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Lime application reduces potassium and nitrate leaching on sandy soils

Die Kalkanwendung reduziert das Auswaschen von Kalium und Nitrat auf sandigen Böden

Abstract

Potassium (K) leaching is common in light-textured soils and reduces soil available K to plants. This study examined the effect of lime application and K rates (nil, 20, 60 kg K/ha) on K leaching and other leachate parameters of four sandy soils in Western Australia. Three out of four soils did not differ in K leaching between the rates of nil and 20 kg K/ha, whereas 60 kg K/ha increased K leaching in all four soils. For the Merredin soils, lime application markedly delayed K leaching at 60 kg K/ha, showing K leaching peak at 4.75 pore volume (PV) in the limed soil ($pHCaCl_2$: 6.20) but at 3 PV in the non-limed soil ($pHCaCl_2$: 4.50), and liming also reduced total amount of leached K and NO_3. Similarly, the peak of K leaching occurred at 2–3 PV in the other two non-limed soils. Maximum leachate NO_3 concentrations at 60 kg K/ha were 46 mg/L at 2 PV with lime versus 110 mg/L at 1.25 PV without lime, while the amount of leached NO_3 from nil K soils was greater than from the K treated soils. The results suggest that liming of an acid sand can slow down and reduce K and NO_3 leaching and have significant implication for K-fertilizer management on such soils.

Key words: K fertilizer, K leaching, Lime, Nitrate, Soil pH

Zusammenfassung

Kalium (K)-Auslaugung kommt in leicht strukturierten Böden häufig vor und reduziert die im Boden für die Pflanzen verfügbare Menge K. Diese Studie untersuchte die Auswirkung der Kalkanwendung und der K-Raten (null, 20, 60 kg K/ha) auf die K-Auslaugung und andere Sickerwasserparameter von vier sandigen Böden im Westen Australiens. Drei von vier Böden unterschieden sich in der K-Auslaugung nicht zwischen den Raten von Null und 20 kg K/ha, während 60 kg K/ha die K-Auslaugung in allen vier Böden erhöhten. Bei den Merredin-Böden verzögerte die Kalkanwendung die K-Auslaugung bei 60 kg K/ha deutlich und zeigte einen K-Auslaugungspeak bei 4,75 Porenvolumen (PV) im gekalkten Boden ($pHCaCl_2$: 6,20), jedoch bei 3 PV im nicht gekalkten Boden ($pHCaCl_2$: 4,50), und das Kalken reduzierte auch die Gesamtmenge an ausgelaugtem K und NO_3. In ähnlicher Weise trat der Peak der K-Auslaugung bei 2–3 PV in den anderen beiden nicht gekalkten Böden auf. Die maximalen NO_3-Konzentrationen von Sickerwasser bei 60 kg K/ha betrugen 46 mg/l bei 2 PV mit Kalk gegenüber 110 mg/l bei 1,25 PV ohne Kalk, während die Menge an ausgelaugtem NO_3 aus Böden ohne K-Zugabe größer war als aus den mit K behandelten Böden. Die Ergebnisse legen nahe, dass die Kalkung eines sauren Sandes die K- und NO_3-Auswaschung verlangsamen und verringern kann und erhebliche Auswirkungen auf das K-Dünger-Management auf solchen Böden hat.

Stichwörter: K-Dünger, K-Auslaugung, Kalk, Nitrat, Boden-pH

Introduction

Potassium is leachable in soils and leaching losses can be expected when K supply exceeds soil retention capacity

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and plant demand in well-drained soils (Johnston et al., 1993; Mendes et al., 2016). Sandy soils are generally poor in K-bearing minerals and in non-exchangeable K; they release little K by weathering and have low adsorption capacities (Mengel & Kirkby, 1987). The cycling and availability of K in these soils are therefore quite dynamic and easily affected by management practices (Askegaard et al., 2003). The application of K fertilizers to most sandy soils with low clay content and low K buffer capacity can result in localized increases in K concentration in the soil solution, and subsequently K is susceptible to leaching by rainfall or irrigation water.

The loss of soil K due to leaching largely depends upon the amount of soil available K (soluble and exchangeable) (Malavolta, 1985; Wulff et al., 1998). Pal et al. (1999) reported that soluble K is negatively related to coarse sand content but positively related to clay and silt. Sandy soils typically have lower native K supply but higher potential for leaching of fertilizer K than clayey soils (Craig et al., 2015; Phillips & Burton, 2005). For example, on sandy loams the rates of K leaching ranged from 9.4–10.0 kg/ha in the fertilized soil and 7.5 kg/ha in non-fertilized soil in a year (Masauskas & Masauskriene, 2010) to 20–80 kg/ha over 1.5 years (Johnston et al., 1993). In the arid and semi-arid regions, K leaching was enhanced on sandy soils where crops were irrigated with water containing significant Ca and other cations and ion exchange took place (Kolahchi & Jalali, 2007). Soil K leaching also increased with N leaching ($R^2 = 0.69$) across a range of K loss from 6 to 84 kg K/ha (Kayser et al., 2012). A good understanding of K leaching on sandy soils is important for optimizing K use efficiency in grain production.

