Predicting the potassium requirements of crops

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Abstract

There are a number of techniques for predicting the amount of fertiliser K required by crops. These include: maintaining soil test K at a target level; estimating the minimum K fertiliser required for a target yield; replacing the K removed by the crop, or applying sufficient K to maintain optimum ratios between Ca, Mg and K in the soil or plant. Any of these first three strategies, or a combination of them, may be suitable; the fourth strategy does not appear to be supported by scientific studies unless the cation ratios are extremely out of balance. This discussion paper examines the current methods of making K fertiliser recommendations for crops, and investigates whether there is a need for K to be included in decision support systems. The paper concludes that the soil test K method and the replacement K method are quite simple and do not need to be in a DSS. However the inclusion of K in a decision support system (DSS) would be convenient for those who use them already to predict nitrogen or phosphorus requirements, and a DSS would allow rapid calculation of costs if linked to fertiliser product and price lists. The strategy of determining the minimum K fertiliser required for a target yield is more complicated and probably best calculated using a DSS, however more research is required to estimate rates of soil K supply from non-exchangeable sources before such a DSS is developed.

Additional keywords: decision support system, fertiliser, soil testing

Introduction

Potassium (K) is an essential plant nutrient. Crop requirements for K are large, being exceeded only by nitrogen (N) (Marschner, 2002). For example, a 28 t ha^{-1} crop of maize silage will remove about 170 kg K ha^{-1} (Fleming, 2003). All or part of this K requirement may come from the soil, with the remainder being supplied by fertiliser or from large applications of manure or compost. The question a grower wants to know is “How much K should be applied?” To answer this question effectively a series of secondary questions need to be answered: “How much K can the soil supply? Should all the K that is removed from the soil be replaced, or can soil reserves of K be exploited?” and “Although average crop requirement may be 200 kg K ha^{-1}, can the same yield be produced with 100 kg K ha^{-1}?”

Making a fertiliser recommendation is a complicated process with a large number of factors to take into account. A recommendation can be done by an experienced agronomist or soil scientist or with a well-designed computer decision support system (DSS). A DSS can help to provide consistency in recommendations amongst different staff members and can be linked in with prices so that the most economic fertiliser choice can be calculated when there are a range of fertiliser combinations that could supply the recommended amounts of nutrients. The use of DSSs has been shown to help growers reduce their fertiliser use (Jamieson *et al*., 2006) which is important in an age where growers, consumers and regulatory bodies are becoming increasingly concerned about nutrient use efficiency and sustainability. A nutrient management plan is required for K (as well as N, P, and S) in the Code of Practice for Nutrient Management (FertResearch, 2007) that is part of the New Zealand quality assurance programme NZGAP (New Zealand Good Agricultural Practice). Efficiency of fertiliser use is becoming increasingly important as the cost of K fertiliser is rising quickly - tripling in the last twelve years.

There are a number of DSSs available to estimate the amount of nitrogen (N) that crops require: The Potato Calculator (Jamieson *et al.*, 2006), AmaizeN (Li *et al.*, 2006), *Sirius* (Jamieson *et al.*, 1998); and some that estimate phosphorus (P) requirements, e.g. APSIM (Keating *et al*., 2003). However to date there are no DSSs available in New Zealand that estimate crop K requirements. This discussion paper examines the current methods of making K fertiliser recommendations for crops, and investigates whether there is a need for K to be included in DSSs.

Forms of K in the soil

There are excellent reviews on soil K (e.g. Sparks, 1987; Kirkman *et al*., 1994; Mengel *et al*., 2001), but to provide essential background for this discussion paper brief information on the forms of K in the soil is provided here. Plants take up K as the K^+ ion from the soil solution. Potassium removed from the soil solution is rapidly replaced by exchangeable K (Figure 1). Exchangeable K is K that is attached to negatively charged sites on soil minerals or on organic matter. The exchange of K between the soil solution and exchangeable K sites is extremely rapid, with equilibrium between exchangeable K and solution K being restored within minutes or hours after K is removed from solution (Kirkman *et al*., 1994). Two way exchange also occurs between exchangeable K and lattice K, which is K that is bound between the layers of 2:1 minerals such as illite and weathered micas. The exchange between these two pools is much slower, with a new equilibrium being reached in several hours to several weeks after a disturbance in either pool (Kirkman *et al*., 1994). All of these first three pools of K are important for plant K nutrition within a growing season. The final pool of K in the soil is the structural K, which is part of the chemical structure of minerals such as mica, feldspar and volcanic glass. This K is very slowly available, with release of K from this source taking years.

