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Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean in Iowa

by

Andrew John Stammer

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Soil Science (Soil Fertility)

Program of Study Committee:
Antonio P. Mallarino, Major Professor
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Ames, Iowa

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CHAPTER 1. GENERAL INTRODUCTION

Phosphorus and potassium are two nutrients that frequently limit crop production in the U.S. and other regions of the world. These nutrients are important for crop growth and development. Phosphorus has important roles in nucleotide molecule composition, plant metabolism, and energy transfer within the plant. Potassium has a major role in membrane function, water transport, and cellulose synthesis. Yield potential can be expressed with proper assessment of the nutrient needs and appropriate fertilization. Nutrient status is typically estimated with soil test results. Soil sampling in the fall or spring allows farmers to assess the nutrient status of their fields and decide fertilizer application rates. Tissue sampling may provide an in-season complement to soil sampling and testing by a more direct method of assessing nutrient status.

Successful use of tissue testing to guide fertilization requires further correlative research to interpret test results. Previous research has shown that nutrient concentrations in plant tissue vary greatly, not only with soil fertility but also with the plant growth stage, crop species or variety, the plant part sampled, and various environmental conditions. Therefore, tissue test results must clearly refer to specific plant parts sampled and growth stage, although to be useful in production agriculture, tissue testing needs to be useful across a wide range of cultivars and growing conditions. The most widely used method of implementing tissue testing in production agriculture is based on the sufficiency level concept. The basis for this concept is that there is a critical nutrient concentration above which there is luxury accumulation (the concentration increases but does not translate into increased yield) and below which there is deficiency. The concept

has been further developed and explained by others to address critical concentrations and ways for establishing sufficiency ranges.

Research on critical tissue P and K concentrations for corn and soybean for Iowa and neighboring states that included several experiments across several sites or years are scarce, and most studies were conducted before the 1980s. These experiments have provided inconsistent results about the value of tissue testing for phosphorus and potassium in corn and soybean. Therefore, interpretations for tissue test results do not exist in Iowa, and in most states of the Corn Belt and few universities recommend tissue testing as a diagnostic tool to decide fertilization. Interpretations do exists for other regions, but these may not apply to Iowa conditions, genetics of cultivars grown, and both soil and climatic conditions. Therefore, the objective of this research was to determine critical P and K concentrations for corn and soybean for early vegetative and early reproductive growth stages.

THESIS ORGANIZATION

This thesis is organized as a paper titled “Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean in Iowa” for submission to the Soil Science Society of America Journal. It is organized into the following sections: Abstract, Introduction, Materials and Methods, Results and Discussion, References, Tables, and Figures. The paper is preceded by a General Introduction, and followed by General Conclusions.

CHAPTER 2. PLANT TISSUE ANALYSIS TO ASSESS PHOSPHORUS AND POTASSIUM NUTRITIONAL STATUS OF CORN AND SOYBEAN IN IOWA

A paper to be submitted to the Soil Science Society of America Journal

Andrew J. Stammer and Antonio P. Mallarino

ABSTRACT

Interest in re-evaluating the value of tissue testing to assess P and K status in corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) is increasing. The objective of this research was to study relationships between grain yield response to P and K and the concentration of these nutrients in plant tissue. Single-year and multi-year response trials were conducted in Iowa at 30 sites for P (32 sites-years with corn and 34 with soybean) and at 53 for K (67 sites years with corn and 52 with soybean) that encompassed 17 soil series. We sampled above-ground plant parts at the V5-V6 growth stage, corn ear-leaf blades at the R1 stage, and uppermost trifoliolate soybean leaves at R2-R3 stage. Critical concentration ranges were defined using linear-plateau and quadratic-plateau models. All models fit significantly ($P \leq 0.01$) and R^2 values were 0.31-0.45 for corn plants P, soybean plants and leaf P, and soybean plant K; 0.51-0.53 for K in corn plants and leaves and soybean leaves K; and 0.62-64 for corn leaf P. Critical concentration ranges were 4.8-5.5 and 2.5-3.1 g P kg^{-1} and 18.8-25.4 and 10.6-14.2 g K kg^{-1} for corn plants and leaves; and 3.3-4.1 and 3.5-4.7 g P kg^{-1} and 18.9-22.7 and 15.6-19.9 g K kg^{-1} for soybean plants and leaves. We conclude that P testing of corn ear-leaves at R1 was better than of young plants at V5-V6 but either tissue provided similar K assessments. Testing soybean

plants for P at V5-V6 was better than testing leaves at the R2-R3 stage but K testing of leaves was better than K testing of plants.

Abbreviations: LP, linear-plateau; OM, organic matter; QP, quadratic-plateau; STP, soil-test P by the Bray-1 method; STK, soil-test K by the NH_4OAc method.

INTRODUCTION

Plant-tissue analysis directly assesses crop nutrient status. Tissue testing could identify symptomless or developing deficiencies, evaluate effects of nutrient management practices on plant nutrient uptake, help understand the physiology of nutrient utilization by plants, guide complementary fertilization for the current or future crops, and to recommend additional diagnostic procedures (Aldrich, 1973). The majority of P and K fertilization guidelines for row crops and forages are based on soil testing, but tissue testing is used in some regions as a complement of soil testing, and there is renewed interest in using tissue testing to guide nutrient management from agribusinesses, farmers, and crop consultants. Appropriate interpretation of tissue testing to guide fertilization requires correlation research to interpret test results. Early research summarized in thorough reviews and recent research has shown that the nutrient concentrations reported with plant analysis vary greatly not only with soil fertility but also with the plant growth stage, crop species or variety, the plant part sampled, and various environmental conditions (Jones, 1990; Munson and Nelson, 1990; Jones, 1996; Slayton et al., 2010). Results can be ineffective at describing soil nutrient status if the plant's growth and nutrient uptake are limited by deficiency of other nutrients, restricted

root growth, or weather conditions. For these reasons, tissue test critical levels must clearly refer to specific plant parts sampled and growth stage, although to be useful in production agriculture tissue testing needs to be useful across a wide range of cultivars and growing conditions.

The most widely used method of implementing tissue testing in production agriculture is based on the sufficiency level concept. The basis for this concept was developed by Macy (1936) and Steenbjerg (1951), who suggested that there is a critical nutrient concentration above which there is luxury accumulation (the concentration increases but do not translate into increased yield) and below which there is deficiency and "poverty adjustment". The concept has been further developed and explained by others to address critical concentrations and ways for establishing sufficiency ranges (Ulrich and Hills, 1967; Munson and Nelson, 1990; Bryson et al., 2014). Interpretation methods based on ratios between the concentrations of several nutrients have been proposed to alleviate effects of growth stage, hybrids or varieties, and environmental conditions on tissue nutrient concentrations. These include the diagnosis and recommendation integrated system (DRIS) (Beaufils, 1973), its modifications (Hallmark, 1990), and combinations of sufficiency levels and DRIS (Baldock and Schulte, 1996). These systems have had mixed success for P and K in corn and soybean compared with the simpler sufficiency level approach (Hallmark et al., 1991; Bell et al., 1995; Soltanpour et al., 1995; Baldock and Schulte, 1996), analyses and interpretations are more complex and costly, and few universities or laboratories have adopted them as the basis for fertilization guidelines for these crops.

The vast majority of research on tissue P and K critical concentrations for corn and soybean has focused on analysis of mature leaves at early reproductive stages, because early research suggested that nutrient deficiencies were better reflected in this plant part and growth stage than in others (Jones, 1990; Munson and Nelson, 1990). Some research has suggested this may not always be the case, however, and that sampling of leaves or above-ground plant material earlier in the season can provide similar or better results across a variety of conditions (Baker et al., 1970; Terman et al., 1972; Walker and Peck, 1972; Walker and Peck, 1974; Mallarino, 1996).

Tissue test interpretations for various nutrients and corn and soybean plant parts (reported as specific critical concentrations or suggested sufficiency ranges) before the middle 1990s were summarized in several reviews (Jones, 1967; Chapman, 1967; Small and Ohlrogge, 1973; Jones and Eck, 1973; Jones et al., 1990). Several versions of a "plant analysis handbook" have attempted to summarize available information from a wide variety of regions and growing conditions into suggested sufficiency ranges (Jones, 1990; Mills and Jones, 1996; Bryson et al., 2014). Bryson et al. (2014) defined a sufficiency range as "a range that has been established by research, identifying that concentration range for a specified plant part and stage of growth of an essential plant nutrient element within which optimum plant growth and/or product yield is obtained". Suggested sufficiency levels for corn tissue, for example, are 3.0 to 5.0 g P kg^{-1} and 25 to 35 g K kg^{-1} for above-ground "whole tops < 12 inches tall" (30 cm) and 25 to 50 g P kg^{-1} and 18 to 30 g K kg^{-1} for ear-leaves at "initial silking". Suggested sufficiency levels for soybean tissue, for example, are 3 to 6 g P kg^{-1} and 17 to 25 g K kg^{-1} for "most recently mature trifoliate leaves at early growth" and 3 to 6 g P kg^{-1} and 15 to 22.5 g K kg^{-1} for

"mature leaves from new growth prior to pod set". Specific sufficiency ranges for corn and soybean in the southern region of the US have been described over time (Campbell and Plank, 2013).

