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Growth and yield responses in wheat and barley to potassium supply under drought or moderately saline conditions in the south-west of Western Australia

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Abstract

This study assessed whether more potassium (K) was required for optimal growth and grain yield of cereal crops under drought and salinity than under non-stressed conditions. In 2011, three experiments on wheat (Triticum aestivum L.) with four K rates (0, 20, 40, 80 kg K/ha), four application times (0, 5, 10, 15 weeks after sowing, WAS) and two sources (KCl, K2SO4) were conducted in the central and southern grainbelts of Western Australia. The lack of plant response to K supply at the sites of Bolgart (36 mg K/kg at 0–30 cm) and Borden (25 mg K/kg at 0–30 cm), compared with significant gain in K uptake, dry matter and grain yield at Dowerin (29 mg K/kg at 0–30 cm), was not explained by differences in soil K levels. However, rain fell regularly through the growing season at Bolgart and Borden, whereas a dry spell occurred from stem elongation to grain development at Dowerin. The effectiveness of K application time followed the trend of 0, 5 > 10 > 15 WAS. In 2012, barley (Hordeum vulgare L.) was grown on a moderately saline (saturation extract electrical conductivity
~4 dS/m) and low K (20 mg K/kg) farm in the central grainbelt and treated with 0, 20, 40 and 120 kg K/ha. Applying K increased K uptake but decreased Na uptake, especially at 120 kg K/ha. Plant growth and grain yield increased with K supply, but the difference between the K rates was relatively small, indicating possible partial K substitution by Na. Higher than normal fertiliser K supply on low K soils would enhance the adaptation by cereals to water-limited environments, but K-fertiliser management on moderately saline soils may need to account for both K and Na uptake and use by the crops.

Additional keywords: K source, K and Na uptake, low K soil, Na substitution, rainfall.

Introduction

The potassium (K) requirement for optimal plant growth is 2–5% of the plant dry weight (Marschner 1995). Often, however, this requirement is not met because of adverse soil and agronomic factors. Soil K deficiency is widespread on highly weathered soils in the tropics and subtropics (Mengel and Kirkby 2001). For example, large areas of low-K Arenosols (deep sands) (FAO 1974) are important for crop production in many parts of the world, including the Mekong Basin (e.g. Bell and Seng 2004). In sandy soils or acid lateritic soils containing kaolinitic clay minerals with low cation exchange capacity, the rates of K leaching are usually high and considerable amounts of K can be lost (Wulff et al. 1998; Sitthaphanit et al. 2009). In these soils, K depletion may take place over relatively short periods if the loss of K is not balanced by regular K supply with mineral fertilisers or by adequate recycling of crop residues and organic manures. In the south-west of Western Australia (WA), greater removal of K in hay, grain and straw than fertiliser K input has steadily increased the incidence of K deficiency on sand-plain soils (uniform deep sand) and sandy duplex soils (sand over loam, clay or lateritic ironstone gravel) (Wong et al. 2000; Brennan et al. 2004; McArthur 2004; Brennan and Bell 2013).

The climate in south-west WA is characterised as Mediterranean, with short, mild, wet winters and long, hot, dry summers. In this environment, crops are often subjected to intermittent drought in the
early growing season and terminal drought after anthesis. Plant nutrients in the drying topsoil, particularly when stratified in the topsoil under no-till farming, become less available at the root surface when soil water deficit restricts nutrient transport via mass flow (nitrogen (N) and sulfur (S)) and diffusion (phosphorus (P) and K) (Mackay and Barber 1985; Marschner 1995; Seiffert et al. 1995). Drought can also decrease nutrient uptake by causing root shrinkage and the loss of soil–root contact (North and Nobel 1997). In addition to drought, soil salinity and/or sodicity severely affect ~1 Mha of agricultural lands in south-west WA, and this area is expected to expand because of rising saline groundwater due to the landscape water balance under annual pastures or crops (Clarke et al. 2002). Salinity causes plant water deficit as a result of low water potential in the rooting medium, nutrient imbalance by impaired root uptake and/or shoot transport of mineral nutrients, and ion toxicity due to excessive uptake of sodium (Na) and chloride (Cl) (Marschner 1995; Shabala and Cuin 2008). Sodium has similar hydrated ionic radius to K, and can inhibit K-influx under both high- and low-affinity transport (Kronzucker et al. 2006, 2008; Nieves-Cordones et al. 2007; Wang et al. 2007) and also stimulate K efflux (Shabala et al. 2006; Britto and Kronzucker 2008; Coskun et al. 2013), and thus depress K-use efficiency.

