Chapter 12
Considerations for Selecting Potassium Placement Methods in Soil

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Abstract Placement strategies can be a key determinant of efficient use of applied fertilizer potassium (K), given the relative immobility of K in all except the lightest textured soils or high rainfall environments. Limitations to K accessibility by plants caused by immobility in the soil are further compounded by the general lack of K-stimulated root proliferation in localized soil zones enriched with K alone, compared with root proliferation due to concentrated N and P. Further, effects of K fixation reactions in soils with certain clay mineralogies and the declining concentration and activity of soil solution K with increasing clay content can also limit plant K acquisition. Variation in root system characteristics among crops in a rotation sequence and fluctuating soil moisture conditions in fertilized soil horizons in rain-fed systems increase the complexity of fertilizer placement decisions to ensure efficient K recovery and use. This complexity has resulted in extensive exploration of fertilizer K application strategies, with this chapter focusing on K applications to the soil. Issues discussed include comparisons of broadcast versus banded applications, depth of fertilizer placement, and the impacts of co-location of K with other nutrients. While research findings are often specific to the crop, soil, and seasonal conditions under which they are conducted, we attempt to identify strategies that most consistently deliver improved crop recovery and utilization of fertilizer K.

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12.1 Introduction

Plants typically accumulate potassium (K) in similar quantities to nitrogen (N), with the potential for luxury accumulation of plant K resulting in greater K accumulation than N in some situations. The scale of crop K requirements and the time-critical nature of K uptake, with maximum uptake rates often well in advance of biomass accumulation, means that soil K availability and appropriate fertilizer application methods are critical to ensure adequate crop K nutrition. While foliar applications of K are practiced in the culture of some crops including cotton (Coker et al. 2009) and some horticultural crops (Jifon and Lester 2011) fertilizer K applications are typically limited to supplementing K uptake from the soil, with the quantity of foliar K supplied relatively small compared to total crop K accumulation. Foliar application of K is discussed explicitly in Chap. 13 of this book, while this chapter focuses on soil K fertilization strategies.

12.2 Factors Affecting Root Access to Zones of K Enrichment

The main factors affecting the efficiency of applied K recovery involve: (1) the interactions between crop root systems and the soil physical and chemical properties that affect the movement of K to plant roots and (2) the replenishment of depleted soil solution K concentrations in response to plant K uptake. Plant root factors are discussed in detail in Chap. 4, but relate primarily to the temporal coincidence of active crop roots and K-enriched soil profile layers, the proportion of the crop root system that is in the enriched zone, the extent to which those roots can deplete soil solution K concentration and/or exploit non-exchangeable soil K. The mobility of K through the soil profile, and hence the possible expansion of the zone of K enrichment beyond the original fertilized soil volume, is an important factor to consider in order to understand the interactions between soil-applied K and crop root systems that collectively determine plant K uptake.

Important physical properties such as pore size and pore continuity influence the diffusion path length (tortuosity) and hence the rate of diffusive resupply of soil solution K depleted by plant uptake. Chemical factors include those that influence the impact of applied K on the activity of K in the soil solution (i.e., the K buffer capacity—BC_K), which is a function of the number and specificity of potential K sorption sites (estimated by measurement of cation exchange capacity) and the presence of clay minerals that can fix (usually temporarily) some of the applied K. These chemical factors also influence the relative importance of diffusion and mass flow in meeting crop K requirements.

12.2.1 Crop Root Distribution

Underlying genetics determine the potentially different patterns of root distribution among species and genotypes. Some of those differences are fundamental, such as the contrast in root system morphology and distribution between fibrous-rooted monocots like wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) and tap-rooted dicots like cotton (*Gossypium spp*.) and grain legumes, as illustrated by Gulick et al. (1989). In that study, barley exhibited much higher root length densities than cotton, especially in the uppermost 12 cm of the soil columns. Cotton was characterized by low root length densities throughout the soil profile. Finer-level differences between genotypes can also have important implications for functional traits like accessing water stored deep in the soil profile (e.g., Liakat et al. 2015) and potentially for responding to nutrient-rich patches like fertilizer bands or layers in cropped fields. Further, substantive K acquisition differences among cultivars have been linked to the root surface area (Brouder and Cassman 1990), although such studies remain sparse. However, the contribution of these differences to root system function and the crop it supports will be largely determined by the interaction of soil characteristics and seasonal conditions in the field (Rich and Watt 2013). As a result, the combination of soil type and seasonal conditions, modified by management inputs such as tillage system and irrigation, can have major impacts on the root distribution of the same genotype of a given species. Statistical analyses of many studies suggest that 70% of the root mass of many crop species is usually found in the upper 30 cm of the soil profile (Jackson et al. 1996), with irrigation (Gan et al. 2009) and the adoption of reduced or zero tillage systems (Williams et al. 2013) tending to increase the density of roots in the upper horizons.

This zone of high root density tends to coincide with the zones of greatest nutrient enrichment, including fertilizer application, microbial activity, and nutrient cycling; in natural systems surface concentration of nutrients is expected as aboveground residues accumulate and decompose largely without mechanical soil incorporation. Therefore, the acquisition of nutrients from these layers is clearly important. However, there is limited evidence that applications of K fertilizer alone impact the root distribution within the soil profile (Brouder and Cassman 1994), except perhaps for the situation where K application contributed to a reduced severity of crop water stress and an extended period of biomass accumulation and root growth (Grzebisz et al. 2013). An example is shown from a soybean (*Glycine max* (L.) Merr.) crop in Indiana, USA in Fig. 12.1. The uppermost 5 cm of soil has at least 1.5-fold the root length density (RLD) of any other soil profile segment, and the RLD of soybean in this study was very low (~ 1 cm cm^{-3}) below 20 cm (Fig. 12.1b). Contrasting rates of K addition resulted in large differences in soil test K in the 0–5, 5–10 cm soil profile increments, but these differences did not impact RLD. Unlike N and P that stimulate localized proliferation of fine roots, localized high concentrations of K do not appear to enhance root growth (Rengel and Damon 2008). The only recent reports of root proliferation in a fertilizer K-enriched soil volume was a report for maize by Perna and Menzies (2010) that showed some evidence of root proliferation when 6–12% of

