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Long-term rundown of plant-available potassium in Western Australia requires a re-evaluation of potassium management for grain production: a review

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ABSTRACT

Negative potassium (K) balances on farmlands globally are widespread because fertiliser K input is often less than losses (leaching) and removal of K in hay, straw and grain, which leads to a rundown of plant-available K. When soil K reserves are not large and the plant-available K pools are not well buffered, the risk of K rundown in soils is high. In the south-west of Western Australia, soil K rundown, particularly by continuous cropping or in systems where a large portion of crop biomass is removed, is increasing the prevalence of crop K deficiency even on soils where K was not previously a limiting factor for crop yields. While fertiliser K is required for adequate supply of plant-available K, maximising K use efficiency is also important for cropping profitability and sustainability in dryland agriculture. Plant K uptake and use efficiency can be affected by soil types, crop species and sequences, seasonal conditions, and K management. In water-limited environments, crop K nutrition, especially root access to subsoil K, plays a crucial role in promoting root growth, regulating plant water relations and alleviating biotic and abiotic stresses. Optimised use of both soil and fertiliser K is increasingly necessary to sustain crop yields under stressed conditions in the context of K rundown in soils.

Keywords: crop K deficiency, crop stress, dryland cropping, fertiliser K, K use efficiency, potassium deficiency, potassium use efficiency, soil K supply.

Introduction

Crops and pastures require large quantities of potassium (K) since the K concentration for optimal plant growth is 20–50 g/kg of the dry weight of vegetative parts (Marschner 1995). However, K fertilisation in broadacre agriculture is still limited in many countries including Australia, and the supply of K to crops and pastures mostly relies on uptake from, and recycling of, plant-available K in soils. Based on agricultural production and fertiliser use data but excluding recycled materials and manures, Australia has a negative K balance of around 400 kt/year, which is a removal to use ratio of 3.2 across all agricultural areas (Norton 2017*a*). The rundown of soil K is also often accompanied by unbalanced fertilisation, e.g. sole application or overuse of nitrogen (N) and phosphorus (P) fertilisers (Römheld and Kirkby 2010; Zörb *et al.* 2014). In south-western Western Australia (WA), soils are derived from mostly ancient and highly weathered materials, and soil K deficiency has become increasingly common due to continuous removal of K in grain and hay (Weaver and Wong 2011; Bryce and Neuhaus 2020; Harries *et al.* 2021). An increasing frequency of K deficiency on a range of soil types has also been reported in Queensland, where the majority of the broad-scale cereal and legume crops grown on moderately fertile Black and Grey Vertosols with moderate to high clay contents are characterised by negative K balances (Bell and Moody 2001; Bedrossian and Singh 2004; Bell *et al.* 2008).

Agronomic practices and cropping sequences can affect soil K supply via K cycling. In no-till dryland farming, K is concentrated near the soil surface and becomes less available for plant uptake when frequent surface drying occurs. Stratification of K close to the soil surface is also exacerbated by K topdressing or K application in bands with seed (Seiffert *et al.* 1995; Ma *et al.* 2009; Bell *et al.* 2021*a*). Surface broadcasting of K fertilisers is favoured by some farmers to reduce application costs, but may not suit crop K uptake on heavier textured soils because there is insufficient penetration of K into the root zone of crops in clay-rich soils with moderate cation exchange capacity, e.g. in the Red Ferrosols and the Vertosols in north-eastern Australia (White 2002; McKenzie *et al.* 2004). In contrast, deep placement of K fertilisers can offer significant productivity benefits, especially in seasons where topsoils are dry for extended periods (Ma *et al.* 2009; Bell *et al.* 2015). The uptake of K by deep roots from the subsoil redistributes K to the surface layer and counteracts K loss via leaching from the surface soils (Edwards 1993; Barré *et al.* 2009). In this paper we review the limitations of soil, crop and farming practice to improving K use efficiency in dryland agriculture and develop strategies to address those limitations particularly with reference to the cropping systems in WA.

Soil K rundown

Temporal soil K changes

When first cleared of native vegetation for agriculture, most soils in south-western WA had adequate indigenous K for crop and pasture production (McArthur 2004). However, soon after establishment of pastures based on subterranean clover (*Trifolium subterraneum* L.) on sandy soils in the high rainfall areas (>800 mm), soil K deficiency became evident and regular K supply was required for pasture and crop production (Cox 1980). Subsequently, pasture K deficiency was reported in the medium rainfall areas (400–600 mm) (Wong and Witwer 1997). Since the early 1990s, soil K depletion and wheat K deficiency were apparent on sandy duplex soils in the Great Southern region of WA (Reuter *et al.* 1997; Wong *et al.* 2000; Brennan *et al.* 2004). The incidence of K deficiency on sand-plain soils (uniform deep sand) and sandy duplex soils (sand over loam, clay or lateritic ironstone gravel) has steadily increased (Brennan *et al.* 2004; McArthur 2004; Brennan and Bell 2013). Weaver and Wong (2011) reported that among 109 000 topsoil samples (0–10 cm) collected across the south-west of WA in 2009–2010, 8% of the soils had <35 mg/kg Colwell K (a responsive level for wheat; Wong *et al.* 2000), and 49% of the soils had <100 mg/kg Colwell K (a responsive level for subterranean clover-based pastures; Angell 1999). By comparison, Brennan and Bell (2013) reported a critical value for 90% relative yield in wheat of 32–52 mg/kg Colwell K on Tenosols, while Gourley *et al.* (2019) reported a critical value for 95% relative yield in pasture on sandy soils of 126 mg/kg Colwell K. More recently (Bryce and Neuhaus 2020), soil samples were analysed across agricultural zones in WA (Agzones, which are based on environmental regions giving similar crop performance). The locations of Agzones are shown in Fig. 1, with the distributions of soil types being illustrated for the Soil Orders of Australia Soil Classification (Isbell 2002). For the last 5 years, 15% of >195 000 topsoil samples (0–10 cm) across the agricultural zones contained <35 mg K/kg and 62% contained <100 mg K/kg, with the areas of lowest K status being in the coastal plain south of Geraldton and highest K in the drier eastern margins of the cropping zone (Fig. 2) (Bryce and Neuhaus 2020). Of greater concern, 42% of 66 000 subsoil samples (10–30 cm) contained <35 mg K/kg and 79% contained <100 mg K/kg (Fig. 3) (Bryce and Neuhaus 2020), indicating low quantities of available K below 10 cm.

The trends in soil K at 0–10 cm of six Agzones in WA from 1998 to 2021 are shown in Fig. 4, which summarises 690 000 soil samples analysed by CSBP Plant and Soil Laboratories. Time-series analysis of the 50th percentile data (median soil K) indicates non-stationary K status in all Agzones, i.e. a temporal decline exists. Linear regression shows median soil K was decreased (P < 0.05–0.001) by 2.6, 0.9, 0.9, 0.9, 0.8 and 0.7 mg/kg Colwell K per year from 1998 to 2021 in Agzones 4, 5, 2, 3, 6 and 1, respectively. A comparison of the percentile data with the critical value of Colwell K for all soils (45 mg/kg, Brennan and Bell 2013) shows that in Agzone 1, 25% of samples were near or below the critical value for the entire period and 50% of samples were below this value from 2017 to 2019. The 25th percentile for Agzones 2, 3 and 6 were also below the critical value in 2017–2019.