Sandy soils represent about 70% of the cropping soils across the southwest of Western Australia (Tennant et al., 1992). The incidence of K deficiency in this region has increased steadily: currently in the 0–10 cm layer, 8% of the soils contain < 35 mg bicarbonate-extractable K/kg and 49% of the soils contain < 100 mg K/kg (Weaver & Wong, 2011). Although soil K depletion could be largely due to greater removal of K in hay, straw and grain than fertilizer K input, there has been little research about the effect of K leaching in the region, where large amounts of K can move out of the root zone in pasture fields through leaching, especially in high rainfall (> 600 mm average annual rainfall) sandy areas (Edwards, 1993). This study aimed to examine the effect of fertilizer K rate and soil pH on K-leaching in sandy soils. We hypothesize that lime application to alleviate topsoil acidity may reduce leaching of K and NO_3 by increasing cation and decreasing anion exchange capacities of the soils with variable charge.

Materials and Methods

Soil description

Soil materials were collected (0–10 cm depth) from the non-limed and limed sandy soils at a low rainfall site in Merredin, 240 km northeast of Perth in Western Australia (32°04′S, 115°50′E). The limed soil was previously treated with limestone (85% $CaCO_3$) at 3 t/ha. Sandy soils were also collected (0–10 cm) from a farm, at Whitby 50 km south and a Ballidu farm, 200 km north of Perth. Merredin and Ballidu sands are of typical sandy soils from the grains belt in Western Australia) Stoneman, 1992 (, whereas Whitby sand is similar to the coastal sandy soils used as pasture land. Collected soils were air dried and analysed for chemical properties (Table 1). Soil tests included soil pH in 1:5 soil: 0.01 M $CaCl_2$, electrical conductivity in saturated soil extract (ECe), bicarbonate P and K (Colwell, 1963), soil organic carbon (Walkley-Black method, 1934), NO_3-N and NH_4-N (Rayment & Lyons, 2011). Soil exchangeable Al, Ca, Mg and Na were extracted using 0.01 M silver thiourea (Rayment & Lyons, 2011) and measured by inductively coupled plasma – optical emission spectrometry (PerkinElmer Inc, Waltham, MA). In experiment, the soils were packed into leaching columns giving a bulk density of 1.4 g/cm^3.

Column description

Based on previous leaching studies in small columns (Kolahchi & Jalali, 2007; Wong & Wittwer, 2009), this study used small plastic columns of 10.6 cm in length and 3 cm in diameter. Each column contained 90 g of dry soil. A Whatman No. 42 filter paper was placed at the top of the column to minimize soil disturbance and ensure an

Table 1. Chemical properties of Merredin sands (limed, unlimed), Whitby and Ballidu sands (unlimed)

Soil type	pH ($CaCl_2$)	EC	OC	NO_3	NH_4	P Colwell	K Colwell	Exch Ca	Exch Mg	Exch Al	ExchK	ExchNa	CEC Cmolc kg^{-1}
		dS/m	g/kg	----------- mg/kg -----------				-------------------- cmol/kg ----------------------					
Merredin (limed)	6.20	0.09	9.2	32	1	64	85	4.31	0.45	0.12	0.16	0.07	5.11
Merredin (unlimed)	4.5	0.11	8.2	22	4	86	70	1.55	0.37	0.49	0.15	0.11	2.67
Whitby	4.6	0.02	12.0	1	2	19	< 15	0.75	0.16	0.57	0.03	0.05	1.56
Ballidu	5.8	0.05	4.3	6	1	21	34	1.50	0.19	0.02	0.12	0.03	1.86

even distribution of leaching solutions, and another filter paper was at the bottom of the column to prevent soil loss (Fig. 1a). In the process of soil leaching, 0.005 mM $CaCl_2$ was applied to avoid soil dispersion (DOLLING & RITCHIE, 1985). The flow velocity of the leaching solutions was controlled at 1 mm/min using a peristaltic pump (Fig. 1b). One pore volume (PV) is equal to the volume of leaching solution held at saturation by the soil and is calculated from the bulk density and particle density (e.g. 2.65 g/cm^3) of the soil (ROWELL, 1994). In this study, 1 PV was equal to 24 ml of leaching solution. After 1 PV was applied to saturate the soil column, the leachates were collected every 0.25 PV (6 mL) until 5 PV was reached. Our preliminary experiment of up to 20 PV leaching showed that minimal soil K was leached after 5 PV in sandy soils, and similar findings were previously reported (WONG et al., 1990; KOLAHCHI & JALALI, 2006).