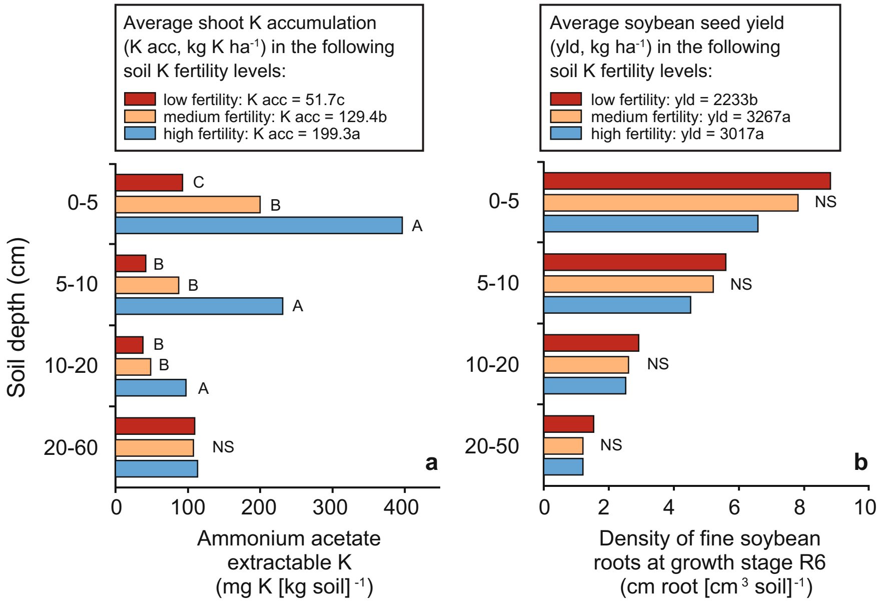

Fig 12.1 Distribution of (**a**) soil exchangeable K (ammonium acetate extraction) and (**b**) soybean roots by soil depth in plots previously fertilized for 6 years with varied rates of K (0–900 kg ha^{-1} cumulative additions). Low, medium, and high correspond to soil test K levels less than, approximately equal to, and greater than 104 mg kg^{-1} measured at 0–20 cm one year after the last K addition. Four replicates per category were assessed over 2 years at planting (soil) and R6 (roots). Within each graph and depth increment, bars followed by a different letter are significantly different ($P \leq 0.05$). Legends show a 2-year mean total aboveground K accumulation (A) and seed yields (B). Adapted from Fernandez et al. (2008) and Navarrete-Ganchozo (2014) (graph **a**) and Fernández et al. (2009) (graph **b**)

the available root volume was enriched with K. Ma et al. (2007) also suggested that there was some evidence of roots proliferating in K-enriched compartments of split-pot systems relative to unfertilized compartments in the same pot, but effects were quite inconsistent.

Collectively, the literature suggests that large changes in rooting patterns are unlikely to occur in response to the application of fertilizer K alone. This then suggests that either the volume of K-enriched soil needs to be large enough to encompass a significant proportion of the crop root system or that other strategies to enhance root activity in the fertilized zone, such as irrigation strategies that ensure synchronous availability of soil moisture and K, are enacted. The minimal effect of K on root proliferation may partly explain, along with salt effects, the usually small effects of starter K applications (fertilizer applied in or near the seeding row at planting) on early crop growth and yield, compared to effects of N and P (Kaiser et al. 2005; Mallarino et al. 2010).

12.2.2 Mobility of K in Soil in Soil Profiles

Fertilizer K applied to soils initially enriches the soil solution K pool, which is then depleted by plant uptake, by rapid adsorption onto exchange sites on clay or organic matter surfaces, or by more gradual fixation in wedge and interlayer positions of weathered micas, vermiculite, and high-charge smectite (e.g., Goulding 1987, Chap. 7). The most important factors affecting the mobility of K in the soil are: (1) the cation exchange capacity (CEC) of the soil and the specificity of exchange sites for K (both determined by the clay and organic matter content as well as the type of clay present); (2) the presence of K-fixing minerals; (3) the formation of sparingly soluble reaction products in bands containing K and other nutrients; and (4) the seasonal moisture dynamics—specifically the frequency and duration of wetting and drying cycles (affecting K fixation and release) and the extent of through drainage or leaching (Luo and Jackson 1985; Sparks and Huang 1985). In light-textured soils with low CEC and organic matter content, there is a limited capacity to adsorb significant amounts of K on the exchange complex. In these soils, a large proportion of applied K will remain in the soil solution and may be subject to leaching into deeper soil horizons. In terms of increasing the volume of K-enriched soil in the crop root zone, this can be beneficial to crop growth; but in high rainfall environments, it may result in leaching of K too deeply for access by plant roots. In contrast, soils with even moderate CEC will typically adsorb K leached from crop residues or applied as fertilizer, such that K is considered as sparingly mobile or effectively immobile in the soil profile. This is illustrated in Fig. 12.2 (adapted from Bell et al. 2009), with fertilizer incorporated into the top