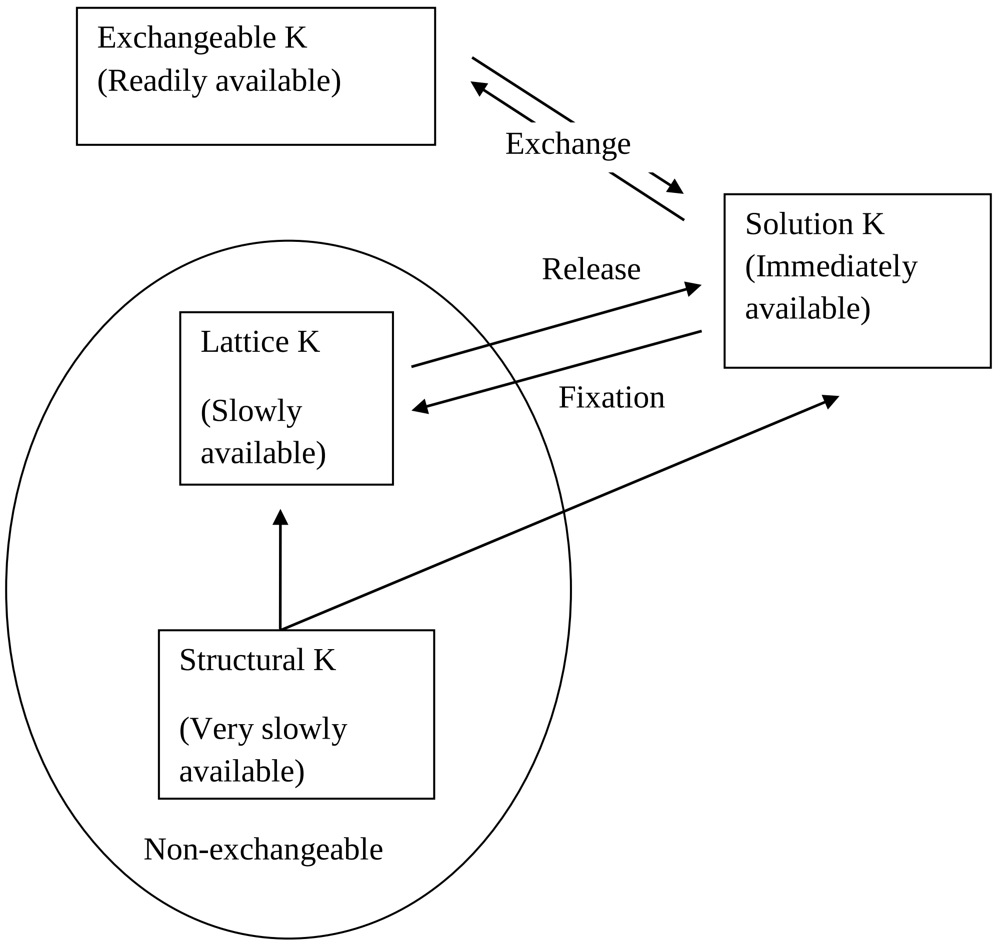

Figure 1: Forms of K in soil (adapted from Kirkman *et al.*, 1994).

