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# Simulating wheat growth response to potassium availability under field conditions in sandy soils. II. Effect of subsurface potassium on grain yield response to potassium fertiliser

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ABSTRACT

Subsurface potassium (K) supply can make a significant contribution to total K uptake in wheat (*Triticum aestivum* L.) although its influence on grain yield response to K fertiliser is unresolved. Previous work has shown that the inclusion of subsurface (>10 cm depth) soil extractable K (SEK) did not improve the prediction of relative yield (RY) compared to a prediction based on SEK in the 0–10 cm soil layer only. Our understanding of the influence of subsurface SEK is constrained by the incomplete nature of the interactions between season × surface SEK × subsurface SEK directly measured in field experiments. To understand these interactions, we simulated wheat growth for two locations in a rain fed environment in south-west Western Australia (SWWA) and two soil types using the crop growth simulation model APSIM, which has been calibrated for the sandy-surfaced soils of SWWA. Sensitivity analysis of the effect of subsurface SEK on grain yield showed that the effectiveness of subsurface SEK relative to surface SEK declined exponentially as the depth of the K-enriched subsurface layer increased. We implemented a Monte Carlo simulation for a deep sand and a sand over clay soil profile for a range of surface SEK levels, subsurface SEK depths, subsurface SEK levels, locations, years, subsurface root constraint and rates of K fertiliser applied. Global sensitivity analysis showed that SEK in the 0–10 cm depth was the most important factor for RY in the deep sand and sand over clay profiles followed by SEK 10–20 cm and location. We used the results from the Monte Carlo simulation to develop a K fertiliser recommendation model based on SEK 0–10 cm only and a recommendation model based on SEK 0–10 cm together with subsurface SEK, root constraint and stored soil water at sowing. A net economic benefit (change in income exceeds extra costs) only occurred in a limited number of scenarios where SEK 0–10 cm was between 40 and 60 mg $kg^{-1}$ for the deep sand and where SEK 0–10 cm was less than 40 mg $kg^{-1}$ for the sand over clay. The greatest potential for improvement in profit from K fertiliser recommendation systems for soils in SWWA is for sand over clay soils where SEK 0 to 10 cm is less 40 mg $kg^{-1}$.



## 1. Introduction

Soil potassium (K) supply is the main determinant of the grain yield increase (response) to K fertiliser for wheat (*Triticum aestivum* L.). Where plant-available soil extractable K (SEK) supply is insufficient to sustain the maximum growth rate, an asymptotic grain yield response is usually observed to increasing rates of K fertiliser (e.g. Wong et al., 2001; Brennan and Bolland, 2007). The grain yield with no K fertiliser applied relative to the K-non limited grain yield (relative yield), and the rate of grain yield response to fertiliser K (kg grain per kg K fertiliser) determine the economically-optimum rate of fertiliser K in combination with the maximum yield achievable, and the prices of grain and fertiliser. Typically, RY is predicted based upon a measure of SEK (e.g. Colwell and Esdaile, 1968) in the soil surface layer [0–10 cm] (e.g. Wong et al., 2000). However, the accuracy of the prediction is frequently poor because of other site-specific factors: seasonal rainfall (timing and amount) and subsurface (>10 cm soil depth) SEK levels (Bolland et al., 2002; Brennan and Bolland, 2006; Brennan and Bell, 2013; Kautz et al., 2013).

*Abbreviations:* SEK, soil extractable potassium; $pH_{Ca}$, soil pH 0.01M $CaCl_2$.

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Subsurface K has been shown to be a significant contributor to plant K uptake although the value of this in fertiliser recommendation systems is unresolved. For example, Kuhlmann (1990) found that 9–70% of shoot K uptake in wheat was supplied from soil layers deeper than 30 cm, and that for a constant soil surface SEK the amount of K supplied from the subsurface increased from 12 to 61% as the subsurface SEK increased. Similarly, Haak (1981) showed that the proportion of total K uptake from the subsurface increased as the subsurface SEK increased. The depth to the K-rich soil is important; the shoot K concentration of corn (*Zea mays* L.) grown on soils with deficient levels of SEK in the top soil and a K-rich horizon within 50 cm of the soil surface was higher than where the depth to the K-rich horizon was greater than 50 cm (Woodruff and Parks, 1980). While differences in plant K uptake due to the presence of subsurface K reserves have been observed, this has not been translated into an improvement in prediction of yield response to K fertiliser. Wong et al. (2000) found that the inclusion of subsurface K using a depth weighting function did not provide a better prediction of RY for field experiment data than soil surface SEK alone. However, this study involved a limited selection of sand over clay soil profiles and hence may not represent the broader role of subsurface K. The contradiction between reports of the availability of subsurface K to crops and the inability of subsurface K to explain differences in RY most likely reflects the interactions between crop response to surface and subsurface SEK, constraints to root growth and seasonal rainfall (timing and amount).