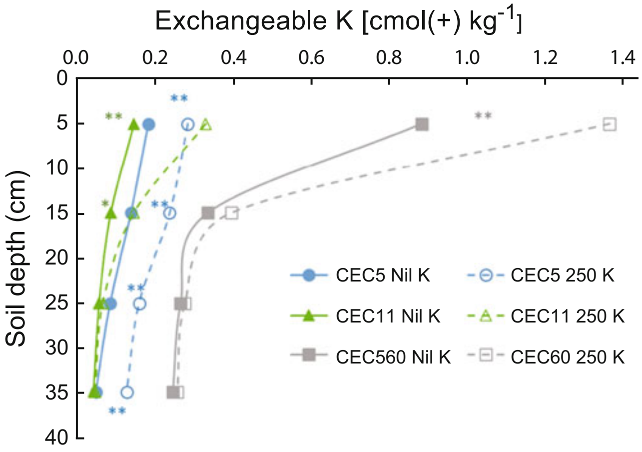

Fig. 12.2 Examples of the mobility of K through the soil profile after an application of 250 kg ha^{-1} of K (as KCl) applied into soils with contrasting cation exchange capacities (5–60 cmol(+) kg^{-1}) in northeast Australia (Bell et al. 2009; Halpin et al. 2019). Fertilizer was incorporated into the top 10 cm of each field profile using mechanical tillage, and soil samples were collected in 10 cm increments to 40 cm at 12 months and 750–950 mm of rainfall after fertilizer application. Exchangeable K (cmol(+) kg^{-1}) data are plotted at the midpoint of each depth increment

10 cm of the soil showing no redistribution into deeper soil layers in a Vertisol with CEC of 60 cmol(+) kg^{-1}, movement into the next 10 cm profile increment in the Oxisol with CEC of 11 cmol(+) kg^{-1} and leaching beyond the depth of measurement in a Chromosol with CEC of 4 cmol(+) kg^{-1}.

Because of their permeability with regards to K, low CEC soils require careful management of K applications to ensure efficient use by crops rather than leaching losses in high rainfall environments. However, the situation in higher CEC soils represents real challenges in ensuring that applied or recycled K enriches the zone where crop roots are most active. Particularly in reduced or zero-tillage cropping systems, where physical mixing of profile layers has been minimized or eliminated entirely, plant-available K reserves become increasingly concentrated near the soil surface in a situation commonly described as K stratification (Grant and Bailey 1994; Mallarino and Borges 2006). The impact of K stratification will depend on the frequency with which those K-enriched topsoil layers are rewet and can support active root growth during the period of crop K accumulation. In situations where in-season rainfall events are infrequent and the crop is reliant on subsoil reserves of moisture and nutrients for extended periods, such as the northern Australian grain growing regions on Vertisol soils (Bell et al. 2010), root activity and K acquisition from these topsoil layers is minimal.

12.2.3 Movement of K to Plant Roots

In most situations, the concentration of K in the soil solution is low, primarily due to the propensity for rapid adsorption of K onto exchange surfaces. As a result, the extent to which mass flow contributes to K supply to the plant root is limited to typically $<5\%$ of overall plant uptake (Jungk 2001), although this proportion can be higher when soil solution K concentration is high. Examples include when high rates of K are applied to light-textured soils with low CEC (Rosolem et al. 2003), or when soils are irrigated with wastewaters containing elevated K concentrations (Arienzo et al. 2009). In most conditions, K supply is dominated by diffusion through the soil solution along a concentration gradient established between the plant root surface and the undepleted soil solution (Barber 1985). The efficiency of diffusion is determined by a variety of soil and seasonal factors, including: (1) the moisture content of the soil—effective diffusion rates increase with increasing volumetric water content; (2) the impedance or tortuosity of the diffusion path—effective diffusion slows as clay content increases or as soil structure is degraded; (3) the concentration gradient established between the rhizosphere and surrounding undepleted soil—soil solution K concentrations typically decrease as BC_K increases, lessening the potential concentration gradients; and (4) the soil temperature—diffusion rates increase with increasing temperature due to lower viscosity of the soil water (Barber 1995).

These factors obviously interact with the crop root system, with root density and inter-root competition in a given soil volume affecting the root depletion profile and hence the uptake of K per unit of root length (Jungk 2001; Mengel et al. 2001). Species differences in root hair length and mycorrhizal colonization will also affect the volume of soil K depletion.

12.3 Fertilizer K Application Strategies in Soil

Potassium fertilizer strategies typically involve applications that are broadcast onto the soil surface or placed in discrete bands (alone or in combination with other nutrients) in the topsoil layers, with or without subsequent incorporation with tillage implements. The latter application method is particularly prevalent in reduced or no-till systems where soil structure and retention of surface residue cover are important management considerations. There is also some use of K in “starter” fertilizer programs, where small amounts of nutrients (typically compound fertilizers containing N–P or N–P–K, maybe with micronutrient additives) are placed in the seeding row or in bands immediately beside or below the seeding trench to ensure early contact between developing roots and the nutrient source. However, the amount of K applied in this approach is often limited by the risk of salt-induced damage to the developing seedlings and their root systems. Although benefits of this application method have been observed occasionally, they have been linked to very specific circumstances (e.g., delayed planting of full-season maize hybrids in the upper US Midwest (Bundy and Andraski 1999). Generally, the impact on the yield of this application method has been shown to be inconsistent and sometimes detrimental (Mallarino et al. 2010).

While broadcast applications to the soil surface are typically more cost-effective in terms of rate of land area treated, their efficiency in supplying K to the crop depends on the extent to which either tillage or rainfall/irrigation can redistribute K deeper into the soil profile where roots can access the applied fertilizer. In light-textured soils, the low water-holding capacity, high internal drainage rates, and low capacity to adsorb K on the exchange complex can facilitate the redistribution of broadcast K into deeper profile layers (e.g., the low CEC soil in Fig. 12.2). However, in some situations, K can be leached completely from the crop root zone (Alfaro et al. 2003; Askegaard et al. 2004). More typically, broadcast K redistributes down the profile slowly, and the rate of leaching is greatly exceeded by crop uptake and deposition on the soil surface in crop residues. The result is “stratification” of soil K, where the concentration of labile K in the top 5–10 cm typically exceeds that in the soil layers immediately below (e.g., 10–20 cm and beyond), with the extent dependent on root distribution and K removal rates (Saarela and Vuorinen 2010). This situation is exacerbated by minimum and no-till systems, and K fertilization of perennial species where the physical redistribution of K throughout the cultivated layer by plows or discs has been minimized or discontinued entirely (Robins and Voss 1991; Holanda et al. 1998; Vyn et al. 2002).

