **0.01** | 0.44 | 0.06 | **0.01** |
| **Nrate\*Crate** | **0.04** | 0.70 | **0.01** | 0.20 | 0.09 | 0.59 | 0.87 | 0.55 | 0.91 | 0.27 | 0.86 | 0.55 | 0.88 | 0.46 |
| **Prate\*Crate** | 0.12 | 0.67 | 0.51 | 0.85 | 0.13 | 0.07 | 0.25 | 0.33 | 0.31 | 0.51 | 0.43 | 0.93 | 0.46 | 0.81 |
| **Nrate\*Prate\*Crate** | 0.36 | 0.30 | 0.47 | 0.06 | 0.02 | 0.91 | 0.50 | 0.63 | 0.67 | 0.25 | 0.53 | 0.38 | 0.86 | 0.09 |
| **Srate\*Crate** | 0.57 | 0.27 | 0.77 | 0.28 | 0.09 | 0.33 | 0.75 | 0.75 | 0.30 | 0.74 | 0.91 | 0.77 | 0.37 | 0.78 |
| **Nrate\*Srate\*Crate** | 0.67 | 0.72 | 0.37 | 1.00 | **0.01** | 0.44 | 0.34 | 0.29 | 0.54 | 0.28 | 0.46 | 0.70 | 0.76 | 0.73 |
| **Prate\*Srate\*Crate** | 0.67 | 0.14 | 0.67 | 0.82 | **0.03** | 0.60 | 0.11 | 0.19 | 0.66 | 0.44 | 0.70 | 0.43 | 0.18 | 0.20 |
| **Nrate\*Praet\*Srate\*Crate** | 0.07 | 0.05 | 0.74 | 0.37 | **0.01** | 0.10 | 0.41 | 0.25 | 0.22 | 0.20 | 0.89 | 0.75 | 0.97 | 0.32 |

† P-ase: phosphatase enzyme activity; S-ase: sulfatase enzyme activity; G-ase: glucosidase enzyme activity; FDA: fluorescein diacetate enzyme activity.

Table 33. Summary of statistical analysis for the selected 2014 soil properties.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | **Nitrate** | | **Ammonium** | | **Bray-P** | | **P-ase†** | | **S-ase** | | **G-ase** | | **FDA** | |
| V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 |
|  | *Probability Level* | | | | | | | | | | | | | |
| **Nrate** | **0.01** | **0.01** | **0.01** | **0.01** | 0.83 | 0.45 | 0.57 | 0.30 | 0.28 | 0.49 | 0.13 | 0.14 | 0.14 | 0.61 |
| **Prate** | 0.12 | 0.07 | 0.66 | 0.80 | **0.01** | **0.01** | 0.86 | 0.69 | 0.57 | 0.86 | 0.49 | 0.18 | 0.09 | 0.31 |
| **Nrate\*Prate** | **0.01** | **0.03** | 0.36 | 0.06 | 0.89 | 0.91 | 0.85 | 0.75 | 0.72 | 0.78 | 0.92 | 0.21 | 0.91 | 0.44 |
| **Crate** | 0.62 | 0.11 | 0.42 | 0.77 | 0.80 | 0.16 | **0.01** | **0.01** | 0.51 | **0.01** | 0.40 | **0.01** | **0.01** | **0.01** |
| **Nrate\*Crate** | **0.01** | 0.26 | 0.48 | 0.51 | 0.70 | 0.92 | 0.37 | 0.29 | 0.43 | 0.76 | 0.81 | 0.41 | 0.44 | 0.67 |
| **Prate\*Crate** | 0.32 | 0.79 | 0.50 | 0.50 | 0.56 | 0.32 | 0.78 | 0.78 | 0.64 | 0.50 | 0.42 | 0.73 | 0.31 | 0.81 |
| **Nrate\*Prate\*Crate** | 0.20 | 1.00 | 0.96 | 0.09 | 0.38 | 0.20 | 0.09 | 0.32 | 0.15 | 0.76 | 0.60 | 0.83 | 0.55 | 0.55 |

† P-ase: phosphatase enzyme activity; S-ase: sulfatase enzyme activity; G-ase: glucosidase enzyme activity; FDA: fluorescein diacetate enzyme activity.