Current methods for predicting soil K supply and soil fertiliser requirements in New Zealand

In the 1950s the Quick test (QT, Table 1) was developed to determine soil K status (Hogg, 1957). The QT extracts most of the exchangeable K. Hogg (1957) reported that crops grown on soils with a QTK of > 10 (approximately 0.4 meq K $100g^{-1}$) were unlikely to respond to added K. Hogg (1957) also acknowledged that the test did not work well on sedimentary soils that received <1100 mm of rain per year. These soils may have low QTK values, yet be unresponsive to K fertiliser. A more accurate method of measuring exchangeable K is leaching with 1 *M* ammonium acetate (Blakemore *et al.*, 1987), but this has the same limitations in predicting K responsiveness as QTK. Craighead and Martin (2003) found that the K response of main crop potato yield bore no relation to soil exchangeable K and suggested that the TBK test (Carey and Metherell, 2003a; 2003b; Carey *et al.*, 2011) may help with making K fertiliser recommendations.

Table 1: Soil tests to assess K availability.

Test	Abbrev.	Extraction procedure	Pools of K measured	Reference
Quick Test K	QTK	2 min. shake with 1 M NH_4-acetate (5 ml g^{-1} soil)	Sol. K + part of exch. K	(Hogg, 1957)
Exchangeable K	Exch K	Leach for > 1 h with 1 M NH_4-acetate (50 ml g^{-1} soil)	Sol. K + exch. K	(Blakemore *et al*., 1987)
Tetraphenyl boron K	TBK	Boil 4 h in 3 ml of 0.1 M NaTPB	Sol. K + exch. K + part of non-exch. K	(Jackson, 1985; Carey and Metherell, 2003a; 2003b; Carey *et al*., 2011)
Step K		Boil 2 g soil in 200 ml 1 M HNO_3 for 20 min. Subtract QTK	Part of exch. K + part of non-exch. K	(Haylock, 1956; Surapaneni *et al*., 2002a)
Intermediate K	K_{int}	Boil 2 g soil in 200 ml 1 M HNO_3 for 20min. Subtract exch. K	Part of non-exch. K	(Beckett, 1970; Hay *et al*., 1976)
Constant rate K	K_c	Average K released on repeated extraction with 1 M HNO_3	Part of non-exch. K, presumably primary mineral K and less available interlayer K	(Haylock, 1956; Metson *et al*., 1956)
Delta K	ΔK	$\sum$ six K extractions with 1 M HNO_3 - $6\times K_c$	Part of non-exch. K, presumably the more available interlayer K	(Metson *et al*., 1956)
Colwell K		Extract soil with 0.5 M $NaHCO_3$, pH 8.5 (1:50 ratio) for 16 h	Sol. K + exch. K + part of non-exch. K	(Colwell, 1963)

There have been a number of methods developed to measure the non-exchangeable K that can be supplied to a crop (Table 1). In the 1980s, Jackson (1985) developed a modified tetraphenyl boron test for K (TBK), which was designed to measure the amount of exchangeable plus mineral K in the soil that was available in the short term. Jackson argued that the existing QT had well recognised limitations on young sedimentary soils and that existing tests for measuring non-exchangeable K, such as constant rate K (Table 1), were relatively insensitive to management changes such as the addition of K fertiliser or crop removal of K. They were also not suitable for routine laboratory analysis. Jackson's test took 16 h, but this has been modified into a 4 h technique (Carey and Metherell, 2003a; 2003b; Carey *et al*., 2011). Similarly, Surapaneni *et al*. (2002a) simplified the step K procedure (Haylock, 1956; Table 1), and developed an index that proved to be better than reserve K in explaining variations in the uptake of non-exchangeable K by ryegrass in a pot trial.

Another test that has been reported to have some success in predicting the requirements of plants for K is the inverse of the buffer power (Schneider *et al*., 2003). The K buffer power b_K is the ability of a soil to maintain the concentration of K in solution when a portion of the K is removed. Schneider *et al*. (2003) determined the critical concentration of K in the soil solution of 15 soils based on measuring the concentration of K in plant sap. They found that the critical concentration of K in the soil solution differed among soils, and that it was highly correlated (R^2 = 0.98) with the inverse of b_K, or the inverse of the square of b_K (R^2 = 0.99). The problem in applying this approach is that b_K is not easy to measure routinely in the laboratory.