Research on critical tissue P and K concentrations for corn and soybean for Iowa, or similar conditions in the Corn Belt of the US that included several sites or years are scarce, and most studies were conducted before the 1980s (Tyner, 1946; Tyner and Webb, 1946; Melsted et al, 1969; Peck et al., 1969; Voss et al., 1970; Walker and Peck, 1975). Corn and soybean yields have increased greatly since then and there have been significant changes in crop genetics which may make results of little current relevance. Based on trials conducted in Iowa during 1989 and 1990, Mallarino and Higashi (2009) reported a critical concentration for corn ear leaves of 12.3 g K kg^{-1} but did not find a significant correlation between grain yield response and the K concentration of young plants at the V5 to V6 growth stage. Mallarino (1995) summarized results from Iowa P response field trials with corn conducted from 1980 until 1990 and reported a critical concentration range for ear leaves of 2.3 to 2.5 g P kg^{-1}. Mallarino (1996) reported relationships between corn yield responses to P and the P concentration of several corn plant parts for 23 trials conducted in Iowa during 1989 and 1990. He concluded that tests of young plants at V5 to V6 and ear-leaves at the R1 stage provided better assessments of plant P status than tests based on cornstalks at maturity or harvested grain. They reported critical concentrations of 3.4 and 2.4 g P kg^{-1} for young plants and ear-leaves, respectively, but the R^2 of fitted quadratic-plateau models were only 0.18 for plants and 0.14 for leaves.

The reviewed research indicates that critical P and K concentrations in corn and soybean tissue may vary between regions due to genetic variability of hybrids and cultivars grown, soil conditions, and climate. Historical research in the region has been unable to determine reliable critical concentrations for these crops. Therefore, the objective of this research project was to determine critical P and K concentrations for corn and soybean for early vegetative and early reproductive growth stages.

MATERIALS AND METHODS

Sites, Soils, and Trials

The grain yields and plant tissue data used in this study were collected from several P or K field-response trials with corn or soybean that were conducted in Iowa from 2003 to 2006, in 2009 and 2010, and in 2013 and 2014. Data from K trials conducted from 2003 until 2006 were published before (Clover and Mallarino, 2013), whereas data from P trials conducted in 2009 and 2010 and also P and K trials conducted in 2013 and 2014 have not been published. The published data were pooled with more recent data to have a larger data set encompassing more years and sites. The trials were clustered at fields of Iowa State University research farms located in central, northeast, north-central, northwest, south, southeast, and southwest regions of the state having different soils and slightly different climate conditions. Most farms are large and include fields with different soil series and management systems.

Grain yield data and plant-tissue samples were collected from single-year trials or established long-term trials that included a non-fertilized control and one to six fertilizer

application rates (reapplied each year at the long-term trials). In some P or K long-term trials the treatments were the combinations of fertilizer rates and tillage systems, in others similar fertilizer rates were applied to adjacent areas with the same soil but having different management practice histories (such as grain or total biomass harvest, different timing of P application, or different sources of other nutrients). Also, in some there were two adjacent trials of identical design so corn and soybean crops could be planted each year to complete rotations over time. In all these cases, each set of P or K fertilizer rate treatments was considered as a separate site.

Tables 1 and 2 summarize the locations, soil information, and years of evaluation for 30 P sites and 53 K sites. There were 66 site-years for P (32 for corn and 34 with soybean) and 119 site-years for K (67 for corn and 52 for soybean). The sites contained seventeen soil series found in Iowa and surrounding states where row-crop production predominates. The soil-test P and K values shown in these tables are initial soil-test values for new trials and values for the control plots receiving no P or K of already established trials. Reported samples are for the first year in sites that were evaluated two years. Each soil sample was a composite of 10 to 12 cores (0.75-in. diameter) taken to a depth of 15 cm. Samples were dried at 40° C and ground to pass through a 2-mm sieve, and were analyzed for P by the Bray-1 method and for K by the NH_4OAc method following procedures described by Frank et al. (1998) for P and by Warncke and Brown (1998) for K.

The soil-test P and K values (Tables 1 and 2) ranged from very low to very high for corn and soybean according to Iowa State University interpretations (Mallarino et al., 2013). The boundaries for the categories very low, low, optimum, high, and very high for

P are ≤8, 9-15, 16-20, 21-30, and ≥31 mg P kg^{-1}, respectively, and those for K using dried soil samples are ≤120, 121-160, 161-200, 201-240, and ≥ 241 mg K kg^{-1}, respectively. Soil pH and organic matter (OM) ranged widely (Tables 1 and 2). Soil pH was measured using 1:1 soil/water ratio, and OM was measured by the combustion method described by Wang and Anderson (1998). Some sites were managed with chisel-plow/disk tillage (25 sites for P and 47 sites for K) and others were managed with no-till (5 sites for P and 6 sites for K). In sites managed with tillage, soil with corn residues was chisel-plowed after crop harvest in the fall (in October or early November) and disked or field cultivated in the spring, whereas soil with soybean residues only was disked or field cultivated in the spring.

At all sites the fertilizer treatments were applied in the fall (October or early November) or in spring one to three weeks before planting (in late March or early April). At sites managed with tillage, the fertilizers were incorporated into the soils by chisel-plowing and disking or field cultivating at sites that had corn residue and by disking or field cultivating at sites that had soybean residue. The fertilizers were not incorporated at sites managed with no-till. A non-limiting N fertilizer rate was applied to all plots planted with corn, a non-limiting K rate was applied to all plots of the P sites, and a non-limiting P rate was applied to all plots of the K sites. All trials used a conventional plot methodology (each plot measured 5 to 18 m in length and 3 to 6 m in width depending on the site), randomized complete-block design, and included several application rates of granulated P or K fertilizers that were replicated three to six times.

Potassium Sites 1-20 were two-year trials with corn-soybean or soybean-corn rotations that began in 2003, 2004, or 2005, the treatments sampled were five broadcast

K rates (0 to 168 kg K ha^{-1}), and details were previously described by Clover and Mallarino (2013). Potassium Site 21 was a long-term trial with soybean in 2013 and corn in 2014, and each year we sampled six treatments (a non-fertilized control, a broadcast annual rate of 100 kg K ha^{-1}, and four other treatments with different histories of broadcast K application rates prior to 2006). Potassium Sites 22-31 were long-term corn-soybean rotation experiments with two different tillage systems and both crops grown each year on adjacent identical trials, and in 2013 and 2014 we sampled three treatments (a non-fertilized control and annual rates of 66 kg K ha^{-1} broadcast or banded with the planter 5 cm beside and below the seeds). Potassium Sites 32-43 were long-term trials with corn-soybean rotations each having one crop per year, and in 2013 and 2014 we sampled five treatments (a non-fertilized control, a broadcast annual rate of 66 kg K ha^{-1}, and three other treatments with different histories of broadcast K application rates prior to 2010). Both K Sites 44 and 45 had a new corn trial established in 2014, with two of the K rate treatments sampled (a non-fertilized control and a broadcast rate of 149 kg K ha^{-1}). Potassium Sites 46-51 were long-term trials with continuous corn, and in 2013 and 2014 we sampled two treatments (a non-fertilized control and a broadcast annual rate of 67 kg K ha^{-1}). Potassium Sites 52 and 53 were long-term experiments with corn-soybean rotation with both crops grown each year on adjacent identical trials, and in 2013 and 2014 three treatments were sampled (a non-fertilized control and broadcast annual rates of 67 or 134 kg K ha^{-1}).

Phosphorus Sites 1-6 were one-year corn trials (four in 2009 and two in 2010) and the seven treatments sampled were a non-fertilized control and six broadcast rates ranging from 12 to 120 kg P ha^{-1}. Phosphorus Sites 7-16 there were long-term corn-

soybean rotation experiments with two different tillage systems and both crops grown each year on adjacent identical trials. In 2013 and 2014 we sampled three treatments (a non-fertilized control and annual rates of 28 kg P ha^{-1} broadcast or banded with the planter 5 cm beside and below the seeds). Phosphorus Sites 17-18 were long-term experiments with corn-soybean rotations and both crops grown each year on adjacent identical trials, and in 2013 and 2014 we sampled three treatments (a non-fertilized control and broadcast annual rates of 22 or 44 kg P ha^{-1}). At each of P Sites 19-26 a new soybean trial was established in 2013, and we sampled three of the P rate treatments (a non-fertilized control and broadcast annual rates of 25 or 50 kg P ha^{-1}). Phosphorus Sites 27-30 were long-term trials with corn-soybean rotations without both crops each year. In 2014 we sampled seven treatments (a non-fertilized control, a broadcast rate 73 kg P ha^{-1}, and five other treatments with different histories of broadcast P application rates prior to 2010).

Corn hybrids, soybean cultivars, seeding dates and rates, and weed control practices were those normally used at each research farm and varied greatly across sites and years (not shown). Seasonal rainfall (April through September) was normal or near normal (within 15%) of the 50-year average (not shown) with few exceptions. The exceptions were higher than normal rainfall in some years of P Sites 3-9, 12-15, 20 and 21 and of K Sites 21-27, 30-32, 35-38, 40-43, 46, 47, 51, 52 (132 to 217% of normal); and lower than normal in some years of P Site 2 and of K Sites 1-4, 11, 14-18 (40 to 80% of normal).

Plant Measurements

The aboveground portion of ten corn and soybean plants was sampled by cutting plants 2-cm above the soil surface at the V5-V6 growth stage (Abendroth et al. 2011; Pedersen 2004) to assess total P or K concentration at early growth stages. Corn and soybean leaves were sampled and analyzed for total P or K concentration by collecting the blade portion of corn leaves opposite and below the uppermost ear of ten plants at the R1 stage (Abendroth et al. 2011) and three top, fully mature trifoliolate leaves (including the petioles) of ten soybean plants at the R2-R3 stage (Pedersen, 2004). Samples were taken from most trials at both growth stages. Exceptions were that corn leaves were not sampled in any site-year of P Sites 1-6 because leaf sampling and analysis was not an objective of this early project. At a few other sites either plant or leaf samples were lost due to processing errors or could not be taken at the planned growth stage. We could not sample small corn plants or soybean leaves in one year of P Site 9 (in 2013), soybean leaves at P Site 10 (in 2013), corn leaves at K Site 12 (in 2004), soybean small plants and leaves at K Sites 28 and 29 (in 2013 and 2014), and corn small plants at K Sites 51 and 52 (both in 2014).