While the existence of soil profiles with stratified labile K is not necessarily a constraint to crop K acquisition, provided those topsoil layers are moist for extended periods and characterized by an extensive network of active roots (Fernandez et al. 2008; Fernández et al. 2009), intensive cropping can deplete the upper layers of the subsoil. This results in an increased reliance on optimal conditions in the topsoil layers throughout the period of maximum K uptake (e.g., Cassman et al., 1989). Even in growing areas where growing season rainfall for grain production ensures moist top soils for K uptake, significant periods of temporal drought may limit K availability. This problem is accentuated in growing areas relying on stored soil moisture, and in many situations, K application strategies other than broadcasting have been adopted. These include banding (Bordoli and Mallarino 1998; Borges and Mallarino 2001) as well as occasional tillage operations designed to "redistribute" stratified K reserves (Yin and Vyn 2004).

In reduced- and no-tillage systems, the favored alternative to broadcast application is to apply K in bands. The strategies that determine effective K fertilizer banding have been developed by considering a number of key principles. These include: (1) not placing high fertilizer concentrations close to the seed row to avoid high salt concentrations that have a negative impact on germination and seedling establishment (Gelderman 2007); (2) band placement that maximizes root interception and crop K acquisition (e.g., below and/or beside the plant line, or in the planting hill); and (3) co-locating other nutrients with K to encourage root proliferation in and around the fertilizer band (Officer et al. 2009). Bands can be particularly effective in situations where the rate of root development and access to a larger soil volume is constrained by cold soils or high soil strength/compaction (Oborn et al. 2005), with the higher soil solution concentration in the vicinity of the band allowing rapid K uptake. Banding K deeper than the common 5–10 cm depth is sometimes beneficial in conditions where the topsoil is frequently dry but deeper soil layers have moisture (Bordoli and Mallarino 1998). However, the effectiveness of applying K into deeper soil profile layers will represent a compromise between placing fertilizer into soil layers that are moist enough to allow K acquisition for a greater part of the growing season and also having sufficient root length density to enable a significant amount of K uptake. In the example in Table 12.1, broadcast application of K to alfalfa resulted in the highest yield and greatest K recovery when compared to K injected at discrete soil depths; adequate rainfall likely enabled uptake of surface-applied K and precluded K recovery from greater soil depths even in a deep-rooted species like alfalfa.

Another consideration with banded K applications is that as the crop grows and the K demand increases, the proportion of plant K that can be supplied from a localized fertilizer band enriching a small soil volume diminishes. This suggests that where banded K applications are necessary (e.g., no-till systems on heavier textured soils), strategies to enhance K diffusion into larger soil volumes or to encourage a greater proportion of the crop root system to develop in the proximity of the bands (e.g., co-location with other nutrients like N and P; Ma et al. 2011) need to be considered. An example of the latter is shown in Fig. 12.3 where the addition of P to a band of KCl fertilizer, either alone or in combination with N, enhances the uptake of rubidium (RB) tracer added in the band. While the effects of N are transitory and

Table 12.1 Influence of K placement depth on tissue K concentrations, K recovery, and yield of alfalfa. (Petersen and Smith 1973)

Depth of K placement	Tissue K	K recovery	Yield
cm	g kg^{-1}	%	Mg ha^{-1}
Check, No K	10.7	–	4.46
Broadcast	21.7	28	5.06
7.5	16.5	15	4.92
722.5	14.5	9	4.66
37.5	12.2	4	4.59
52.5	11.6	4	4.72
67.5	12.0	5	4.82
82.5	11.4	–	4.12
LSD[a]	2.6		0.51

Potassium as K_2SO_4 was surface broadcast or injected as a solution into the silt loam soil at specific depths using a Leur-Lok syringe. The fertilization rate of 224 kg K/ha was applied on April 15 and the yield of this 2-year-old alfalfa stand determined on June 3

[a] LSD: least significant difference at $p < 0.05$

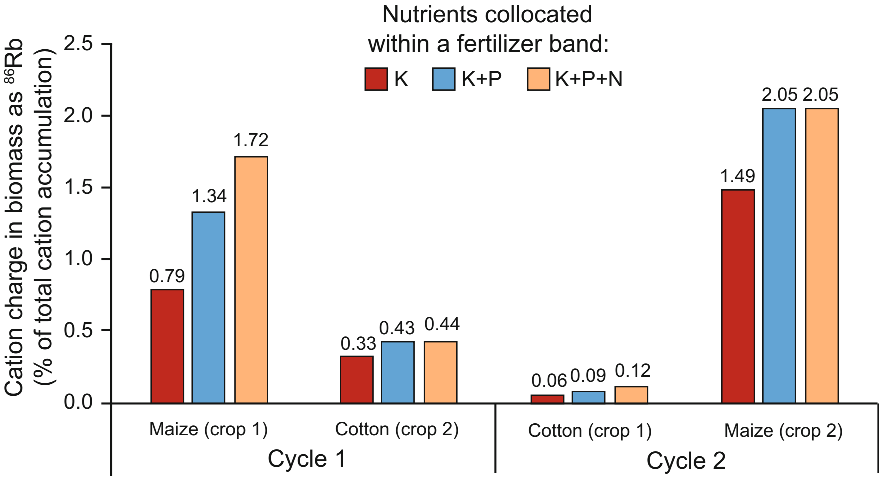

Fig. 12.3 Impact of co-locating P or (N and P) on the exploitation of KCl bands by maize and cotton plants grown in a Vertisol soil over two experimental cycles with contrasting crop sequences. Effects were assessed by quantifying the uptake of Rb (applied as RbCl mixed into a KCl band), expressed as a percentage of the total cation accumulation in plant biomass, cmol(+) kg^{-1} dry matter. (MJ Bell and PW Moody, unpublished data)

limited to the first crop in each sequence, the effects of P co-location with K are more persistent.