Problems with the current methods

The correlation between responsiveness to fertiliser K and either QTK or TBK is still low on some soils (Edmeades *et al*., 2010), possibly due to considerable plant-available K being present at depths lower than the soil sampling depth (Weeda, 1978; Williams *et al*., 1990; Carey and Metherell, 2003a). This is particularly true for pastures, where only a 7.5 cm deep core is taken, or in deep rooting crops, especially tree or vine crops in deep soils. For annual crops the sampling depth is 15 cm, which provides a better indication of K availability than a 7.5 cm sample. Haak (1981) found that spring cereals took up 80% of their K from the Ap horizon (0-25cm) and 20% from the subsurface horizon. One important fact to consider is that if large amounts of K are present at depth, they are not immediately available to the plant but do become available once the root front has moved down into that depth. Sampling to a greater depth should improve fertiliser recommendations for crops. This is much more laborious, but would not have to be done each year.

There have also been undocumented reports (D. Curtin, pers. comm.) of short term K deficiencies in spring cereals grown in parts of Canterbury. Many South Island soils (sedimentary soils) can supply large amounts of K from non-exchangeable sources (Miller, 1968a), however a reliable soil test is needed to identify these soils. Research to date on the TBK test has focussed on pastures (Jackson, 1985; Carey and Metherell, 2003a; 2003b; Carey *et al.*, 2011) and there has been little on rapidly growing crops. Maximum pasture growth rates are usually in the order of 90 kg DM ha^{-1} day^{-1} (Harris, 1990), whereas fast growing crops such as wheat (Jamieson *et al*., 1991) or maize (Wilson *et al*., 1995) may grow at more than two to three times this rate. Further research is needed to identify suitable TBK values for these fast growing crops.

Current methods for making fertiliser recommendations

In general, soil tests are used to help make fertiliser recommendations. Current fertiliser recommendations for K generally employ one of four strategies:

1. maintain soil test K at a target level (Clarke *et al*., 1986; Morton *et al*., 2000),
2. estimate crop K requirements for a target yield, and then apply the amount of K that is the difference between crop requirements and what is supplied by the soil (Wong *et al*., 2001; Yost and Attanandana, 2006),
3. replace the K removed by the crop (White, 2000),
4. apply sufficient K to maintain optimum ratios between Ca, Mg and K in the soil or plant (Graham, 1959).

Sometimes a combination of the above strategies is used; for example, the amount of K removed by the crop might be replaced if the soil test value is below or close to a target level, but if the test value is high then little or no K may be applied (e.g. Steele, 1984).

Maintain soil test K at an optimum level

This is a relatively straightforward technique that involves testing the soil, and if the soil test value is low then sufficient K is applied to raise the soil concentration to the desired value. As seen from the previous section on soil testing, there are problems with identifying what the optimal soil test K level is for some crops.

The optimum soil test value will change depending on a number of factors, such as crop type, soil mineralogy, cation exchange capacity (CEC), and the amounts of exchangeable Ca and Mg in the soil (Pettiet, 1988; Oliveira *et al*., 2001). Soils with a low CEC cannot hold as much K as soils with a higher CEC, and therefore the recommended K level for a low CEC soil will be lower than for a soil with a high CEC. In the New Zealand guide to fertiliser recommendations for vegetable crops (Clarke *et al*., 1986), this difference in CEC is crudely accounted for by having different target K values for soils with different textures. The effects of soil mineralogy are illustrated in the paper of Edmeades *et al*. (2010), which shows that pastures on andisols require a higher level of available soil K (as measured by the Quick Test) to achieve their yield potential than those on pumice soils.

Estimate crop K requirements for a target yield

The amount of K fertiliser required for a target yield may be determined by a fertiliser response curve or by models that predict how much extra K the crop will need above that which is supplied by the soil. Fertiliser response curves are limited by the fact that they relate to a specific crop grown on a particular soil type with particular management history. Beckett (1969) showed that soil K supply is significantly influenced by management history. Models are potentially useful but, currently, no model is available for making K recommendations for crops in New Zealand.