While there has been little work on the impact of seasonal rainfall on the availability of subsurface K, work on deep placement of fertiliser indicates that the temporal dynamic of soil moisture in the surface and subsurface will be a key driver of subsurface nutrient uptake. With adequate soil moisture, little or no difference in nutrient uptake or grain yield has been observed in response to different depths of K fertiliser placement (Bell et al., 2005; Ma et al., 2009). However, differences in nutrient uptake or grain yield have been observed where dry conditions have occurred early in the growing season (Bordoli and Mallarino, 1998). It is likely that a combination of reduced root growth rate and diffusion of K in dry soil (Mackay and Barber, 1985) are the main process behind this season × K applied interaction. The interaction between the timing of soil surface drying and grain yield response to deep placement of K fertilisers provides a framework for studying the analogous problem of the interactions between soil surface and subsurface K availability. However, the depth to adequate SEK reserves (up to 100 cm) can be much greater than deep placement of fertiliser K (<30 cm) which introduces another important factor affecting acquisition of subsurface K to crops in field conditions: the arrival time of roots in the K-rich subsurface soil.

The K-deficient crops occur in the south-west of Western Australia (SWWA) mostly on deep sands and sand over clay (duplex) soils and the temporal pattern of root growth can vary greatly between these soil types. For wheat, root depth at anthesis is typically 60–80 cm for sand over clay soils (Dracup et al., 1992) and 140 (Hamblin et al., 1982; Hamblin and Hamblin, 1985) to 200 cm (Anderson et al., 1998) for deep sands and reflect different root penetration rates in the major soil types where K deficiency in wheat occurs. For example, Tennant (1976) found that the root penetration rate for wheat between 35 and 105 days after sowing was 1.47 to 1.95 cm day$^{-1}$ in a deep sand and 0.48 to 0.88 cm day$^{-1}$ in the sand over clay soil. In separate studies, root penetration rate was: 0.86 cm day$^{-1}$ in a deep pale sand (C. Scanlan, G. Sarre, R. Brennan, unpublished data), 1.75 cm day$^{-1}$ in a loamy sand (Hamblin et al., 1982) and 0.39–0.59 cm day$^{-1}$ in a sand over clay soil (Gregory et al., 1992). The lower rate of root penetration rate in sand over clay soils is due to physical and chemical constraints: waterlogging, acidity, salinity or high soil strength (Dracup et al., 1992). High soil strength and acidity (soil $pH_{Ca}$ < 4.5) are common constraints in the surface, or near surface of both sand over clay and deep sands (Dracup et al., 1992; Tang et al., 2003). Clearly, such constraints that affect the timing of root interception with subsurface K will affect the response of crops to subsurface K.

The aim of this study was to gain a better understanding of the interactions between surface SEK, subsurface SEK and depth, season and root constraints on yield response to K fertiliser in wheat using process-based modelling. This modelling approach allows the integration of season, soil and plant characteristics to study the impact of subsurface K on the grain yield response to K fertiliser (Kautz et al., 2013). Wheat growth (dry matter & grain yield) was simulated using the crop model APSIM (Keating et al., 2003), which has been modified to include K dynamics and calibrated for sandy-surfaced soils in SWWA (Scanlan et al., 2015). Firstly, we quantify the response in grain yield for changes in subsurface SEK compared to changes in surface SEK. Secondly, we assessed the importance of surface SEK, subsurface SEK, root growth constraints, season and interactions among these on grain yield response to K fertiliser based upon a Monte Carlo simulation. Finally, we quantify the economic benefit from predicting fertiliser K requirements based on knowledge of both surface and subsurface SEK levels.

## 2. Methods

The modelling analysis was completed in three discrete steps. Firstly (step one), we quantified the sensitivity of grain yield to subsurface SEK using local sensitivity analysis, where we used two well-defined soil profile types as our baseline scenario, and systematically modified SEK at different depths. Secondly (step two), we quantified the sensitivity of grain yield response to fertiliser K to SEK levels and to climatic conditions using global sensitivity analysis of a Monte Carlo simulation. Finally, we use the results from step two to propose a fertiliser K recommendation model that is inclusive of subsurface K supply for the deep sand and the sand over clay profile types and present an economic analysis of the benefit from using the proposed model.

### 2.1. Simulation details

The same simulation model was used for modelling grain yield response to subsurface K and for the Monte Carlo simulation. Wheat growth was simulated in response to varying levels of surface and subsurface SEK, levels of soil constraint, fertiliser K rates using APSIM-K (Scanlan et al., 2015). For the Monte Carlo simulation, we also used randomly generated values for the parameters we introduced in APSIM-K (Scanlan et al., 2015) to include predictive uncertainty in our analysis. Wheat growth was modelled for Badgingarra (30.389° S, 115.501° E) and Katanning (33.690° S, 117.556° E) from 2003 to 2012. The two sites represent distinct climatic regions where K deficiency frequently occurs. Although the average annual rainfall for Badgingarra (488 mm) and Katanning (448 mm) is similar, Badgingarra has a higher proportion of growing season rain in the winter months (June to August) and the average daily temperature is 1.5–4.5 °C higher than Katanning (Fig. 1).

Two reference soils were parameterised for this study: deep sand and sand over clay (Table 1). The deep sands of SWWA [Tenosol – Australian Soil Classification (Isbell, 2002)] typically range from a coarse sand to a loamy sand in the surface 100 cm, and are characterised by low plant essential nutrients when initially cleared for agricultural production, low water holding capacity and high permeability (McArthur, 2004). The physical and chemical properties of the deep sand were parameterised based upon two soils previously characterised for APSIM on soil data from field