On-farm K balance

Declining soil K fertility on cropping farms is largely attributed to continuously negative K balances, i.e. K inputs (inorganic, organic) being less than K outputs (crop removals, losses via runoff and leaching, etc.). A survey of 184 fields from the WA grains belt in 2010–2015 showed that average K inputs per paddock-year were 4.6, 4.1 and 4.3 kg K/ha in the Northern, Central and Southern Agricultural Regions, respectively (Harries *et al.* 2021). By comparison, grain harvests in WA remove 5–10 kg K/ha, based on current yields and grain K contents of 4–5 kg/t in wheat and barley, 8.8 kg/t in lupins and 9.2 kg/t in canola (Table 1) (Harries *et al.* 2021). Consequently, K inputs to 90% of the fields were inadequate to balance crop K ouputs, despite increasing amounts of K fertiliser being used in recent decades (Harries *et al.* 2021). Even with annual fertiliser applications of 15 kg K/ha, which is above the median rate for farmers applying K fertiliser, there was an increment of Colwell K in the 0–10 cm layer, but not deeper in the soil profile (i.e. 10–50 cm) (Harries *et al.* 2021).

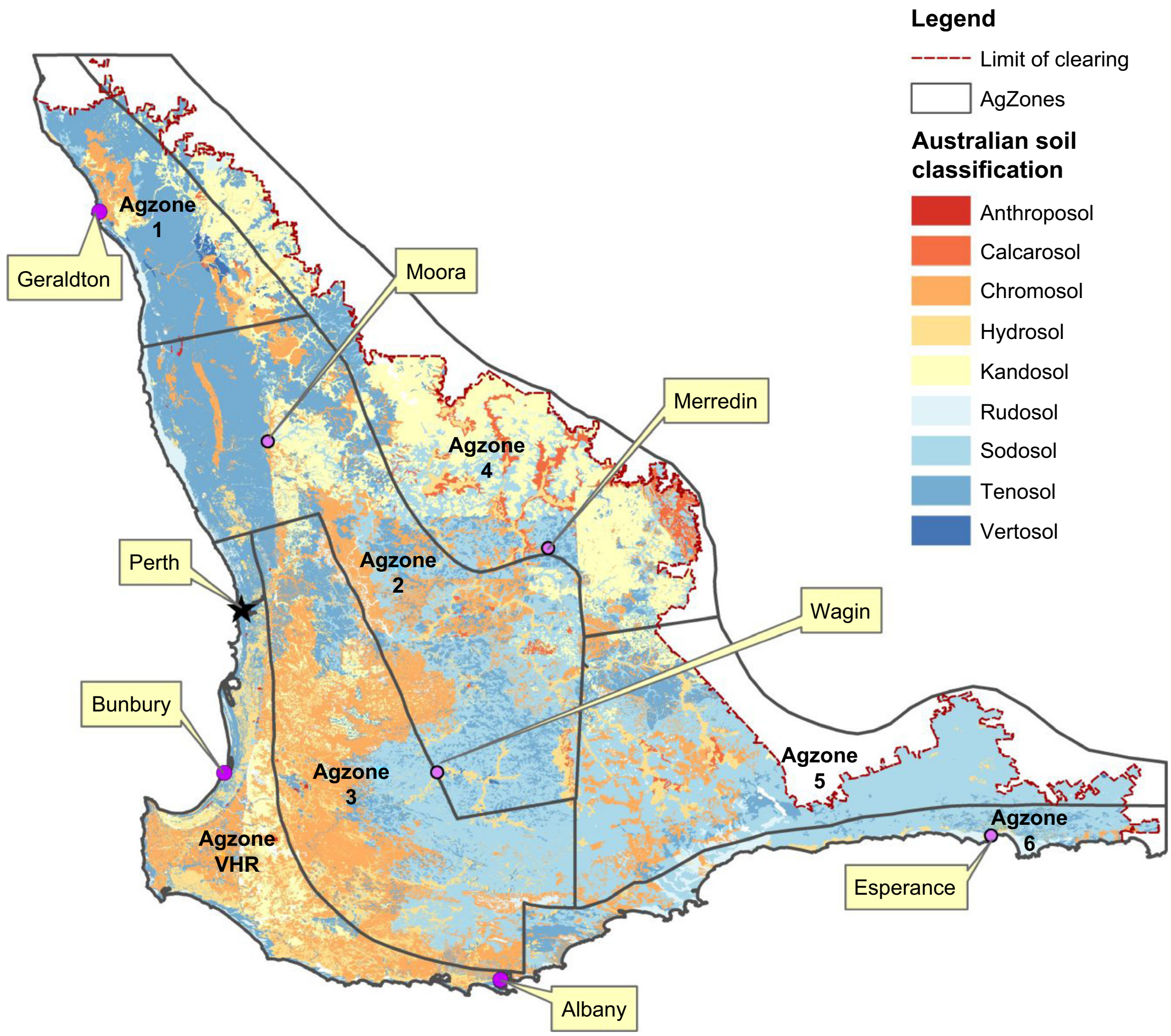

Fig. 1. Soil landscape mapping of all agricultural zones in Western Australia, grouped in Soil Orders of the Australian Soil Classification (Isbell 2002). VHR, very high rainfall.

In no-till farming, the return of K from crop residues to soil surfaces may mask the rundown of topsoil K, as shown in a 5-year experiment by CSBP on a deep sand at Esperance, where soil Colwell K was uniformly low up to 50 cm depth at the start, and modestly increased at 0–10 cm but declined at 10–50 cm at year 5 in the case of no input of K fertiliser (Fig. 5). However, a long-term study on sandy duplex soils at Newdegate Research Station from 1985 to 2005 showed that soil Colwell K (0–10 cm layer) consistently decreased at 1.6–5.1 mg K/kg per year in all 11 paddocks, and soil test K continued to decrease in the 0–10 cm layer after application of 20–50 kg K/ha when soil critical K was reached (<50 mg K/kg for cereals and canola, <80 mg K/kg for clover-based pasture) (Brennan *et al.* 2013). The rundown of soil K by cropping can be even more significant under hay production which takes away large amounts of nutrients from the soil, especially K, e.g. an oat crop (*Avena sativa* L.) removes 250 kg K in a yield of 10 t/ha in hay in WA (source: Summit Fertilisers). Therefore, cultivating high-yielding hay crops requires special attention to avoid soil K depletion.

Soil K cycling

Crop residue K

Crop residues contain the majority of absorbed K in cereals, e.g. >70% of it is in the straw of wheat and barley. With stubble retention and no-till, the residue K is recycled mostly to the topsoil and can be, in turn, available for the next crops. The straw of wheat at maturity in the WA fields contains around 8 kg K/t (Q. Ma, R. Bell, unpublished), and the residues of other crop species contain 9 kg/t in lupin, 8 kg/t in canola, 23 kg/t in oat hay and 14 kg/t in barley (Singh and Rengel 2007). Potassium release from crop

