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CROP POTASSIUM NUTRITION – IMPLICATIONS FOR FERTILIZER RECOMMENDATIONS

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Summary

During the past 35 years, average corn yields in the North Central Region (NCR) have increased at a rate of 1.7 bu/acre per year, mainly due to the adoption of improved crop management technologies and genetic improvement of corn hybrids. Fertilizer K rates used on corn are typically within a range of 0 to 110 lb K_2O/acre, but average usage varies widely among states. Commercial fertilizer use rose sharply in the 1960s and 1970s, but corn yield increases since 1980 were achieved with stagnating fertilizer-N use and declining rates of P and K. Signs of emerging K deficiencies have become more common in recent years, particularly in no-till systems. This includes unusual visual symptoms such as K deficiency on younger leaves, but also an unknown range of less visible K deficiencies that are not easily detected based on leaf symptoms. A key question is whether present K management recommendations are adequate to meet future needs. Recent research suggests that (a) commonly used soil tests may not always reflect the actual crop response to K, (b) crop K requirements per unit yield are not constant, but vary with the absolute yield levels and crop management factors, (c) spatial variability of soil K affects K management strategies, (d) genotypic differences exist in the response to soil and fertilizer K, and (e) non-yield traits such as stalk strength or product quality must be taken into account in K management decisions. Therefore, future, fertilizer recommendation algorithms should be more robust and accommodate different crops, cropping systems, crop management technologies, soil conditions, and climate-driven yield potential. Such refinements can be made at different levels of complexity such that a general recommendation can be broken down into more specific recommendations. Agroecological zoning and crop simulation models should play a major role in making these refinements.

Trends in Fertilizer Use in the North-Central Region

Rainfed and irrigated systems in which corn (*Zea mays L.*) is grown either in rotation with soybean (*Glycine max* L.) or as a continuous monocrop are the predominant cropping systems in North America. About 30 million ha of corn are harvested annually for grain in the USA, of which eleven states in the Corn Belt produce more than 210 million t or 35% of the global corn supply. During the past 35 years, average corn yields have increased linearly at a rate of 109 kg ha^{-1} yr^{-1} (1.7 bu/acre per year; Fig. 1), mainly due to the adoption of improved crop management technologies and genetic improvement of corn hybrids that complements these management practices (Duvick and Cassman, 1999).

Commercial fertilizer use rose sharply in the 1960s and 1970s in response to the adoption of improved corn hybrids and favorable economic forces (Uri, 1998). However, corn yield increases since 1980 were achieved with stagnating fertilizer-N use and declining rates of P and K, leading to significant increases in the partial factor productivity (PFP, kg grain per kg nutrient applied) of these macronutrients (Fig. 1). Three factors have probably contributed to the improvement in nutrient efficiency: (i) increased yields and more vigorous crop growth associated with increased stress tolerance of modern hybrids (Duvick and Cassman, 1999), (ii) improved management of production factors other than fertilizer (conservation tillage, seed quality, higher plant densities, etc.) and (iii) improved N management. Many farmers also invested in building soil fertility through P and K applications that exceeded crop removal (Fig. 1). Average fertilizer rates used by corn farmers since 1965 exceeded the net nutrient removal, but the difference is declining in recent years (Fig. 1). For example, the average K surplus (fertilizer amount minus K removal with grain) on corn decreased from 47 kg K ha^{-1} per crop (50 lb K_2O/acre) in 1980-1984 to just 28 kg K ha^{-1} (30 lb K_2O/acre) in 1996-2000. Considering that these numbers must be further adjusted for nutrient removal by soybean in corn-soybean rotations, it is likely that since the late 1970s many farmers have been taking advantage of residual soil P and K supplies built up by previous nutrient applications. Accounting for nutrients supplied with farmyard manure only slightly offsets his average trend across the whole region because only 17% of the corn area and 6% of soybean area receive an application of livestock manure (Padgitt et al., 2000).

Differences exist among the major corn-producing states in K use and the K input-output balance (Fig. 2). Fertilizer rates used on corn are typically within ranges of 95 to 185 kg N ha^{-1} (85 to 165 lb N/acre), 10 to 34 kg P ha^{-1} (20 to 70 lb P_2O_5/acre), and 0 to 95 kg K ha^{-1} (0 to 110 lb K_2O/acre), but differences among states and among farms and fields within each state are large (Padgitt et al., 2000). Average K use per acre corn planted ranges from less than 3 lb K_2O/acre in Nebraska to a high of 105 lb K_2O/acre in Indiana (Fig. 2). Because there is less variation among states in the average K removal, apparent K input-output balances are negative in states such as NE, KS, and SD, but positive in states with higher K use. Potassium use in the western Corn Belt has traditionally been low. State differences in the ratio of K to N applied generally follow a West-East gradient in the NCR (Fig. 3), which is associated with a reverse trend in soil test K levels (Fig. 4). Concerning is, however, that the K:N fertilizer ratio has declined since 1975 in practically all states, suggesting that unbalanced plant nutrition may emerge over time.

Emerging K Deficiencies in the North-Central Region

Should we be concerned about the trends described and have they already affected corn and soybean growth in the NCR? It is impossible to provide a quantitative analysis of the spatial extent and severity of K deficiencies, but casual field observations and recently collected data suggest the following (based on publications, personal communications and recent presentations given by several scientists working in the NCR):

- Emerging occurrence of classical as well as unusual symptoms of K deficiency in SD, north-west IA, and north-east NE. Potassium deficiency normally leads to marginal chlorosis and necrosis first seen on older leaves, but, under severe deficiency, marginal chlorosis and necrosis has been observed on younger as well as older leaves. In soybean, symptoms occurring on only the newer tissue (upper leaves of the plant) have also been observed, e.g. as chlorotic spots or interveinal chlorosis. Some of the symptoms may be related to other (hidden) nutrient disorders.
- K deficient plants sometimes show increased disease incidence.
- K deficiency symptoms and yield response vary widely within fields, but often show up in specific, small areas (SD, IA). Deficient areas may test anywhere from low to high in soil K. Yield response to K may occur on low and high testing soils (IA).

- K deficiency symptoms are more frequent with deficient topsoil moisture after V6/V7 stage of corn and may disappear after a rain (IA).
- K deficiency symptoms are more frequent in no-till or ridge-till fields than with conventional tillage (IA, IN, MN, SD).
- K deficiency symptoms and yield response to applied K vary among corn hybrids or soybean varieties (IA, MN, NE, SD).

