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Potassium nutrition in Australian high-yielding maize production systems - a review.

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Abstract

High yielding maize production systems require an adequate supply of potassium (K) to meet production potential. A mature maize crop can contain up to 300 kg K/ha in aboveground plant material. In silage production systems, much of this is exported from the field. The K uptake pattern of maize is distinctive in that K is taken up rapidly and early in the crop's growth cycle, with some crops accumulating more than 5 kg K/ha daily during the period between 4 to 7 weeks after planting.

Several factors impact on the ability of a soil to meet the K demands of a growing maize crop, including:

- the soil solution K concentration
- the capacity of the soil to buffer the soil solution K concentration
- soil moisture content
- soil texture and structure, and
- the distribution of soil K reserves.

In many cases, one or more of these factors may restrict the supply of K to maize crops.

Soil solution K is buffered by the exchangeable K pool and, in soils that contain 2:1 type clay minerals, the fixed K pool. Current routine soil analyses estimate only the size of the exchangeable K pool and do not provide information about the rate at which the exchangeable and fixed K pools are able to buffer soil solution K. Consequently it is often difficult to predict from soil tests if responses to K fertilisers are likely to be observed, particularly for soils with significant amounts of 2:1 clay minerals.

In lieu of robust soil analytical predictors, other indicators can be used to identify potential K deficiency in maize crops. These include soil type, paddock history, windrow effects, early wilting and variation in lodging, frost and disease resistance with soil type.

Potassium nutrition of high-yielding maize production systems in Australia needs to be critically considered in the light of crop demand, removal and quantitative soil supply factors.

The role of potassium in maize production

Potassium is taken up in large quantities by plants, is highly mobile within plant vascular systems and plays an essential role in a number of metabolic functions. Over 60 enzymes require K for catalytic activity, some of which play a role in protein synthesis and sugar degradation (Suelter 1985). Water relations of plant cells rely on the rapid movement of K ions in order to maintain and regulate turgidity (Mengel and Arneke 1982) and stomatol control can be affected if K is deficient (Graham and Ulrich 1972). The detrimental effect on stomatal regulation can result in reduced photosynthetic capacity and Smid and Peaslee (1976) found a close correlation between K concentration in maize leaves and rate of carbon dioxide assimilation. Potassium also promotes the translocation of photosynthetic assimilates from leaves to grain through the phloem and Haeder and Beringer (1981) demonstrated that both the rate at which grain fills and the period for which it fills can be increased by K fertilisation of wheat.

Reduced stress resistance in plants has also been attributed to K deficiency. Pest and disease resistance can be improved by K application through several mechanisms including by (Perrenoud 1990):

- altering the metabolic compatibility of a host plant for the pest or pathogen
- enhancing the accumulation of inhibitory chemicals in the plant
- hastening plant wound healing
- improving the structural integrity of plant tissues
- stimulating healthy growth to avoid infection.

The impact of K nutrition on the morphology of maize leaf cells was microscopically photographed by Daohua *et. al.* (1992). Figure 1 shows contracted epidermal cells, incomplete epidermal cover and reduced cell size in K deficient leaves, compared with a thick and contiguous epidermis in a maize leaf which had recieved 125 kg/ha of K.

Potassium fertilisation has been shown to decrease the impact of several diseases of maize including boil smut (*Ustilago maydis*; Kolomiets 1960), turcicum leaf blight (*Exserohilum turcicum*; Ellett 1973) and stalk rot (*Fusarium* spp.; Farina *et. al.* 1983). Improved structural integrity and increased resistance to stalk diseases may also contribute to the well-documented role of K nutrition in lodging resistance (Walker and Parks 1969, Welch and Flannery 1985). Potassium deficiency often results in the abortion of kernels at the end of cobs and a smaller grain size (Munson 1968, Bly *et. al* 2002).