One of the reasons why no model is available is due to the difficulties in predicting soil supply discussed previously, but there are also difficulties in estimating minimum crop K requirements for a target yield. This is because some of the functions of K can be performed by other ions such as sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), ammonium (NH_4^+), some organic cations or other osmotica such as sugars or amino acids (Leigh and Wyn-Jones, 1984). The substitution of K by Na is demonstrated in the work of Mundy (1983), who found that ryegrass produced high yields when the leaves contained at least 4.8% K in the absence of Na; however, with abundant Na present, high ryegrass yields were achieved with leaf K concentrations of only 1.4%. Smith *et al*. (1982) found that the minimum leaf K concentration for maximum yields of lucerne was 2.8% when grown in with a low Mg supply, but only 1.9% when grown with high Mg supply. This indicates that the minimum crop K requirement for a target yield also depends on the amount of other cations present in the soil. If the goal of fertilising is to apply the minimum K for maximum yield, then a system of accounting for the amount of other cations in the soil is important. In New Zealand these other cations would be Mg and Ca, because Na concentrations are generally low (Miller, 1968b). There may be some interest in replacing a portion of fertiliser K with Na, since Na is cheaper than K. This may have some merit in pastoral systems where Na is beneficial to animal health (Smith and Middleton, 1978), but Na should be used with caution since it is more easily leached than K and can have detrimental effects on soil structure (Black and Abdul-Hakim, 1984).

Estimating crop K requirements for a target yield is the lowest cost fertiliser strategy, but applying the minimum K required for maximum yields without replacing the K removed will reduce the K-supplying power of the soil (Beckett, 1971). In situations where little K fertiliser is applied, this may accelerate weathering of K-rich minerals by plants because roots employ mechanisms to release mineral K (Hinsinger *et al*., 1993). One example of such a mechanism is proton release, where the release of H^+ solubilises the mineral, releasing K^+ into solution. This weathering leads to irreversible changes in soil mineralogy and permanently reduces the capacity of the soil to hold K (Surapaneni *et al*., 2002b). Release of K from soil minerals occurs at a significant rate once soil solution K concentrations drop below a certain threshold (Datta and Sastry, 1989; Hinsinger and Jaillard, 1993). Maintaining adequate soil solution K concentrations through K fertiliser addition may reduce or prevent K release from mineral sources (Datta and Sastry, 1989), and slow the changes in mineral K that occur under intensive cropping (Bortoluzzi *et al*., 2005). However, proton release may continue despite high soil solution K concentrations; for example, for the purpose of balancing excess cation uptake, or to induce P release from soil minerals (Grinsted *et al*., 1982). To develop a long-term sustainable fertiliser strategy it is important that further research is conducted on the effects of fertiliser K rate on the rate of mineral weathering under intensive cropping. It is likely that detailed mechanistic models will be required to understand the interactions between the uptake of K and other nutrients, and the acceleration of weathering induced by intensive cropping.

Replace the K removed by the crop

This strategy appears to be sustainable because it aims to maintain the soil in original condition. For this strategy it is important to know how much K is needed by the crop, because plants have the ability to take up more K than they require for maximum yield (e.g. Demiral and Koseoglu, 2005). For example, there is little point in applying 200 kg K ha^{-1} and producing a crop with K concentration of 3%, when the same yield could have been achieved by applying 100 kg K ha^{-1} with a crop K concentration of 1.5%. Although, in some cases, plant K concentrations above that required for maximum yield may be beneficial because crop quality is improved (Demiral and Koseoglu, 2005; Lester *et al*., 2010). The amount of K removed by the crop will depend on the amount of K available in the soil. British research (Allison *et al*., 2001) predicted that a 48 t ha^{-1} potato crop grown on a soil with a K index of 0 would remove 167 kg K ha^{-1}, whereas a 48 t ha^{-1} crop grown on a soil with a K index of 3 would remove 240 kg K ha^{-1}. Therefore soil tests or plant tests (preferably both) will be required to help decide what is a suitable amount of K to apply as replacement K. On soils with a high soil test K value the decision must be on whether K should be applied at all. Current recommendations for New Zealand arable crops are not to apply K if soil test values are above a certain value (Morton *et al*., 2000).