In K-deficient soils, the reduction in plant growth is greater in roots than shoots of wheat and barley (Ma et al. 2011, 2013), likely attributable to the critical role of K in photosynthate transport between source leaves and sinks (roots, seed or fruits) (Cakmak et al. 1994; Marschner et al. 1996; Römheld and Kirkby 2010). The favouring of shoot growth at the expense of roots under K deficiency may have a negative feedback on plant uptake of soil water and nutrients, thus making the low-K plants more vulnerable to drought and/or salinity.

In this study, we examined whether K fertilisation would reduce the adverse effects of drought and/or salinity on crop growth and grain yield of wheat and barley grown in low-rainfall and moderately saline environments. The efficiency of KCl and K₂SO₄ was compared by assuming that K₂SO₄, because of its chemical composition, may perform better than KCl in saline and low-sulfur (S) soils. Finally, although K is often applied by topdressing, the effect of time of application on the efficacy of K supply under drought or on saline soils is little known, and this was investigated.
Materials and methods

2011 experiment

Field sites

Wheat (*Triticum aestivum* L.) cv. Wyalkatchem was grown on farms near Bolgart, Dowerin and Borden, which are, respectively, ~100 km north-east, 150 km north-east, and 300 km south-east of Perth, WA (32°04′S, 115°50′E). A pre-sowing soil analysis showed that the Dowerin site had ~30 mg K/kg (bicarbonate extraction, Colwell-K; Colwell and Esdaile 1968) in soil profile to 30 cm, and ~14 mg S/kg in the top 10 cm but 2–4 mg S/kg in the profile below (KCl-40 test, Blair-S; Blair *et al.* 1991). At the Bolgart site, soil Colwell-K was 30–40 mg/kg at 0–30 cm depth but S was low (<7 mg/kg) in the whole profile. At the Borden site, both K and S were low in the top 30 cm soils (Table 1).

The experiments were sown at 80 kg seeds/ha on 2 June at Bolgart, 13 June at Dowerin and 17 June at Borden. Individual plots had an area of 2 m by 22 m and seven rows at 0.25-m row spacing, with an untreated area 0.4 m wide between neighbouring plots. At sowing, 100 kg/ha of Agflow® copper (Cu)–zinc (Zn)–molybdenum (Mo) fertiliser (CSBP, Kwinana, WA) was banded 5 cm below the seed. The fertiliser consisted of 12.6 nitrogen (N), 17.7 phosphorus (P), 5.5 S, 0.25 Cu, 0.35 Zn, and 0.025 Mo (w/w %). At 5 weeks after sowing (WAS), urea (200 kg/ha, 46% N) and gypsum (100 kg/ha of CaSO₄, 17% S) were topdressed, except that one of the K treatments received no gypsum (see below).

Soil K treatments

All three experiments incorporated two K sources (KCl, K₂SO₄), four K rates (0, 20, 40, 80 kg K/ha), and four application times (0, 5, 10 or 15 WAS), with the method of topdressing by hand. A treatment of 80 kg K/ha using KCl without gypsum was also applied at 5 WAS to compare the growth response of plants treated at the same rate of KCl plus gypsum. In total, 22 K treatments were applied in a randomised block design with three replications (Table 2).
Measurements

At anthesis (15 WAS), plant shoots randomly selected from three quadrats (1 m by 0.5 m) in each plot were cut at the soil surface and dried in a forced-draught oven at 60°C for 72 h. A subsample of ~1 g of ground material of the whole shoots (including young and old leaves) was digested in 0.5 M nitric acid in a microwave oven (CEM Mars5; CEM Corp., Matthews, NC, USA) after the method of Huang et al. (2004). Shoot K concentrations were determined by inductively coupled plasma-atomic emission spectroscopy (VISTA Simultaneous ICP-AES spectroscopy; Varian, Palo Alto, CA, USA). Total K uptake was calculated by the product of shoot K concentration and dry weight. At maturity, individual plots were machine-harvested for grain yield.