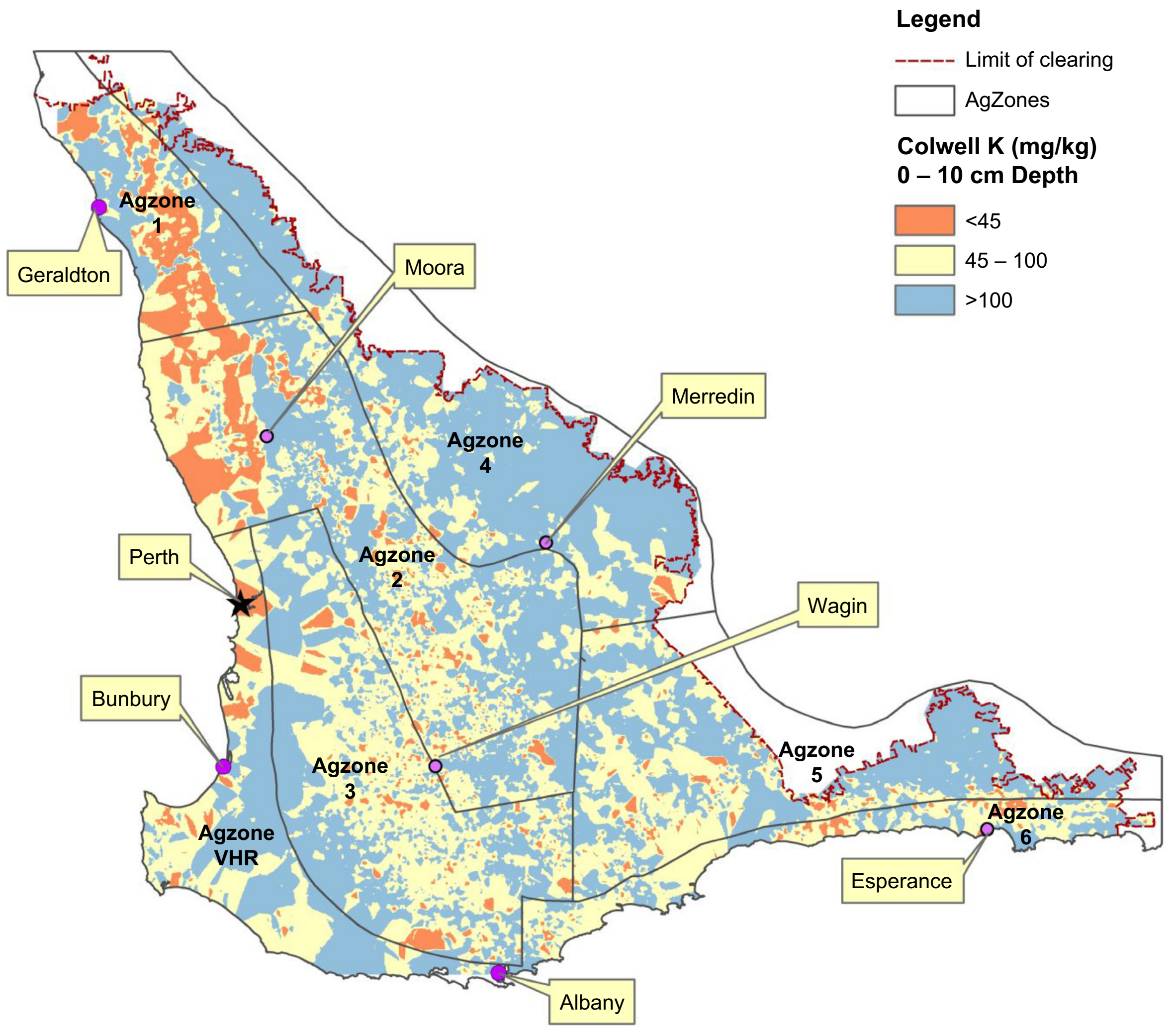

Fig. 2. A topsoil K map (0–10 cm) of all agricultural zones (refer to Fig. 1 for soil types) in Western Australia, based on about 195 000 data points from 2016 to 2021. Source: CSBP soil test results. VHR, very high rainfall.

residues is affected by plant species, rainfall and time after desiccation, and increases with physical treatments, e.g. humidification and particle size reduction (Collins 2009). Residues left on the soil surface under no-tillage decompose and release K more slowly than those incorporated into the soil under conventional tillage (Lupwayi *et al.* 2004, 2006). In the field, if heavy rains wash K out of the residues when there is no crop K demand, e.g. during summer in WA, the K may be lost via leaching in deep sands (Edwards 1993) or move into deeper root zones.

The amounts of residue K released in the field are estimated from 20 to 32 kg K/ha in wheat and 31–118 kg K/ha in legume green manures (Lupwayi *et al.* 2006). A study in New South Wales showed a K balance of +8 kg/ha with the retention of wheat straw, but −102 kg/ha with the removal of wheat straw (Whitbread *et al.* 2000). Removal of crop residues was responsible for negative K balances equivalent to −76 to −93 kg K/ha when no K fertiliser was applied to irrigated peanut crops on sands in southern-central Vietnam (Hoang *et al.* 2019). From our study in the Avon Valley of WA, straw redistribution by harvesters caused substantial differences in soil K collected under the windrows versus that between the windrows, with one site showing Colwell-K levels at 0–10, 10–20, 20–30 cm of 60, 35, 30 mg K/kg under the windrows and 43, 19, 19 mg K/kg between the windrows, respectively (Q. Ma *et al.*, unpublished). These results show that stubble retention and redistribution play a crucial role in soil K cycling and balance and need consideration when making K fertiliser recommendations.

Soil K leaching

Potassium is leachable in soils and its leaching losses can be expected when K supply exceeds soil retention capacity and the plant demand in well-drained soils (Johnston 2003). On sandy-textured soils that have low K adsorption capacities,

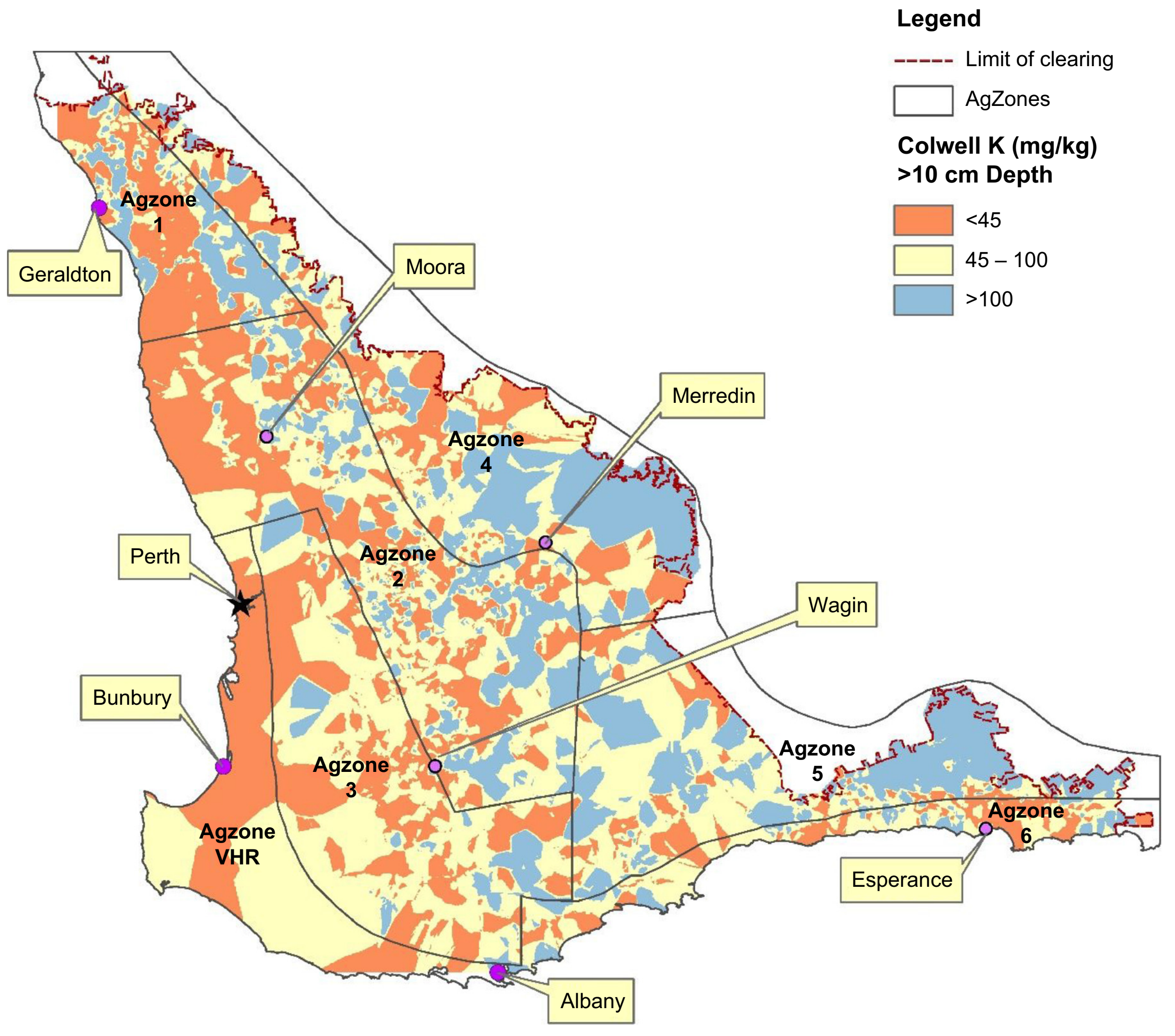

Fig. 3. A subsoil K map (10–30 cm) of all agricultural gzones (refer to Fig. 1 for soil types) in Western Australia, based on about 66 000 data points from 2016 to 2021. Source: CSBP soil test results. VHR, very high rainfall.

