CROP POTASSIUM UPTAKE AND UTILIZATION

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Abstract

Cropping systems currently face dual challenges of maximizing yields in a sustainable approach. The importance of a balanced nutrition is critical for increasing crop production. In the past decades, comprehensive studies were performed for nitrogen (N) in corn and for phosphorus (P) in soybean. From a physiological standpoint, a synthesis-analysis on potassium (K) content, utilization, interaction with other nutrients and final impact on yield is relevant and needed for properly understanding scientific knowledge gaps on this nutrient. Potassium (K) plays a critical role in corn and soybean nutritional scheme. Historical and geographical (USA vs. World – excluding USA) grain yield and K content was characterized for corn and soybean. For both crops, USA historical yield trend demonstrated an improvement, which was followed by a parallel increment in K uptake [except for the last yrs (2012 season, drought stress)]. For corn, high-yielding data points were closely related with balanced N/K 1:1 ratio (isometry); while for soybean, increasing productivity was linked to N/K ratio close to 2:1. Increasing K utilization efficiency was tightly connected with lower K content in the stover (reduction in stover %K). Prospects for concurrent yield and nutrient use improvements are great challenges that need to address the biofortification issue.

Introduction

Although the nutrient focus on high-yielding corn is often on N and for soybean is on P nutrition, importance of K in a balanced nutrient scheme should be further considered. Nutrient uptake and partitioning was previously evaluated for corn (Jones and Huston, 1914; Latshaw and Miller, 1924; Sayre, 1948, 1955; Jordan et al., 1950; Chandler, 1960; Hanway, 1962a, 1962b; Karlen et al., 1987, 1988; and recently by Abendroth et al., 2011 and Ciampitti et al., 2013) and soybean (Borst and Thatcher, 1931; Hammond et al., 1951; Henderson and Kamprath, 1970; Hanway and Weber, 1971A,B; Kollman et al., 1974; Vasilas et al., 1984; and recently by Sikka et al., 2012) crops. Nonetheless, the effect of K uptake and partitioning on increasing crop productivity and nutrient utilization efficiency is not yet clearly understood. A recent review study focus on corn and other crops (Mueller et al., 2012) identified that the main two factors limiting yield around the globe were related to water and nutrients. In nutrient-limited regions (Central America, east-central South America, eastern Europe, Sub-Saharan Africa, and southern and eastern Asia), corn yield gap can be potentially reduced by 18, 7, and 29% via increasing N, P, and K applications, respectively (Mueller et al., 2012). In other regions of the world, nutrient imbalances are presented as an excess of fertilizer nutrient applications, which exacerbates inefficiencies in nutrient use (Vitousek et al., 2009, Liu et al., 2013) and threaten future system productivity. For corn, a review analysis of long-term studies demonstrated that close to 60% of the yield improvement was related to nutrient inputs such as the application of N, P, and K fertilizers (Stewart et al., 2005).

Balanced nutrition is needed to maximize nutrient use efficiency and production at the cropping system-scale. From a crop improvement perspective, a better understanding of the contribution of K to the productivity of corn and soybean systems must be achieved before real nutrient use efficiency gains can be attained. Increasing K use efficiency might be tightly connected with sustainable and high-yielding cropping systems, but a summary of past and current research literature is needed in order to properly quantify and understand the physiological causes related to this nutrient use improvement.

The study was performed with the goal of reviewing, summarizing, interpreting, and expanding the understanding of corn and soybean yield and nutrient uptake associations from both historical and geographical perspectives. A question postulated on a previous review paper (Ciampitti and Vyn, 2012): Are improvements in yield jeopardizing grain nutritional quality? The latter question is still a valid one. Historical corn yield improvement demonstrated a clear declination of grain N concentration (Ciampitti and Vyn, 2014). Thus, from the plant perspective, nutrient use efficiency –here understood as nutrient internal or physiological efficiency- can be understood as the ratio between yield and the whole-plant nutrient uptake at physiological maturity.