2012 experiment

Field site

Barley (Hordeum vulgare L. cv. Hindmarsh) was grown on a farm at Beverley in the central grain belt (~100 km east of Perth). A pre-sowing soil analysis showed 20 mg Colwell-K/kg in the 0–40 cm profile, 10 mg S/kg in the top 10 cm, and 6 mg S/kg at the lower depths. Soil electrical conductivity (EC) in a 1 : 5 soil : water suspension (EC_{1:5}) was 0.4 dS/m, equivalent to a soil saturation extract EC (EC_{se}) of ~4 dS/m. Soil pH (0.01 M CaCl$_2$) was 4.7 in the 0–20 cm layer and 5.1 in the 20–40 cm layer.

The experiment was sown on 3 June, and individual plots had an area of 2 m by 20 m at a row spacing of 0.25 m. Basal Agflow® Cu-Zn-Mo fertiliser at 200 kg/ha and urea at 70 kg/ha were topdressed just before sowing; at 2 WAS, an additional 50 kg/ha of urea was applied to the soil surface.

Soil K treatments

At 2 WAS, fertilisers KCl and K$_2$SO$_4$ were broadcast at rates of 0, 20, 40 and 120 kg K/ha. A randomised block design was used to include individual treatments comprising one nil-K control and three K rates of both KCl and K$_2$SO$_4$ sources. All treatments were replicated three times.
Measurements

At anthesis, the rates of net photosynthesis and stomatal conductance of the flag leaves were determined using the LCpro+ advanced photosynthesis system (ADC BioScientific Ltd, Hoddesdon, UK) between 11:00 and 14:00 on a sunny day, followed by collection of the uppermost three leaves for K analysis. At maturity, three quadrats (1 m by 0.5 m) of plant shoots in each plot were randomly selected and cut at the soil surface, and dried in a forced-draught oven at 60°C for 72 h. About 1 g of ground material of the top leaves at anthesis and the whole shoots (including young and old leaves) at maturity was digested in 0.5 M nitric acid in a microwave oven (CEM Mars5), and the K and Na concentrations were determined using Model 410 flame photometer (Sherwood Scientific Ltd, Cambridge, UK). Ear number and grain yield were measured from the quadrat cuttings.

Statistical analyses

For the three experiments at three locations in 2011, the factorial treatments of K rates and application time were assessed for the two K sources of KCl and K2SO4 separately, and the effectiveness of KCl v. K2SO4 was evaluated in the plots without gypsum. In the 2012 experiment under moderately saline conditions, the factorial treatments of K rates and sources were compared with the nil-K control. Data of leaf gas exchange, K and Na uptake, crop growth and grain yield were subjected to one-way analysis of variance. Treatment differences were separated by Fisher’s protected l.s.d. test and accepted at \( P \leq 0.05 \). Statistical analyses were carried out by GENSTAT 10 (Laws Agricultural Trust, Rothamsted, UK).

Results

Wheat K response under drought

During the growing season of May–October, mean minimum and maximum temperatures were respectively 8.2°C and 20.1°C at Bolgart and 7.8°C and 19.9°C at Dowerin in the central grain belt. The Borden site in the southern grain belt was colder, with mean minimum temperature 7.3°C and
mean maximum temperature 17.2°C. Growing-season rainfall was 323 mm at Bolgart, 247 mm at Borden and 204 mm at Dowerin. The rainfall distribution through the growing season differed among the sites, notably Dowerin had a dry spell of < 30 mm total rainfall from mid-August (stem elongation) to mid-October (grain development) at (Fig. 1), compared with regular rainfall over the season at Bolgart and Borden (48 and 37 mm, respectively, in May; 53 and 36 mm in June; 78 and 39 mm in July; 46 and 45 mm in August; 39 and 28 mm in September; 59 and 62 mm in October).