An example for hybrid differences in response to K supply is shown in Table 1. Two corn hybrids with different growth characteristics were grown on a sandy soil with full irrigation and an adequate supply of N and P, with or without K application. In one hybrid, P34R07, K application did not increase yield, total dry and fresh matter at both V12 stage or maturity. There was also little effect on stalk strength parameters at physiological maturity (PM), whereas K application even decreased stalk strength at final harvest. The second hybrid, 33G27, accumulated 30 to 40 kg K ha^{-1} more at both K levels tested and had significantly higher yields than 34R07. It accumulated K more rapidly during vegetative growth, maintained 20 to 30% greater stalk and leaf K concentrations throughout the whole growth period, and produced a much larger amount of plant biomass. The differences between hybrids were most striking at the V12 stage, when 33G27 had accumulated 5.6 (at 0 K) or 8.8 Mg/ha (at 152 lb K_2O/acre) more plant fresh matter than 34R07, suggesting greater cell expansion, which was further enhanced by K application. In 33G27, K application also increased stalk moisture content, diameter and stalk strength, both at physiological maturity and harvest. Moreover, stalks of 33G27 lost less moisture and the stalk diameter remained unchanged during the 3-wk period from PM to final harvest, resulting in maintained stalk strength during this period. This is an important consideration to avoid harvest losses from stalk lodging induced by diseases or strong winds.

The actual reasons for such hybrid differences have not been identified and the key issue is whether they are due to intra-species differences in the regulation of K^+ transport systems in cells (Leigh, 2001) or due to genotypic variation in hybrid root architecture (Allan et al., 1999) that would favor greater exploitation of soil K resources. Studies in Minnesota have indicated that certain corn hybrids may have more of their root uptake activity in the surface soil layer (0-6 inches), whereas others have greater root length and activity below 6 inches, even though total root length density may be the same (Allan et al., 1999). Thus, hybrid choice in combination with appropriate K management for a certain type of soil tillage may increase both yield and yield stability, probably due to a more vigorous root system capable of exploiting greater indigenous and added K resources.

Physiological Explanations

The abnormal K deficiency symptoms observed in soybean and corn in the NCR are not new. Similar observations were made for rape in Germany (Pissarek, 1973) and cotton in California (Weir et al., 1988; Maples et al., 1989). Bergmann (1992) shows examples for other crops. Although K is considered mobile in the plant, even younger leaves may develop red pigmentation or become interveinally chlorotic (Grundon et al., 1997). Insights into the role of K at the cellular and molecular level (Leigh, 2001) may help explaining the recent observations in the NCR. To do so, one must distinguish between the role of K in different cell compartments, i.e., the vacuole and the cytoplasm.

Because the majority of K^+ is located within the central vacuole of plant cells where it functions as an osmoticum, changes in measured tissue K concentrations mostly reflect changes in vacuolar K levels. Vacuolar K^+ concentrations respond rapidly and directly to external K supply and can fall to very low levels under severe deficiency. Contrary to what was thought earlier, it now appears that there is no lower limit to vacuolar K^+ concentrations, but there is evidence for species-specific upper limits, beyond which further increase in K supply does not increase vacuolar K^+ concentrations (Leigh, 2001). Once the upper limit is reached, plant K uptake and growth are closely matched to maintain vacuolar (and therefore the average tissue) K^+ concentrations relatively constant. Moreover, it was found that the upper limits of vacuolar K^+ differ among crops and even between different plant parts such as roots and shoots of the same species. For example, when grown in rapidly flowing nutrient solution barley and pea had upper limits of tissue K concentrations in shoots of about 200 and 150 mmol L^{-1}, respectively. In roots, upper limits were about 120 mmol L^{-1} for barley and 100 mmol L^{-1} for pea (Asher and Ozanne, 1967). Field studies at Rothamsted later confirmed that tissue K concentrations in barley and grasses did not exceed about 200 mmol L^{-1}, irrespective of further increasing soil K supply (Leigh and Johnston, 1983). It was suggested to use this value as a benchmark against which the adequacy of K supply can be determined (Leigh and Wyn Jones, 1984; Leigh, 1989).

However, growth and essential plant requirements for K^+ appear to relate more to its role as an activator of biochemical processes in the cytosol (Leigh and Wyn Jones, 1984). Cytosolic K is not replacable in its functions by other cations and any decrease in cytosolic K^+ concentration will affect many K-specific processes in the plant, particularly a large number of enzyme reactions that completely depend on K^+ or are stimulated by it (Läuchli and Pflüger, 1978; Marschner, 1995). Interestingly, recent microelectrode studies suggest that cytosolic K^+ activity (not concentration) in plant cells is typically maintained at about 80 mmol L^{-1} in both leaf and root cells and is less sensitive to changes in K supply than vacuolar K^+ concentration (Walker et al., 1996; Walker et al., 1998). Cytosolic K decreases only slightly under moderate K stress, but may decrease to much lower values during severe K deficiency (Leigh, 2001). Due to its high concentration in the cytosol K^+ neutralizes organic and inorganic anions, which stabilizes the pH between 7 and 8, the optimum for most enzyme reactions. For example, a K-deficiency induced decrease in cytosolic pH from 7.7 to 6.5 almost completely inhibits nitrate reductase activity (Pflüger and Wiedemann, 1977). Any decrease in cytosolic K will therefore have a severe effect on growth and yield.

Considering these physiological functions of K, the evolution and location of symptoms of K deficiency within plants depend on the severity of decline in both vacuolar and cytosolic K concentrations, which are a function of (i) rates of crop K demand for developmental and growth processes at different growth stages, (ii) rates of external K supply, (iii) the potential reservoir and maximum rate of re-translocation, and (iv) possible substitution mechanisms. Presumably, in a K deficiency situation, cells will first attempt to maintain cytosolic K concentrations at the cost of vacuolar K, particularly in plant parts that are most vital for further crop development. This may then lead to increased root K uptake or, if supply is limiting, relocation of K from other plant parts or increased uptake of cations such as Na^+, Mg^{2+}, and Ca^{2+} or organic solutes (Marschner, 1995) to at least partially substitute for the possible loss of non-specific (vacuolar) functions of K. The latter mainly involves maintenance of the osmotic potential of cells. If these resources are insufficient, K deficiency will proceed further, possibly causing a drop in osmotic potential in the vacuole and turgor pressure, and therefore cell contraction. In severe cases, cytosolic K concentration may decline as well, decreasing cytosolic pH and the rate of enzyme reactions. Moreover, in K-deficient plants, export rates of photosynthates from source leaves (e.g., young, photosynthetically active leaves) to other organs decline due to a decrease in osmotic potential in the sieve tubes (Marschner, 1995). In legumes, this may even cause inadequate supply of sugars to root nodules, which greatly reduces rates of N_2 fixation and export of bound N (Collins and Duke, 1981). Many of these processes may cause an accumulation of soluble carbohydrates and nitrogen compounds in K deficient plants (Marschner, 1995), but only in more severe cases of stress will visible chlorotic/necrotic spots appear because of shrinking or completely collapsing tissue.

The true causes of the new upper-canopy K deficiency symptoms have not been identified yet. However, it is likely that in situations of K demand-supply shortages the processes described may also affect young tissue because K demand is greatest in rapid growth zones but may have to compete with other developmental processes. In cotton, it is thought that modern varieties develop bigger yields over a shorter fruiting period so that K moving upward from the roots is intercepted by the developing boll load, causing deficiency in upper leaves (Oosterhuis, 1999). Similar processes may occur in modern corn hybrids or soybean varieties. These hypotheses require further study, but they illustrate the importance of K during all growth stages and that it may become even more important as yields continue to rise. The existence and understanding of real genetic differences may provide a basis for engineering "high-K" crops to reduce their K requirements (Leigh, 1989).