Greater crop nutrient recovery has sometimes been recorded when fluid forms of nutrients have been deployed at similar nutrient rates compared to granular products. The improved availability of fluid P over granular P to crops grown on highly calcareous soils in South Australia is a good example (Lombi et al. 2004). The mechanism for this response was shown to be increased P diffusion away from the point of fertilizer injection, thus enhancing the volume of soil enriched with P and so accessible to plant roots. However, there are no reports of similar advantages for fluid forms of K fertilizer over granules, perhaps because of the generally greater solubility of K fertilizers. Choice of a fluid K formulation would be based on factors related to ease of application and the ability to blend different products rather than an expected increase in K use efficiency.

12.4 Quantifying Fertilizer K Recovery

There has been less research focused on the efficient recovery of applied K fertilizer by crops and the utilization of that K in the production of crop or forage biomass and harvestable yield than there has for nutrients that are more mobile and/or cause off-site impacts in the atmosphere or adjacent water bodies (i.e., N and P). While concerns about excessive K applications after land application of wastewaters do arise (Arienzo et al. 2009), most scientists consider excessive K application as reducing the profitability of crop production and an inefficient use of a natural resource, but not having off-site impacts on the environment. The K fertilizer placement method can have an impact on the K recovered by plants and what is removed from the field at harvest or recycled to the soil, but studies focusing on this issue are scarce. Research with corn (*Zea mays* L.) and soybean has demonstrated that banded K fertilizer almost always greatly increases the K uptake during vegetative growth periods relative to broadcast K application for several tillage systems (Mallarino et al. 1999; Borges and Mallarino 2000; Borges and Mallarino 2003), although the persistence of these effects through to maturity was not measured. However, the impact of increased K uptake with banding on net K removal will depend greatly on the crop species (Oltmans and Mallarino 2015) and the crop part harvested, such as biomass removed in forage or silage production compared to harvested grain.

The metrics used to quantify fertilizer K recovery by crops and the efficiency of use to increase yield are discussed in detail in Chap. 5. Interestingly, the use-efficiency data (mainly for cereal crops) suggest applied K is used less efficiently to produce additional grain yield than either N or P, which may reflect the lower critical grain K concentrations for these species and the fact that most crop K is returned to the field in roots and residues in these species. This is supported by published fertilizer K recoveries in crop biomass that are more in line with reported values for N and P (Fixen et al. 2015).

Reported fertilizer K recovery figures may underestimate crop uptake of applied K, as they are generally based on an assumption that only the additional crop K uptake in the fertilized treatments, when compared to a 0 K control, are due to fertilizer recovery. Given the impact of K fertilizer on soil solution K concentrations, especially in the vicinity of bands, and hence the likely improved efficiency of diffusive supply across a stronger concentration gradient to a plant root, there may well be some unaccounted preferential fertilizer K exploitation in the fertilized layers and some sparing of soil K reserves elsewhere in the soil profile.

The phenomenon of preferential fertilizer exploitation by crop roots has been commonly observed for P through the use of radioactive P isotopes, but there seems to have been little published work on the topic for K. There are real opportunities to re-examine the use of tracers like Rb to provide more accurate determinations of fertilizer K uptake and better assess the efficiency of different K application strategies. Strategies could include either enriching a K fertilizer band (Hafez and Rains 1972) or simply by using the relative abundance of K and Rb in unfertilized and fertilized treatments (Hafez and Stout 1973). The example of using Rb-enriched KCl bands provided in Fig. 12.3 illustrates the insights that can be obtained from using such techniques. In that study, biomass K concentration and plant uptake were similar in the banded treatments with K alone as in those with added P, or N and P. However, the Rb tracer data clearly illustrates more extensive exploitation of the fertilizer band, presumably sparing K reserves in the bulk soil, when these other nutrients were co-located with K in the fertilizer band.

12.5 Crop Characteristics Influencing K Application Strategy

To optimize recovery of applied K there must be a spatial coincidence of active roots and enriched K layers or patches. Several studies by Barber and collaborators, summarized in Barber (1995), have suggested that optimal K recovery required fertilizer K to be mixed through a greater proportion of the root zone than for P. However, the implications for fertilizer application strategy will vary with the physiological characteristics of the root cells, with the inherent root distribution of the different plant species or genotype and with the continuity of moisture availability in the fertilized soil layer.

A recent review by Fan et al. (2016) concluded that at least half of the total root mass of agricultural crops grown in temperate regions could be found in the top 20 cm of the soil profile, while Gan et al. (2009) suggested that these proportions may be conservative for a range of winter cereal, oilseed, and pulse crops (i.e., >75% of roots in the top 20 cm). These reports showed slightly shallower root distributions in temperate systems than the broader global analysis of Jackson et al. (1996), suggesting that effective K fertilizer strategies in temperate environments should be able to focus on the upper part of the soil profile—a zone that is relatively easily accessible to most fertilizer application/tillage equipment. However, the applicability of these results to rain-fed cropping systems in the more variable rainfall environments of the tropics and subtropics (Bell et al. 2009), or to flood-irrigated cotton on heavy clay soils (Lester and Bell 2015) is questionable. In such environments, either extended dry periods or excessive moisture and low oxygen availability limit root activity and nutrient acquisition from the uppermost zones of the soil.