The difference in weather conditions, particularly the amount and pattern of seasonal rainfall between three sites, was related to crop response to soil K treatments. By contrast, the differences in Colwell-K concentrations at 0–30 cm depth did not explain a grain yield response to K at Dowerin and an absence of response at Borden or Bolgart. There was little K response by wheat at Bolgart and Borden (data not shown) with well-distributed rainfall, whereas K application with either K₂SO₄ or KCl at Dowerin increased shoot K concentrations and total shoot K contents at anthesis, with a trend of 0, 5 >10 >15 WAS (Fig. 2). The K status in shoots was also related to the rates of K supply at 5 WAS, but less so at later K application times.

Application of K₂SO₄ at 0 or 5 WAS increased shoot dry weight at anthesis and grain yield at the Dowerin site, with little difference between the rates of 20, 40 and 80 kg K/ha (Fig. 3). Late K₂SO₄ applications reduced crop responses. Shoot growth and grain yield were also improved by applying KCl with gypsum at Dowerin. At Bolgart and Borden, however, neither the rate nor the time of K application affected crop growth and grain yield compared with nil K control (data not shown).

At Dowerin, the supply of 80 kg K/ha at 5 WAS using KCl without gypsum lowered shoot S concentration (1.8 mg S/g) at anthesis compared with the same rate of K using KCl and other K treatments including the nil-K control (2.2–2.3 mg S/g) all of which received supplementary S from gypsum. The KCl-treated plants without gypsum also had lower shoot K concentration than plants with gypsum and substantially reduced total shoot K content (Fig. 2), especially compared with the equivalent rates of K supply using K₂SO₄ (Table 3). Consistently, crop dry matter and grain yield in the KCl treatment without gypsum were significantly lower than in treatments with gypsum (Fig. 3) and showed greater reduction than in the K₂SO₄ treatment (Table 3). At the Bolgart and Borden sites,
however, applying K$_2$SO$_4$ and KCl fertilisers with or without gypsum resulted in similar shoot dry weight, shoot K and S contents at anthesis (15 WAS) and grain yield of wheat (Table 3).

**Barley K response under salinity**

The rainfall for Beverley from May to October was 179 mm, with regular falls early in the season (44.6 mm in May, 54.8 mm in June) but low falls or no rain mid and late season (21.6 mm in July, 20.8 mm in August, 31.8 mm in September, 5.6 mm in October). Mean minimum and maximum temperatures during the growing season were 5.9°C and 21°C, respectively.

At anthesis, K concentrations of the uppermost three leaves in barley were increased, relative to nil K treatment, by treatment with 120 kg K/ha as KCl and by both 40 and 120 kg K/ha as K$_2$SO$_4$ (Fig. 4a, b). Under moderately saline conditions, K application also improved net photosynthesis and stomatal conductance in the flag leaves, especially at high K levels (Fig. 5). By contrast, K supply reduced plant Na uptake, and leaf Na concentration was lowered by treatment with 120 kg K/ha as KCl and by both 40 and 120 kg K/ha as K$_2$SO$_4$.

At maturity, whole-shoot K concentrations were related to the levels of soil K supply with both KCl and K$_2$SO$_4$. Plants with 20, 40 kg K/ha as K$_2$SO$_4$ generally tended to have higher shoot K concentration and lower shoot Na concentration than plants from treatments with the same K rates of KCl (Fig. 4c, d), although the difference was not significant ($P > 0.05$). Applying 120 kg K/ha as K$_2$SO$_4$ or KCl further increased K concentration and decreased Na concentration in shoots. Plants treated with nil K had the lowest K concentration and the highest Na concentration in shoots. An increase in the K$^+/Na^+$ ratio in the uppermost three leaves or the whole shoot was observed in the plants treated with 20, 40 kg K/ha, especially with 120 kg K/ha, compared with plants in the nil-K treatment (Table 4). Applying 40 kg K/ha as K$_2$SO$_4$ produced higher leaf K$^+/Na^+$ ratio than the same rate of K as KCl. However, for plants treated with 120 kg K/ha, the two K sources resulted in similar K$^+/Na^+$ ratios.