New Diagnostic Tools

Potassium deficiency symptoms in plants typically follow the sequence of (1) smaller young leaves, but normal looking and dark green, (2) normal looking leaves (but with sub-optimal K concentration), (3) chlorotic or necrotic spots and/or patches on leaves (early visible symptoms), (4) larger necrotic patches and necrotic leaf edges and tips (late symptoms), and (5) dying old leaves (Bergmann, 1992). Yield reductions due to K deficiency always occur before deficiency symptoms are visible and K deficiencies occurring during early growth cannot be fully compensated by improved K supply at later stages (Bergmann, 1992). In cotton, K deficiency is first detectable in roots, followed by stems, petioles and leaves. Due to storage of K prior to peak demand, K deficiency symptoms only became visible 2 to 3 weeks after K was withheld (Bednarz and Oosterhuis, 1999). Obviously, early stages of K deficiency are hard to identify so that it is likely that subtle forms of K deficiency are widespread, but are not recognized in the field. This particular refers to sub-optimal K concentrations in plant tissue water that may reduce crop growth rates (see above), but do not show up in visible deficiency symptoms. Under the microscope, K deficiency symptoms can be detected as shrinking/collapsing leaf tissue at a very early stage (Bergmann, 1992), but diagnostic tools are required for field situations.

Because of the physiological roles of K in the plant (see above), plant tissue K concentrations measured on a fresh weight basis or expressed as tissue water K^+ concentration (mmol L^{-1}, calculated or directly measured in pressed plant sap) are often better correlated with dry matter production and yield than using crop K concentration as a % in dry matter (Leigh, 1989; Springob et al., 1995). In routine work, distinguishing between vacuolar or cytosolic K^+ is not feasible, but pressing plant sap to quickly measure the average tissue water K^+ concentration is an option. The Horiba Cardy K meter (Spectrum Technologies, Inc.) may offer such new opportunities for quick field diagnosis of K deficiency based on plant sap pressed from leaves. The instrument uses a small ion-selective electrode sensor, is relatively cheap ($350) and easy to use. It can be equipped with sensors for either K^+ or Na^+, which is of importance for diagnostic approaches that include the availability of K and other cations. First tests with wheat, canola and sunflower have been conducted (Qian et al., 1995), but no use in soybean or corn has been reported. Field tests with rice under tropical conditions have shown great stability of instrument calibration and little sensitivity to temperature (A. Dobermann, unpublished data). This is because K concentrations measured in pressed plant sap are mostly in the 10 to 250 mmol K L^{-1} range (~390 to 9750 ppm), a range with linear and stable sensor response.

Diagnostic indices should be developed for real-time K management as well as screening/breeding of hybrids for increased K uptake and use efficiency. Measuring a single tissue water K concentration value is not a sensitive index of K deficiency/adequacy because it mainly reflects vacuolar K concentration, which may drop below levels of 100 mmol L^{-1} before growth is affected, mainly due to cation substitution to maintain osmotic potential (Leigh, 1989). Approaches that could be studied are (i) the ratio of tissue water K concentration in the whole leaf to K concentration in leaf edges and (ii) the ratio of tissue water K concentration in upper (younger) leaves to K concentration in lower (older) leaves. In both cases, a value of 1 or less would suggest sufficient K nutrition, whereas values above 1 would indicate K deficiency because K had been transported to deficient sites in the plant. Both approaches could be further modified by measuring both K and Na concentrations or by also measuring K concentrations in other plant parts, e.g., stalks of corn.

Crop Potassium Requirements

Practitioners using "buildup-and-maintenance" approaches to K management need values of crop K removal per unit yield as the basis for deciding on how much K to apply. Long-term research on corn in Nebraska concluded that crop removal-based fertilizer recommendations lead to an uneconomically high use of P and K fertilizer with no significant yield gains as compared to a sufficiency approach based on critical soil test levels (Olson et al., 1982). Questions must be raised whether correct estimates of crop nutrient requirements per unit yield are currently used because they (i) are typically derived from field experiments conducted at few sites, which are often located at research stations with high background levels of indigenous soil nutrient supply, (ii) assume linearity between crop yield and nutrient accumulation, and (iii) do not account for nutrient interactions and climatic yield potential as a driving force for optimal nutrient requirements (Witt et al., 1999). Although research experiments supply valuable information for a given site, results can only partly be extrapolated to estimate nutrient requirements in farmers' fields because of the much broader range of soil, climatic, and agronomic conditions at the farm level.

Table 2 illustrates some of these problems with data from two field experiments recently conducted in Nebraska. In the first study, on a sandy soil at Pierce, a moderate K application had no effect on corn yields at a level of 175 bu/acre and the average uptake requirements ranged from 0.95 to 1.04 lb K_2O/bu yield. In a second study, on a very fertile soil at Lincoln, grain yield at 30,000 plants/acre was 234 bu/acre, requiring 1.41 lb K_2O/bu in the aboveground biomass. Increasing plant density to 44,000 plants/acre boosted the yield to 257 bu/acre, but at the cost of an even larger K requirement (1.75 lb K_2O/bu). As yields approach existing ceilings internal plant K requirements increase to sustain the physiological functions of a vastly increased amount of aboveground biomass. No such effect was observed for nutrients such as P, Mg, and S, whereas the extra yield increase at Lincoln was also associated with a slight increase in plant N requirement. In contrast, at both sites, net nutrient removal with grain was similar (0.20 to 0.25 lb K_2O/bu yield) and there was no effect of different absolute yield levels on this. These numbers compare with K removal values of 0.25 to >0.30 lb K_2O/bu that are often used in current fertilizer recommendations.

How can we model this for practical purposes? Across a wide range of sites, varieties, and possible nutrient combinations, the relationship between grain yield or total plant dry matter with plant nutrient accumulation is widely scattered. In earlier work, C.T. de Wit and later H. van Keulen (van Keulen and Van Heemst, 1982; van Keulen, 1986) studied the relationship between yield and plant nutrient accumulation for several crops, including corn. They showed a linear range followed by a parabolic-plateau and also concluded that an upper boundary exists at which nutrient concentrations in plant biomass become diluted to the maximum possible extent, which is when that nutrient is the sole factor limiting yield. Similarly, the recent physiological studies on constant crop-specific upper limits of tissue K concentrations suggest that there is also a lower boundary of maximum K accumulation in the plant. The latter does not necessarily represent "luxury consumption" of K because where "luxury consumption" appears to occur, it often expresses reductions in the crop growth rate due to other factors (e.g., unbalanced nutrition, pests, etc.).