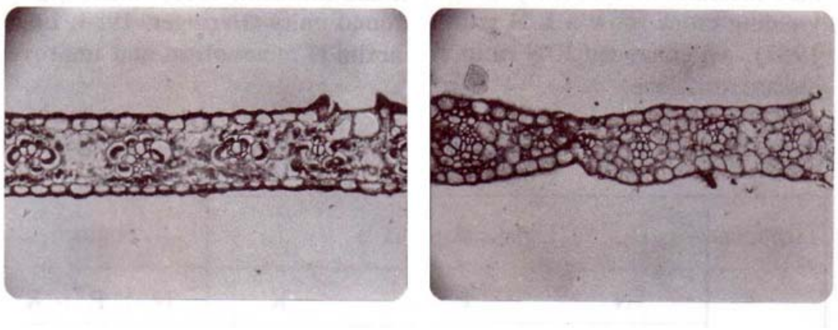

Figure 1. The morphology of cells on the surface of maize leaves is affected by K nutrition. In this experiment, the walls of epidermal cells were thick in maize treated with K (left) but where K was deficient (right), epidermal cells contracted, the epidermal cover was incomplete, and turgor pressure and cell size were reduced (Daohua *et. al.* 1992).

The availability of K will also impact on the efficient use of other nutrients. A four-year study undertaken in the US showed that fertiliser N uptake efficiency of maize was improved with increasing soil K, resulting in higher marginal returns to N inputs and less fertiliser N remaining in the soil after harvest (Johnson *et. al.* 1997).

Maize potassium demand

The total amount of K required by a high yielding maize crop is large. A mature maize crop may contain up to 300 kg K/ha in aboveground plant material, most present in vegetative plant parts (Karlen 1988). The fate of the K accumulated in a maize crop will depend on the ultimate purpose of the crop. Grain K content is usually around 0.3% (range 0.25 - 0.45%), and so a crop yielding 10 t/ha of grain will remove only around 30 kg K/ha. Removal is much higher where vegetative material is harvested, as with a silage crop. Potassium is readily leached from plant material (McColl 1970) and so any K remaining in trash and roots will be rapidly returned to the soil.

The pattern of K accumulation in a maize crop is characterised by early and rapid uptake. More than 90% of total K uptake is commonly accumulated between 4-7 weeks after planting and before 50% of the final aboveground dry matter has been produced (Welch and Flannery 1985, Corazzina *et. al.* 1991). Figure 2 shows the K and DM accumulation pattern of a maize crop grown in the South Burnett which yielded 8 t/ha of grain. During the most rapid period of K accumulation (between 24 and 43 days after planting), daily K uptake was calculated as 4.9 kg K/ha. A range in peak daily demand for K by maize of 2.3 to 10.7 kg/ha has been reported in the literature (Welch and Flannery 1985). Figure 2 alo highlights the reduction in K content immediately prior to harvest maturity, which is often due to the leaching of K from leaves and stalks during this late growth stage.

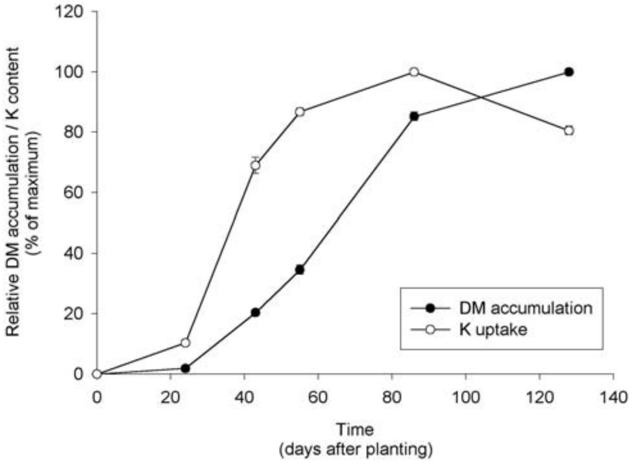

Figure 2. Accumulation of aboveground dry matter and K by a South Burnett maize crop yielding 8t/ha (QDPI unpub).

The large total requirement for K, coupled with the narrow and early window in which it is accumulated has important implications for the K nutrition of maize. Firstly, the K concentration of plant tissue will change rapidly during the early part of the crop's life cycle due to the relative differences in K uptake and DM production rates (Walker and Peck 1975). Figure 3 shows the K concentration of whole plant tissues from the same South Burnett maize crop compared to the K concentration of soybean and peanut samples. The importance of sample time to the interpretation of tissue analyses sampled during early growth periods of maize is apparent. Samples which have been taken at a given growth stage should not be compared with samples or critical concentrations determined at a different stage.