Shoot growth and yield components were significantly increased by applying KCl and K$_2$SO$_4$, compared with nil K (Fig. 6). Unlike the strong response of K and Na concentrations in the top leaves
or whole shoot to 120 kg K/ha, the growth differences between 20, 40 and 120 kg K/ha were relatively small and generally not significant \( (P > 0.05) \). Nevertheless, at the same rate of K supply, plants with K\(_2\)SO\(_4\) sometimes produced more shoot dry weight than those with KCl (e.g. 120 kg K/ha). A similar trend was observed for the effects of K\(_2\)SO\(_4\) v. KCl on the number of ears and grain yield (Fig. 6).

**Discussion**

**Soil K supply and drought**

In the 2011 season, all three sites in the central and southern grainbelts of south-west WA had soil Colwell-K levels < 40 mg/kg in the 0–30 cm soil profile, which is considered K-deficient for wheat. Brennan and Bell (2013) reported critical Colwell-K values of 40–41 mg/kg for the 0–10 cm depth in Tenosols (deep sands) and Chromosols (sandy duplex). However, plant response to soil K supply was minimal in terms of K uptake, dry matter and grain yield at the Bolgart and Bolden sites, where rains fell regularly through the growing season. By contrast, wheat growth and yield responded to soil K supply at the Dowerin site, where a long dry spell with <30 mm rainfall occurred from stem elongation to grain development. Fertiliser K supply at Dowerin increased K concentration and content in shoots, total dry matter and grain yield. During soil drying period, the decrease in soil water potential would likely impair K movement to the root surface and reduce plant K uptake (Marschner 1995; Römheld and Kirkby 2010; Oosterhuis et al. 2013). On the other hand, soil K deficiency reduces root growth to a greater extent than shoot growth in wheat and barley (Ma et al. 2011, 2013), likely attributable to the critical role of K in supplying sucrose from leaves to roots to meet the energy requirements for root growth and ion uptake (Cakmak et al. 1994; Marschner et al. 1996). When root growth is restricted by both soil K deficiency and water deficit, a negative feedback may occur, whereby the resulting lower plant K status and smaller root system could further depress K acquisition and thus plant resistance to drought. Increasing the level of soil exchangeable K by fertiliser application would render more K available to plants for the needs of physiological functions (e.g. photosynthesis and turgor maintenance) and for better root growth under soil-water deficit.
Consistently in the present study, the positive response of wheat growth and grain yield to soil K supply was observed at the drought-affected site but not at the non-stressed sites. The finding suggests that drought increases the K requirement of plants and that higher than normal fertiliser K supply on low K soils may be necessary for cereal crops to adapt to low-rainfall environments.