Table 34. Summary of statistical analysis for the selected 2015 soil properties.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Main Effects and Interactions** | **Nitrate** | | **Ammonium** | | **Bray-P** | | **P-ase†** | | **S-ase** | | **G-ase** | | **FDA** | |
| V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 | V6 | R1 |
|  | *Probability Level* | | | | | | | | | | | | | |
| **Nrate** | **0.01** | **0.01** | **0.01** | 0.22 | 0.11 | 0.32 | 0.16 | 0.24 | 0.20 | 0.40 | 0.22 | 0.20 | 0.79 | 0.26 |
| **Prate** | 0.12 | 0.62 | 0.13 | 0.72 | 0.11 | **0.01** | 0.90 | 0.90 | 1.00 | 0.94 | 0.83 | 0.80 | 0.84 | 0.60 |
| **Nrate\*Prate** | 0.27 | 0.85 | **0.01** | 0.41 | 0.56 | 0.44 | 0.84 | 0.42 | 0.41 | 0.45 | 0.62 | 0.66 | 0.80 | 0.49 |
| **Crate** | **0.01** | 0.99 | 0.05 | 0.76 | 0.45 | 0.78 | 0.36 | **0.02** | 0.13 | 0.10 | 0.94 | **0.02** | 0.84 | 0.83 |
| **Nrate\*Crate** | 0.83 | 0.92 | 0.43 | 0.16 | 0.95 | 0.22 | 0.49 | 0.68 | 0.53 | 0.79 | 0.82 | 0.86 | 0.12 | 0.37 |
| **Prate\*Crate** | 0.73 | 0.48 | 0.44 | 0.45 | 0.44 | 0.24 | 0.06 | 0.29 | 0.25 | 0.20 | 0.37 | 0.07 | 0.06 | 0.12 |
| **Nrate\*Prate\*Crate** | 0.96 | 0.72 | 0.31 | 0.34 | 0.53 | 0.53 | 0.29 | 0.09 | 0.09 | 0.67 | 0.46 | 0.42 | 0.66 | 0.09 |

† P-ase: phosphatase enzyme activity; S-ase: sulfatase enzyme activity; G-ase: glucosidase enzyme activity; FDA: fluorescein diacetate enzyme activity.

Table 35. Summary of statistical analysis for soil nitrate and ammonium first sampling in 2013 and nitrate first sampling in 2014.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Nitrate V6 2013** | | **Ammonium V6 2013** | | **Nitrate V6 2014** | |
| **Residue Removed** | | | | | |
| **ppm** | | | | | |
| 0 | 3.4 | gh† | 4.4 | g | 3.3 | ef |
| 40 | 5.2 | g | 4.8 | fg | 1.2 | f |
| 80 | 8.7 | ef | 5.1 | efg | 3.2 | ef |
| 120 | 13.2 | d | 5.3 | def | 5.9 | cde |
| 160 | 17.4 | c | 5.8 | de | 8.2 | c |
| 200 | 21.6 | b | 5.9 | de | 19.0 | a |
|  | **Residue Incorporated** | | | | | |
| 0 | 2.0 | h | 6.1 | cd | 4.5 | def |
| 40 | 3.6 | gh | 6.9 | bc | 5.5 | cde |
| 80 | 5.9 | fg | 7.0 | b | 5.0 | cde |
| 120 | 9.5 | e | 7.6 | b | 7.9 | cd |
| 160 | 16.6 | c | 9.2 | a | 7.2 | cd |
| 200 | 24.6 | a | 9.3 | a | 13.0 | b |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 36. Available nitrate in the first sampling of 2013 as affected by nitrogen and sulfur application rate.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Sulfur Application Rate (lbs acre-1)** | | | | | | | |
| **0** | | **5** | | **10** | | **15** | |
| **Extractable nitrate (ppm)** | | | | | | | |
| 0 | 3.0 | jkl† | 3.0 | jkl | 2.3 | l | 2.5 | kl |
| 40 | 4.5 | ijkl | 3.9 | ijkl | 4.7 | ijkl | 4.5 | ijkl |
| 80 | 6.9 | hij | 7.7 | hi | 6.7 | hijk | 7.8 | hi |
| 120 | 14.1 | fg | 10.3 | gh | 10.6 | gh | 10.4 | gh |
| 160 | 16.9 | def | 19.3 | bcd | 17.5 | def | 14.4 | efg |
| 200 | 18.5 | cde | 22.0 | bc | 23.4 | b | 28.5 | a |