Therefore, a modeling framework can be used in which two linear boundaries describe an envelope ranging from maximum accumulation to maximum dilution of a nutrient in the plant (Janssen et al., 1990; Witt et al., 1999). If those "envelopes" are developed for different nutrients, they can be mathematically combined into linear-parabolic-plateau curves of optimal (balanced) nutrition that take into account the interaction among those nutrients. Fig. 5 shows an example for this approach to model the relationship between yield and potassium uptake as affected by nitrogen uptake, but the same applies to modeling other nutrients. In Fig. 5a, a specific K uptake estimate would result in two yield estimates, one estimate for the situation where K is maximally accumulated (YKA) and one for the situation where K is maximally diluted (YKD). In Fig. 5b, an estimate of the K-limited yield as affected by N supply (YKN) is obtained from a mathematical overlay of the possible yield ranges identified for both K and N uptake. A certain N uptake resulted in two K-limited yield estimates depending on whether N is maximally accumulated (YNA) or diluted in the plant (YND). Within the yield range that is possible based on the N uptake (YNA-YND), a parabolic equation is then used to estimate YKN from K uptake. Fig. 5c takes this one step further by showing an optimal curve of the relationship between yield and K uptake (Yopt) for a particular environment with a specific climatic-genetic yield potential (Ymax). This curve was obtained by simultaneously optimizing the plant-internal utilization efficiency of all three macronutrients (N, P, K) for achieving different levels of yields, following the principles shown in Fig. 5a and 5b.

Fig. 6 and Table 3 show preliminary examples of such envelopes and optimal nutrient requirement curves for corn. Balanced nutrient requirements for corn were simulated for different yield goals at a location with a theoretical yield potential (Ymax) of about 300 bu/acre. Up to yield levels of about 210 bu/acre (70% of Ymax) nutrient uptake requirements per unit yield remain constant. However, with yields approaching Ymax, more nutrients per bushel yield are required. For example, whereas a total uptake of 1.08 lb K_2O/bu is required to achieve a grain yield of 210 bu/acre, that number increases to 1.27 K_2O/bu for obtaining 270 bu/acre at the same site.

Such graphs also offer diagnostic opportunities. For example, uptake of N per unit corn yield was mostly below the optimal curve at field sites in North Vietnam, whereas K values were above that line at the same sites (Fig. 6). This indicates that K deficiency was a major cause of sub-optimal internal N use efficiency. Most of the soils at these sites were low in K. In contrast, K data for Nebraska (see Table 2) include both situations of K deficiency (above the curve, mostly on a sandy soil at Pierce) and situations of K accumulation in the plant (below the curve, sites/treatments with high K). In those cases, K was not a limiting factor for yield, i.e., the actual amount of plant K taken up was not proportionally related to yield increase because other factors limited yield. This may include climate affecting pollination and grain filling, but also some geographical and hybrid variation in yield potential, insufficient N management and water supply, sub-optimal plant density and plant spacing, or some incidence of pests. Fig. 6 also suggests that the envelope between yield and nutrient uptake is much narrower for N than for K. In other words, whereas N is tightly bound to crop performance, K can be diluted or accumulated in the plant in a much wider range.

Perhaps the biggest advantage of the approach described is that it provides a generic platform for simultaneously modeling requirements of several macronutrients across different environments, both in terms of variation in yield goals and variation in the climatic yield potential. Witt et al. (1999) demonstrated how this method can be used to develop families of yield – optimal NPK accumulation curves for rice grown in environments with different climatic yield potential across Asia. A similar exercise should be done to develop and verify such models for corn and soybean grown in the NCR. Key requirements for this are (i) understanding of the geographical variation in yield potential across this region and (ii) the collection of accurate yield – nutrient uptake data sets across a wide range of soils and cropping conditions using a standardized sampling methodology.

Implications for Fertilizer Recommendations

Recommendations for managing P and K typically follow “sufficiency”, “buildup and maintenance”, or “replenishment of crop removal” concepts (Hergert et al., 1997). Although critical soil test levels for K vary somewhat among states in the corn belt, they have changed little during the past 30 to 40 years. Current fertilizer recommendations were the result of many years of multi-site calibration and correlation research. In most states, these recommendations continue to work for average conditions, but problems arise due to changes in crop management, germplasm, and absolute yield levels. As discussed above, fine-tuning of nutrient management is not much of an issue for a 150 bu/acre corn crop, but it becomes one for a 220 bu/acre crop. Widely varying interpretation of soil test values and the relative insensitivity of current recommendations to different soil types and crop management practices have raised concern that the traditional correlation and calibration approach cannot keep pace with changes in soil test methods and intensifying cropping systems (Hergert et al., 1997). Direct implications from the observations described above are:

1. Where a “sufficiency” concept is used, existing soil test categories for K may need to be revised upwards or made more specific to different tillage systems to account for K stratification in soil resulting from different tillage practices. For example, preliminary data from SD suggest that the critical range in soil test K may need to be increased to 140 to 150 ppm (Gerwing et al., 2001). In Nebraska, studies conducted on a soil testing at 110 ppm K (40 lb K_2O/acre recommended) showed a yield response in one corn hybrid even at the highest K rate tested (152 lb K_2O/acre). In addition, research must be conducted to verify whether present soil sampling procedures and soil extractants are appropriate for specific situations such as no-till systems (Allan et al., 1999). Among promising soil testing methods, sodium tetraphenylboron-K (Cox et al., 1996) has recently received much attention in the NCR, but it remains to be seen if this method can be introduced into commercial soil testing in the near future.

2. Where crop removal for a certain yield goal is used in making a fertilizer-K decision, using a single "crop removal coefficient" may lead to erroneous nutrient use and low efficiency because those numbers tend to overestimate the true optimal nutrient requirements at yield levels that are below about 70% of the climatic and genetic yield potential. In contrast, using the same number may be insufficient to achieve yields that are near optimal levels, i.e., above the 70% of yield potential mark. Quantitative approaches that simultaneously account for yield potential and interactions between N, P, and K in estimating the crop requirements for each of them are likely to be more precise, particularly at high yield levels (Witt et al., 1999)
3. Whatever approach is used, future fertilizer recommendations must become more generic and specific at the same time. Generic by being based on the general quantitative principles of plant nutrition, specific by fine-tuning K management to the key determinants of K supply and demand in a particular production system. For corn-soybean systems in the NCR, this mainly involves fine tuning recommendations to (i) soil types and agroecological zones with different yield potential, (ii) different groups of key plant traits that affect the external and internal K use efficiency (<u>not</u> individual hybrids), and (iii) key differences in crop management technologies such as crop rotation, tillage and plant density. Single levels in a recommendation should then be based on standard conditions (e.g., tall corn hybrid with strong stalks planted in May on a no-till deep silt loam soil in eastern Nebraska) that take into account the major factors governing crop response to the nutrient of interest.
4. Feasible, reliable, and profitable approaches for site-specific nutrient management will be required to manage spatial variability in soil K supply and crop K demand. Concepts tested so far have produced mixed results and future success will depend very much on how issues (1), (2), and (3) can be resolved.