**Soil K supply and salinity**

We also found that K fertiliser improved leaf photosynthesis, stomatal conductance, plant growth and grain yield in barley in a K-deficient and moderately saline field, where the soils had a Colwell-K level of 20 mg/kg and an ECse of 4 dS/m. Numerous studies have reported that soil salinity, mainly associated with NaCl, can disrupt both cellular and whole-plant K homeostasis, which is critical for proper cell function and plant growth (reviewed by Kronzucker et al. 2013). Although the maintenance of a high K⁺/Na⁺ activity ratio in the cytosol is frequently described as a key determinant of salt tolerance (e.g. Maathuis and Amtmann 1999; Shabala and Cuin 2008; Wakeel 2013), direct evidence supporting this contention is, by comparison, scant (Chen et al. 2007). In this study, soil K supply increased the K⁺/Na⁺ ratio in leaves or shoots, particularly when plants were treated with 120 kg K/ha, by enhancing K uptake but suppressing Na uptake in the salt-affected field (Fig. 4). Plant growth and grain yield increased with K supply, but the difference between rates of 20 to 120 kg K/ha was relatively small in the saline conditions. The beneficial effects of Na on the growth of some plant species are well documented (Marschner 1995). For example, low to moderate Na may improve crop growth, depending upon soil K levels and genotypic difference in salt tolerance (Ma et al. 2011; Kronzucker et al. 2013), and there is a strong substitution of K by Na in barley (Ma et al. 2011). It is suggested that Na can substitute for non-specific biophysical functions of K by maintaining cell turgor especially in stomatal guard cells and ionic balance (Marschner 1995; Subbarao et al. 2003; Gattward et al. 2012; Kronzucker et al. 2013). In this study, the findings of positive response of leaf gas exchange to soil K supply and small differences in growth and grain yield of barley among the treatments of 20, 40 and 120 kg K/ha suggested at least partial substitution of K by Na under low K and moderate salinity. Plants treated with 20 kg K/ha had K⁺/Na⁺ ratios in
leaves and shoots similar to those with 40 kg K/ha, likely attributable to an increase in K uptake induced by moderate soil Na. More noticeably, the sum of shoot K and Na concentrations was similar across treatments, an indication of 1 : 1 exchange, which may also complement the K/Na ratio, at least in barley. Our previous study found that barley, compared with wheat, had similar K concentration but higher Na concentration in the shoot at the same levels of K and Na supply and was more responsive to Na substitution under K deficiency (Ma et al. 2011). A recent study (Krishnasamy et al. 2014) also shows that wheat responses to soil Na vary with K-use efficiency of cultivars, i.e. the K-efficient cultivars are less affected by excess Na than the K-inefficient cultivars. Therefore, the management of K fertilisation needs to consider not only soil K status and crop requirement, but also soil Na status and genotypic variation in the uptake and use of K and Na.

**Timing of K application**

The majority of K uptake in wheat occurs when the shoot is undergoing its rapid phase of growth (Gregory et al. 1979), and maximum K accumulation in the shoot is reached at anthesis (Ma et al. 2013). The occurrence of K uptake mostly during the vegetative growth and substantial K redistribution at the reproductive stage in wheat suggests the benefit of early K fertilisation. Early K fertilisation should also avert decreases in tillering, which is a major effect of K deficiency in wheat and barley (Ma et al. 2011). In a water-limited environment, drought events in the early to mid-growing season would have further impact on the efficiency of K uptake and utilisation as K in the drying topsoil becomes less available at the root surface. In this study, application of K fertilisers at sowing or 5 WAS at the Dowerin site was significantly more effective for dry matter and grain yield production than later applications (10, 15 WAS). Early K application would allow time for surface-applied K to move into the root-zone and match the pattern of K uptake and growth demand in wheat, particularly during tillering. Adequate plant K status would remove restrictions on translocation of photoassimilates to support root growth during the long dry spell and therefore enhance drought resistance. At the sites with regular rainfall, however, roots were likely able to acquire sufficient K from the moist soil profile for growth even without K fertiliser application.
Efficacy of KCl compared with K$_2$SO$_4$

Worldwide, >90% of total K fertiliser is applied as KCl, due to its lower cost than K$_2$SO$_4$ (Imas and Bansal 2004). However, KCl has higher salt index (116) than K$_2$SO$_4$(46), which also contains 18% S, suggesting that KCl would be less effective for dry matter and grain yield production than K$_2$SO$_4$ under conditions of low S, salinity and/or drought. In this study, the Dowerin site, with soil Colwell-K of ~30 mg/kg throughout the 0–80 cm profile, had adequate extractable S (14.6 mg/kg) in the top 10 cm of soil, but was deficient (2–4 mg S/kg) at 10–60 cm depth. The treatment supplying 80 kg K/ha as KCl without gypsum lowered S and K concentrations and contents in shoot at anthesis, compared with the same rate of K using KCl and other K treatments, including the nil-K control, all of which received supplementary S from gypsum. The decrease in S and K uptake was possibly caused by the long dry spell from mid-August to mid-October resulting in the restriction in movement of soil S and K, particularly with no-till farming where nutrients are highly stratified in the dried topsoil (Ma et al. 2009). Applying K$_2$SO$_4$ or adding gypsum would increase soil available S and K levels, and as a result, plant growth and grain yield were improved at the drought-affected site but, largely, not at the non-stressed sites. A previous study in alkaline, calcareous clay loam also showed that K$_2$SO$_4$ was superior to KCl for grain yield and protein content in wheat (Bakhsh et al. 1986).