An additional complication is apparent in no-till systems. While the proportional allocation of root biomass in the topsoil can be pronounced, the spatial heterogeneity of the root distribution may limit the effectiveness of exploiting this zone for K. For example, an analysis by White and Kirkegaard (2010) suggested that 20–30% of wheat roots at 20 cm were confined to pores and cracks wider than normal root diameters, with this proportion rapidly increasing to 60% by 60 cm and effectively 100% at depths of 80–90 cm. This “clumping” of roots around existing pores and root channels, rather than being distributed through the bulk soil, may have significant implications for the acquisition of a relatively immobile nutrient like K. Theoretically, new roots will exploit the same (previously depleted) soil volume around these channels, while homogenous fertilizer K distribution would be much less effective at replenishing depleted K soil around such biopores. These effects would likely be more pronounced in subsoils (i.e., >20 cm depth), where the interaction between the distribution of K bands, crop row spacings, biopore density, and soil water availability may explain the lack of consistent response to deep bands in the literature.

Given the limited evidence of increased root density in response to soil K enrichment in zones/patches, it could be assumed that enrichment of as much of the active root zone as possible would be a desirable strategy. Such an approach requires either redistribution of surface broadcast K into deeper layers with soil water movement (in light-textured soils), or through soil inversion/tillage—including occasional strategic tillage operations in otherwise no-till systems (Dang et al. 2015). The effectiveness of this general approach to K replenishment in the entire rooting zone will be determined by soil properties that regulate the extent to which K application increases soil solution K activity (e.g., K buffering) and the extent to which fertilizer K is fixed into slowly available forms by clay minerals. An example of where mixing K through a greater proportion of the root zone has been very effective is shown in Fig. 12.4, with crop biomass (15%) and K content (55%) increasing with the degree of profile mixing at the same rate of K application.

An alternative approach is employed when fertilizer K is banded, with very small soil volumes enriched. The effectiveness of this K application strategy could be considered risky in some soils, given the greatly reduced volume of fertilized soil and hence the smaller chance that enough roots will encounter K-enriched soil to optimize crop K uptake. However, co-location of K with other nutrients that do cause root proliferation such as P (Barber 1995; Ma et al. 2011) can be used to increase root density around the fertilizer band and enhance recovery of banded K (e.g., Fig. 12.3). There are limited reports of the benefits of this approach in the literature, although Brouder and Cassman (1994) were able to demonstrate enhanced K uptake in cotton in response to root proliferation in zones where K had been co-located with NH_4^+-N. A possible limitation with a strategy of nutrient co-location in bands is the potential to precipitate insoluble K minerals (pool 13—neoformed K minerals, discussed in Chap. 7), as a result of radical changes in the pH and ionic strength of the soil solution over short periods. Circumstantial evidence of this

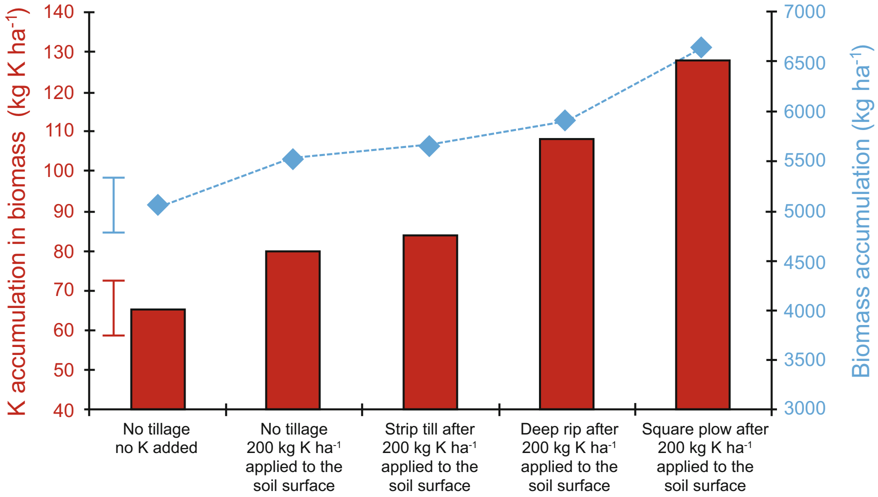

Fig. 12.4 Impact of various degrees of profile mixing on biomass production (diamond symbols) and K accumulation (solid bars) by a peanut crop grown on an Oxisol in NE Australia (Bell et al. 2009). Treatments range from a surface broadcast application with no incorporation, through to aggressive tillage with profile inversion (square plow) to a depth of 25 cm

phenomenon has been recorded in Australian studies (MJ Bell and DW Lester, unpublished data), but further definitive research is needed.

Finally, the K accumulation dynamics of different crop species may also influence the fertilizer application strategies. Different K application strategies may be suitable for crops in which the intensity of K demand varies within the growing season (e.g., due to the duration of the period of rapid K uptake or internal redistribution). As an example, crop K accumulation in a uniculm species like maize occurs mainly in a sharply defined period early in the growing season, well in advance of maximum dry matter accumulation (Welch and Flannery 1985). However, in species with a greater reliance on staggered tiller addition (e.g., grain sorghum), or in less determinate species such as cotton (Mullins and Burmester 1990) or soybean (Hanway 1985), K uptake occurs at lower rates over a longer period, mirroring dry matter accumulation. These differences in crop K demand may influence the choice of application method (banding vs. broadcast) and the timing of K application relative to crop establishment (Chap. 13), including the use of supplementary foliar K applications during periods of rapid K uptake (maize) or redistribution (boll loading in cotton).