Refinements can be made at different levels of complexity such that a general recommendation can be broken down into more meaningful and detailed specific recommendations. A key issue is, however, whether all this can be achieved with the classical approaches used in soil fertility research. The correlation/calibration yield-response approach would require frequent empirical verification in response to management changes, but the requirement for repeated multi-year and multi-location evaluation is both costly and slow. Therefore, improvements could possibly follow a two-stage approach that involves (1) updating existing soil test methods and fertilizer recommendations with information that has already become available or can be obtained quickly and (2) conducting research towards recommendations that are based on a more quantitative understanding of crop nutrient needs.

Agroecological zoning and crop simulation models should play a major role in making these refinements. Attempts have been made to model the complete soil-plant K cycle (Greenwood and Karpinets, 1997) and apply such a model to estimate fertilizer requirements. However, process-based models still have a long way to go before becoming validated, feasible management tools. Thus, over the short term, robust, step-wise empirical models that encompass a wide range of conditions (as opposed to a narrowly defined local calibration or response curve) should be tested within the NCR. The QUEFTS model (Janssen et al., 1990; Smaling and Janssen, 1993) is a usefuly concept for this because it allows estimating the fertilizer requirements of N, P, and K using the same theoretical approach, i.e., as a function of (i) climatic yield potential, (ii) the relationship between grain yield and plant accumulation of N, P, and K,

(iii) the potential indigenous N, P, and K supplies, and (iv) recovery efficiencies of fertilizer N, P, and K. In this approach (i) can be estimated using a validated crop simulation model, (iii) must be measured using a soil test or a crop-based estimate, and (iv) is usually adjusted to local soil types and cropping conditions. Estimates for (ii) can be obtained from a generic relationship between grain yield and nutrient accumulation obtained from a large database from a wide range of production environments to account for nutrient interactions and differences in yield potential (Witt et al., 1999). This modeling approach has been successfully used in developing site-specific nutrient management in rice (Wang et al., 2001; Dobermann et al., 2002). It remains to be seen whether it may also be of advantage for corn-soybean systems in the NCR.

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Table 1. Response of two corn hybrids to potassium application on a Valentine sand.[1]

Plant traits	Pioneer® 34R07[2]		Pioneer® 33G27[3]	
	K rate (lb K_2O/acre)			
	0	152	0	152
Grain yield (bu/acre)	170.4	173.6	180.0	188.0
Plant fresh matter at V12 (Mg/ha)[4]	33.9	32.6	39.5	41.4
Plant K accumulation at V12 (kg ha^{-1})	104	139	157	192
Stalk tissue water K at V12 (mmol/L)	39	46	52	51
Leaf tissue water K at V12 (mmol/L)	172	253	234	309
Plant dry matter at PM (Mg ha^{-1})[4]	17.0	17.2	18.3	19.5
Plant fresh matter at PM (Mg ha^{-1})	30.9	30.1	33.6	36.6
Plant K accumulation at PM (kg ha^{-1})	146	164	175	207
Stalk moisture content at PM (%)	69	68	63	71
Stalk moisture content at harvest (%)	28	35	35	55
Stalk diameter at PM (mm)	19.9	19.7	19.3	20.0
Stalk diameter at harvest (mm)	18.2	17.8	19.5	20.6
Load to break stalk at PM (kg)[5]	19.0	17.3	17.6	18.6
Load to break stalk at harvest (kg)[5]	14.8	13.2	15.3	17.5

[1] Field experiment conducted in 2000 at Pierce, Nebraska. Average initial exchangeable soil K content was 109 mg K kg^{-1} in 0-15 cm depth and 61 mg K kg^{-1} in 15 to 60 cm depth. Values shown are means of five plot replicates (A. Dobermann, C. Shapiro, and T. Doerge, unpublished data).

[2] P34R07 – Scores on a scale from 1 (poor) to 9 (outstanding): stalk strength 3, ear height 5, staygreen 7, stalk rot resistance 3.

[3] P33G27 – Scores on a scale from 1 (poor) to 9 (outstanding): stalk strength 7, ear height 7, staygreen 8, stalk rot resistance 5.

[4] V12 – V12 stage, late vegetative growth (July 7). PM – physiological maturity (September 18).

[5] Measured at the 4th internode below the ear on Spetmber 18 (PM) and October 10 (final harvest).

Table 2. Nutrient uptake and removal of corn at different levels of plant density, fertilizer use, and yield. At both sites, corn was grown after soybean.

Site	Plant pop	Fertilizer	Yield	N	P_2O_5	K_2O	Mg	S
		lb/acre N-P_2O_5-K_2O	bu/acre	**Nutrient uptake (lb/bushel yield)**				
Pierce[1]	31,000	233 - 27 - 0	175	1.12	0.28	0.95	0.13	0.10
	31,000	233 - 27 - 76	175	1.15	0.27	1.04	0.13	0.10
Lincoln[2]	30,000	201 - 92 - 93	234	1.04	0.45	1.41	0.10	0.09
	44,000	201 - 92 - 93	257	1.10	0.40	1.75	0.10	0.09
				Nutrient removal with grain (lb/bushel)				
Pierce	31,000	233 - 27 - 0	175	0.76	0.24	0.21	0.06	0.06
	31,000	233 - 27 - 76	175	0.77	0.22	0.20	0.05	0.06
Lincoln	30,000	201 - 92 - 93	234	0.66	0.34	0.25	0.07	0.06
	44,000	201 - 92 - 93	257	0.65	0.31	0.22	0.06	0.05

[1] Northeast Nebraska. Average of three hybrids, 2000, Valentine sand, 110 ppm soil test K.
[2] East Nebraska, 1999, Pioneer 33A14, Kennebec silt loam, 350 ppm soil test K.

Table 3. Simulated optimal nutrient uptake requirements for corn grown in eastern Nebraska. Values shown are based on a preliminary calibration of the QUEFTS model (Janssen et al., 1990; Witt et al., 1999) to this region.[1]

Grain yield (15.5 m.c.)		Nutrient uptake			Nutrient uptake per bushel yield		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
(Mg/ha)	(bu/acre)		(lb/acre)			(lb/bu)	
6000	95.6	79.3	14.6	84.7	0.83	0.35	1.07
8000	127.4	105.7	19.4	113.0	0.83	0.35	1.07
10000	159.3	132.2	24.3	141.2	0.83	0.35	1.07
12000	191.1	159.2	29.3	170.2	0.83	0.35	1.07
14000	223.0	190.0	34.9	203.0	0.85	0.36	1.10
15000	238.9	211.7	38.9	226.2	0.89	0.37	1.14
16000	254.9	236.7	43.5	253.0	0.93	0.39	1.20
17000	270.8	267.5	49.1	285.8	0.99	0.42	1.27
18000	286.7	310.6	57.1	331.9	1.08	0.46	1.40

[1] Based on crop growth simulation and average yields achieved by irrigated corn contest winners during the past five years, a climatic/genetic yield potential of 18.8 Mg ha^{-1} (300 bu/acre) was assumed. Due to cooler temperatures and longer growing season the yield potential is likely to be larger than 300 bu/acre in the eastern parts of the Corn Belt.