The site for the barley experiment in 2012 was moderately saline with soil EC$_{se}$ of ~4 dS/m. If the salinity is assumed to be derived from NaCl only, the soil solution would have ~40 mM NaCl. Applying 120 kg K/ha of KCl added ~2.2 mM Cl to the top 10 cm soil or 15 mM Cl in soil solution. Chloride is classified as a micronutrient, but plants often take up 2–20 g Cl/kg in tissue dry weight (Marschner 1995). Although Cl toxicity can be seen in sensitive plant species with external Cl concentrations of >20 mM, 4–5 times higher Cl concentrations do not reduce growth in tolerant species such as barley, spinach, lettuce and sugar beet (Marschner 1995). Chloride can have a positive effect on the control of powdery mildew in barley (Brennan and Jayasena 2007). In addition, Cl is readily removed from the soil by leaching, except in very dry environments. Therefore, it was unlikely that application of KCl would impose a detrimental effect of Cl on barley growth under the field conditions of this study. However, the site had a moderate level of S (10 mg/kg) in the top 10 cm
soil but was deficient (6 mg S/kg) at the lower depths. Application of K$_2$SO$_4$ provided extra available S for plant requirements and thus was more effective in promoting growth and yield than application of KCl, as shown in the study.

**Conclusion**

This study shows that more K is required for optimal growth and grain yield by wheat under drought than non-water-stressed conditions, with increased effectiveness by early K supply. Applying Cl in KCl is unlikely to have had a detrimental effect on crop growth in the present study, whereas K$_2$SO$_4$ was more effective under S-deficient, saline or drought conditions by providing extra available S. With moderate salinity, there is a possibility of partial K substitution by Na on low-K soils, i.e. Na may reduce plant demand for K. The management of K fertilisation on saline soils needs to consider not only soil K status and crop requirement, but also soil Na status and genotypic variation in the uptake and use of K and Na.

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**References**


Table 1. Pre-sowing soil potassium (Colwell-K) and sulfur (KCl-40 S) (mg/kg soil) at three experimental sites in the central and southern regions of grain belt in Western Australia

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Dowerin (central region)</th>
<th>Bolgart (central region)</th>
<th>Borden (southern region)</th>
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<tbody>
<tr>
<td></td>
<td>K</td>
<td>S</td>
<td>K</td>
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<tr>
<td>0–10</td>
<td>31</td>
<td>14.6</td>
<td>40</td>
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<tr>
<td>10–20</td>
<td>29</td>
<td>1.8</td>
<td>30</td>
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<td>40–60</td>
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<td>60–80</td>
<td>33</td>
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<td>59</td>
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</tbody>
</table>
Table 2. Treatments applied on all three experiments with wheat cv. Wyalkatchem comprising two potassium sources, four rates and four application times (weeks after sowing, WAS) in the central and southern regions of the grain belt in Western Australia 

All treatments, except Trt 22, were supplied with 100 kg of gypsum/ha at 5 WAS

<table>
<thead>
<tr>
<th>K rate (kg/ha)</th>
<th>0 WAS</th>
<th>5 WAS</th>
<th>10 WAS</th>
<th>15 WAS</th>
<th>0 WAS</th>
<th>5 WAS</th>
<th>10 WAS</th>
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<td>Trt 20</td>
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</tbody>
</table>
Table 3. Effects of potassium at 80 kg K/ha as K₂SO₄ or as KCl without gypsum on shoot growth, K and sulfur (S) contents at anthesis, and grain yield of wheat cv. Wyalkatchem in the central and southern grain belts of Western Australia