K leaching can be a significant contributor to poor K use efficiency in farming systems. When K fertilisers are applied to sandy soils causing localised K increases in the soil solution, K is susceptible to leaching by rainfall or irrigation water. Large amounts of soil K could move out of the root zone in pasture fields via leaching under >600 mm average annual rainfall in the south-west of WA (Edwards 1993). In intensively managed cropping systems, K leaching may closely correlate with nitrate-N leaching (Brye and Norman 2004), e.g. for silage maize production on sandy soils with conditions of high N leaching (86–152 kg N/ha), K leaching was large (6–84 kg K/ha) constituting a large proportion of the net K losses of 84–127 kg K/ha (Kayser *et al.* 2012).

Crop species differing in root depths and distributions may also affect soil K leaching and redistribution. A 4-year experiment on a sand-plain soil at Badgingarra in WA found soil K distribution changed little through the profile in the nil K treatment and showed a gradual increase in plant-available K down the profile where 40 or 150 kg K/ha were applied under continuous subterranean clover, but K at the soil surface increased even with nil K treatment under continuous *Lupinus cosentinii* (Edwards 1993). Annual net change in soil Colwell K with the treatments of 40 and 150 kg K/ha ranged from 45 to 67 kg/ha in the top 100 cm where *L. cosentinii* was grown, compared from 10 to −33 kg/ha with subterranean clover, indicating the redistribution of K from below 100 cm by the deep-rooted lupins. Hence, the losses of K via leaching may vary, from negligible as a result of subsoil K recycling under deep-rooted crops to significant under shallow-rooted annual pastures. For WA, more extensive studies of K leaching, covering a range of soil types, cropping systems and climatic zones, are needed since the above review has identified only one experiment on one soil.

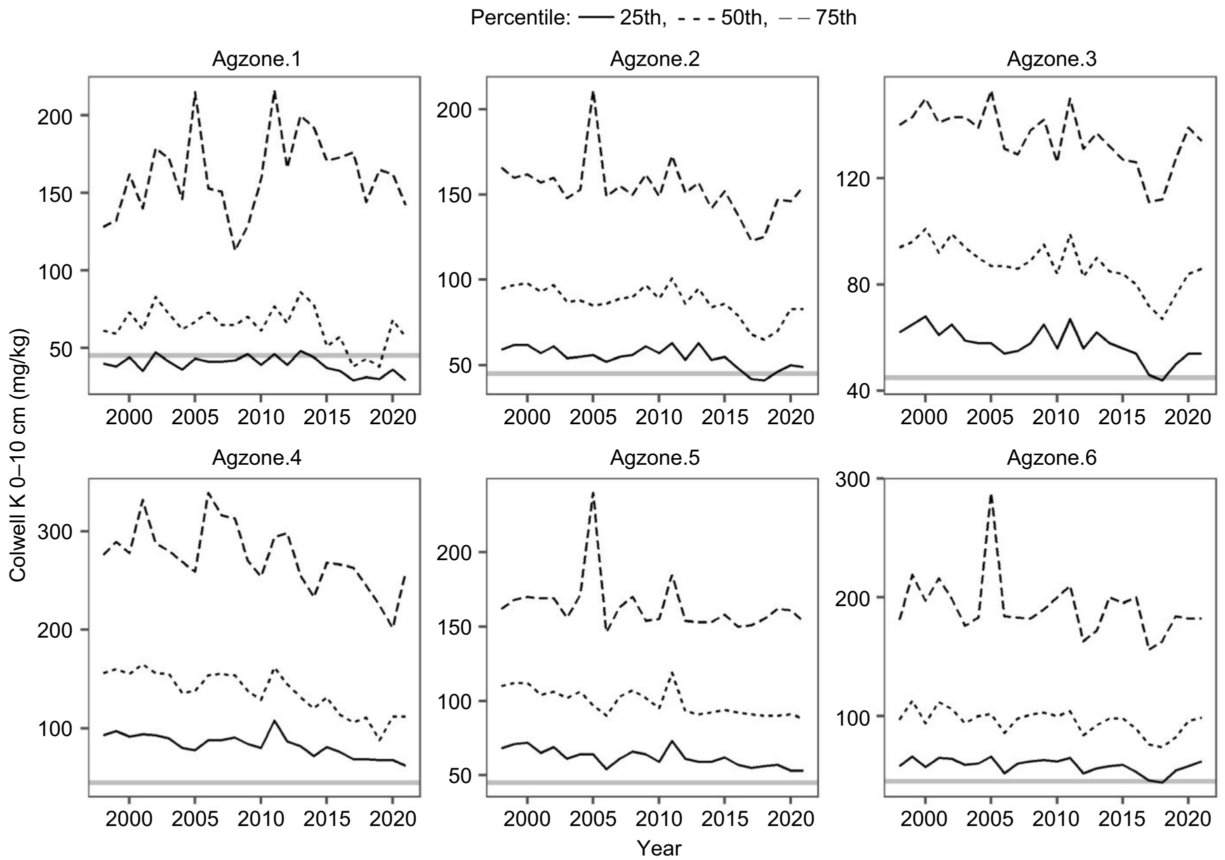

Fig. 4. Changes in the 25th, 50th (median) and 75th percentiles of soil Colwell K at 0–10 cm in six agricultural zones (refer to Fig. 1 for soil types and locations) of Western Australia from 1998 to 2021, including 690 000 soil samples (source: CSBP soil test results). The horizontal grey line indicates the critical level for wheat of 45 mg K/kg for all soils (Brennan and Bell 2013). Linear regression shows a temporal decline of the median soil K by 0.7 ($P = 0.048$), 0.9 ($P < 0.001$), 0.9 ($P < 0.001$), 2.6 ($P < 0.001$), 0.9 ($P < 0.001$), 0.8 ($P = 0.005$) mg/kg per year in Agzones 1, 2, 3, 4, 5, 6 respectively.

Table 1. Quantities of K removed from the field by crops in a Mediterranean climate and rainfed cropping system (source: Harries *et al.* 2021).