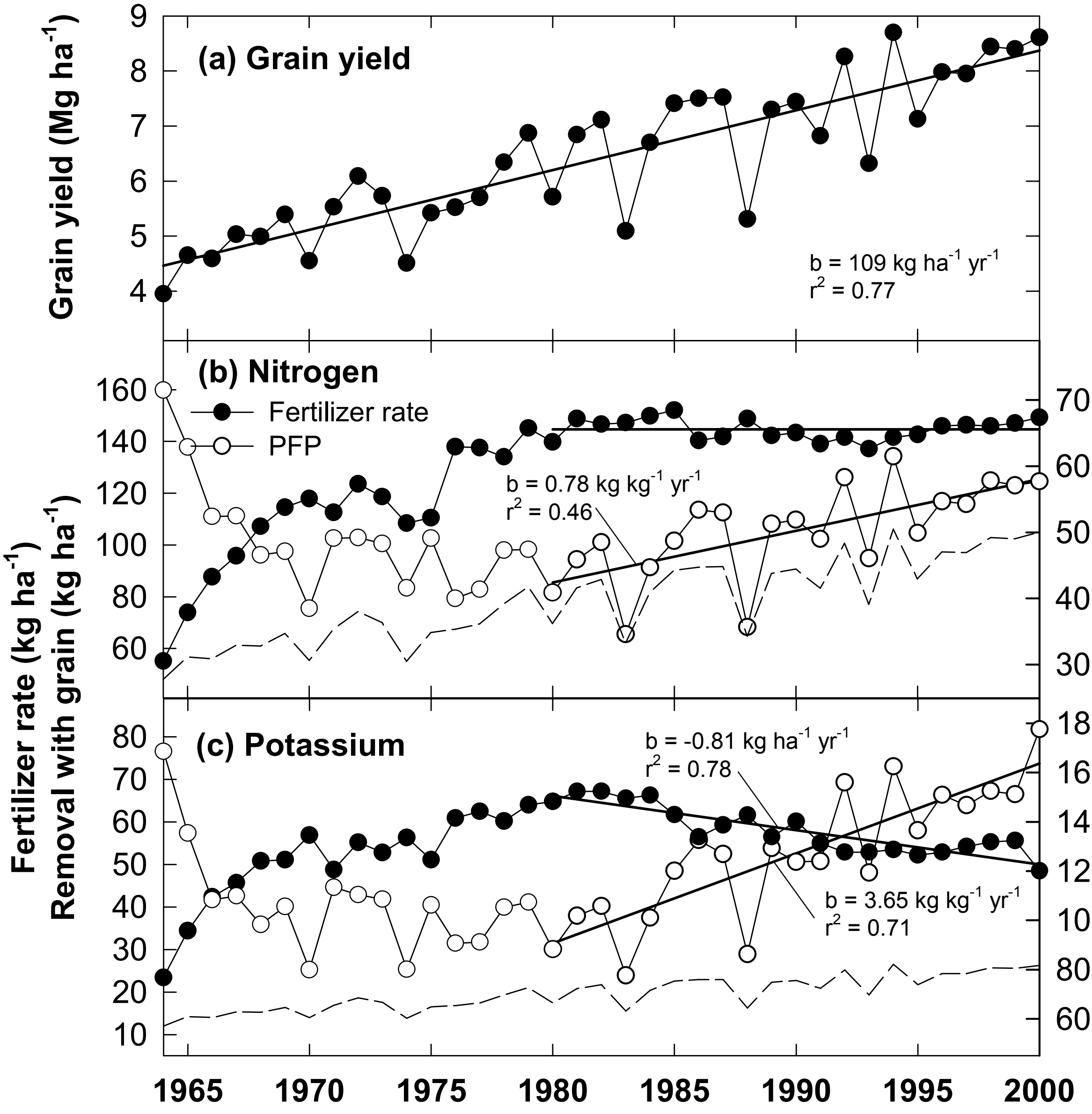

Figure 1. Trends in grain yield, N and K use (filled circles), partial factor productivity of fertilizer nutrients (open circles, PFP = kg grain yield per kg nutrient applied), and nutrient removal with grain (dashed line, kg element ha^{-1}) in corn grown in the USA (Dobermann and Cassman, 2002). Values shown for N and K are both on elemental basis, not K_2O. Data sources: USDA National Agricultural Statistics Service, and USDA-ERS Annual Cropping Practices Surveys of more than 2000 farms representing 80 to 90% of the corn area. Nutrient removal with grain was calculated by assuming average concentration of 1.4% N, 0.27% P, and 0.35% K in grain.