Materials and Methods

The information collected for this synthesis-analysis is based on a previous publication (Ciampitti and Vyn, 2014) for corn and a new analysis for soybean (Ciampitti and Balboa, unpublished). The data was collected from studies conducted since 1880's for corn and 1920's for soybean. The research studies included in this literature summary represent a diverse range of genotypes from different Eras, in all regions capable of corn and soybean production around the globe, and across a wide-ranging of fertilizer nutrient applications and management practices. As in our previous review papers (Ciampitti and Vyn, 2012; 2013; 2014), only experimental treatment "means" were used on this evaluation. Multi-year and -site information was included for capturing environmental variation. Data sources needed to meet several criteria (minimum reporting of yield, whole-plant N, P, and K uptake) to be included in the historical and global database. The term K uptake will be utilized in this paper to describe the aboveground whole-plant K uptake at physiological maturity, so K taken up and accumulated in the root system is not considered in this synthesis-analysis. The term for K utilization efficiency (K internal efficiency, KIE) was calculated as:

KIE = Grain Yield/ K Uptake (1)

Where KIE is calculated on a per unit area basis (bu Yield /lb K uptake)

For the plant-scale analysis, envelopes portraying the maximum and minimum boundaries (0.99 and 0.01 quartiles) were calculated using the R program (R Development Core Team, 2009). Bubble graphs were employed to describe yield effects (larger bubble sizes refer to high-yielding points) in figures displaying N/K ratio. Relationships between grain yield and K uptake were implemented with GraphPad Prism 6 software (Motulsky and Christopoulos, 2003) using the power function, GraphPad equation: $Y_1 = \beta_2 X$^β_1 (Fig. 1A, B), forcing intercepts to zero. Final functions were selected by comparing independent fits with a global fit that shared selected parameters. In addition, both β_1 and β_2 were selected to test whether one curve adequately fit the entire data set after testing with the extra sum-of-squares *F* test (P □ 0.05).

Historical yield and nutrient uptake relationships were also performed with the GraphPad Prism 6 software. Bar figures were used for graphing the grain yield (Fig. 1C, G) and plant K uptake (Fig. 1D, H) both geographical clusters (USA vs. World).

Results and Discussion

Yield and Plant K Uptake Association

Corn

Historical USA corn yield research trend followed the pattern at the country-level recorded by the USDA (1920-2012) yield database, increasing from the early 1900s until 2005, and declined thereafter (Fig. 1A). The corn yield reduction registered in the last Era was related to the 2012 drought. Corn yields documented in the trend obtained from all research studies consistently exceeded the country-scale average by 32 bu A^{-1}. Similar trend was followed by K uptake, with a greater K reduction during the final period (2006-2012) (Fig. 1B). In overall, USA corn yield values exceeded the average for the World database in almost two-fold (Fig. 2C), 163 vs. 89 bu A^{-1}, respectively. For the USA, yield trend depicted a positive association with the historical analysis (except for the last period, 2006-2012); while for the World, the historical yield evolution was stagnant or slightly improved in the last decades evaluated (Fig. 1C). Potassium followed a similar behavior as documented for grain yield, with the exception of the last period, for which plant K reduction was more proportional as compared with the yield trend (Fig. 1D). Mean plant K uptake at maturity was almost twofold greater for USA vs. the World (273 vs. 150 lbs K A^{-1}, respectively).

Soybean

Historical USA soybean yield research trend mimicked a similar pattern as portrayed by the USDA (1920-2012) yield database, climbing from 1920's until 2012 (Fig. 1E). As compared with corn, soybean did not showed a yield penalty related to the 2012 drought season, but plant K content depicted an abrupt reduction from the last section of the 1990's until 2012. The latter scenario might be related to the drought experienced in 2012, which may consequently impacted K uptake and final content at physiological maturity. Soybean yields registered from all research studies consistently exceeded the USA national average by 15 bu A^{-1}. Potassium uptake followed a similar trend until mid-1960 with a plateau and a greater K reduction during the final period (2006-2012) (Fig. 1F). In overall, USA soybean yields were greater as compared with the World database (Fig. 1G), 41 vs. 26 bu A^{-1}, respectively. In addition, USA historical soybean yields portrayed a positive association with crop improvement history; while for the World, yield trend showed negligible to small improvement (Fig. 1G). For USA, plant K uptake followed a similar behavior as documented for grain yield, with the exception of the last period, which was represented by a large reduction in plant K uptake (Fig. 1I). For the world, historical evolution for plant K uptake mimicked a similar pattern as the one previously documented for the grain yield evolution (Fig. 1I). Mean plant K content was greater for the United States vs. the World (84 vs. 69 lbs K A^{-1}, respectively).