Crop species	Grain or seed (kg/t)
Wheat	4.0
Barley	4.4
Oats	4.0
Canola	9.2
Lupins	8.8
Chickpeas	8.9
Faba beans	9.8
Field peas	8.2

Subsoil K role

Although more than two-thirds of nutrients in the root zone can be found in the subsoil (Kautz *et al.* 2013), the uptake of subsoil nutrients is still poorly described due to a lack of adequate and simple methods for subsoil investigation and also the complexity by variable topsoil K contributions under different seasonal conditions. Kuhlmann (1990) provided a quantitative assessment of the contribution of subsoil K to the uptake by wheat (*Triticum aestivum* L.), and reported the proportion ranged from 7 to 70%, with an average of 34% in Luvisols of Northern Germany. Where subsoils below 15 cm depth were enriched with 100 mg K/kg in a column experiment, wheat and canola plants took up large amounts of subsoil K and increased shoot weight regardless of topsoil K levels (Rengel 2011). Rooting depth is an important determinant of K uptake from soils having significant resources of K at depth, which is common in temperate conditions and even more so when accounting for non-exchangeable K pools (Hinsinger *et al.* 2021). According to Witter and Johansson (2001), the deep-rooted lucerne (*Medicago sativa* L.) obtained about 67% of plant K from the subsoil, while ryegrass (*Lolium* spp.), with a fibrous root system, obtained only 42% of plant K from the subsoil under the same conditions. The differing ability of plant species to exploit K at depth reinforces the need to take subsoil K into consideration in future research and in

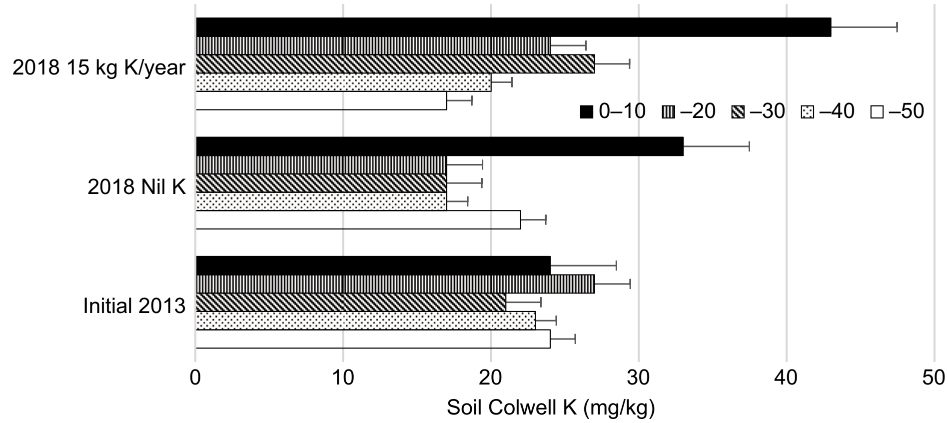

Fig. 5. Effect of nil or 15 kg K/ha.year on Colwell-K concentrations at 10 cm increments to 50 cm depth in deep sand at Esperance before and after 5 years of crop production. Capped lines are standard errors. Source: Scott Nelson, CSBP.

K fertiliser recommendations, as well as when selecting for more K-efficient ideotypes of crops in breeding programs (Thorup-Kristensen *et al.* 2020).

Clay mineralogy in WA soils

Clay mineralogy can determine the level of plant-available K in soils due to its effects on the mobility of soil K, cation exchange capacity (CEC) and non-exchangeable K fractions. Based on the Reference Soils in the south-west of WA (McArthur 2004), clay fractions are dominated by low-CEC kaolinite (30–80%) across the whole region, whereas high-CEC illite (5–30%) mostly occurs deep in the profile (>30 cm) of heavy-textured soils (e.g. red earth, red and yellow duplexes) in the eastern and northern areas. There were few sites that had significant smectite (20–50%) in the subsoil, with vermiculite (6–20%) mainly found in the southern area. Singh and Gilkes (1992) and Pal *et al.* (1999, 2001) also reported that 80% of the virgin soils from Geraldton in the north to the Great Southern district contained >75% of kaolinite in clay fractions, and the sand and silt fractions were dominated by quartz but also with considerable amounts of K-feldspars. Loam and clay soils in WA may contain large amounts of non-exchangeable K in the interlayer of clay minerals such as illite (Pal *et al.* 2001), but the effect of illite on K supply to crops has not been demonstrated. There is evidence that feldspars, that are relatively prevalent in soils of WA, can contribute significant quantities of bioavailable K to plants, potentially from sand-sized fractions rather than clay-sized fractions (Bell *et al.* 2021*b*). More research is warranted to investigate the role of non-exchangeable K and feldspar K in crop K supply and availability in order to better predict the rates of K rundown where negative K balances occur.

Crop K response

Soil K test

There are many analytical methods for soil K, but if a 'quick' pre-sowing soil test is used to predict bioavailable K for an annual crop, then exchangeable K is probably the best indicator of K that the crop is likely to access, despite different 'critical ranges' for different crops and the soils having different CEC (Bell *et al.* 2021*c*). Exchangeable K is generally determined by rapidly replacing K on the exchange sites, often with ammonium (NH_4^+), barium (Ba) or sodium (Na). The NH_4^+ ion has similar size, charge and hydration energy to the K^+ ion, and is most likely to replace K that is surface-adsorbed or located in readily accessible interlayer positions of soil minerals (Bell *et al.* 2021*c*). In Australia, the Colwell-K soil test (0.5 M $NaHCO_3$ extraction, Colwell 1963) is extensively used by soil testing laboratories and most frequently reported in the field datasets (Brennan and Bell 2013).

Soil K testing, in combination with crop response calibration curves, is a primary tool for predicting the likely yield loss from not applying K fertiliser. Critical soil Colwell-K ranges for achieving 90 or 95% of the maximum relative yield (RY) were mostly derived for wheat and canola from the Better Fertiliser Decisions for Cropping program (bfdc.com.au) but only for a limited range of soil types, e.g. sandy soils in WA, Tenosols and Kandosols (Brennan and Bell 2013; Speirs *et al.* 2013). Even within WA, there have been limited numbers of K-crop response experiments for the southern and central wheatbelt regions relative to the northern region (Anderson *et al.* 2015). The assessment of soil K supply for crop growth and yield has been mostly based on the 0–10 cm soil samples (Chen *et al.* 2009; Brennan and Bell 2013). The Colwell-K test at the top 10 cm is appropriate for wheat in Tenosols (deep sands;

Brennan and Bell 2013), where most of the available K is associated with organic matter, while the K concentration is generally low deeper in the soil profile (Wong and Witwer 1997). In the environments with low rainfall or periodical drought, however, the Colwell-K soil test at 0–10 cm may not be a reliable predictor of crop response because frequent surface soil drying can reduce the uptake of topsoil K while severe drought might prevent roots from growing deeper for access to subsoil K (Ma *et al.* 2009; Ma and Bell 2020; Bell *et al.* 2021*c*). The Colwell-K levels at 0–30 cm depth gave a better prediction of canola yield in soils of WA than at 0–10 cm depth (Anderson *et al.* 2015). However, for the widespread duplex soils (sand over loam, clay or lateritic ironstone gravel) the extractable K may increase, decrease or show no change in the subsoil relative to the topsoil (Edwards 1998; Brennan and Bolland 2006). A simulation (APSIM) of wheat response to subsoil K on deep sands and duplex soils suggests that with low K in topsoil, increased plant-available K in the 10–50 cm layer can significantly increase crop yield and net profit (Kautz *et al.* 2013; Scanlan *et al.* 2015*b*).

The critical Colwell-K ranges for crops vary with soil texture (Brennan and Bell 2013; Gourley *et al.* 2019). For example, the critical Colwell-K range at 90% RY at 0–10 cm for wheat varies from 32 to 52 mg K/kg on Tenosols to 57–70 mg K/kg on Brown Ferrosols (Table 2) (Brennan and Bell 2013). The sandy-textured soils (Tenosols and Kandosols) have much lower cation exchange capacities (CEC, 1–3 cmol$^+$/kg; McArthur 2004) than the heavier-textured Brown Ferrosols (9.5–10 cmol$^+$/kg; Bell *et al.* 2009). There is less confidence for grain crops in critical K ranges on the loam and clay-textured soils due to a scarcity of field experiments Australia-wide. In comparison, critical values for Colwell K (0–10 cm) in pasture are 126 mg K/kg in sand, 143 mg K/kg in sandy clay loam, and 161 mg K/kg in clay loam (Gourley *et al.* 2019).