Comparisons are within site; for each parameter, different letters indicate significant effect ($P \leq 0.05$) of K source; absence of letters for a site indicates no significant difference ($P > 0.05$)

<table>
<thead>
<tr>
<th>Response parameters (kg/ha)</th>
<th>Dowerin</th>
<th>Bolgart</th>
<th>Borden</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₂SO₄ KCl</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Shoot dry wt</td>
<td>2295a</td>
<td>1054b</td>
<td>4284</td>
</tr>
<tr>
<td>Shoot K</td>
<td>19.5a</td>
<td>7.8b</td>
<td>66.4</td>
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<tr>
<td>Shoot S</td>
<td>4.9a</td>
<td>2.4b</td>
<td>7.1</td>
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<tr>
<td>Grain yield</td>
<td>1365a</td>
<td>792b</td>
<td>1776</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1848</td>
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<tr>
<td></td>
<td></td>
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<td>2684</td>
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</table>
Table 4. The K⁺/Na⁺ ratios of top three leaves of barley cv. Hindmarsh at anthesis and in the whole shoots at maturity in plants treated with KCl or K₂SO₄

Within a column, means followed by the same letter are not significantly different at $P = 0.05$

<table>
<thead>
<tr>
<th>K source</th>
<th>K rate (kg/ha)</th>
<th>Leaf K⁺/Na⁺</th>
<th>Shoot K⁺/Na⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil</td>
<td></td>
<td>1.18d</td>
<td>0.16c</td>
</tr>
<tr>
<td>KCl</td>
<td>20</td>
<td>1.75c</td>
<td>0.53b</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>1.90c</td>
<td>0.68b</td>
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<tr>
<td></td>
<td>120</td>
<td>3.71a</td>
<td>1.57a</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>20</td>
<td>1.61c</td>
<td>0.56b</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>2.57b</td>
<td>0.81b</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>4.09a</td>
<td>1.63a</td>
</tr>
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</table>
Fig. 1. Daily rainfall in 2011 at three experimental sites. There was a dry spell with <30 mm rainfall from mid-August to mid-October (days 230–290) at Dowerin, compared with regular rainfall through the growing season (days 121–304) at Bolgart and Borden.
Fig. 2. Shoot potassium status at anthesis of wheat cv. Wyalkatchem in response to K source, K rate and application time at the Dowerin site in 2011. Capped lines are standard errors. Except for 5* denoting 80 kg K/ha as KCl without gypsum at 5 weeks after sowing, all other treatments received 100 kg/ha of gypsum.
Fig. 3. Shoot dry matter and grain yield of wheat cv. Wyalkatchem in response to potassium source, rate and application time at the Dowerin site in 2011. Capped lines are standard errors. Except for 5* denoting 80 kg K/ha as KCl without gypsum at 5 weeks after sowing, all other treatments received 100 kg/ha of gypsum.
Fig. 4. Effect of KCl and K$_2$SO$_4$ supply on K and Na concentrations in the uppermost three leaves at anthesis, and in shoots at maturity of barley cv. Hindmarsh grown in moderately saline soil. Within a graph, means (+s.e.) with the same letter are not significantly different at $P = 0.05$. 
Fig. 5. Effect of KCl and K$_2$SO$_4$ supply on leaf photosynthesis and stomatal conductance at anthesis of barley cv. Hindmarsh grown in moderately saline soil. Within a graph, means (+s.e., $n = 9$) with the same letter are not significantly different at $P = 0.05$. 
Fig. 6. Effect of KCl and K$_2$SO$_4$ supply on total dry matter, ear number and grain yield of barley cv. Hindmarsh grown in moderately saline soil. Within a graph, means (+s.e., $n = 3$) with the same letter are not significantly different at $P = 0.05$. 