All plant-tissue samples were shaken by hand to dislodge as many attached soil particles as possible, dried at 65 °C in a forced-air oven, and ground to pass through a 2-mm screen. Most tissue samples were digested in an open vessel using a nitric acid HNO_3 – H_2O_2 procedure and measuring P and K by inductively coupled plasma spectrometry (Zarcinas et al., 1987), except for samples from K sites 1-20 which were analyzed by digesting samples with a H_2SO_4 – H_2O_2 procedure (Digesdahl Analysis System, Hach, Boulder, CO) and measuring K in digests by emission spectroscopy. Grain was harvested

from a central area of each plot (two to five rows in width and 3.7 to 15 m in length depending on the trial) with a plot combine except in K Sites 44 and 45 where corn ears were picked by hand and shelled in a stationary thresher. A subsample of grain was collected for determination of moisture, and grain yields were adjusted to 130 and 155 g kg^{-1} moisture for soybean and corn, respectively.

Data Management and Statistical Analyses

Data points in figures describing the relationships between yield response and the tissue nutrient concentrations correspond to pairs of relative grain yields and tissue P or K concentrations for each treatment and site-year. Relative grain yields were calculated for each site-year by expressing the yield for each treatment as a percentage of the maximum yield with fertilization. For trials in which we sampled only a control and one fertilized treatment, the maximum yield was defined as the mean of plots receiving fertilization. For trials with more than two fertilized treatments, the maximum yield was determined according to results of analysis of variance assuming a RCBD using the GLIMMIX procedure of SAS with fixed treatment effects and random block effects (SAS Institute, 2011). In site-years showing no significant yield response ($P \leq 0.10$), the maximum yield was defined as the mean of all treatments receiving fertilization. In site-years showing a yield response, the differences between treatment means were assessed by using the LINES option of the LSMEANS statement of GLIMMIX, and the maximum yield was defined as the mean of the highest-yielding treatments ($P \leq 0.10$).

Linear and non-linear regression were used to study relationships across all site-years between the tissue P and K concentrations in young plants and leaves at

reproductive stages, and also between relative grain yield and tissue P and K concentrations. We used the REG and NLIN procedures of SAS (SAS Institute, 2011). A range of critical concentrations for each crop and tissue test was determined by fitting the segmented polynomials linear-plateau (LP) and quadratic-plateau (QP) response models using the NLIN procedure of SAS (SAS Institute, 2011). Several procedures can be used to estimate critical concentrations or ranges for soil and tissue tests (Waugh et al., 1973; Nelson and Anderson, 1977; Dahnke and Olson, 1990; Mallarino and Blackmer, 1992). We chose the LP and QP models to compare relationships and critical concentrations for the different tissue tests because critical concentrations are directly determined at a 100% sufficiency level and have been used in many published studies. The fit of LP and QP models for each combination of crop, nutrient, and plant part sampled was compared by an *F* test of the model residual sums of squares.

RESULTS

The study included a wide range of soils and growing conditions which resulted in a wide range of crop yields and responses to fertilization (not shown). In the P trials, mean grain yields across replications ranged from 8.47 to 14.91 Mg ha^{-1} for corn and 1.48 to 4.91 Mg ha^{-1} for soybean. There were statistically significant yield responses ($P \leq 0.10$) to P fertilization in 27 of the 32 corn site-years and in 22 of the 34 soybean site-years. The yield increases were $\leq$ 4.81 Mg ha^{-1} for corn and 1.24 Mg ha^{-1} for soybean. In the K trials, grain yields ranged from 4.87 to 14.64 Mg ha^{-1} for corn and 1.87 to 5.01 Mg ha^{-1} for soybean. There were statistically significant yield responses to K fertilization in

37 of the 67 corn site-years and in 22 of the 53 soybean site-years. The yield increases were ≤ 6.99 Mg ha^{-1} for corn and 1.62 Mg ha^{-1} for soybean.

Figures 1 and 2 show the observed tissue P and K concentrations and the relationships between the concentrations in young plants at the V5-V6 growth stage and in leaves at the reproductive stages R1 in corn and R2-R3 in soybean. There were wide ranges in P and K concentrations for both crops and plant parts sampled. The P tissue concentrations ranged from 2.2 to 6.9 and 1.0 to 4.6 g P kg^{-1} in corn plants and leaves, respectively (Fig. 1a) and from 2.0 to 5.0 and 1.7 to 5.0 g P kg^{-1} in soybean plants and leaves, respectively (Fig. 1b). The K tissue concentrations ranged from 8.9 to 60.7 and 3.2 to 25.6 g K kg^{-1} in corn plants and leaves, respectively (Fig. 2a) and from 8.1 to 36.6 and 5.7 to 36.0 g K kg^{-1} in soybean plants and leaves, respectively (Fig. 2b). There were significant ($P \leq 0.05$) linear relationships between nutrient concentrations in young plants and leaves for both crops and nutrients. The strength of the relationships was weaker for P in corn (Fig. 1, R^2 0.20) and soybean (Fig. 1, R^2 0.27) than for K in corn (Fig. 2, R^2 0.62) and soybean (Fig. 2, R^2 0.51). The poorer relationships for P in both crops may suggest that the value of tissue testing to assess plant P nutritional status may be different for young plants and leaves at mid-season.

The sites confounded factors such as climate, hybrids or varieties, management, and soil-tests levels so it is very difficult to relate differences to growing conditions. In most instances, there are no obvious clusters of observations that could be identified with a specific factor or combination of factors. For relationships for P in corn, however, there is a cluster of six observations that clearly deviate from the general trend (Fig. 3a) at the far right of the graph with high leaf P values, which also were very obvious in plots of

distributions of residuals from the linear model (not shown). These points represent high fertilizer rates at four sites in 2014 (Sites 7, 8, 28, and 29 in Table 1). This result suggests that there may be a factor causing these sites to have higher than expected differences between the P concentrations in young plants and leaves. Study of available site data did not allow for a clear identification of such a factor (not shown). This obvious difference does suggest, however, that at least for P in corn, one of the tissue test stages may be better correlated to P sufficiency and yield response to fertilization.

Relationship between Grain Yield Response and Tissue Phosphorus Concentration

The corn and soybean grain yield response to P fertilization decreased (the relative yield increased) with increasing P concentrations in plants at the V5-V6 growth stage and in leaves at reproductive stages R1 for corn and R2-R3 for soybean (Figs. 3 and 4). In all cases the LP response model consistently determined lower critical concentrations compared with the QP model although they had approximately similar coefficients of determination (R^2). The models fit did not differ ($P \leq 0.10$) for most crop, nutrient, and tissue test combination according to tests of models residuals with the only exception of soybean plants when the LP model fit better, although the standard errors of the estimated critical concentrations always were slightly larger for the QP model than for the LP model (Tables 3 and 4). These two models often have determined different soil or plant tissue nutrient critical concentrations even when R^2 values have been similar (Mallarino and Blackmer 1992; Mallarino, 1995; Mallarino, 1996; Mallarino and Higashi, 2009; Clover and Mallarino, 2013).

The critical P concentrations for V5-V6 corn plants determined by LP and QP models were 4.8 and 5.5 g P kg^{-1}, respectively and R^2 values were 0.34 and 0.35, respectively (Fig. 3 and Table 3). When corn leaf P concentrations at R1 were correlated with relative yield, the LP and QP models determined critical P concentrations of 2.5 and 3.2 g P kg^{-1}, respectively, and the R^2 values were 0.64 and 0.62, respectively (Fig. 3 and Table 3). Therefore, the R^2 values of the relationships were higher for the leaves than for the small plants, and the standard errors of the estimated critical concentrations were lower for the leaves (Table 3).

Earlier research correlating small corn plants at V5-V6 and corn or soybean yield is very scarce or old. A previous study in Iowa with data collected in 1989 and 1990 identified a critical concentration of 3.4 g P kg^{-1} (Mallarino, 1996), and a recently published plant analysis handbook indicates a sufficiency range of 3 to 5 g P kg^{-1}, (Bryson et al. 2014). Critical concentrations for P in corn leaves determined by previous research in Iowa with data collected during the 1980s until 1990 were 2.3 to 2.5 g P kg^{-1} (Mallarino 1995) and 2.4 g P kg^{-1} (Mallarino, 1996). The sufficiency range for corn leaves at this stage suggested for the southern region of the US is 2.5 to 5 g P kg^{-1} (Campbell and Plank, 2013) and Bryson et al. (2014) recommend 2.5 to 5.0 g P kg^{-1}. Therefore, the critical concentration range for P in corn leaves identified in our study is higher than values identified in previous Iowa studies (Mallarino, 1995 and 1996) and within the range of sufficiency levels suggested in other literature. The coefficients of determinations of the models in our study (R^2 0.64 and 0.62) were much higher than in the older studies (R^2 0.14 to 0.32), probably because our study included more sites with a better frequency distribution of sites with low to high concentrations.

Figure 4 shows the relationships between soybean relative yield and tissue P concentrations in plants at the V5-V6 growth stage and in leaves at the R2-R3 stage. The LP and QP models estimated P critical concentrations for young plants of 3.3 and 4.1 g P kg^{-1}, respectively. The R^2 values for the LP and QP models were 0.41 and 0.45, and the LP model fit better (Table 3). When tissue P concentrations in leaf samples taken at the R2-R3 growth stage were correlated with relative yield, the LP and QP models determined a critical concentration of 3.5 and 4.7 g P kg^{-1}, respectively, and R^2 value was 0.31 for both models (Table 3). Previous research has not determined a soybean tissue P critical concentration for young plant parts at the V5-V6 stage of growth. A sufficiency range of 3-6 g P kg^{-1} is suggested for early flowering soybeans leaves (Bryson et al. 2014). Based on research conducted before the early 1970s, Small and Ohlrogge (1973) suggested a sufficiency range of 2.6 to 5.0 g P kg^{-1} for soybean leaves prior to pod set. An identical range was suggested by Jones et al. (1991). A sufficiency range of 3 to 6 g P kg^{-1} is suggested for early flowering soybeans leaves in the latest version of a plant analysis handbook (Bryson et al., 2014). Therefore, the critical concentration range for P in soybean leaves determined in our study is narrower but within recently suggested sufficiency ranges.