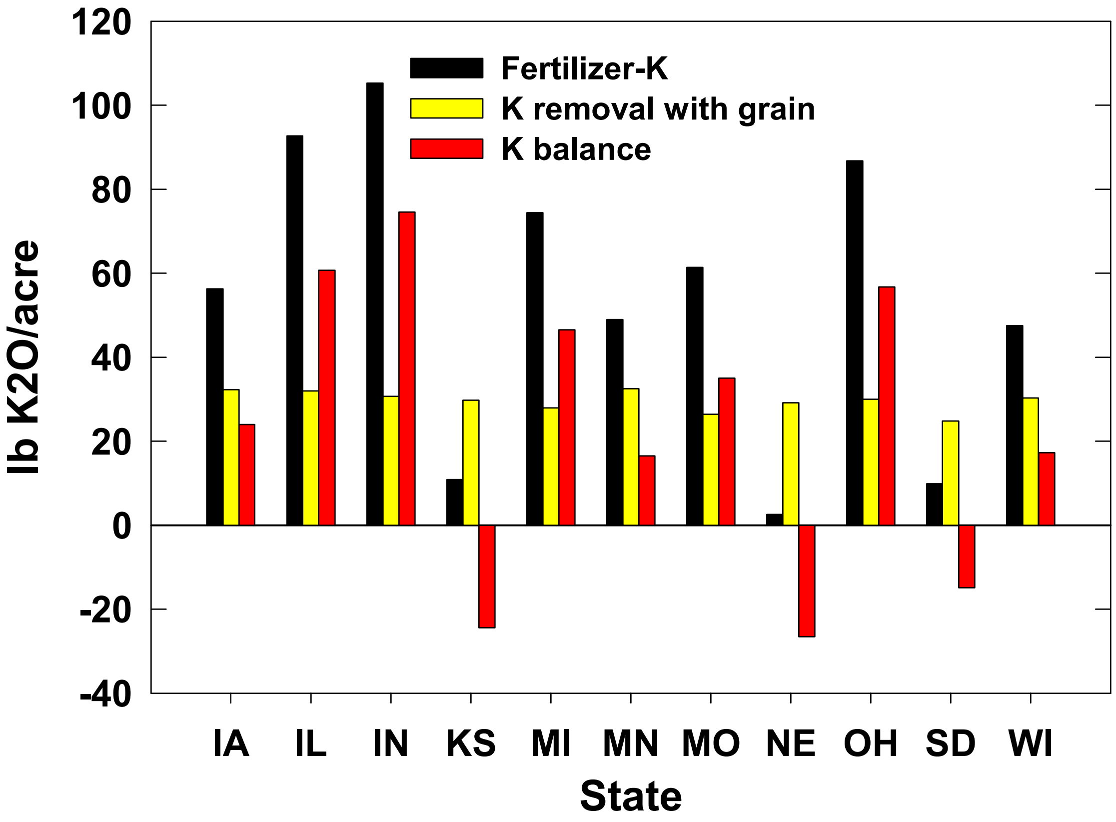

Figure 2. Annual K use on corn, K removal with grain, and K input-output balance in the major corn states of the North-Central Region. Data sources: USDA-ERS annual cropping practices surveys. All numbers shown refer to planted corn acres and are averages of 1999 and 2000. Average K removal of 0.22 lb K_2O per bushel yield was assumed.

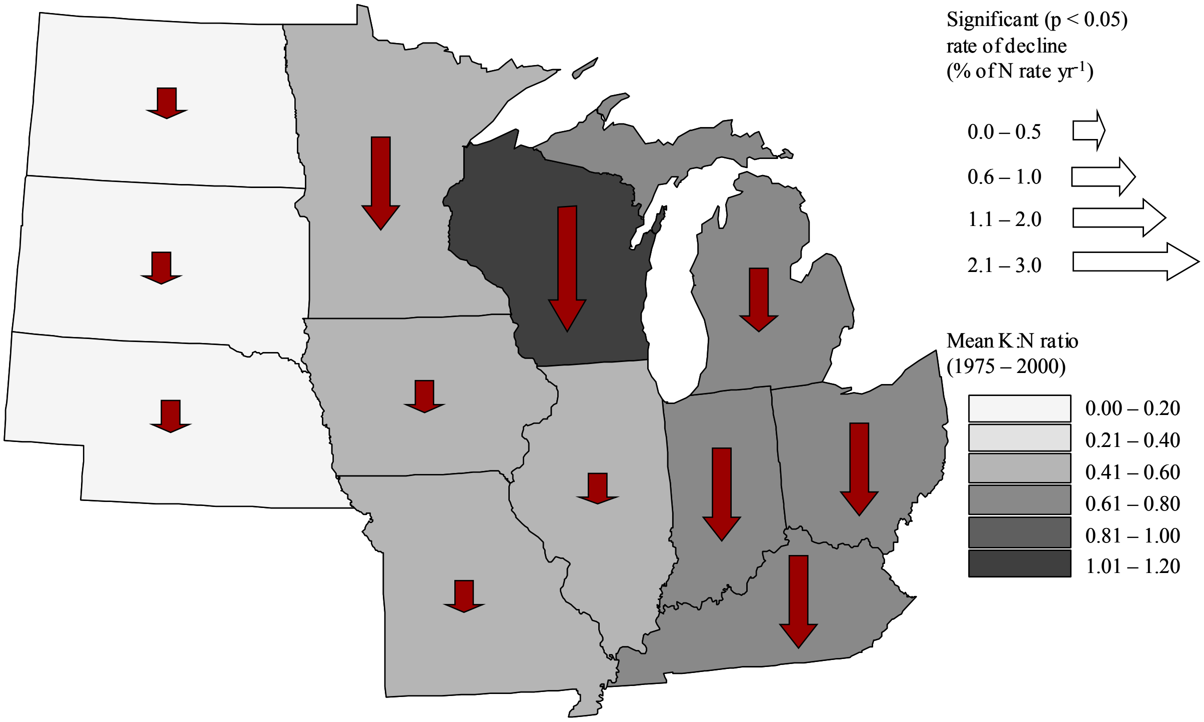

Figure 3. Trends in the ratio of K_2O : N usage in the North Central Region, 1975 to 2000 (T.S. Murrell, personal communication). Data sources: Assoc. Plant Food Control Officials and The Fertilizer Institute

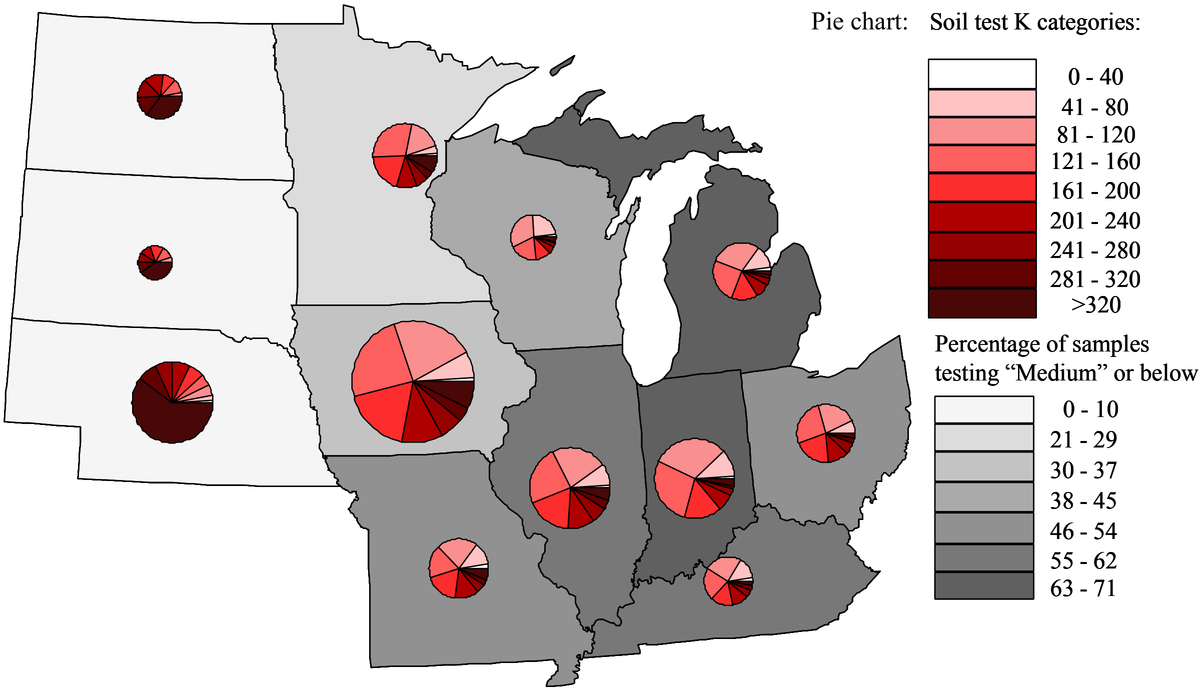

Figure 4. PPI potassium soil test summary for the North-Central Region, 2000-2001 (T.S. Murrell, personal communication). Data sources: Soil test data provided by public and private soil test laboratories.