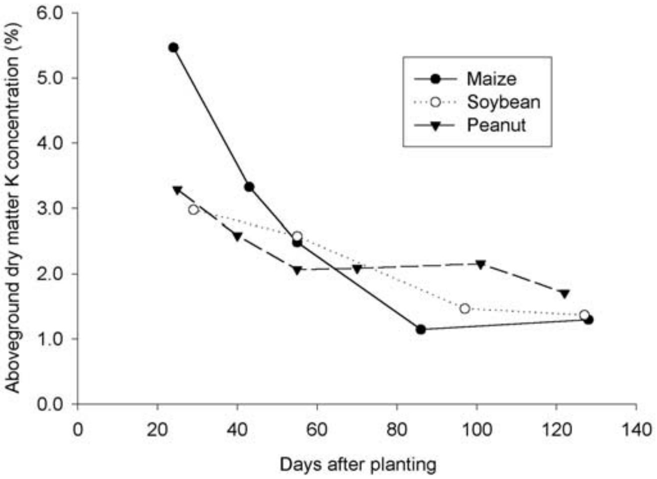

Figure 3. Concentration of K in aboveground dry matter during the growing season of maize, peanut and soybean (QDPI unpub).

A further consequence of the K uptake pattern of maize is the need for a rapidly available supply of soil K during peak uptake periods. Many factors impact on the availability of soil K, both over the length of the growing season and during intense periods of rapid uptake. While a soil profile may contain sufficient K to meet the total demand of a crop over a growing season, demand during peak uptake periods may outstrip the soil's capacity to supply sufficient K in a plant available form at any given time.

Soil potassium supply

Release of K into plant available forms

Potassium exists in several soil pools of varying availability to plants. Figure 4 illustrates the four soil K pools as described by Sparks (1987):

- solution K, ions dissolved in the soil solution
- exchangeable K, ions adsorbed to exchange sites on the surface of soil particles
- fixed K, ions adsorbed strongly to sites within the expanded interlayers of certain clay minerals
- structural K, K which forms part of the chemical structure of minerals and is released only slowly and upon irreversible weathering.

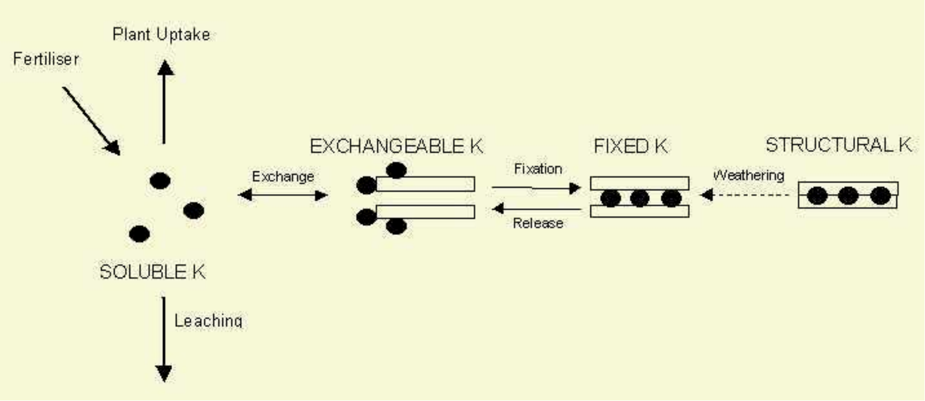

Figure 4. A representation of the pools of soil K.

Plants absorb K directly from the soil solution, which is by far the smallest pool of K in soils. The concentration of solution K is buffered by the much larger exchangeable K pool. In turn, exchangeable K exists in a reversible equilibrium with the fixed K pool. Some K ions will be released from the fixed pool over the growing season of a crop and can make a significant contribution to plant K uptake (Fergus and Martin 1974, Juhari 1984). Conversely, K added in fertiliser can be fixed and will not be immediately available for plant uptake. The capacity of a soil to fix or release K is closely related to the type of clay minerals it contains, with soils dominated by 2:1 type clays (recognisable for their shrink-swell properties) having more fixation sites than soils dominated by 1:1 type clays or other highly weathered minerals. The buffering of solution K by exchangeable K and the release of fixed K are both rate-controlled processes. If demand is very high, the rate of these reactions may not be sufficient to maintain solution K concentration and supply a growing crop.