† Means followed by different letters are significantly different (P<0.05).

Table 37. Available nitrogen measured as nitrate and ammonium in several samplings during the three years of the study as affected by nitrogen and phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Phosphorus Application Rate (lbs acre-1)** | | | | | | | | | | |
| **0** | | | **25** | | **50** | | **75** | | **100** | |
| **Nitrate sampling R1 2013 (ppm)** | | | | | | | | | | |
| 0 | 6.4 | | gh† | 6.3 | gh | 6.3 | gh | 7.7 | gh | 7.3 | gh |
| 40 | 6.6 | | gh | 5.2 | h | 8.4 | fgh | 9.3 | efgh | 8.1 | gh |
| 80 | 6.2 | | gh | 7.4 | gh | 8.0 | gh | 11.5 | cdef | 9.0 | efgh |
| 120 | 9.6 | | defgh | 7.7 | gh | 9.5 | efgh | 10.8 | cdefgh | 15.8 | bc |
| 160 | 14.1 | | cdef | 15.9 | bc | 11.6 | cdefg | 9.9 | defgh | 11.7 | cdefg |
| 200 | 23.2 | | a | 21.1 | ab | 14.5 | cde | 16.2 | bc | 15.4 | bcd |
|  | **Nitrate sampling V6 2014 (ppm)** | | | | | | | | | | |
| 0 | 4.9 | efgh | | 3.2 | gh | 4.1 | fgh | 4.2 | fgh | 2.9 | gh |
| 40 | 1.7 | h | | 4.4 | efgh | 3.0 | gh | 3.8 | fgh | 3.8 | fgh |
| 80 | 2.8 | gh | | 5.2 | efgh | 5.6 | efgh | 2.2 | gh | 4.8 | efgh |
| 120 | 9.0 | bcdef | | 5.3 | efgh | 7.7 | bcdefg | 6.9 | defgh | 5.4 | efgh |
| 160 | 6.0 | efgh | | 6.0 | efgh | 10.0 | bcde | 9.3 | bcdef | 7.4 | cdefgh |
| 200 | 13.2 | bc | | 13.0 | bc | 13.3 | b | 11.6 | bcd | 28.9 | a |
|  | **Nitrate sampling R1 2014 (ppm)** | | | | | | | | | | |
| 0 | 8.5 | bc | | 4.5 | bc | 4.7 | bc | 6.4 | bc | 6.7 | bc |
| 40 | 4.7 | bc | | 5.4 | bc | 3.6 | c | 5.3 | bc | 5.0 | bc |
| 80 | 5.1 | bc | | 4.9 | bc | 4.5 | bc | 5.7 | bc | 5.4 | bc |
| 120 | 8.6 | bc | | 7.2 | bc | 7.3 | bc | 5.0 | bc | 6.0 | bc |
| 160 | 5.7 | bc | | 6.4 | bc | 5.5 | bc | 4.4 | c | 6.5 | bc |
| 200 | 10.9 | b | | 4.9 | bc | 8.3 | bc | 8.2 | bc | 23.6 | a |
|  | **Ammonium sampling V6 2015 (ppm)** | | | | | | | | | | |
| 0 | 3.5 | bc | | 3.8 | bc | 3.1 | bc | 3.4 | bc | 3.3 | bc |
| 40 | 3.5 | bc | | 2.8 | c | 3.4 | bc | 3.3 | bc | 3.1 | bc |
| 80 | 3.7 | bc | | 3.3 | bc | 4.4 | bc | 4.0 | bc | 3.4 | bc |
| 120 | 4.3 | bc | | 4.0 | bc | 4.1 | bc | 4.4 | bc | 4.0 | bc |
| 160 | 3.4 | bc | | 4.6 | bc | 4.4 | bc | 8.1 | a | 4.2 | bc |
| 200 | 4.1 | bc | | 3.7 | bc | 4.2 | bc | 5.3 | b | 9.4 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 38. Available phosphorus measured in several samplings during the three years of the study as affected by phosphorus application rate.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Phosphorus Rate**  **(lbs acre-1)** | **Bray-1 extractable P (ppm)** | | | | | | | | | |