It is possible that replacement K may be inadequate on soils with extremely low plant-available K, since the amount of K required to grow a crop is more than what is finally removed at harvest. For example, K removed in the grain is less than half of the total K in a cereal crop, and less than one third of the total K in a maize crop (Fleming, 2003). However to the author's knowledge an instance where replacement K has been inadequate has not been reported in New Zealand.

Apply sufficient K to maintain optimum ratios between Ca, Mg and K in the soil or plant

In this strategy, sufficient K is applied to achieve desirable ratios between the other major cations in the soil: Ca and Mg. This strategy of fertilisation arose from work by Firman Bear and William Albrecht in the 1940s, and assumes that an 'ideal basic cation saturation ratio' of 65-85% Ca, 6-12% Mg and 2-5% K in the soil CEC will result in optimum crop growth and quality (Graham, 1959). The idea of optimum ratios is widely promoted in the USA, Australia and by a number of consultants and (minor) fertiliser companies in New Zealand. However, Kopittke and Menzies (2007) argue that subsequent work has found that several aspects of Albrecht's experiments were fundamentally flawed, and that the ratios between Ca, Mg and K generally do not influence plant yield within the ranges commonly found in soils. They state that the total availability or supply is typically more important. McLean *et al*. (1983) tested the concept of ideal basic cation saturation ratio and concluded that there was no ideal ratio of basic cations. Their results agreed with the statement by Kopittke and Menzies (2007) that what mattered was having sufficient quantity of each nutrient in the soil.

This conclusion agrees with experiments of Mengel (1963) and Wild *et al*. (1969). These authors examined K uptake from soil at a range of concentrations of Mg and Ca and found that K uptake was related to the concentration or activity of K in the solution, rather than being affected by its ratio with other cations. In contrast, the uptake of Ca (Ohno and Grunes, 1985) and Mg (Jakobsen, 1993; Marschner, 2002) is affected by competition or antagonisms from other cations. In the work of Adams and co-workers (cited by Black, 1993) the uptake of Ca was best described by the concentration of Ca relative to the proportion of Ca on the effective CEC. Aso and Bustos (1981) found that Mg deficiency symptoms appeared in lemons when the exchangeable K:Mg concentration was greater than 0.4. It may be that ions, such as K^+ and phosphate, that are usually found in low concentration in the soil solution (and are therefore often absorbed by active uptake rather than passive processes), are relatively insensitive to the activity of other ions (Black, 1993).

In more extreme situations high Mg or Ca may suppress K uptake. High concentrations of plant-available Mg in the serpentine-rich soils of California are known to suppress K uptake in grapes (Kocsis and Walker, 2003), and Mississippi cotton plants were K deficient when the base saturation for Mg exceeded 30%, even though adequate exchangeable K was present (Pettiet, 1988). Potassium deficiency was observed in a glasshouse experiment in soybeans when the ratio of exchangeable (Ca+Mg):K exceeded 36 (Oliveira *et al*., 2001). Havlin *et al*. (1999) argue that high concentrations of Ca^{2+} ions in calcareous soils can limit K uptake by competing for binding sites on root surfaces.

Use of soil tests to provide fertiliser recommendations for crops in New Zealand

Any of the first three of the four methods described in the previous section are useful for making fertiliser recommendations, provided potential limitations of each are taken into account. The section below outlines current methods for predicting soil K supply and soil fertiliser requirements.

For cereals the current recommendations are very simple: maintain soil QTK in the range of 5-8 (depending on the crop species), and if soil test values are below 6 or 7 (again depending on crop species), then apply K fertiliser. More K fertiliser is recommended where soil TBK values are less than 1-1.5 (Morton *et al*., 2000).