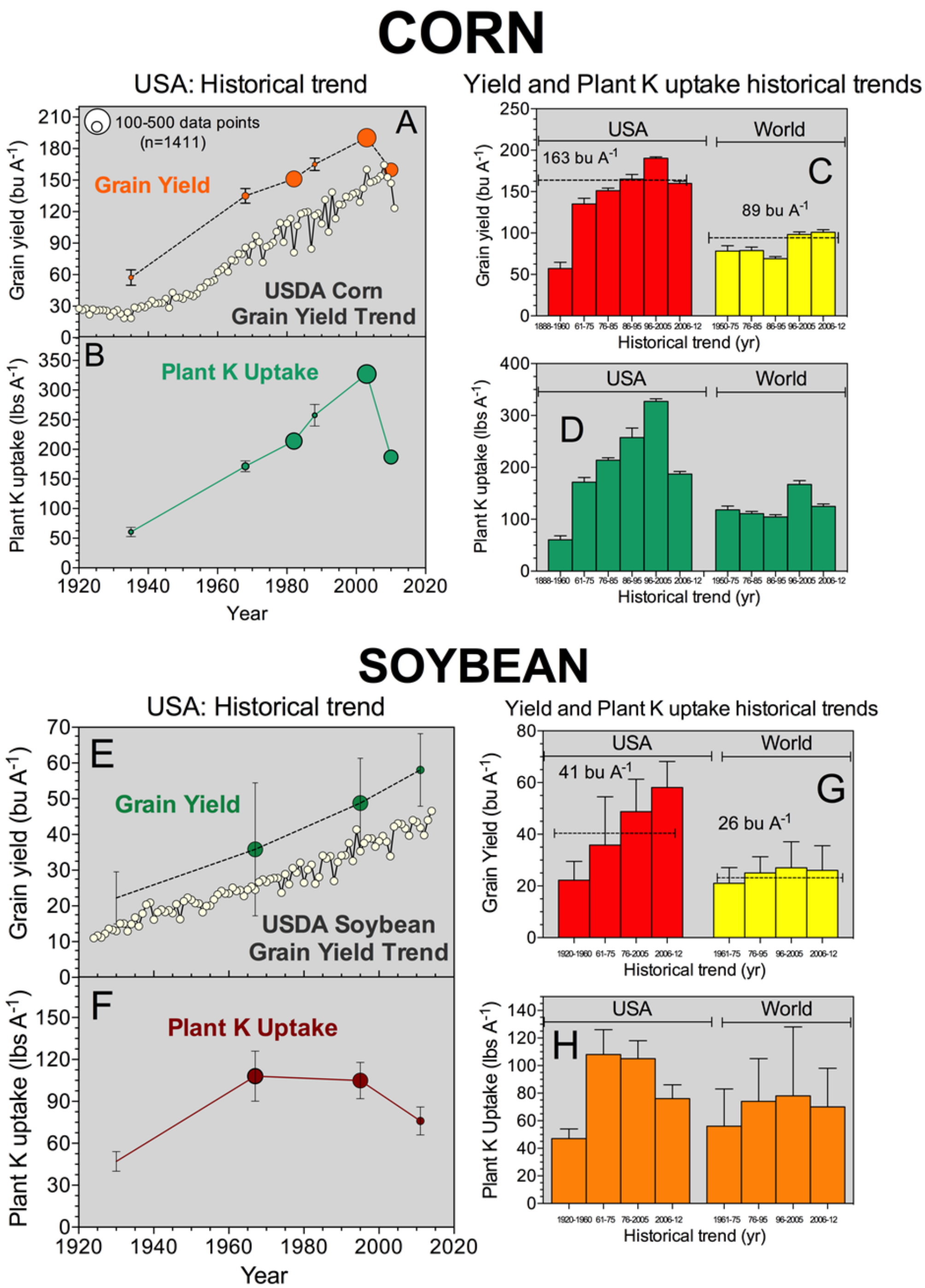

Figure 1. Corn and soybean historical research database for (A, E) yield and (B, F) K uptake, geographical yield (C, G) and whole-plant K uptake (D, H) histograms (USA vs. the World). Bubble sizes represent number of data gathered for each Era evaluated. Error bars represent the standard error. The corn section was adapted from Ciampitti and Vyn, 2014. All data for corn was based on 2300 observations (published and unpublished studies) and for soybean was based on 320 observations (but only from published studies) for both geographical clusters (USA vs. World –excluding USA).

Yield to Plant K Uptake Ratio

For corn, the yield vs. plant K uptake relationship was more robust for USA (greater R^2 value) as compared with the World regardless all evaluated factors (years, genotypes, and management systems) (Fig. 2A). The USA corn yield data displayed consistently more efficient nutrient yield conversion (at similar K uptake). At an equivalent plant K uptake, USA research database presented a greater yield, more efficient nutrient conversion, as compared with the World geographical cluster.