| **Sample R1**  **2013** | | **Sample V6**  **2014** | | **Sample R1**  **2014** | | **Sample V6**  **2015** | | **Sample R1**  **2015** | |
| 0 | 7.9 | e† | 12.5 | c | 11.5 | c | 9.4 | b | 11.1 | c |
| 25 | 9.4 | d | 17.6 | bc | 14.9 | bc | 15.2 | ab | 13.0 | c |
| 50 | 11.5 | c | 19.2 | abc | 16.1 | bc | 11.8 | ab | 14.4 | bc |
| 75 | 13.0 | b | 25.2 | ab | 20.9 | ab | 17.6 | a | 24.1 | a |
| 100 | 15.7 | a | 26.9 | a | 23.4 | a | 19.6 | a | 21.2 | ab |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 39. Available ammonium and nitrate measured in several samplings during the three years of the study as affected by nitrogen application rate.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Available Nitrogen (ppm)** | | | | | | | |
| **NH4-V6**  **2014** | | **NH4-R1**  **2014** | | **NO3-V6**  **2015** | | **NO3-R1**  **2015** | |
| 0 | 4.7 | d† | 7.9 | b | 11.3 | e | 0.6 | c |
| 40 | 5.0 | cd | 8.9 | ab | 16.4 | e | 0.5 | c |
| 80 | 5.3 | bc | 9.1 | a | 30.8 | d | 1.1 | c |
| 120 | 5.6 | ab | 10.0 | a | 47.4 | c | 4.4 | bc |
| 160 | 5.7 | ab | 9.6 | a | 60.3 | b | 9.7 | b |
| 200 | 6.0 | a | 9.8 | a | 78.5 | a | 31.5 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 40. Glucosidase and FDA enzyme activity in the second sampling as affected by N application rate in 2013.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **Glucosidase R1** | | **FDA R1** | |
| **Enzyme activity in mg of p-nytrophil released hr-1** | | | |
| 0 | 1011 | cd | 465 | b |
| 40 | 1001 | d | 460 | b |
| 80 | 1051 | bc | 485 | ab |
| 120 | 1068 | ab | 505 | a |
| 160 | 1075 | ab | 494 | a |
| 200 | 1103 | a | 487 | ab |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 41. FDA enzyme activity in the second sampling as affected by P application rate in 2013.

|  |  |  |
| --- | --- | --- |
| **Nitrogen Rate**  **(lbs acre-1)** | **FDA activity R1** | |
| **Enzyme activity in mg of p-nytrophil released hr-1** | |
| 0 | 471 | b |
| 25 | 483 | ab |
| 50 | 507 | a |
| 75 | 467 | b |
| 100 | 488 | ab |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 42. Enzyme activity measured in 2013 as a function of residue management.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Residue Management** | **Phosphatase V6** | | **Phosphatase R1** | | **Sulfatase V6** | | **Sulfatase R1** | | **Glucosidase V6** | | **FDA R1** | |
|  | **Enzyme activity in mg of p-nytrophil released hr-1** | | | | | | | | | | | | |
| Removed | 1,198 | b† | 1,159 | b | 1,225 | a | 894 | a | 1,170 | a | 425 | b |
| Incorporate | 1,466 | a | 1,479 | a | 933 | b | 812 | b | 1,354 | b | 540 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