K supply and crop growth

Limitations in soil K supply can directly limit root growth and seed size as well as tillering in cereals, and these effects are mostly attributable to a depression in K-regulated plant photosynthesis and assimilate translocation (e.g. Römheld and Kirkby 2010).

Table 2. Critical Colwell-K soil test ranges (mg/kg) at 0–10 cm for a variety of soil types (Brennan and Bell 2013).

Soil type	Wheat	Canola	Lupin
Tenosols	32–52	44–49	22–27
Tenosols (2–3 t/ha)	37–48		
Tenosols (>3 t/ha)	51–57		
Chromosols	35–45		
Kandosols	45–52		
Ferrosols (brown)	57–70		

Ranges are the 95% confidence interval associated with achieving 90% of maximum grain yield.

Roots, tiller, grain weight

Root growth is specifically limited by K deficiency. Tennant (1976) found that severe K deficiency stopped root growth of wheat completely at 10–12 days after planting. Potassium deficiency in an Inceptisol reduced root growth by 23% in lowland rice, by 30% in dry bean, by 12% in corn, and by 11% in soybean (Baligar *et al.* 1998). Soil levels of 15–30 mg K/kg caused a greater reduction in root growth relative to shoot growth of wheat during the whole growing period, i.e. a decreased root-to-shoot ratio (Fig. 6) (Ma *et al.* 2013). The decrease in root depth and density observed with K deficiency may in turn adversely affect nutrient and water uptake, and make the low-K plants more vulnerable to crop stress due to salinity, drought and frost in a water-limited environment.

Tillering and branching are also sensitive to K supply. Low K decreased the number of spike-bearing tillers per plant in wheat (Edwards 2000; Ma *et al.* 2013) and barley (Andersen *et al.* 1992; Mäkelä *et al.* 2012). In the field, K applied at sowing or up to 5 weeks after sowing was more effective for grain yield in wheat than later application (Ma *et al.* 2015), likely attributed to the beneficial effect of early K supply on tillering. Adequate supply of K to barley also improved straw strength and reduced head loss (C. Li, pers. comm.). Under K deficiency, narrow-leafed lupins would produce smaller, less-branched plants, and canola crops develop fewer, thinner flowering stems that set smaller pods (C. Scanlan, pers. comm.).

Soil K deficiency may produce small grains of crops by shortening the duration of grain filling (Marschner 1995). In wheat, the grain weight closely responded to soil K, increasing from 4 to 5 mg at 15 and 22.5 mg K/kg, 13–18 mg at 30 and 45 mg K/kg to 30–31 mg at 75 and 135 mg K/kg, which was consistent with the K-induced increases in leaf photosynthesis and K use efficiency in both

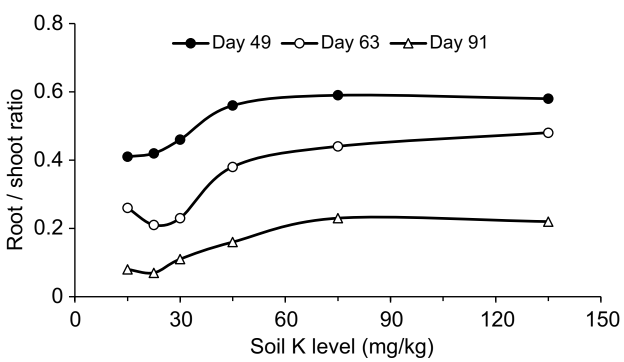

Fig. 6. The root/shoot ratio of wheat in response to soil K supply over time (Ma *et al.* 2013).

shoot biomass and grain yield (Ma *et al.* 2013). The fit of the APSIM crop simulation model for wheat grain yield was also improved by adjusting the rate of grain filling according to crop K status (Scanlan *et al.* 2015*a*).

Drought response

For a crop growing in increasingly dry soils, the maintenance of plant turgor and water uptake requires further reduction of osmotic potential by increasing cellular osmolyte concentrations. As the quantitatively most important osmoticum in plants, K is a main determinant of turgor for cell expansion and plays a central role in regulating stomatal aperture and water loss (Römheld and Kirkby 2010; White 2013). High K fertilisation frequently mitigates drought effects in particular in crops with small root systems, such as many legumes (Sangakkara *et al.* 2000). In dry soil, root growth is impeded and the smaller size of root systems leads to more reduction of K uptake (Hu and Schmidhalter 2005). Consequently, low K supply on dry soils may make crops less drought-resistant, which further impairs root growth and K uptake. Our field experiments with wheat grown on low K soils (25–40 mg Colwell K/kg at 0–30 cm) in the central and southern grain belts of WA showed that K treatments (20–80 kg K/ha) enhanced K uptake, dry matter and grain yield (by 0.3–0.6 t/ha) at the drought-affected sites but not at the non-stressed sites (Ma *et al.* 2015; Bell and Ma 2017). The findings suggest that drought stress may increase plant K requirement, and higher than normal fertiliser K supply on low K soils is likely to improve crop adaptation to low rainfall environments.

Frost response

High K supply can alleviate frost damage in potato (Grewal and Singh 1980), tomato, pepper and eggplant seedlings (Hakerlerler *et al.* 1997). Prompted by anecdotal reports from the WA growers and agricultural advisers that wheat crops are often more susceptible to frost damage on low K soils, field experiments were conducted to assess the alleviating effect of K on frost induced sterility (FIS) in wheat (Bell and Ma 2017; Ma *et al.* 2019). Soil K supply at 20–80 kg K/ha decreased FIS by 10–20% and increased grain yield by 0.2–0.4 t/ha. The decrease in FIS of wheat by K fertilisation was associated with increasing leaf K concentrations in the range of 1.5–2.6% at anthesis, higher leaf photosynthesis and lower activity of reactive oxygen species. However, there was no further reduction in FIS at leaf K >2.6% at anthesis. Similarly, on a sandy soil containing 22 mg Colwell K/kg at 0–30 cm at Lake Grace WA with multiple frost events in 2016, applying 20 kg K/ha reduced FIS by up to 20% and doubled grain yield in wheat (0.5 t/ha at nil K to 1.1 t/ha with K, likely due to a combination of lowered FIS and increased viable tillers). Therefore, unless frost events are too severe, improving plant K status is able to increase grain set and alleviate yield loss in wheat.

Potassium use efficiency

In south-west WA, the incidence of K deficiency has increased steadily, and the profitability of crop production on marginal soils relies increasingly on the supply and use efficiency of K and other nutrients. Potassium efficiency is a measure of genotypic tolerance to soils with low K availability and can be quantified using the ratio of growth and yield at deficient to adequate K supply (Damon and Rengel 2007). Potassium use efficiency (KUE) is defined as yield per unit K available to a crop, which is equal to the product of K uptake efficiency (crop K content per unit K available) and K utilisation efficiency (yield per unit crop K content) (White *et al.* 2021). In the field, partial factor productivity (PFP, ratio of crop yield to nutrient applied) is also used to measure nutrient use efficiency, e.g. 85 kg yield/kg K applied in the central and northern agricultural zones and 77 in the eastern agricultural zone in WA (Norton 2017*b*). However, there have been no reports on agronomic KUE, i.e. the increase in grain yield with K fertiliser relative to nil K fertiliser divided by fertiliser K input for contemporary crops grown in WA. Given the diversity of soils, growing environments, the changes in cropping systems and the impact of climate variability, there is a need for deeper insight into the efficiency of crop K use currently. The knowledge of agronomic KUE by individual crops would improve decision support systems for K fertiliser management, particularly on low K soils.