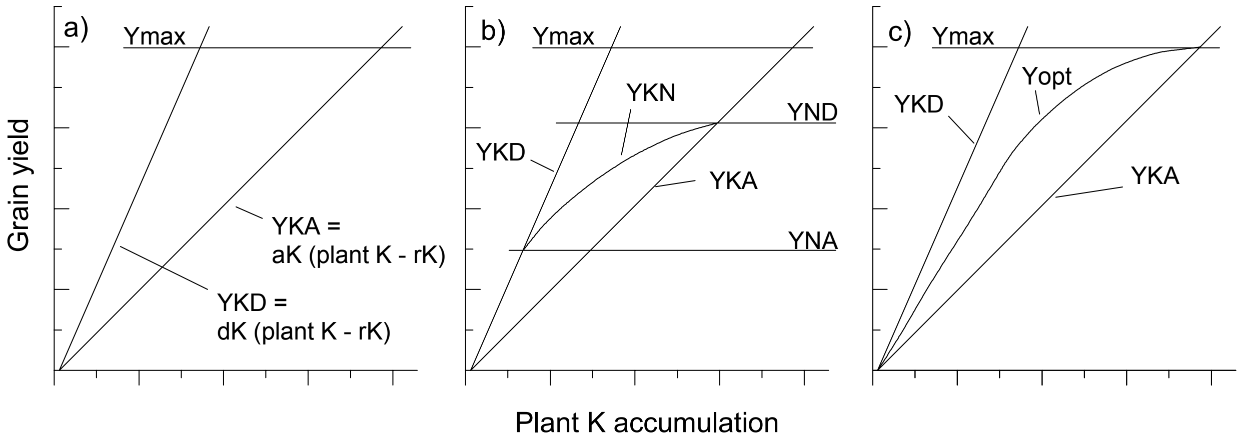

Figure 5. The schematic relationship between grain yield and plant nutrient accumulation. In Fig. 5a, boundary lines represent the maximum dilution (YKD) and accumulation of potassium (YKA) in the above-ground dry matter. Constants aK and dK determine the slope of the respective boundary line while constant rK is the minimum K uptake requirement to produce any measurable grain yield. Ymax is the climatic-genetic yield potential. In Fig. 5b, the yield range that can be achieved with a certain N uptake is indicated by two horizontal lines representing situations of maximum dilution (YND) and accumulation of N (YNA), while YKN is the combined yield estimate for K and N uptake. In Fig. 5c, Yopt represents the optimum K uptake requirement to achieve a certain grain yield target without that other nutrients are limiting (Witt et al., 1999).

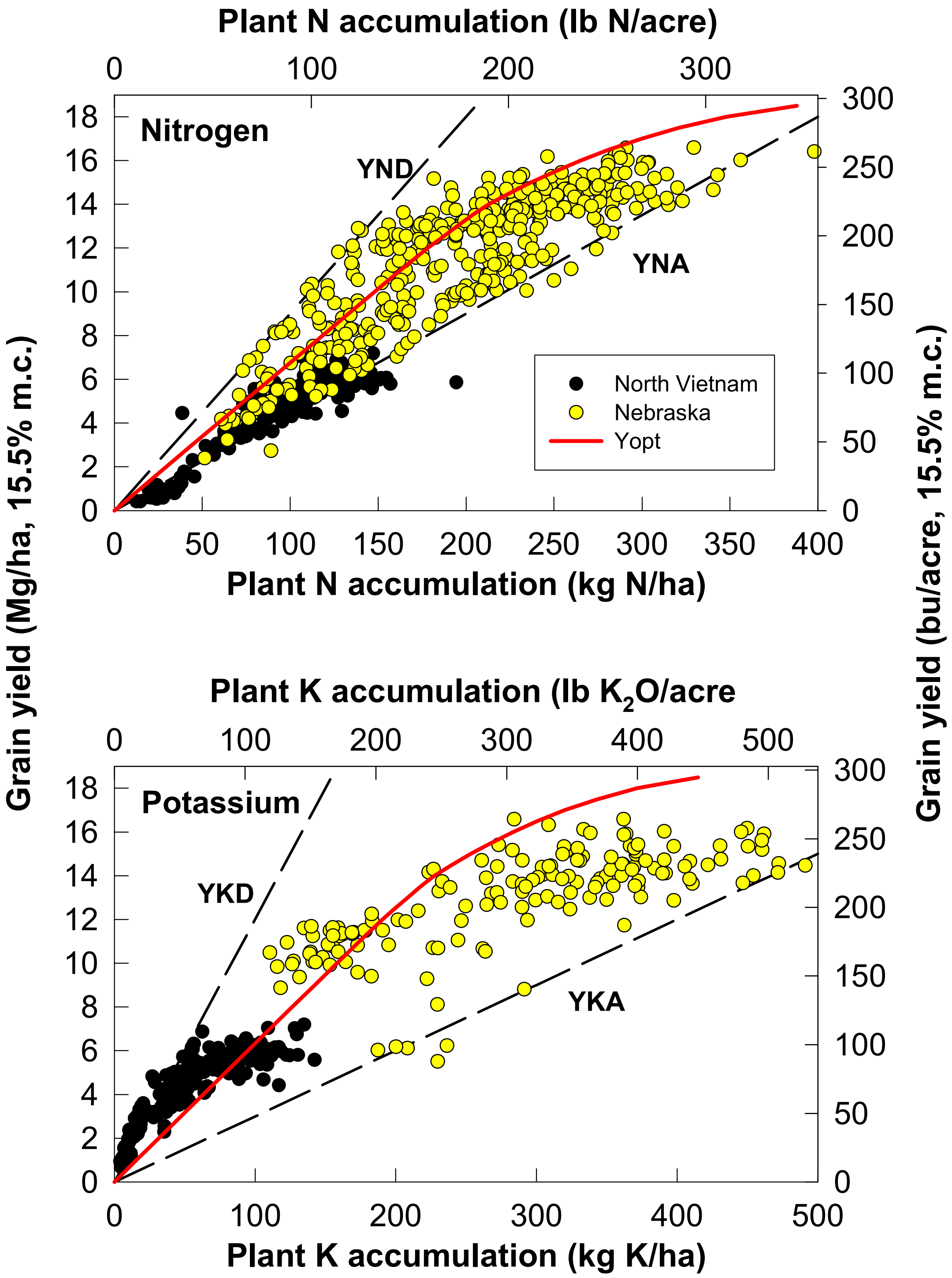

Figure 6. Relationship between grain yield and accumulation of N and K in total above-ground plant dry-matter at maturity of corn based on the approach presented in Fig. 5. Data collected from field and on-farm experiments were used to estimate the boundary lines of maximum nutrient dilution (YND, YKD) and maximum nutrient accumulation (YNA, YKA, dashed lines). The solid line (Yopt) shows the simulated curve of optimal nutrient requirements for the situation of balanced nutrition in the plant for an environment with a climatic yield potential of about 300 bu/acre (18.8 Mg ha^{-1}).