Table 43. Soil parameters measured in 2014 as a function of residue management.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Residue Management** | **Phosphatase V6** | | **Phosphatase R1** | | **Sulfatase R1** | | **Glucosidase R1** | | **FDA V6** | | **FDA R1** | |
|  | **Enzyme activity in mg of p-nytrophil released hr-1** | | | | | | | | | | | | |
| Removed | 1,122 | b† | 1,161 | a | 1,259 | a | 848 | b | 567 | b | 600 | b |
| Incorporate | 1,476 | a | 868 | b | 1,011 | b | 957 | a | 690 | a | 793 | a |

Table 44. Soil parameters measured in 2015 as a function of residue management.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Residue Management** | **Nitrate V6** | | **Phosphatase R1** | | **Glucosidase R1** | |
|  | **ppm** | | **Enzyme activity in mg of p-nytrophil released hr-1** | | | |
| Removed | 36 | b | 1,138 | b | 883 | b |
| Incorporate | 45 | a | 1,332 | a | 940 | a |

† Means followed by different letters within a column are significantly different (P<0.05).

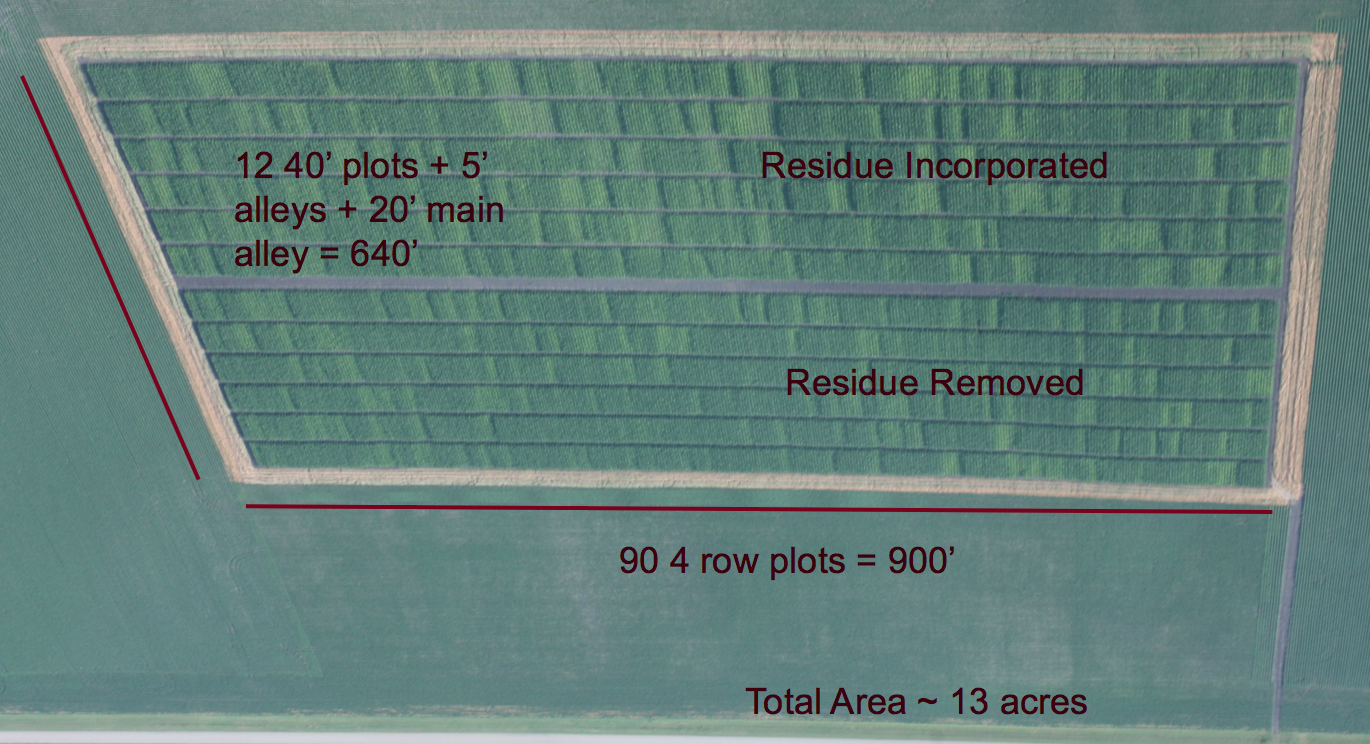


Figure 1. Aerial photo showing the experimental site.

Baseline P heatmap.pdf

Figure 2. Background soil test P (Olsen-P) levels measured in 2012 before the start of the trial.

../../Projects/Data/CNPS/Stats/Gucosidase%20Activity.pdf

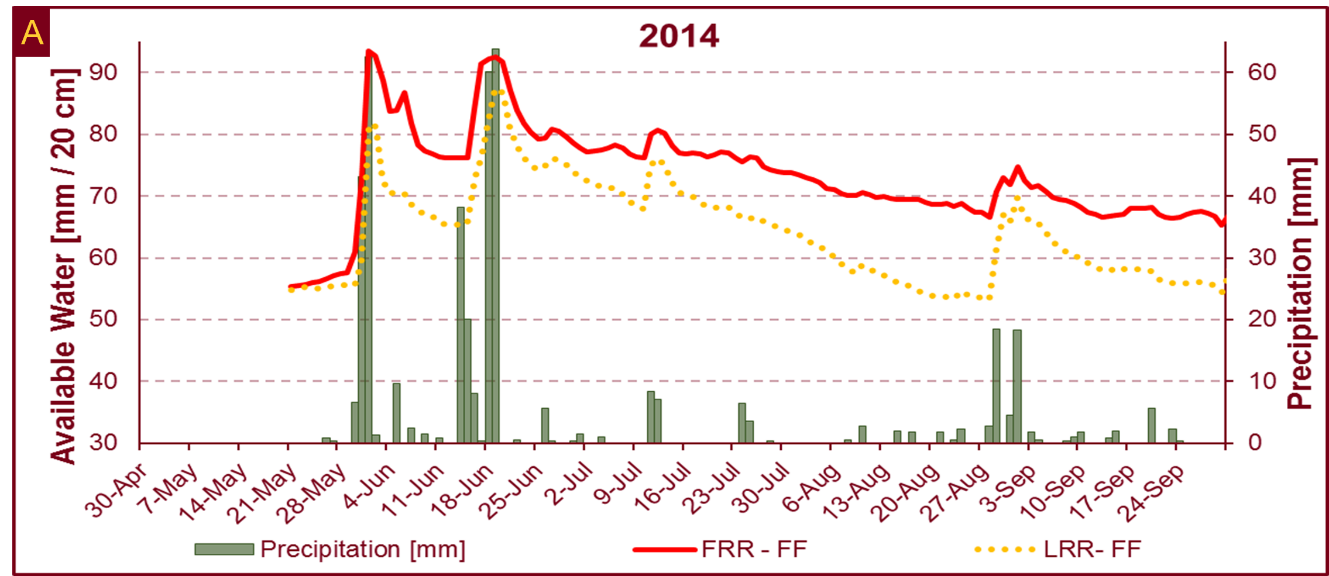
Figure 3. Background soil glucosidase activity measured in 2012 before the start of the trial.