The strength of relationships between corn relative yield response and tissue P concentration as assessed by R^2 and standard errors of estimated critical concentrations for each tissue was much better for leaves at the R1 growth stage than for plants at the V5-V6 stage. For soybean, however, the strength of the relationships was better for the young plants than for the mature leaves at the R2-R3 growth stage. The better relationship for corn leaves indicates that a P test of leaves at R1 would be better than a

test of young plants at V5-V6, but the better relationship for young soybean plants indicates that this would be better than a test based on leaves. A large difference between P tests based on young plants or leaves had been suggested by relationships between P tests shown in Fig. 1a and 1b. Mallarino (1996) reported that the strength of relationships for corn young plants and ear leaves was similar, but the coefficients of determination of the models were extremely low (R^2 0.14 to 0.18). Early research (Tyner, 1946; Tyner and Webb, 1946; Hanway, 1962) showed that nutrient deficiencies (including P and K) in corn were better reflected by nutrient concentrations in ear leaves compared with other plant parts. Perhaps undetermined soil, physiological, or weather conditions affect early corn growth and P uptake and cause more variability in early tissue P concentrations that are not well reflected in grain yield. Research has shown that, for example, moisture and temperature can greatly affect early corn growth and nutrient uptake (Mederski and Jones, 1963; Bryson et al., 2014). Mederski and Jones (1963) found that by increasing soil temperatures, plant samples of corn taken 30 days after planting had twice as much P content and 25% higher K concentration than corn samples from an unheated control.

Relationship between Grain Yield Response and Tissue Potassium Concentration

The crop grain yield response to K fertilization decreased (relative yield increased) with increasing K concentration in young plants at the V5-V6 growth stage and in leaves at reproductive stages R1 for corn and R2-R3 for soybean (Figs. 5 and 6). As for P, the LP response model consistently determined lower K critical concentrations compared with the QP model. The models had approximately similar R^2 values and did

not differ for any crop or tissue, although as for P the LP model showed lower standard errors for the estimated critical concentrations than the QP model (Table 4).

Critical K concentrations for corn plants at the V5-V6 growth stage determined by the LP and QP models were 18.8 g K kg^{-1} and 25.3 g K kg^{-1}, respectively, and R^2 values were 0.51 and 0.53 (Fig. 5 and Table 4).The K critical concentrations for corn ear leaves determined by LP and QP models were 10.6 and 14.2 g K kg^{-1}, and R^2 values were 0.53 for both models (Table 4 and Fig. 5). Early research in Illinois with corn plants 25 cm tall determined a critical concentration of 39.8 g K kg^{-1} (Walker and Peck, 1975). Sufficiency ranges suggested for young plants by Jones (1967), Jones et al. (1990), and Mills and Jones (1996) were 25 to 40 g K kg^{-1}. Mallarino and Higashi (2009) did not find a significant correlation between the K concentration of corn young plants and grain yield response, however, even when K concentrations ranged from 7.6 to 48.6 g K kg^{-1}. More recent Iowa research by Clover and Mallarino (2013) for the subset of Sites 1 through 20 included in this study determined critical tissue K concentration ranges for corn young plants of 20.2 to 25.1 g K kg^{-1}. Campbell and Plank (2013) suggested a sufficiency range of 20 to 30 g K kg^{-1} for plants between 4 inches tall and tasseling. Bryson et al. (2014) suggested a sufficiency range of 25 to 35 g K kg^{-1} for corn plants less than 30 cm tall. Sufficiency ranges for the corn ear-leaf K test based on early research suggested by Jones et al. (1990) were 17.1 to 25.0 g K kg^{-1}, and by both Jones et al. (1991) and Mills and Jones (1996) were 17 to 30 g K kg^{-1}. Mallarino and Higashi (2009), based on 28 Iowa field trials with corn conducted during 1989 and 1990 reported an ear leaf critical concentration of 12.3 g K kg^{-1}. More recent Iowa research by Clover and Mallarino (2013) for the subset of Sites 1 through 20 included in this study determined critical

tissue K concentration ranges for corn ear leaves of 10.2 to 11.0 g K kg^{-1}. Sufficiency ranges suggested for the Southern region of the US by Campbell and Plank (2013) are 18 to 30 g K kg^{-1} and those suggested by Bryson et al. (2014) are 18 to 30 g K kg^{-1}.

Therefore, the critical concentration range for K in corn young plants identified in our study is lower than sufficiency levels suggested in literature based mainly on work conducted in other regions or without clear reference to the source of information. Also, much of the literature has used plant height to describe when plants are sampled, leading to potentially different stages of sample collection and thus different critical concentrations. The values we determined are approximately similar to those reported for Iowa experiments conducted by Clover and Mallarino (2013) (whose data were included in our study). The earlier Iowa study by Mallarino and Higashi (2009) could not identify K critical concentrations for young plants probably because it included fewer sites and few had K deficiency and low tissue K concentrations. The critical concentration range for K in corn ear leaves identified in our study is lower than most previous sufficiency ranges reported for other regions, but similar to values from Clover and Mallarino (2013) and Mallarino and Higashi (2009).

Figure 6 shows the relationship between soybean K concentrations and relative yield along with identified critical concentrations. The critical concentration for soybean plants samples taken at the V5-V6 growth stages was 18.9 g K kg^{-1} by the LP model and 22.6 g K kg^{-1} by the QP model, and R^2 values were 0.35 for both models (Table 4). Critical K concentrations for soybean leaves at the R2-R3 stage were 15.6 g K kg^{-1} by the LP model and 22.6 g K kg^{-1} by the QP model, with a R^2 value of 0.51 for both models. Published information about K critical concentrations for soybean young plants is very

scarce. Recent Iowa research by Clover and Mallarino (2013) for Sites 1 through 20 included in this study could not determine critical tissue K concentration ranges for soybean plants at the V5-V6 stage, but suggested critical concentrations at the R2-R3 growth stage of 17.6 to 20.0 g K kg^{-1}. When these data were merged with our new data, the identified critical concentration ranges were similar but lower for the R2-R3 growth stage, and critical concentrations could be calculated for V5-V6 samples. An early sufficiency range suggested for the uppermost mature soybean leaves at mid flowering by Small and Ohlrogge (1973) was 17.1-25.0 g K kg^{-1}. Critical concentrations of 15 g K kg^{-1} and 19 g K kg^{-1} were found for mature soybean leaves using a LP response model at R1-R2 growth stage for cultivars of maturity groups IV and V in Arkansas (Slayton et al. 2010). Recently suggested sufficiency ranges are 15-22.5 g K kg^{-1} for the Southern region of the US (Sabbe et al. 2013) and 17-25 g K kg^{-1} by Bryson et al. (2014). Therefore, critical K concentrations we identified for soybean leaves at the R2-R3 growth stage are within the range of previously reported critical concentrations or suggested sufficiency ranges.

The strength of relationships between corn relative yield response and the tissue K concentrations as assessed by R^2 of the LP and QP models fit and standard errors of the critical concentration estimates were approximately similar for plants at the V5-V6 growth stage (R^2 0.51 and 0.53) and ear-leaves at the R1 growth stage (R^2 0.53 for both models) (Table 4 and Fig. 6). For soybean, however, the strength of the relationships was better for leaves (R^2 0.51 by both models) than for young plants (R^2 0.35 and higher standard errors of critical concentrations for both models) (Table 4 and Fig. 6). Therefore

a K test of soybean leaves at the R2-R3 stage would be more reliable than a test of young soybean plants at V5-V6.

Conclusions

Critical concentration ranges for P in corn determined by LP and QP models were 4.8 to 5.3 g P kg^{-1} for plants sampled at the V5-V6 growth stage and 2.5 to 3.1 g P kg^{-1} for ear-leaves sampled at the R1 stage. The ear-leaf test provided a better assessment of the relationship between tissue P concentrations and corn yield response. In soybean, critical concentration ranges for P determined by LP and QP models were 3.3 to 4.1 g P kg^{-1} for young plants and 3.5 to 4.7 g P kg^{-1} for mature leaves sampled at the R2-R3 stage. The strength of the relationships was approximately similar for both models and soybean plant parts sampled.

The LP and QP models determined critical concentration ranges for K in corn of 18.8 to 25.3 g K kg^{-1} for plants sampled at the V5-V6 growth stage and 10.6 to 14.2 g K kg^{-1} for ear-leaves sampled at the R1 stage. The strength of the relationships between tissue K concentrations and corn yield response was approximately similar for both models and corn plant parts sampled. In soybean, critical concentration ranges for K determined by LP and QP models were 18.9 to 22.6 g K kg^{-1} for young plants and 15.6 to 19.9 g K kg^{-1} for mature leaves sampled at the R2-R3 stage. The strength of the relationships between K tissue levels and soybean yield response was better for the leaves than for the young plants.

Overall, this research provided new insight into the value of plant analysis to assess P and K status of corn and soybean and of potential critical concentration ranges that could be used to complement soil testing to evaluate the P and K sufficiency in conditions similar to those in the study. In corn, a P tissue test based on ear-leaf blades at the R1 growth stage was better than a P test based on plants at the V5-V6 stages but K tests based on plants or leaves provided similar assessments of K status. In soybean, a P tissue test based on plants at the V5-V6 stages was better than a P test based on mature leaves at the R2-R3 stages but for K a test based on leaves was better than a test based on young plants.

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Table 1. Location, tillage system, soils, and soil properties (15-cm depth) at each site P site.