12.6 Soil Characteristics Influencing K Application Strategy

The most obvious soil characteristic influencing K application strategy is the plant-available K status of the soil itself. There are consistent reports of negative K balances in many agricultural systems (Oborn et al. 2005; Rengel and Damon 2008; Bell et al. 2010) suggesting that depletion of native soil K reserves is widespread in agricultural lands. The first pre-condition for growers to commence a K fertilizer program will be a determination of the plant-available K status and an assessment of the likelihood of an economic response. This will involve the collection of soil samples representative of the available K status within the crop zone, followed by appropriate sample processing, analysis, and result interpretation. As mentioned previously, sampling strategies will need to consider the heterogeneity of K both vertically and horizontally due to differential K enrichment/depletion of profile layers and application of K bands—especially in reduced or zero-till systems. Research on K fertility assessments for different placement strategies and under different tillage systems is clearly required.

As outlined in Chap. 8, most commercial laboratory tests typically estimate plant-available K as the soil solution and adsorbed K pools measured as exchangeable K, although the latter may also contain some K from secondary phyllosilicate minerals, depending on mineralogy and extraction method. However, the dissolution of structural K may reduce the fertilizer K requirement (Moody and Bell 2006), while fixation or release of K from secondary phyllosilicate minerals during the growing season may increase or reduce the fertilizer K requirement, respectively. Identifying different K pools in the soil for which a fertilizer recommendation is being developed is the first step to determine a successful K fertilizer strategy. Unfortunately, the current lack of quantitative diagnostic tests to link the presence of these K pools to their likely release rates under varying rhizosphere conditions can make the decision to apply fertilizer K challenging. The development of simple laboratory indices for K fixation (Chap. 8) or the development of soil classification and landscape indices linked to the likely presence of mineralogy conferring particular K behavior (Chap. 7) may provide some benefits in this regard.

In soils with low BC_K [e.g., those with low CEC and low clay content—Barber (1985)], even small application rates of K dispersed through the soil volume can significantly increase the concentration of K in the soil solution (e.g., the Oxisol soil in Fig. 12.5) and ensure the development of stronger concentration gradients and more rapid diffusion rates of K to plant roots. In these situations, fertilizer K dispersed through the cultivated layer would be expected to result in high efficiency of recovery of applied K, because such applications would ensure exposure of a large proportion of the root zone to elevated soil solution K. In such soils, comparable RE_K values might be expected from banded applications only where soil structure and porosity were such that diffusive supply could efficiently occur over larger distances (i.e., strongly structured and with high permeability). In high rainfall

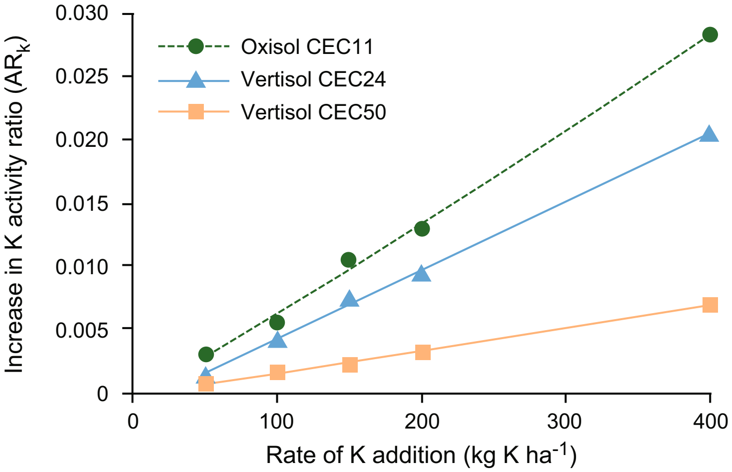

Fig. 12.5 The increase in activity of K in the soil solution (AR_K) in response to varying rates of K fertilizer application for an Oxisol (CEC 11 cmol(+) kg^{-1}) and two Vertisols (CEC 24 and CEC 50 cmol(+) kg^{-1}). Data calculated from Bell et al. (2009)

environments a subset of these soils with very low CEC (<5 cmol(+) kg^{-1}) may experience leaching losses of K, and in these cases split applications of broadcast K may be an appropriate way to ensure fertilizer K is available to meet crop demands and minimize luxury consumption of K by plants.

Conversely, in soils where BC_K is high (e.g., high CEC and high clay contents, such as in the CEC 50 Vertisol in Fig. 12.5), a much higher rate of applied K would need to be dispersed through the soil volume to generate significant increases in either soil solution K concentration or AR_K. As an illustration, the rate of applied K needed to achieve a specified change in AR_K in the CEC 50 Vertisol would be *ca.* 4 times that required to achieve the same impact in the Oxisol if the K were dispersed through the same soil volume. However, if the applied K is concentrated in fertilizer bands there is a much higher effective K application rate in a small soil volume and a much more substantial impact on soil solution K and AR_K. In these soils, banded applications should provide the opportunity for higher fertilizer K recovery efficiencies provided that sufficient root proliferation can be generated in the vicinity of the fertilizer band, or that the spatial density of banding is sufficient to ensure that a greater proportion of the crop root system has access to zones of elevated solution K. Clearly, more research is needed to explore the trade-offs between BC_K in different soil types and the effectiveness of banded or dispersed fertilizer K application strategies.

Similarly, soil physical properties are also likely to affect the efficacy of K application strategies within BC_K classes, with issues such as poor soil structure (e.g., in sodic soils) or compaction likely to reduce the effective diffusion path length, and hence the efficiency of K supply to roots. In such situations, an appropriate response may be to increase the density of K fertilizer bands to ensure a greater number of enriched K patches to compensate for the restricted diffusion path lengths around each band. In a similar vein, soils and cropping systems where moisture availability is seasonally limited will also experience reduced K diffusion rates (Mengel et al. 2001), potentially increasing the frequency of K responses provided crop demand is not substantially decreased simultaneously. Such conditions may prompt use of either higher K application rates (to ensure stronger concentration gradients) or placement strategies that ensure fertilizer K is placed where soil moisture status is more favorable for longer in the growing season (e.g., by placing K bands deeper in the soil profile).