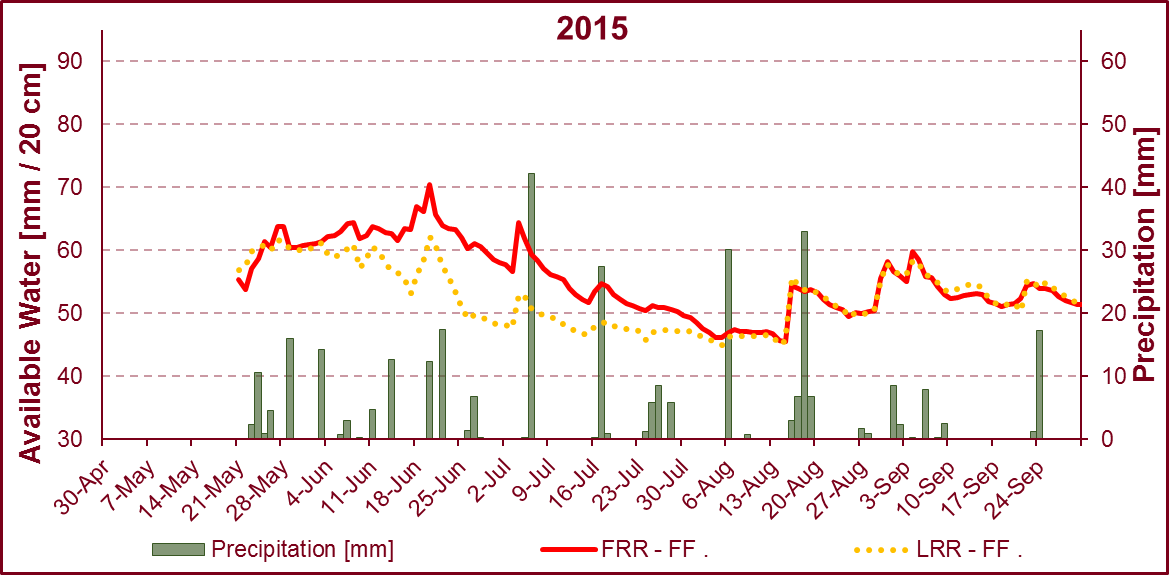
../../Projects/Data/CNPS/Stats/Phosphatase%20Activity.pdf

Figure 4. Background soil phosphatase activity measured in 2012 before the start of the trial.

../../Projects/Data/CNPS/Stats/Sulfatase%20Activity.pdf

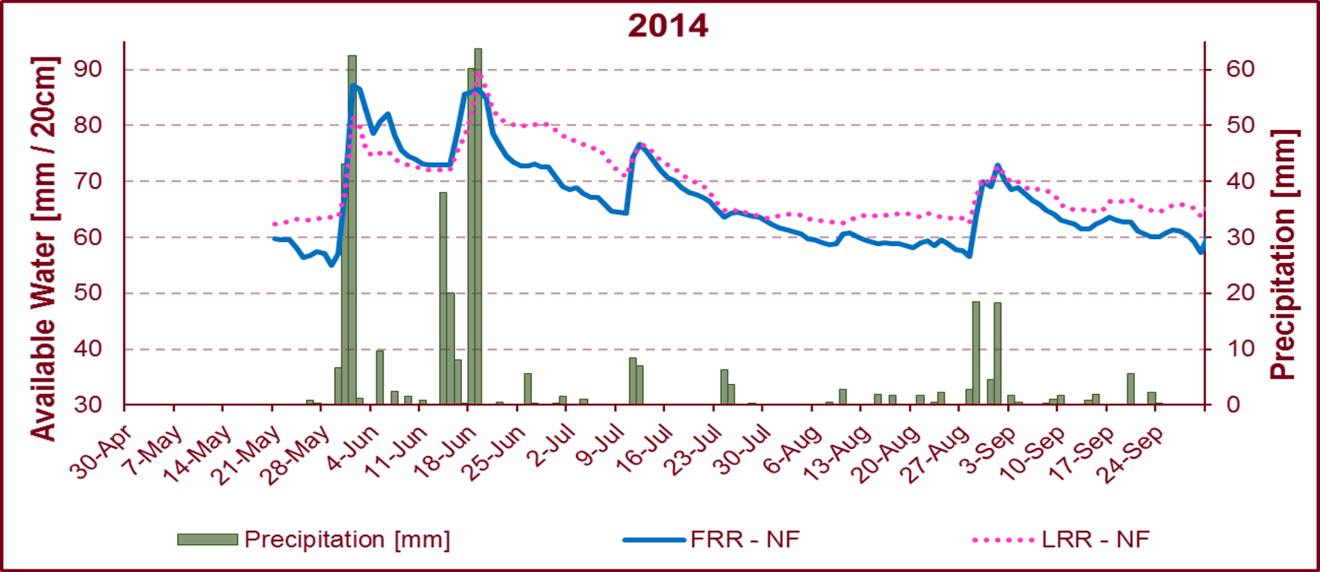
Figure 5. Background soil sufatase activity measured in 2012 before the start of the trial.