Site	County	Till †	Soil classification		OM ‡	STP §	pH
			Series	Subgroup	g kg^{-1}	mg kg^{-1}	
1	Floyd	CH	Floyd	Pachic Hapludoll	33	11	5.8
2	Floyd	CH	Floyd	Pachic Hapludoll	33	7	6.0
3	O'Brien	CH	Marcus	Typic Endoaquoll	50	11	6.5
4	O'Brien	CH	Marcus	Typic Endoaquoll	50	9	6.3
5	Boone	CH	Webster	Typic Endoaquoll	46	7	5.8
6	Boone	CH	Webster	Typic Endoaquoll	46	9	6.0
7	Floyd	CH	Kenyon	Typic Hapludoll	40	9	6.6
8	Floyd	NT	Kenyon	Typic Hapludoll	40	6	6.6
9	Hancock	CH	Canisteo	Typic Endoaquoll	58	7	6.2
10	Hancock	NT	Canisteo	Typic Endoaquoll	58	9	6.2
11	O'Brien	CH	Galva	Typic Hapludoll	47	6	5.7
12	O'Brien	NT	Galva	Typic Hapludoll	47	5	5.7
13	Washington	CH	Mahaska	Aquertic Argiudoll	44	12	5.4
14	Washington	NT	Mahaska	Aquertic Argiudoll	44	11	5.4
15	Pottawattamie	CH	Marshall	Typic Hapludoll	40	6	6.0
16	Pottawattamie	NT	Marshall	Typic Hapludoll	40	5	6.0
17	Floyd	CH	Kenyon	Typic Hapludoll	28	8	5.6
18	Floyd	CH	Kenyon	Typic Hapludoll	28	13	5.7
19	Boone	CH	Clarion	Typic Hapludoll	26	9	6.5
20	Boone	CH	Clarion	Typic Hapludoll	24	14	6.2
21	Hancock	CH	Nicollet	Aquic Hapludoll	57	7	5.8
22	Hancock	CH	Nicollet	Aquic Hapludoll	56	5	6.0
23	O'Brian	CH	Galva	Typic Hapludoll	41	8	6.1
24	O'Brian	CH	Galva	Typic Hapludoll	45	9	6.0
25	Pottawattamie	CH	Marshall	Typic Hapludoll	46	10	6.5
26	Pottawattamie	CH	Marshall	Typic Hapludoll	45	11	6.7
27	Boone	CH	Webster	Typic Endoaquoll	46	8	6.0
28	Boone	CH	Webster	Typic Endoaquoll	46	9	6.0
29	Floyd	CH	Floyd	Pachic Hapludoll	33	8	5.4
30	Floyd	CH	Floyd	Pachic Hapludoll	33	9	5.4

† Till, tillage; CH, chisel plowing followed by disking or field cultivating on corn residue and disking or field cultivating on soybean residue; NT, no tillage.

‡ OM, organic matter.

§ STP, soil-test P by the Bray-1 method.

Table 2. Location, tillage system, soils, and soil properties (15-cm depth) at each site K site.

Site	County	Till †	Soil classification		OM ‡	STK §	pH
			Series	Subgroup	g kg^{-1}	mg kg^{-1}	
1	Boone	CH	Canisteo	Typic Endoaquoll	36	163	6.3
2	Boone	CH	Canisteo	Typic Endoaquoll	38	139	6.6
3	Boone	CH	Nicollet	Aquic Hapludoll	25	150	7.2
4	Boone	CH	Nicollet	Aquic Hapludoll	59	234	7.6
5	Boone	CH	Webster	Typic Endoaquoll	67	153	7.3
6	Boone	CH	Webster	Typic Endoaquoll	47	133	6.6
7	Floyd	CH	Clyde	Typic Endoaquoll	84	196	6.7
8	Floyd	CH	Kenyon	Typic Hapludoll	75	170	6.7
9	Hancock	CH	Nicollet	Aquic Hapludoll	54	162	5.7
10	Hancock	CH	Canisteo	Typic Endoaquoll	47	138	6.7
11	O'Brien	CH	Primghar	Aquic Hapludoll	40	213	6.2
12	O'Brien	CH	Primghar	Aquic Hapludoll	52	154	6.2
13	O'Brien	CH	Galva	Typic Hapludoll	53	173	6.3
14	O'Brien	CH	Galva	Typic Hapludoll	42	170	6.5
15	Washington	CH	Mahaska	Aquertic Argiudoll	44	141	6.4
16	Washington	CH	Nira	Typic Hapludoll	35	148	6.0
17	Washington	CH	Taintor	Typic Hapludoll	34	134	6.2
18	Washington	CH	Mahaska	Aquertic Argiudoll	44	130	6.3
19	Boone	CH	Clarion	Typic Hapludoll	35	102	6.7
20	Boone	CH	Clarion	Typic Hapludoll	40	117	6.7
21	Hancock	CH	Nicollet	Aquic Hapludoll	50	115	5.6
22	Floyd	CH	Kenyon	Typic Hapludoll	40	111	6.6
23	Floyd	NT	Kenyon	Typic Hapludoll	40	96	6.6
24	Hancock	CH	Webster	Typic Endoaquoll	58	160	6.2
25	Hancock	NT	Webster	Typic Endoaquoll	58	169	6.2
26	O'Brien	CH	Galva	Typic Hapludoll	47	202	5.7
27	O'Brien	NT	Galva	Typic Hapludoll	47	212	5.7
28	Washington	CH	Mahaska	Aquertic Argiudoll	44	155	5.4
29	Washington	NT	Mahaska	Aquertic Argiudoll	44	154	5.4
30	Pottawattamie	CH	Marshall	Typic Hapludoll	40	218	6.0
31	Pottawattamie	NT	Marshall	Typic Hapludoll	40	193	6.0
32	Floyd	CH	Floyd	Pachic Hapludoll	61	108	6.6
33	Hancock	CH	Nicollet	Aquic Hapludoll	38	156	6.9
34	Washington	CH	Taintor	Typic Hapludoll	34	216	6.2
35	Pottawattamie	NT	Exira	Typic Hapludoll	28	163	6.3
36	Boone	CH	Clarion	Typic Hapludoll	35	100	5.5
37	Floyd	CH	Kenyon	Typic Hapludoll	67	105	6.6
38	Hancock	CH	Canisteo	Typic Endoaquoll	41	170	5.6
39	Washington	CH	Taintor	Typic Hapludoll	35	137	6.0
40	Lucas	CH	Grundy	Aquertic Argiudoll	36	138	6.3
41	Lucas	CH	Grundy	Aquertic Argiudoll	36	139	6.3
42	Lucas	CH	Haig	Vertic Argiaquoll	39	109	6.9
43	Lucas	CH	Haig	Vertic Argiaquoll	39	107	6.9
44	Boone	CH	Webster	Typic Endoaquoll	35	133	6.4
45	Boone	CH	Clarion	Typic Hapludoll	39	120	5.8

† Till, tillage; CH, chisel plowing followed by disking or field cultivating on corn residue and disking or field cultivating on soybean residue; NT, no tillage.

‡ OM, organic matter.

§ STK, soil-test K by the NH_4OAc method.

(Continued on the next page)

(Table 2 continued)

Site	County	Till †	Soil classification		OM ‡	STK §	pH
			Series	Subgroup	g kg^{-1}	mg kg^{-1}	
46	Hancock	CH	Nicollet	Aquic Hapludoll	39	139	5.9
47	Hancock	CH	Nicollet	Aquic Hapludoll	39	130	5.9
48	Washington	CH	Mahaska	Aquertic Argiudoll	44	156	5.7
49	Washington	CH	Mahaska	Aquertic Argiudoll	44	167	5.7
50	Washington	CH	Mahaska	Aquertic Argiudoll	44	157	5.7
51	Washington	CH	Mahaska	Aquertic Argiudoll	44	161	5.7
52	Floyd	CH	Kenyon	Typic Hapludoll	28	92	5.7
53	Floyd	CH	Kenyon	Typic Hapludoll	28	96	5.7

† Till, tillage; CH, chisel plowing followed by disking or field cultivating on corn residue and disking or field cultivating on soybean residue; NT, no tillage.
‡ OM, organic matter.
§ STK, soil-test K by the NH_4OAc method.

Table 3. Models fit to relationships between relative grain yield (%) and tissue P concentrations for corn and soybean.

Crop	Stage	Model †	Equation ‡	R^2	SE §
Corn	V5-V6	LP	59.28 + 8.50*x*, for $x \leq 4.8$	0.34	0.31
Corn	V5-V6	QP	27.65 + 25.98 *x* - 2.35 x^2, for $x \leq 5.5$	0.35	0.65
Corn	R1	LP	31.00 + 27.48 *x*, for $x \leq 2.5$	0.64	0.08
Corn	R1	QP	0.22 + 63.82 *x* - 10.18 x^2, for $x \leq 3.1$	0.62	0.21
Soybean	V5-V6	LP	27.59 + 21.54 *x*, for $x \leq 3.3$	0.41	0.10
Soybean	V5-V6	QP	- 19.38 + 58.36 *x* - 7.06 x^2, for $x \leq 4.1$	0.45	0.39
Soybean	R2-R3	LP	64.55 + 9.93 *x*, for $x \leq 3.5$	0.31	0.26
Soybean	R2-R3	QP	48.62 + 22.44 *x* - 2.38 x^2, for $x \leq 4.7$	0.31	1.43

† LP, linear plateau; QP, quadratic plateau.

‡ X, tissue P concentration (g kg^{-1}); the equation applies for X ≤ the concentration at which the two portions of each model join (the critical concentration); all models were significant at $P < 0.01$.

§ SE, standard error of the estimated critical concentrations.

Table 4. Models fit to relationships between relative grain yield (%) and tissue K concentrations for corn and soybean.