Movement of plant available K to root surfaces

Before plant demand can be met by K uptake, the ions in solution must also be present at the surface of the root. There are three mechanisms through which solution K reaches plant roots; root interception, mass flow and diffusion (Barber 1995). Table 1 indicates the importance of each of these for providing K to a maize crop as well as what factors can affect the supply of K via each mechanism.

Table 1. Mechanisms via which soil K reaches plant roots, their approximate contribution to K absorbed by maize, and the factors which affect each mechanism.

Mechanism	**Description**	**% of K supplied** (after Barber 1995)	**Factors affecting**
Root Interception	Ions which are displaced by root growth or are at the root surface	2	Impact on root growth by pests (eg. nematodes) or hostile soils (eg. acidity, compaction).
Mass Flow	Ions which move to the root surface in the convective flow of water caused by plant absorption	18	Transpiration rate Soil solution K concentration
Diffusion	Ions which diffuse along the concentration gradient in the zone of depletion towards the root surface.	80	Soil solution K concentration Soil K buffering capacity Soil moisture Soil texture Soil temperature

Diffusion is by far the most important mechanism of K supply to maize roots. The development of a gradient in soil solution concentration from maize root surfaces into the surrounding soil is depicted in the radiographs taken by Walker and Barber (1962) in Figure 5. In this experiment, high concentrations of a radioactive isotope of rubidium (used as a surrogate for K) appear as dark areas and correspond to root tissue and the bulk soil solution, whereas areas of low K concentration immediately surrounding the roots are pale. Diffusion of K to plant roots will be restricted where bulk soil solution concentration is low or where the soil has a poor capacity to buffer the soil solution K. Dry or compacted soils will also reduce K movement by diffusion and may result in visual K deficiency symptoms appearing mid-season then disappearing once rain has fallen.

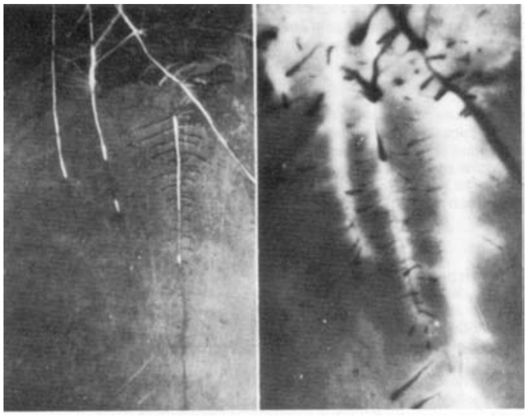

Figure 5. Maize roots growing through soil (photograph on left), generate a concentration gradient between the bulk soil solution and the root surface which is seen in the autoradiograph on the right (Walker and Barber 1962).

Positional availability of K

The vertical distribution of K in the soil profile may also impact on its ability to meet the demand of a growing maize crop, particularly in rain-fed situations. In many instances, soil reserves of K have become stratified with most of the available K found in the surface layers. The absence of plough layer mixing in minimum tillage systems exaggerates this stratification (Robbins and Voss 1991, Cowie *et. al.*1996). As topsoils dry out, crops forage for moisture and nutrients from lower in the soil profile where K reserves are smaller. It is suspected that a combination of dry periods and stratified K reserves have resulted in an increasing incidence of K deficiency symptoms in rain-fed maize in the South Burnett region (White 2002). Deep banding of K has resulted in small but significant effects on maize yield in the US on soils testing optimum to high in K (Mallarino *et. al.* 1999).

Identifying the need for potassium fertilisation

If soil K supply is not sufficient to meet crop demand, K fertilisation may be economical. Identification of fields that will respond to K fertilisers in Australia currently relies on soil analysis for exchangeable K or the appearance of visible deficiency symptoms, neither of which is entirely satisfactory.

Soil analysis

Current routine analyses for cropping soils in Australia estimate the size of the exchangeable K pool by either exchanging with a neutral salt solution (eg. ammonium acetate, calcium chloride) or by the Colwell extraction, and attempt to relate this to crop production (Gourley 1999). The exchangeable K analysis makes no estimate of the supply factors involved in maintaining soil solution K concentration, other than an assumption that a large pool of exchangeable K will be more effective at buffering solution K.