Crop species

There is considerable variation in KUE among and within crop species using a range of strategies to increase K uptake and utilisation (see reviews by Rengel and Damon 2008; White *et al.* 2021). In brief, K uptake efficiency is often correlated with exudation of organic compounds that release more non-exchangeable K, high root-to-shoot ratios, high root length densities and transpiration rates, and efficient utilisation via effective K redistribution within the plant, tolerance of low tissue K status, efficient regulation of photosynthesis and high harvest index (Rengel and Damon 2008; White *et al.* 2021). In WA, earlier research showed that KUE differed among commercial cultivars of wheat and canola (Damon *et al.* 2007; Damon and Rengel 2007), but none of the cultivars in the study are still widely grown. A field study also found that cultivar KUE was affected by drought, e.g. the K-efficient wheat cv. Carnamah had little yield response to K supply compared with the less efficient wheat cvv. Wyalkatchem and Bonnie Rock that responded to 40–120 kg K/ha (Q. Ma *et al.*, unpublished).

Crop species also differ in K requirement for growth and pattern of K uptake during the growth cycle. Both wheat and canola have the same critical soil K concentrations of 41–49 mg Colwell K/kg (Brennan and Bell 2013), but canola was better able to obtain K from the soil than wheat while wheat used the K taken up more effectively than canola to produce shoots and grains (Brennan and Bolland 2007, 2009). In wheat, most K uptake occurs as the shoot is undergoing its rapid phase of growth (Gregory *et al.* 1979) and minimal K is taken up after anthesis (Rose *et al.* 2007; Ma *et al.* 2013). Shoot K accumulation in wheat during early growth followed by K redistribution during later growth suggests a need for K fertilisation early in the season for wheat, especially on sandy soils with low K buffering (Ma *et al.* 2015). By comparison, soil K availability post flowering can be more important to canola than to wheat (Rose *et al.* 2007).

Agronomic practices

Deep placement (including P)

Placement strategies can be a key determinant of efficient use of applied fertiliser K, given the relative immobility of K in all except the lightest textured soils or high rainfall environments (Bell *et al.* 2021*a*). For logistical reasons, WA growers often broadcast K fertilisers on dry soils before sowing. However, the efficiency of broadcast application for K supply to the crop depends on the extent to which either tillage or rainfall can redistribute K into the soil profile where roots can access the applied K. Banding K with or below the seed at sowing may be more effective in the heavier-textured soils with a large capacity to fix K because of less contact between fertiliser and soil clay (Mallarino and Murrell 1998; Mallarino *et al.* 1999). In the soils where CEC is moderate (10–15 cmol/kg) to high (>15 cmol/kg), there are real advantages in applying high rates of K less frequently across a crop rotation rather than low rates on a crop-by-crop basis (Bell *et al.* 2021*a*). Conversely, in light-textured soils with low CEC and limited capacity to adsorb K, K fertiliser management is likely to be on a crop-by-crop basis, possibly even requiring split application within a crop season where the potential for leaching losses is high (Sitthaphanit *et al.* 2009; Bell *et al.* 2021*a*).

In water-limited environments where surface soil is prone to drying, stratification of K and P close to the soil surface may reduce nutrient availability and plant uptake since root growth or diffusion of K and P to the root surface is restricted. Yield responses of winter crops to deep-placed fertilisers mostly occur on infertile sandy soils in low rainfall regions of southern Australia (Ma *et al.* 2009). Deep placement of K also offers significant benefits to crop productivity in the northern Vertosols of Queensland, especially in seasons where topsoils are dry for extended periods (Bell *et al.* 2015). Moreover, since root proliferation occurs in concentrated bands of nutrients for N and P, but not for K (Drew 1975), banding K and P or K and N together may increase K aquisition by plants (Ma *et al.* 2007; Bell *et al.* 2021*a*). The most successful placement strategies will reflect the interaction of plant, soil and climatic conditions to achieve efficient use of the fertiliser K resource.

Liming

Liming is widely practiced to slow down soil acidification and maintain non-limiting soil pH levels, which can be just as important as applying fertiliser for maximising yields in farming systems. Liming also provides Ca to acidic soils where Ca deficiency may occur. In south-west WA, lime (~40% Ca) is often applied at rates of 1–4 t/ha on acidic soils and gypsum (~23% Ca) is also used as a Ca supplement for soil amelioration, commonly prior to planting. Calcium can stimulate net uptake of K on acidic soils and shift the uptake ratio in favour of K at the expense of Na under saline conditions (Marschner 1995). In a CSBP trial conducted on a deep grey sand near Bolgart in 2011–2016, lime (nil or 3 t/ha in 2011, 2.6 t/ha in 2014) and fertiliser K (nil, 15, 30 and 60 kg/ha each year except 2015) were applied to wheat in 2011–2014 and barley in 2016 with volunteer pasture in 2015. Applying K increased wheat and barley yields, e.g. from 1.5 t/ha at nil K to 2.7 t/ha at 15 kg K/ha in wheat, with only marginal additional yield increments at 30 and 60 kg K/ha. Lime also increased plant growth and K uptake by changing soil pH but had little effect on yield response to K fertiliser (Easton 2017). Our recent research showed that lime application (2 t/ha) to an acidic sand delayed the peaks of K^+ and nitrate (NO_3^-) leachings and reduced the total amount of leached K+ and NO_3^- through the effects of increasing soil $pHCaCl_2$ (4.5–6.2) and CEC (2.67–5.11 cmol/kg) in these variably charged soils (Motesharezadeh *et al.* 2021).

Claying and deep ploughing

Claying is often adopted on sandy soils to overcome soil water repellence and improve nutrient retention and water-holding capacity (Hall *et al.* 2010). Clay spreading or delving can increase crop yields on sandy soils by up to 130% (Davenport and Masters 2015). Subsoil claying and deep ploughing may carry a potential risk for crop growth and nutrition in association with the properties of subsoil clay and/or the method of application (Davies *et al.* 2012; Roper *et al.* 2015). The fixation of P and K by clay and calcium carbonate has implications for plant P and K supply (Weil and Brady 2017). In contrast, field experiments have shown significant improvements in plant K nutrition by amending sandy soils with subsoil clay, predominantly of kaolinite which is inherently high in exchangeable K, relative to untreated soils (Hall *et al.* 2010, 2015), but this response was generally limited to the soils initially low in Colwell K (<60 mg/kg; Bell *et al.* 2018).

Nitrogen

Nitrogen management can be a tool to increase plant K use efficiency (Alfaro *et al.* 2017). Conversely, under K deficiency crop response to increasing N supply is small and the yield may be even depressed at high N level (Marschner 1995). When canola was grown on N- and K-deficient sandy soils in the south-west of WA, there were consistently positive N and K interactions, showing significant yield response to applied N rates at 30 kg K/ha but no further yield increase at 60 kg K/ha (Brennan and Bolland 2007). Potassium can also increase plant utilisation of soil and/or fertiliser N, grain yield and quality in cereals by enhancing N uptake and translocation into grain (Fig. 7) (Pluske 2000). The increase in N use efficiency by K supply would not only increase yield productivity, but reduce any unused fertiliser N loss from the soil and economic loss (Zhang *et al.* 2010; Zörb *et al.* 2014). The N–K interactions are likely to become more significant in water-limited environments, considering the roles played by K in promoting root growth (Ma *et al.* 2011, 2013) and optimising plant water relations (Römheld and Kirkby 2010). The optimisation of N and K supply for major crops is necessary for better nutrient management practice in the WA soils, where K deficiency is becoming increasingly common.

Fig. 7. Potassium-deficiency symptoms (marginal and leaf tip yellowing of old leaves and delayed heading) at 40 mg K/kg soil on wheat cv. Wyalkatchem were eliminated by adding 50 mg Na/kg soil.