Crop	Stage	Model †	Equation ‡	R^2	SE §
Corn	V5-V6	LP	21.02 + 4.09 *x*, for $x \leq 18.8$	0.51	0.46
Corn	V5-V6	QP	0.40 + 7.75 *x* - .15 x^2, for $x \leq 25.4$	0.53	1.11
Corn	R1	LP	33.13 + 6.12 *x*, for $x \leq 10.6$	0.53	0.26
Corn	R1	QP	15.73 + 11.69 *x* - .41 x^2, for $x \leq 14.2$	0.53	0.64
Soybean	V5-V6	LP	72.01 + 1.46 *x*, for $x \leq 18.9$	0.35	0.71
Soybean	V5-V6	QP	54.72 + 3.98 *x* - .09 x^2, for $x \leq 22.7$	0.35	1.58
Soybean	R2-R3	LP	60.86 + 2.47 *x*, for $x \leq 15.6$	0.51	0.48
Soybean	R2-R3	QP	45.46 + 5.43 *x* - .14 x^2, for X ≤ 19.9	0.51	1.02

† LP, linear plateau; QP, quadratic plateau.

‡ X, tissue K concentration (g kg^{-1}); the equation applies for X ≤ the concentration at which the two portions of each model join (the critical concentration); all models were significant at $P < 0.01$.

§ SE, standard error of the estimated critical concentrations.

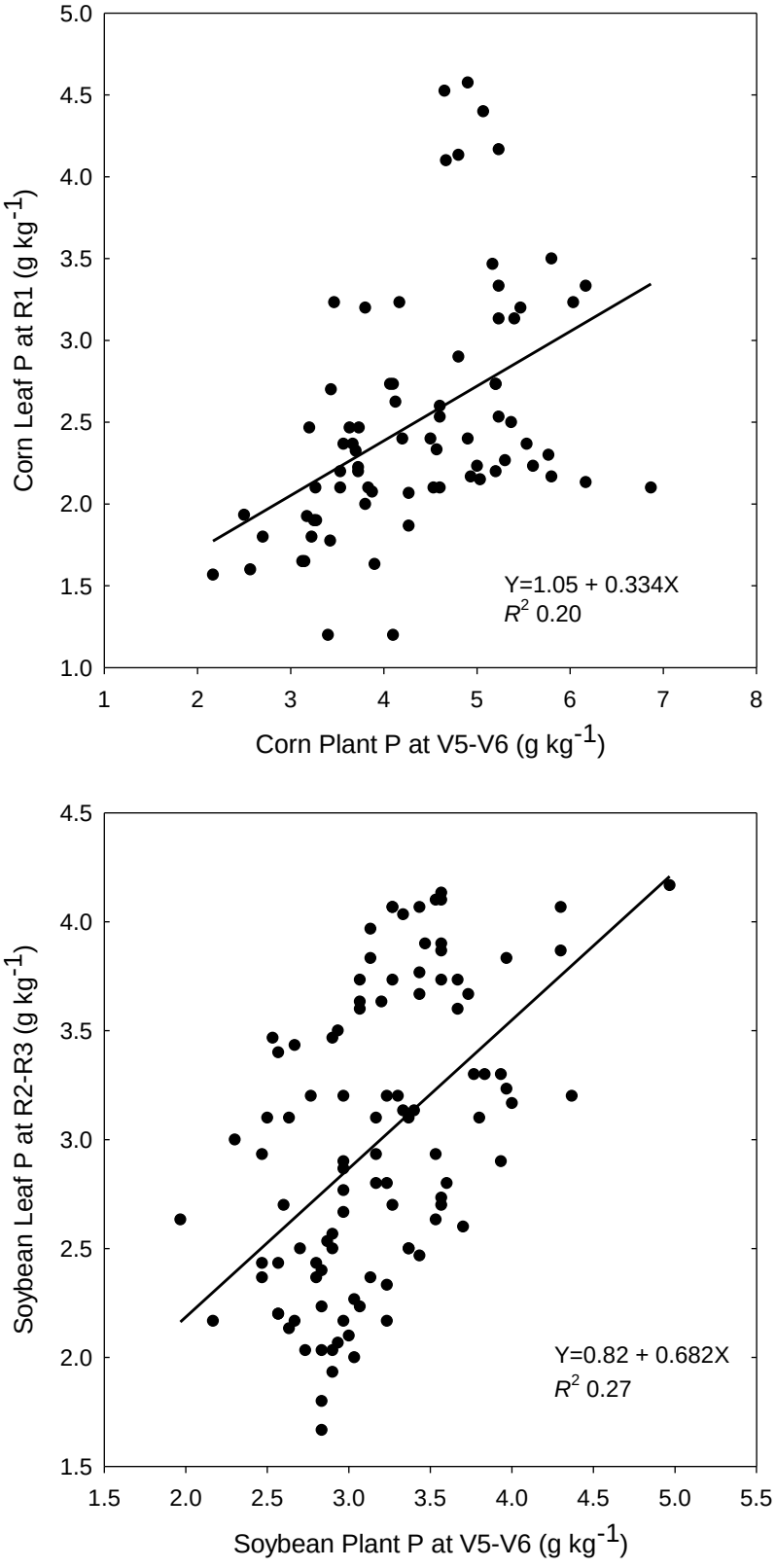
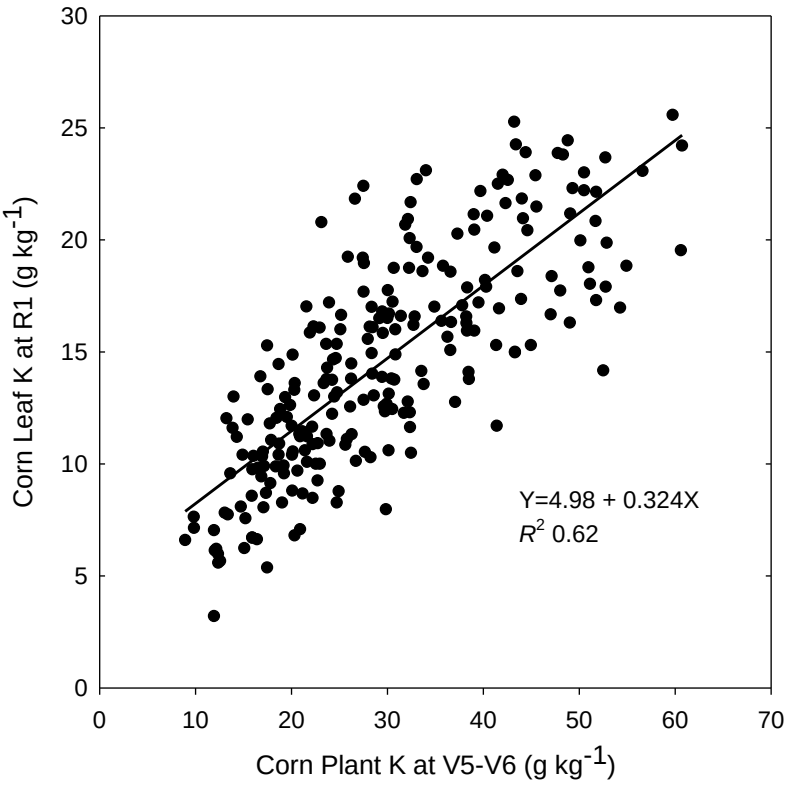


Figure 1. Relationships between P concentrations in plants at the V5-V6 growth stage and in leaves at early reproductive growth stages for corn and soybean.



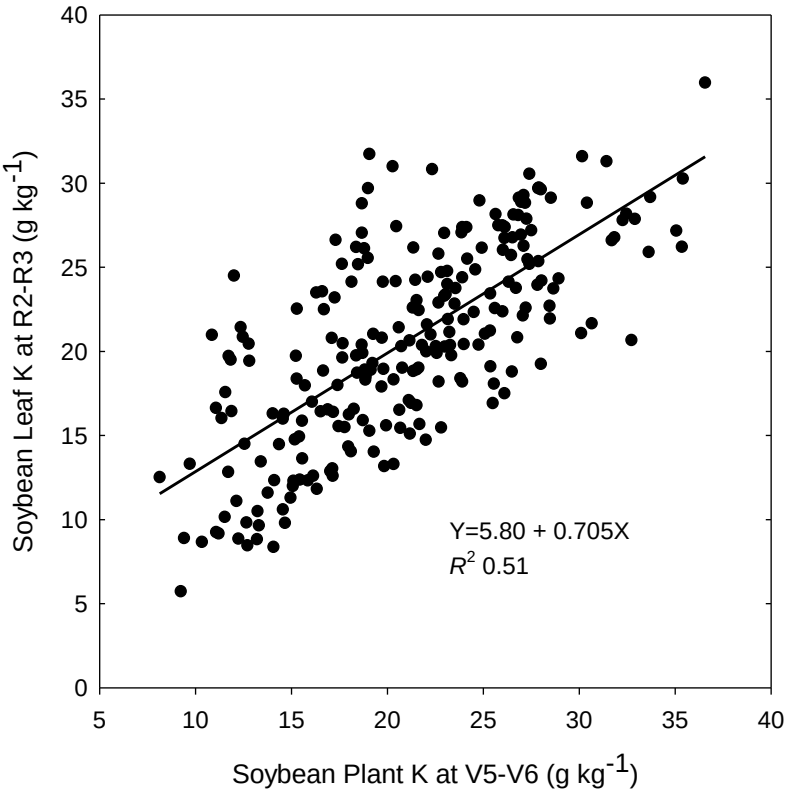
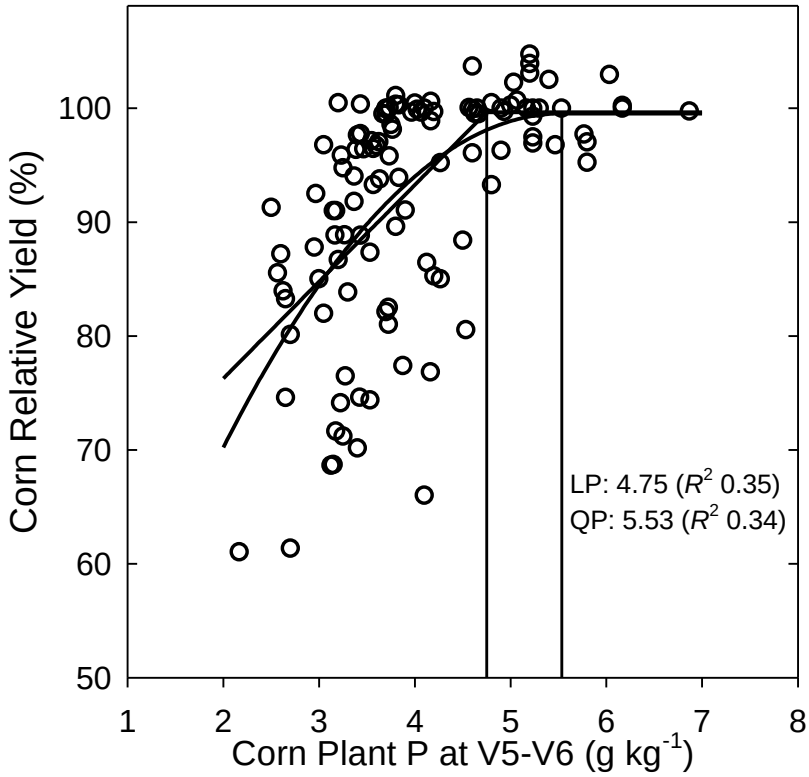