Similar was documented for soybean, the yield vs. plant K uptake ratio was also more robust for the USA geographical cluster as compared with the World (Fig. 2). Notwithstanding the smaller historical and geographical cluster size, the trend documented for the yield-to-K uptake was similar for soybean (Fig. 2B). The average USA yield-to-K uptake ratio was proportionally greater than the ratio documented by the World database; scenario documented by superior soybean yield at comparable plant K uptake levels. The exponential coefficient, β_2, was similar both geographical clusters (similar curvilinearity), but dissimilar nutrient use conversion (yield to K uptake ratio).

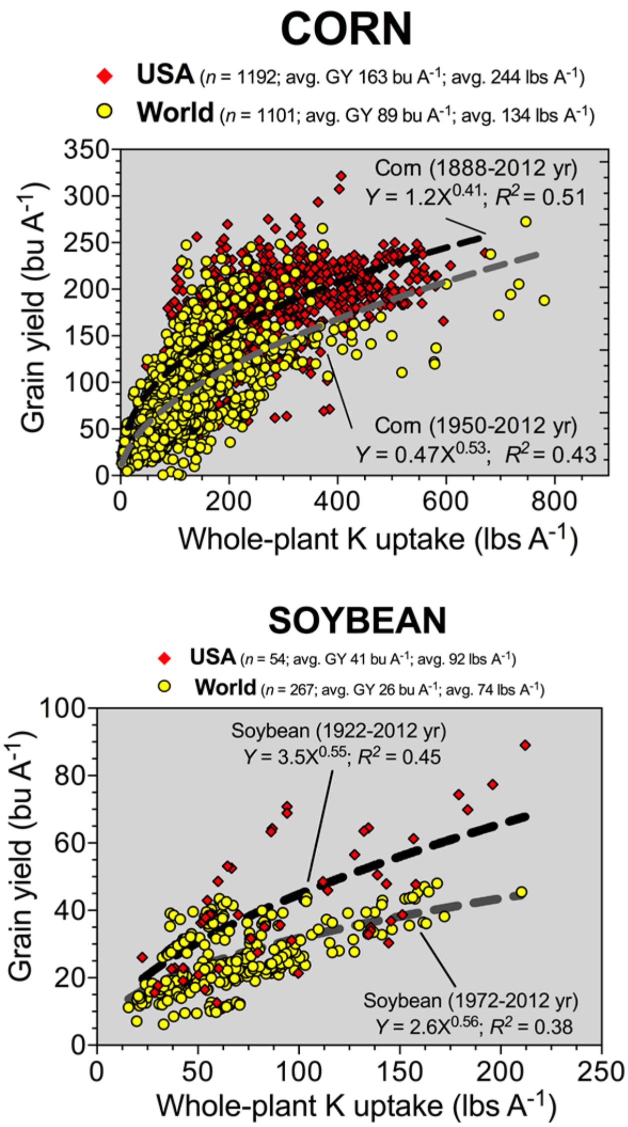

Figure 2. Research data summary for the association between corn and soybean grain yield and K uptake at maturity for both geographical clusters (United States vs. World).