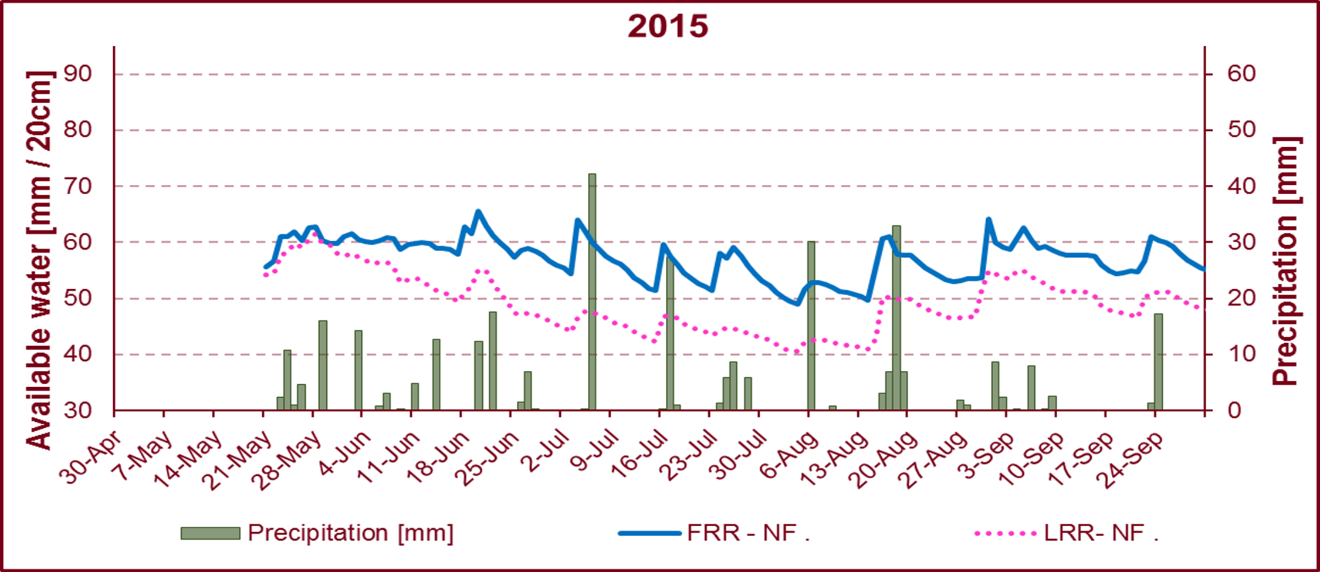


B

Figure 6: Comparison of available water from A) 2014 and B) 2015 for different levels of residue management (FRR: residue removed and LRR: residue incorporated) under Fully Fertilized (FF) conditions.



A



B

Figure 7: Comparison of available water from A) 2014 and B) 2015 for different levels of residue management (FRR: residue removed and LRR: residue incorporated) under No Fertilizer (NF) conditions.



Figure 8. 2014 corn grain yield as a function of nitrogen, phosphorus, and sulfur application rates. Phosphorus application rate is shown in the x-axis, nitrogen application rate is shown in the box title, and sulfur rate is shown by the different symbols and colors within each box.