Figure 2. Relationships between K concentrations in plants at the V5-V6 growth stage and in leaves at early reproductive growth stages for corn and soybean.



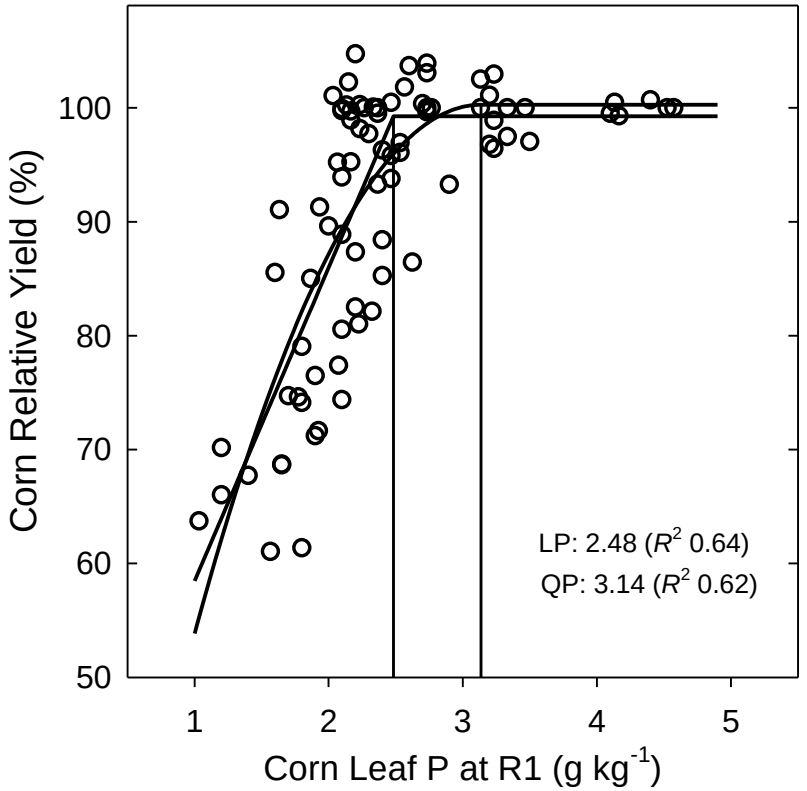
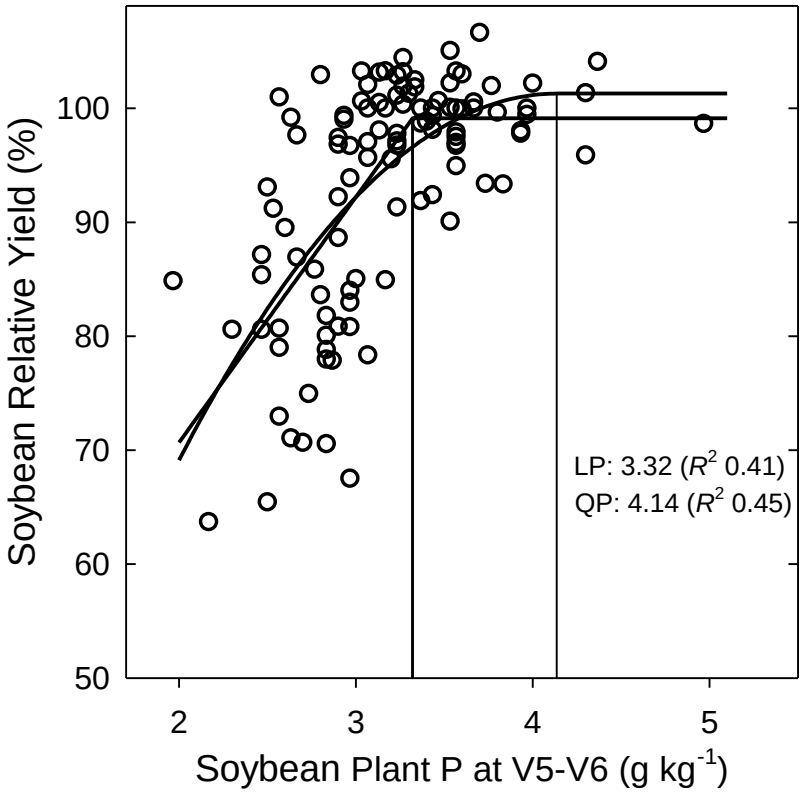


Figure 3. Relationship between corn relative grain yield and the P concentration of plants at the V5-V6 growth stage or ear-leaves at the R1 stage. QP, quadratic plateau; LP, linear plateau; critical concentrations are shown.



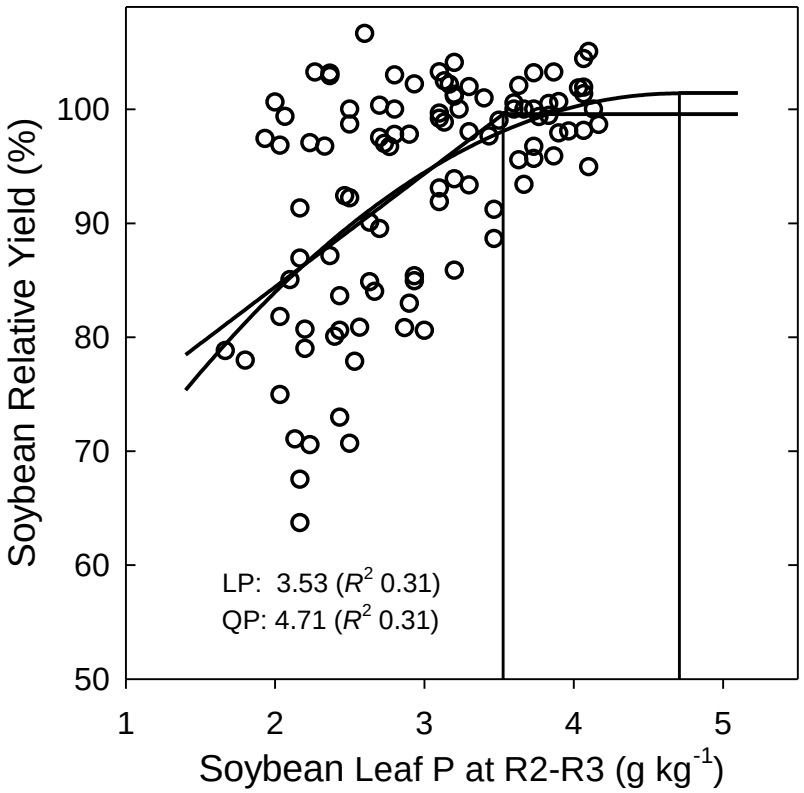
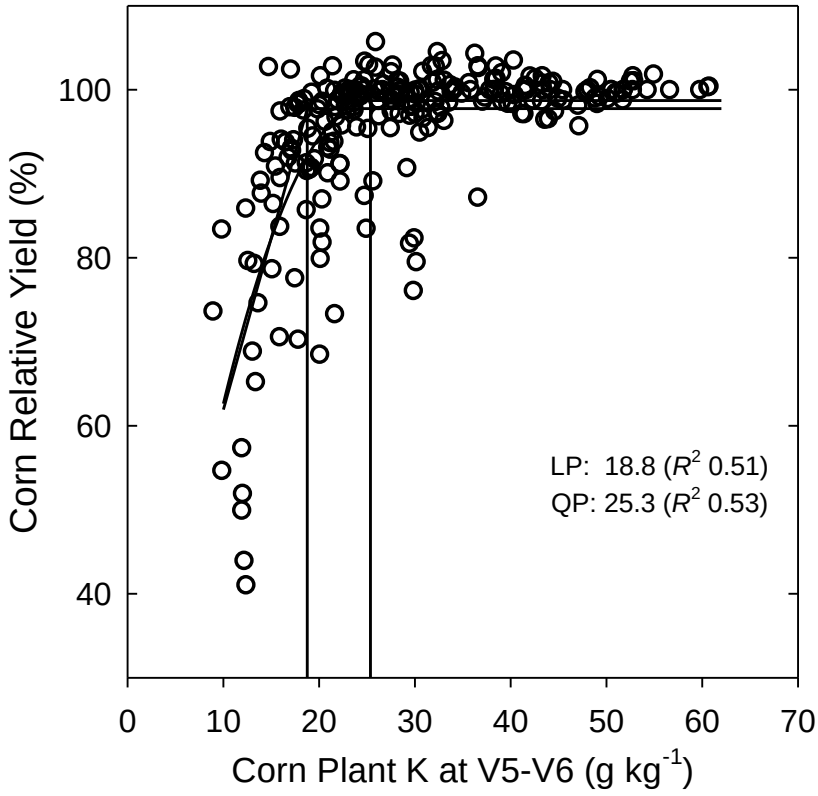


Figure 4. Relationship between soybean relative grain yield and the P concentration of plants at the V5-V6 growth stage or uppermost mature leaves at the R2-R3 stage. QP, quadratic plateau; LP, linear plateau; critical concentrations are shown.