In recent years, anecdotal evidence has suggested that exchangeable K alone is a poor predictor of K responsiveness in Australian cropping systems, particularly in soils with an abundance of K fixation sites or where high K removal rates have exhausted fixed K stores. For example, Grewal and Williams (2000) reported a response to K application by lucerne on a grey-brown clay with 1.03 cmol(+)/kg of K at 0-15cm, much higher than the generally accepted critical concentration for responsiveness of 0.40 cmol(+)/kg. Furthermore, in some instances large applications of K fertiliser have been required to overcome chronic deficiency which develops after prolonged K removal and exhaustion of fixed K supplies (Collett 1997). In the latter case, it is likely that added K is initially drawn into the exhausted interlayer fixation sites which must be replenished before any change is recorded in the amount of exchangeable K measured using routine soil analyses (Carter 2002).

More information about the size and rate of release of the fixed K pool may be able to improve the ability to predict K responsiveness and the fate of applied K fertiliser. Several techniques are being used in other industries and regions to complement an exchangeable K extraction and provide better information about a soil's K supply capacity. The sugar industry in Australia routinely uses a boiling nitric acid extraction in order to estimate the size of the fixed K pool in soils (Calcino 1994) and recently Schroeder and Wood (2002) have suggested continuous leaching with barium chloride in order to estimate both the size and the rate of release of the fixed K pool. In New Zealand, a modified extraction using sodium tetraphenylboron is used to estimate fixed K reserve and release rate in both pasture and cropping systems (Carey *et. al.* 2000). Other techniques using electro-ultrafiltration (Mengel and Uhlenbecker 1993) and cation exchange membranes (Qian *et. al.* 1996) also have their proponents. These techniques need to be evaluated for use in Australian cropping systems.

Visible K deficiency symptoms

In maize, visible K deficiency symptoms will begin as a pale yellow chlorosis, followed by necrosis, on the tips and margins of older leaves (Figure 5). Stems will be short and thin and may develop prominent red stripes. The tips of cobs are often pointed, shrivelled and without grain at maturity.

Transient K deficiency symptoms may be seen if a temporary restriction in K supply is relieved, often by rainfall which improves access to topsoil K reserves, allows root penetration of compacted soils or improves the movement of soil K to the root surface by diffusion.

It is well accepted that visible deficiency symptoms are a coarse tool for managing crop nutrition. A yield penalty will usually have been paid long before visible deficiency symptoms appear. "Hidden hunger" is best identified before it develops into visible deficiency symptoms.

Figure 6. Examples of visible K deficiency symptoms in maize.

Other indicators

In lieu of comprehensive information on soil K supply characteristics, other factors or predisposing conditions may indicate a potential for K responsiveness to an agronomist in the field. These include:

- soil type

  Lighter textured soils in a field or region are more likely to develop K deficiencies first because of lower native reserves of K and poorer nutrient holding capacity, however this does not mean deficiencies will not develop on heavier textured soils.

- paddock history

  Reserves of K will become depleted most rapidly in paddocks with a history of high K removal (eg. from hay or silage production) and little replacement in fertiliser.

- level of productivity

  Where production has been lifted with the correction of other deficiencies or adoption of more productive farming systems, K is more likely to become a limiting factor.

- windrow effects

  Where previous crops have been windrowed, improved growth by a subsequent crop in the windrow areas can signal K deficiency. Potassium in the residue of the previous crop is concentrated in the windrow, and developing K deficiencies are exacerbated in off-windrow areas.

- variation in lodging, frost or disease resistance

  Unexplained variation in the incidence of these problems across a field could be related to spatial variation in soil K - usually related to soil type. Analysis of paired soil or plant tissues from good and bad areas may assist in diagnosing a deficiency.

- early wilting, poor turgor pressure

  Deficiency of K will limit the ability of a crop to regulate internal water relations, and to control stomatal openings.

Conclusion

Management of K nutrition of maize needs to be critically considered in light of crop demand, removal and soil supply factors. Given the K uptake pattern of maize, the soil types generally used for maize production in Australia and the amount of historical K removal where hay or silage has been produced, maize production systems would seem particularly vulnerable to unidentified K deficiencies.

The ability to predict responsiveness of a field based on current routine soil analyses is questionable. A more comprehensive methodology for assessing the K supply characteristics of a field needs to be developed, using experiences from other industries and regions.

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