A standard text for fertiliser recommendations for horticultural crops in New Zealand is that of Clarke *et al*. (1986), which were last updated in 1996 (Wood, 1996). For vegetables, optimum soil QT test values are given, which vary depending on whether the soil is a sand, a loam or a clay. The recommendations also acknowledge that banding the K fertiliser by the seed can decrease the requirement for fertiliser K by 20-30%. These recommendations were published prior to the common use of the TBK test, so soil mineral K supply is not taken into account. Crop removal values for K are also given, which the grower can use to avoid the soil K level declining.

The need for a Decision Support System (DSS)

Regardless of the method chosen to make the fertiliser recommendation a DSS system could be used. For example, even the simple system of recommending K based on an optimum soil test value, which would normally be looked up in tables or calculated from rules of thumb based on soil type or texture, could be obtained from a DSS. This would be convenient if a grower or consultant already used a DSS to develop recommendations for N and or P, then a recommendation for K could be generated at the same time. If the DSS was linked to a fertiliser product and price list then the most economical way to apply the fertiliser could be calculated at the same time. This is particularly useful in a market environment where a large number of fertiliser blends are available. A DSS may also be useful if the grower does not have access to an experienced agronomist and has little knowledge on how to make their own fertiliser recommendations.

The lowest cost strategy of recommending the minimum K fertiliser required for a target yield requires knowledge of the amount of readily available K (exchangeable K), the rate at which non-exchangeable K will be released to the crop over the season, as well as an estimate of crop yield to enable crop K requirements to be calculated. Integrating these three factors may be most simply done using a DSS. However, more research is required to understand the rates of release of non-exchangeable K to fast growing crops and vegetable crops before such a DSS can be developed. A point to consider before spending a large amount of money on developing a system to recommend the least amount of K fertiliser for maximum yields is whether this strategy is the most suitable in the long term, because this method would lead to the fastest depletion of soil K reserves of all four strategies mentioned.

The strategy of applying replacement K could also be incorporated into a DSS. Some may argue that replacement K is not appropriate in soils that contain large amounts of K. Therefore replacement K is recommended only if the soil test K is below a certain value (e.g. Steele, 1984). There are opportunities to reduce K fertiliser recommendations using the replacement K strategy if K is replaced at the minimum K concentration for maximum yield, rather than average K concentrations. Similarly, if a better understanding of the substitution of K by other cations is developed, then it could be possible to reduce recommendations for replacement fertiliser K in these situations. This is likely to be complicated and require a DSS.

Conclusions

The main strategies for recommending K fertiliser are: maintain soil test K at a target level; estimate crop K requirements for a target yield, and then apply the amount of K that is the difference between crop requirements and what is supplied by the soil; replace the K removed by the crop; and apply sufficient K to maintain optimum ratios between Ca, Mg and K in the soil or plant. Any of these first three strategies, or a combination of them, may be suitable, and the fourth strategy may be considered if the cation ratios are extremely out of balance. The strategies that could currently be included into a DSS would be an optimum soil test value, or replacement K - with the proviso that replacement K was not applied if soil test values were high; these strategies are simple to use and do not need to be included in a DSS.

The strategy of supplying the minimum K for maximum yield requires knowledge of a number of factors, and may be best calculated using a DSS; however more research is required to determine rates of K supply from non-exchangeable sources before this a DSS can be created that uses this strategy. More research is also required to determine minimum plant tissue K requirements for maximum yields, and how plant K requirements change depending on the supply of other cations in the soil.

The main advantage of including K in a DSS system would be convenience for those who already use them, and it may be save time in calculating the best fertiliser option for blended products. A DSS is not likely to improve the accuracy of fertiliser predictions over existing techniques except in conditions where it is difficult to predict yield. Regardless of how accurate a method of estimating crop K requirements is claimed to be, there is no substitute for regular soil testing and monitoring changes in soil K over time.

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