Sodium substitution

Plants need a relatively small amount of K for specific functions in the cytoplasm, while a major portion (90%) of K acts as an osmoticum in the vacuoles (Subbarao *et al.* 2000) and Na can partially or substantially replace K in this role (Marschner 1995). Although the beneficial effects of Na on plant growth are obvious in sugar beet, a natrophilic (salt tolerant) crop (Wakeel *et al.* 2009, 2010), the majority of agricultural crops are characterised by more-or-less distinct natrophobic behaviour (salt sensitive). According to Zörb *et al.* (2014), the substitution of K by Na is about 60% in the cells of sugar beet compared with less than 15% in wheat. Our pot and field studies showed that at low K supply growth stimulation occurred in wheat treated with 25–50 mg Na/kg (Fig. 8) and in salt-tolerant barley and canola with 100 mg Na/kg (Ma *et al.* 2011, 2015; Krishnasamy *et al.* 2014; Ma and Bell 2016). The Na alleviation of K deficiency in barley may be explained by two distinct mechanisms: low Na stimulated plant growth mainly via increased K uptake, whereas moderate Na induced more growth mainly by functional K substitution (Hussain *et al.* 2021). In WA, low K soils are often accompanied with 50–100 mg Na/kg within the soil profiles in Yellow Deep Sands and Pale Deep Sands, and also in Grey Shallow Sandy Duplexes and Grey Deep Sandy Duplexes while toxic Na levels occur in the subsoil of some duplex soils. On moderately saline/sodic

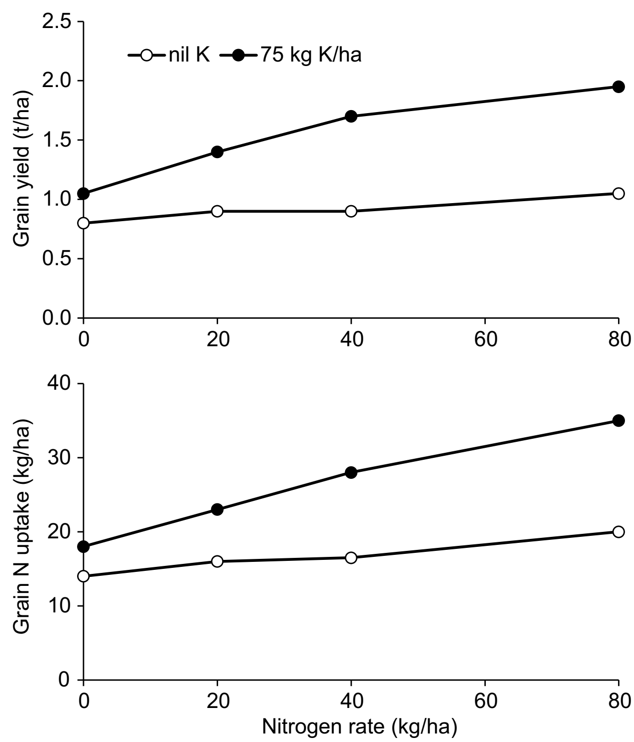

Fig. 8. Potassium supply increases N efficiency in grain yield and N uptake of wheat at Wongan Hills, WA. Source: Pluske (2000).

soils, the difference in K and Na uptake and use between crop species hasan implication for K fertiliser management. More field work needs to assess the possibility of reduced requirement for K by crops on low-K soils that contain low to moderate exchangeable Na levels.

Potassium modelling

Various mechanistic mathematical models have been developed to predict K acquisition by plants from the soil (e.g. Barber 1995; Jungk and Claassen 1997; Tinker and Nye 2000; Scanlan *et al*. 2015*a*, 2015*b*). These models take into account physiochemical processes in the soil as they influence the transport of nutrients through the soil to the rhizosphere and uptake across the root-cell plasma membrane. By and large, the models have been successful in their prediction of K uptake under the conditions of adequate supply, but have under-predicted K uptake at restricted supply. The models have not taken into account the morphological and physiological plant adaptations, e.g. root hairs and exudates, the effects of drought and subsoil K (Römheld and Kirkby 2010; Scanlan *et al*. 2015*a*, 2015*b*). The NST 3.0 model (Claassen 1994), by taking into account the root length and root hairs, demonstrated major differences in K uptake efficiency among maize, wheat and sugar beet in a pot experiment (Samal *et al*. 2010). Sugar beet accumulated more shoot K as a result of a 3- to 4-fold higher K influx compared to wheat and maize.

A K module for the APSIM crop simulation model has been developed for predicting shoot growth, shoot K concentration and grain yield of wheat from K fertiliser supply on sand and sandy duplex soils (Scanlan *et al*. 2015*a*). In the model, root K uptake is simulated based on the concentrations of K in the root system and soil solution, and an equilibration between the root and shoot concentrations. Photosynthetic assimilation rate and water-use efficiency are modified in accordance with shoot K concentrations. Overall, the model provided a satisfactory match to the calibration data set for topsoil K, grain yield and shoot K concentration in early growth stages, but model predictions were most sensitive to the parameter that describes the shape of the K adsorption isotherm. Some discrepancies between simulation and measurement are related to root distribution through the rooting layers and K uptake from the subsoil. Nevertheless, the modelling simulations provide a useful approach for estimating crop K uptake and soil K balance on soils where the plant-available K is predominantly in the exchangeable fraction. Changes to the model may be necessary for it to predict K uptake and growth of crops on soils that take into account non-exchangeable K supply, previous crop stubbles, K leaching, and the K–N interaction.

Future research

Soil K-test methods

A robust K recommendation should include not only the two-factor correlation between soil test K and crop yield, but consider geography and other covariates that may explain variation in yield response across space and time (Brouder *et al*. 2021). Critical levels for soil test K are likely associated with clay type and content, soil CEC and non-exchangeable K. For example, illite is a significant clay mineral in some soils but its role in non-exchangeable K supply to crops has not been well examined in the WA grainbelt soils. Moreover, feldspars, that occur in granitic soils, may contribute K supply in the short and long term. Therefore, more research is needed to characterise the relationship of soil clay, CEC, non-exchangeable K and feldspar K to soil K availability, and determine whether revised critical ranges, a new test or adjusted extractants need to be developed for K soil testing on loamy and clay soils. The influence of soil exchangeable Na levels on the accuracy of K response predictions also needs to be resolved.

Soil K balance

As the use of K fertiliser increases, there is a need to better understand the K balance and cycling in order to develop cost effective K fertiliser strategies that maximise K use efficiency of crops. Paddock-scale information on K removal in harvested products together with soil test K levels is required for deciding fertiliser K rates at paddocks differing in crop sequences. The key factors that need to be quantified are the pattern and amount of K uptake, K recycling from crop residues and pastures, topsoil vs subsoil levels of K, leaching rates, fertiliser placement effects, and K use efficiency of crop species and cultivars.

KUE in breeding

There is little information about comparative K use efficiency of the most commonly-grown cultivars of wheat, barely, oat, canola or pulses. Potassium efficient cultivars will not avert the need for K fertilisation on low K soils, but may increase K use efficiency and stress resilience. Hence screening of current cultivars will provide updated advice to growers on cultivars that might be better suited to low K soils.

Conclusion

Wide-scale depletion of plant-available K in soils is occurring in WA, with up to half of soil samples falling below the critical K level in the coastal plain south of Geraldton and up to 25% in other regions. The depletion of soil K is attributed mostly to greater removal than application, though K leaching may play a role on Tenosols. While higher application rates of K will address some of the issues, a more holistic approach to crop K nutrition is required to maximise K use efficiency and profitability. The use of deep-rooted crops to take up K from subsoils, deep or split application to maximise fertiliser K use efficiency, and adequate supply of other nutrients, particularly N, are management options available at present. Our review has identified some significant knowledge gaps that need to be addressed to improve soil and crop K management: the characterisation of critical K levels for soils other than Tenosols, the level of leaching losses that occur and the impact of K cycling via crop residues on K supply to the following crop.

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