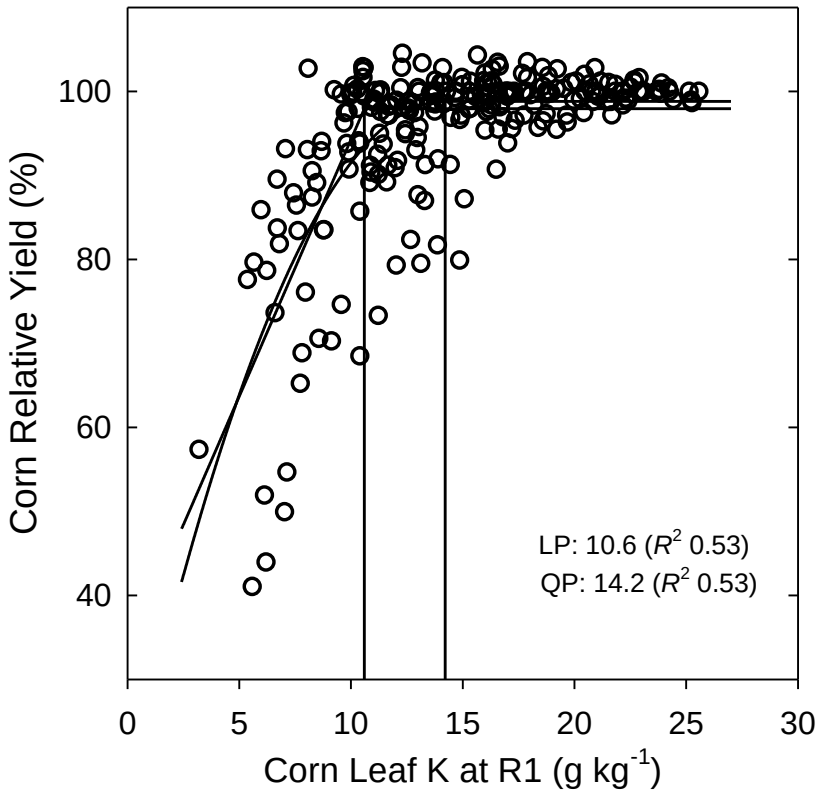


Figure 5. Relationship between corn relative grain yield and the K concentration of plants at the V5-V6 growth stage or ear-leaves at the R1 stage. QP, quadratic plateau; LP, linear plateau; critical concentrations.

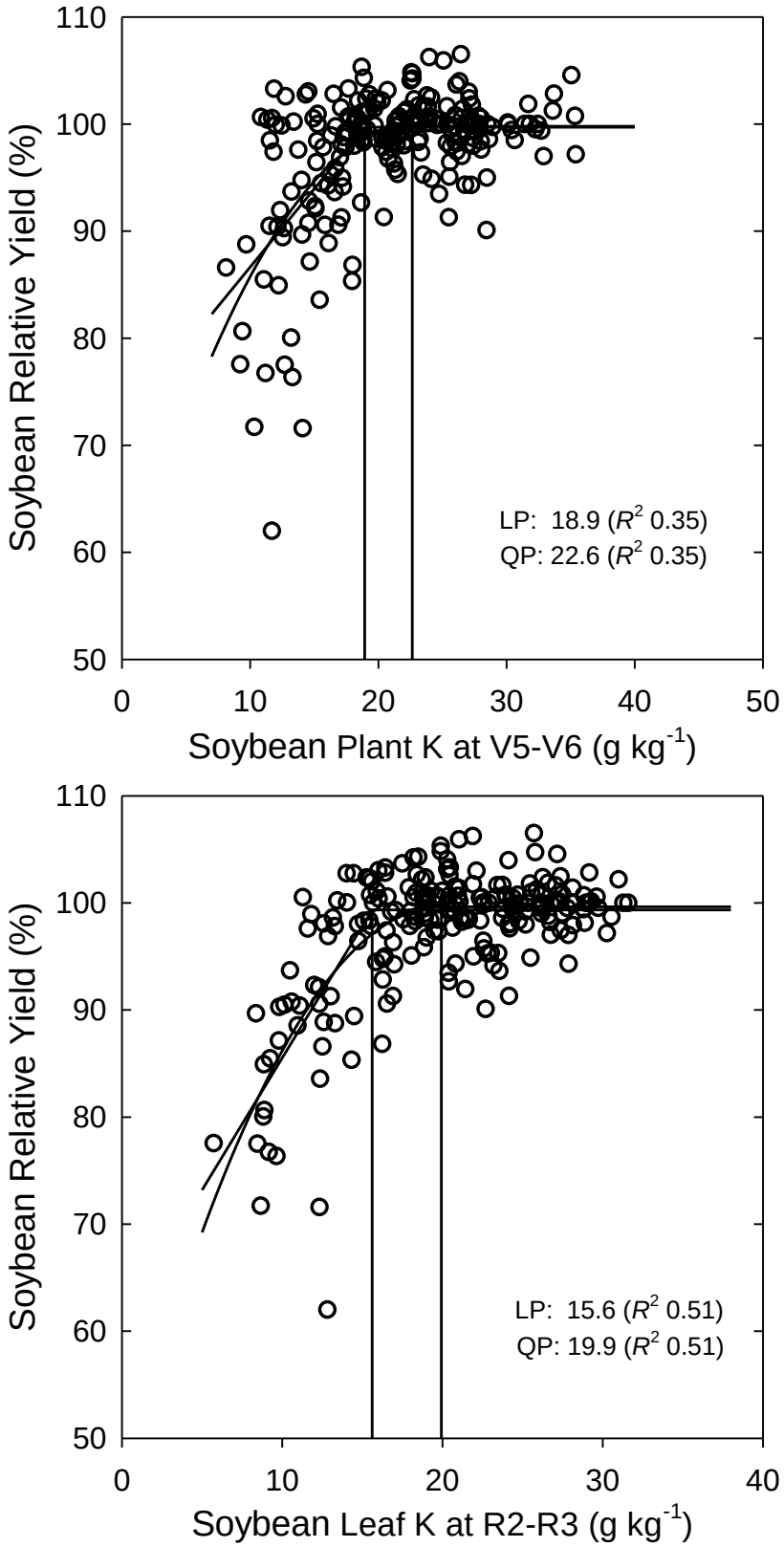


Figure 6. Relationship between soybean relative grain yield and the P concentration of plants at the V5-V6 growth stage or uppermost mature leaves at the R2-R3 stage. QP, quadratic plateau; LP, linear plateau; critical concentrations are shown.

GENERAL CONCLUSIONS

The study included a wide range of soils and growing conditions which resulted in a wide range of crop yields and responses to fertilization. In the P trials, grain yields across sites varied from 8.47 to 14.91 Mg ha^{-1} for corn and 1.48 to 4.91 Mg ha^{-1} for soybean. There were statistically significant yield responses to P fertilization in 27 of the 32 corn site-years and in 22 of the 34 soybean site-years. There were significant yield responses to K fertilization in 37 of the 67 corn site-years and in 22 of the 53 soybean site-years.

The corn and soybean grain yield response to P fertilization decreased with increasing P concentrations in plants at the V5-V6 growth stage and in leaves at reproductive stages R1 for corn and R2-R3 for soybean. In all cases the LP response model consistently determined lower critical concentrations compared with the QP model although they had approximately similar coefficients of determination (R^2). Critical concentration ranges for P in corn determined by LP and QP models were 4.8 to 5. 3 g P kg^{-1} for plants sampled at the V5-V6 growth stage and 2.5 to 3.1 g P kg^{-1} for leaves sampled at the R1 stage. The ear-leaf test provided a better assessment of the relationship between tissue P concentrations and corn relative yield. In soybean, critical concentration ranges for P determined by LP and QP models were 3.3 to 4.1 g P kg^{-1} for young plants and 3.5 to 4.7 g P kg^{-1} for mature leaves sampled at the R2-R3 stage.

The crop grain yield response to K fertilization decreased with increasing K concentration in young plants at the V5-V6 growth stage and in leaves at reproductive stages R1 for corn and R2-R3 for soybean. The LP and QP models determined critical concentration ranges for K in corn of 18.8 to 25.3 g K kg^{-1} for plants sampled at the V5-

V6 growth stage and 10.6 to 14.2 g K kg^{-1} for ear-leaves sampled at the R1 stage. In soybean, critical concentration ranges for K determined by LP and QP models were 18.9 to 22.6 g K kg^{-1} for young plants and 15.6 to 19.9 g K kg^{-1} for mature leaves sampled at the R2-R3 stage. The strength of the relationships between K tissue levels and soybean yield response was better for the leaves than for the young plants. This is lower than previous sufficiency ranges reported for other regions. Critical K concentrations identified for soybean leaves at the R2-R3 growth stage are within the range of previously reported critical concentrations or suggested sufficiency ranges.

Overall, the results of this project provided new insight into the value of plant analysis to assess P and K status of corn and soybean and of potential critical concentration ranges that could be used to complement soil testing to evaluate the P and K sufficiency. In corn, a P tissue test based on ear-leaf blades at the R1 growth stage was better than a P test based on plants at the V5-V6 stages but K tests based on plants or leaves provided similar assessments of K status. In soybean, a P tissue test based on plants at the V5-V6 stages was better than a P test based on mature leaves at the R2-R3 stages but for K a test based on leaves was better than a test based on young plants.