Nutrient balance: NK ratio

From a physiological perspective, plant nutrient stoichiometry ratio (NK) can be utilized as a pragmatic tool for measuring nutrient imbalances. For both geographical clusters and historical data, corn NK ratio presented an overall value of 0.9:1 (N:K) with a variation from 2.5:1 (maximum N concentration) to 0.25:1 (N dilution) (Fig. 3, Corn). The variation registered for the NK envelope function was of 10-fold. High-yielding corn was related to balanced NK nutrient ratio (1:1), isometry between N and K at maturity.

For soybean, the overall plant NK stoichiometry ratio value was of 2:1 with a smaller variation (6-fold) from maximum nutrient concentration to minimum dilution (NK from 6:1 to 1:1) (Fig. 3, Soybean). For both crops, high-yielding data points were related to balanced NK nutrient ratio

(1:1 for corn and 2:1 for soybean), with grain yield values greater than 200 and 40 bu A^{-1} for corn and soybean, respectively.

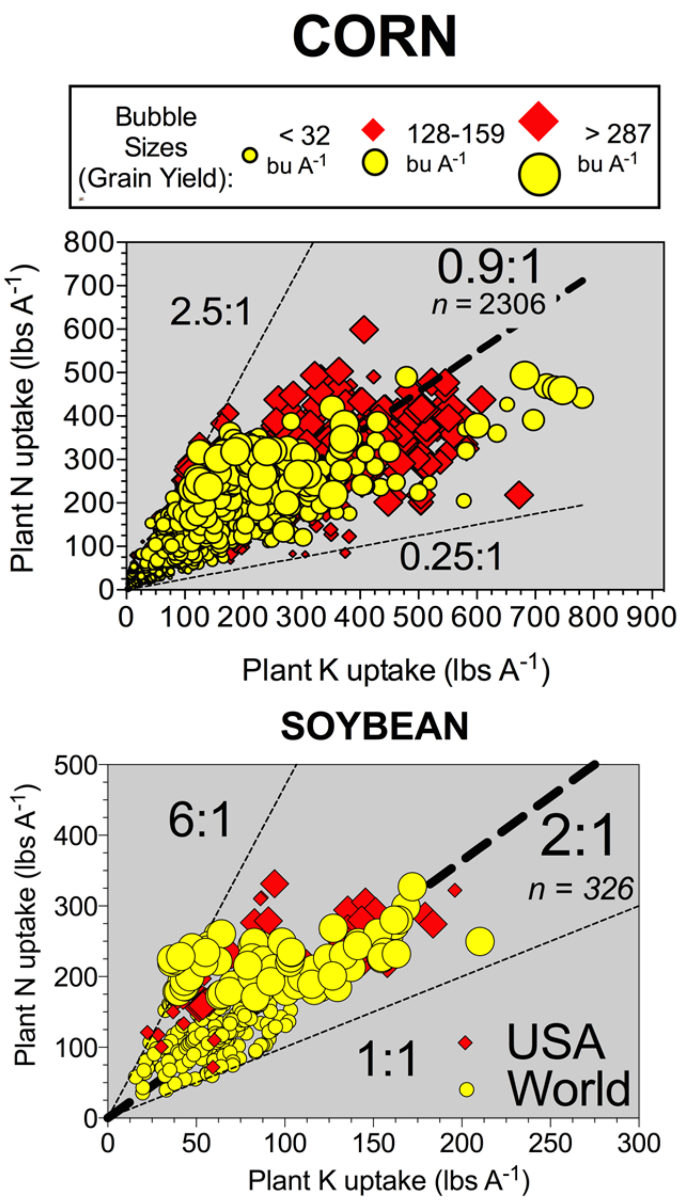

Figure 3. Plant NK balance at maturity for the historical and geographical division of USA vs. World clusters for corn and soybean crops.