There is little published information about how fertilizer K application strategies could be modified for soils where K fixation is significant. As noted by Blake et al. (1999), the recovery of applied K is typically lower on soils with significant K-fixing capacity (i.e., only 70% of that recorded on comparable non-K fixing soils in long-term fertilizer trials). A common application strategy is simply to increase fertilizer K rates to compensate for the lower recoveries. Theoretically, large rates of K addition would be needed to saturate the K-specific fixation sites before application rates that matched crop removal could be safely adopted (Mengel 2007). For nutrients like P, where strong precipitation or fixation reactions can reduce the fraction of the applied nutrient that is available for crop uptake in some soils, a strategy of minimizing the interaction between the fertilizer and the bulk soil by banding has been successfully used to slow the decline in plant-available nutrient and to improve crop recovery. The effectiveness of such a strategy for K in soils with significant fixation capacity or specific tillage systems may offer some benefits, and it may already be occurring in situations where the advantages of banding over broadcast K have been recorded (Bordoli and Mallarino 1998; Borges and Mallarino 2001). This is an area requiring further research.

A tentative framework for considering the impact of the key soil properties of BC_K and K fixation on the choice of fertilizer K application strategy is presented in Fig. 12.6. While hypothetical, it is based on the concepts discussed in this section and could provide the sort of framework upon which to base broader investigations of K application strategies.

12.7 Conclusions

The relative immobility of K in many soil profiles dictates that agricultural K inputs must be managed to ensure a coincidence of K-enriched soil with a significant proportion of the active root system during periods of high K demand. This creates challenges for fertilizer application strategies and equipment, particularly in systems where soil inversion and other forms of aggressive tillage are no longer practiced. A better understanding of the capacity of crop and pasture root systems to utilize K-rich patches (typically fertilizer bands) will be a key prerequisite for developing successful K management strategies, as will an understanding of the potential benefits that can be achieved through the co-location of different nutrients with K in bands to

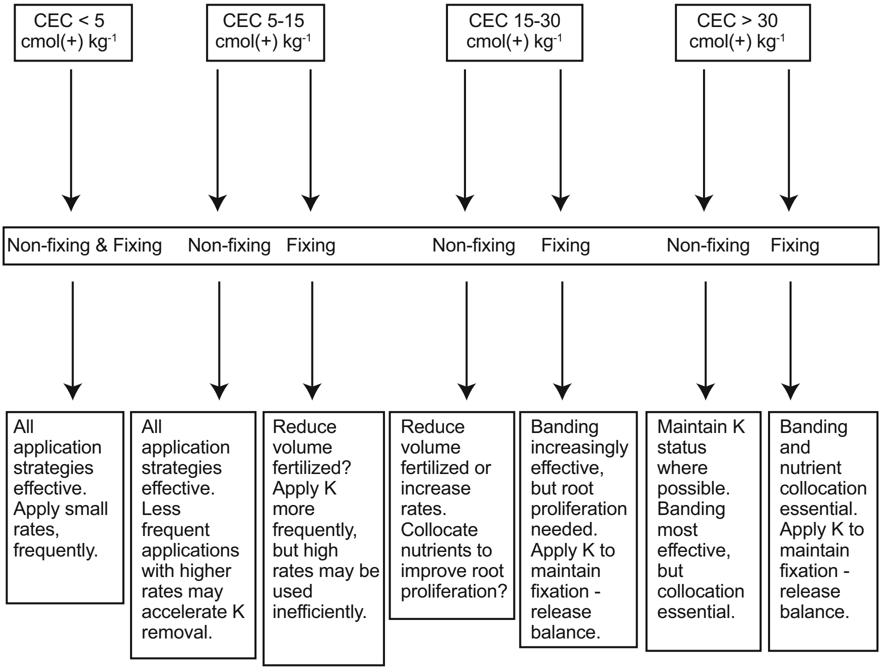

Fig. 12.6 A tentative framework for allowing for the likely impact of key soil properties on choice of banding or broadcast K fertilizer application strategy in the soil. The cation exchange capacity (CEC) classes are tentative at this stage, but a framework along these lines could produce a useful guide for agricultural land managers

encourage root proliferation. The appropriate placement strategy (e.g., depth, band spacing) will also be critical, and it will vary with soil type (e.g., water holding capacity in rainfed situations), climate (temperature and the frequency of effective rainfall events), and irrigation availability and method. However, in soils where CEC is moderate (10–15 cmol(+) kg^{-1}) to high (>15 cmol(+) kg^{-1}), there may be real advantages in applying large rates of K less frequently across a crop rotation, rather than applying lower rates on a crop-by-crop basis.

Conversely, in light-textured soils with low CEC and limited capacity to adsorb K, redistribution of applied K into deeper profile layers is possible if there is sufficient drainage, so a broader range of placement options appear to be available. The challenges in these systems relate more to ensuring that K remains in the crop root zone through the periods of peak K demand, and that leaching losses do not reduce the efficiency of K recovery and use. In these situations, K fertilizer management is likely to be on a crop-by-crop basis, possibly even requiring split applications within a crop season where the potential for leaching losses is high.

Successful soil K placement strategies will therefore need to reflect the interaction of plant, soil, and environmental factors. Development of effective strategies will require an improved understanding of the availability of fertilizer K added to soil, plant root system characteristics for different species in a rotation sequence, the response of roots to dispersed or concentrated patches of K (and other nutrients), and the dynamics of K accumulated in crop biomass and returned to the field in residues. This improved understanding will facilitate optimization of soil K placement strategies that may achieve more efficient use of the fertilizer K resource.

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