For corn, in-season plant N/K ratios increased as the season progressed (Ciampitti et al., 2013). The K content in the stover organ was hypothesized to govern the changes in NK ratio. High-yielding corn presenting a balanced NK ratio (1:1) was also related with greater stover K and lower grain N concentration (Ciampitti and Vyn, 2012; 2013; 2014).

Potassium Internal Efficiency (KIE)

The KIE, grain and stover K concentration, and K harvest index were recorded from all research studies gathered from the scientific literature. For corn, overall KIE was 0.8 bu yield lbs^{-1} K uptake. For a previous study, KIE positively responded to plant density and fertilizer N rates (Ciampitti et al., 2013). The KIE was primarily related with the stover K concentration (Fig. 4), improving K utilization as the stover K concentration decreases. A similar outcome was previously documented by Ciampitti et al. (2013), without registering an association between KIE and grain K concentration.

For soybean, average KIE was 0.35 bu yield lbs^{-1} K uptake (ranging from 0.10 to 0.68 bu yield lbs^{-1} K uptake). Similarly to corn, soybean KIE presented a strong association with the stover K concentration (Fig. 4), with no clear trend as related to grain K content.

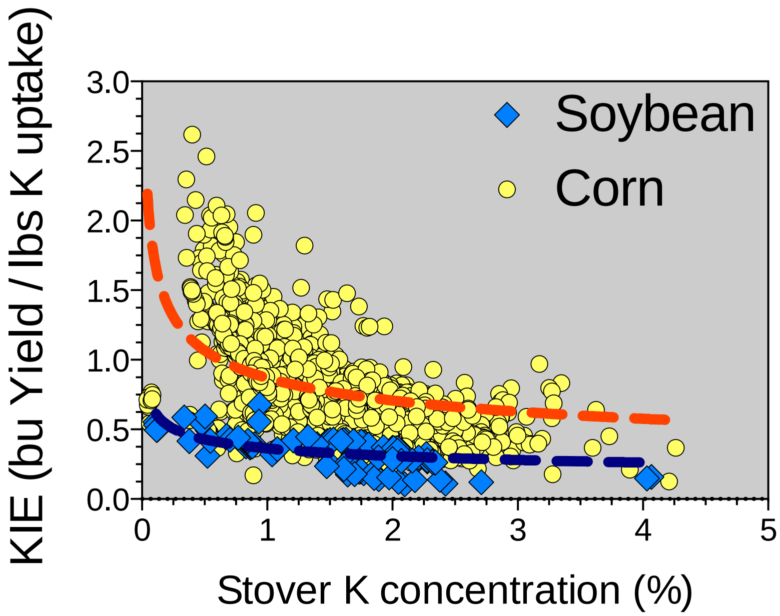

Figure 4. Potassium (K) internal efficiency (KIE), determined as the ratio between grain yield and plant K uptake both measured at maturity, associated with the stover K concentration for both corn (yellow symbols) and soybean (light blue symbols) crops.

Conclusions

Historical USA corn and soybean yield trends followed the pattern at the country-level recorded by the USDA yield database. For the World, historical yield stagnation did occur with slightly improvements in the last decades. In addition, for both crops, a much greater yield conversion (superior yield) was documented at comparable plant K uptake for the USA with the rest of the World. Genetic improvements associated with changes on genetics, management practices, and their interaction with the environment allowed superior yield progress. Better K efficiency expressed with NK nutrient ratios of 1:1 for corn and 2:1 for soybean was related to high-yielding systems, requiring not only more nutrients, but also a more balanced approach. Lastly, in both corn and soybean historical KIE improvements were primarily achieved by reductions in stover K concentration.

Future research should be focus on the interaction of K with other nutrients (besides N) and the potential impact on crop production. More integrated-approaches based on physiological-driven changes needs to be considered to pursue "true" nutrient use efficiency gains based on modification in plant traits. Current and future demand of non-grain plant fractions (e.g., biofuels) will intensify the pressure on the production process, which will need more balanced nutrient schemes in sustainable cropping systems.

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