Treatments and measurements

For each soil, the rates of K applied to soil were equivalent to nil, 20 and 60 kg K/ha using KCl applied on soil surface area basis to the leaching columns and all treatments were replicated three times. Each column had a surface area of 7 cm^2, so 2.8, 8.4 mg KCl/column were added to obtain the treatments of 20 and 60 kg K/ha, respectively. Nitrogen fertilizer was applied at equivalent to 50 kg N/ha as urea. The leaching processes were conducted at room temperature (22–24 ˚C). All leachates of 0.25 PV from each soil were analyzed for K, NO_3 concentrations, pH and electrical conductivity (EC). Leachate K was measured using a flame photometer (Model 410-Sherwood), and NO_3 using ion selective electrode (Model: HORIBA), EC using an EC meter (Model WP-981) and pH using a pH meter (Model PC 700 EUTECH MEAS). The amount of leached K or NO_3 in each leachate was the product of K or NO_3 concentration and volume. Potassium or NO_3 cumulative concentrations milli-molar (PAC, NAC) were the sum of K or NO_3 concentrations from all PV samples (MUWAMBA et al., 2015). The NO_3/K molar ratio was calculated using the amount of K and NO_3 in the leachates.

Statistical analysis

The data of K and NO_3 leaching with three K treatments in each soil were analyzed by one-way analysis of variance, and treatment means were compared using the Duncan test at $P = 0.05$.

Results

The Course of K and NO_3 leaching

With lime application, leachate K concentrations in Merredin sands were 30–40 mg/L up to 0.5 PV and declined to 20–30 mg/L regardless of the rates of K treatments from 0.75 to 3.25 PV. From 3.5 to 5 PV, nil K and 20 kg K/ha maintained leachate K concentrations of 17–20, 25–28 mg/L respectively, while 60 kg K/ha produced a K-leaching peak of 69 mg/L at 4.75 PV (Fig. 2: Merredin sand limed). By comparison, leachate K concentrations in the non-limed Merredin sands increased up to 55–60 mg/L at 0.25 PV, and then quickly declined to ~30 mg/L at 1.5 PV in all three K treatments (Fig. 2: Merredin sand non-limed). Leachate K concentrations continued to decrease till 5 PV when 5 and 10 mg/L were measured at nil and 20 kg K/ha, respectively, whereas 60 kg K/ha increased K leaching after 1.5 PV and reached a peak value of 52 mg/L at 3 PV, before declining to 28 mg/L at 5 PV. Hence, maximum K leaching in the non-limed soils occurred almost 2 PV earlier than that in the limed soils.

In the non-limed sand from Whitby, all three K treatments produced leachate K concentrations of 20 mg/L at 0.25 PV. With successive leaching events, leachate K con-

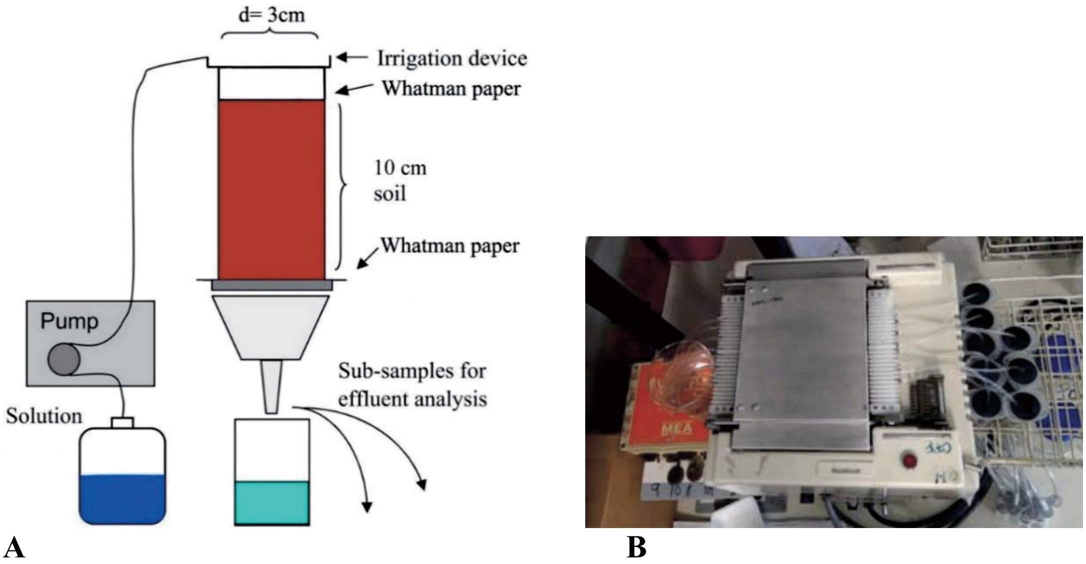

Fig. 1. The set-up for K-leaching experiment (A) diagram; B) laboratory setup)

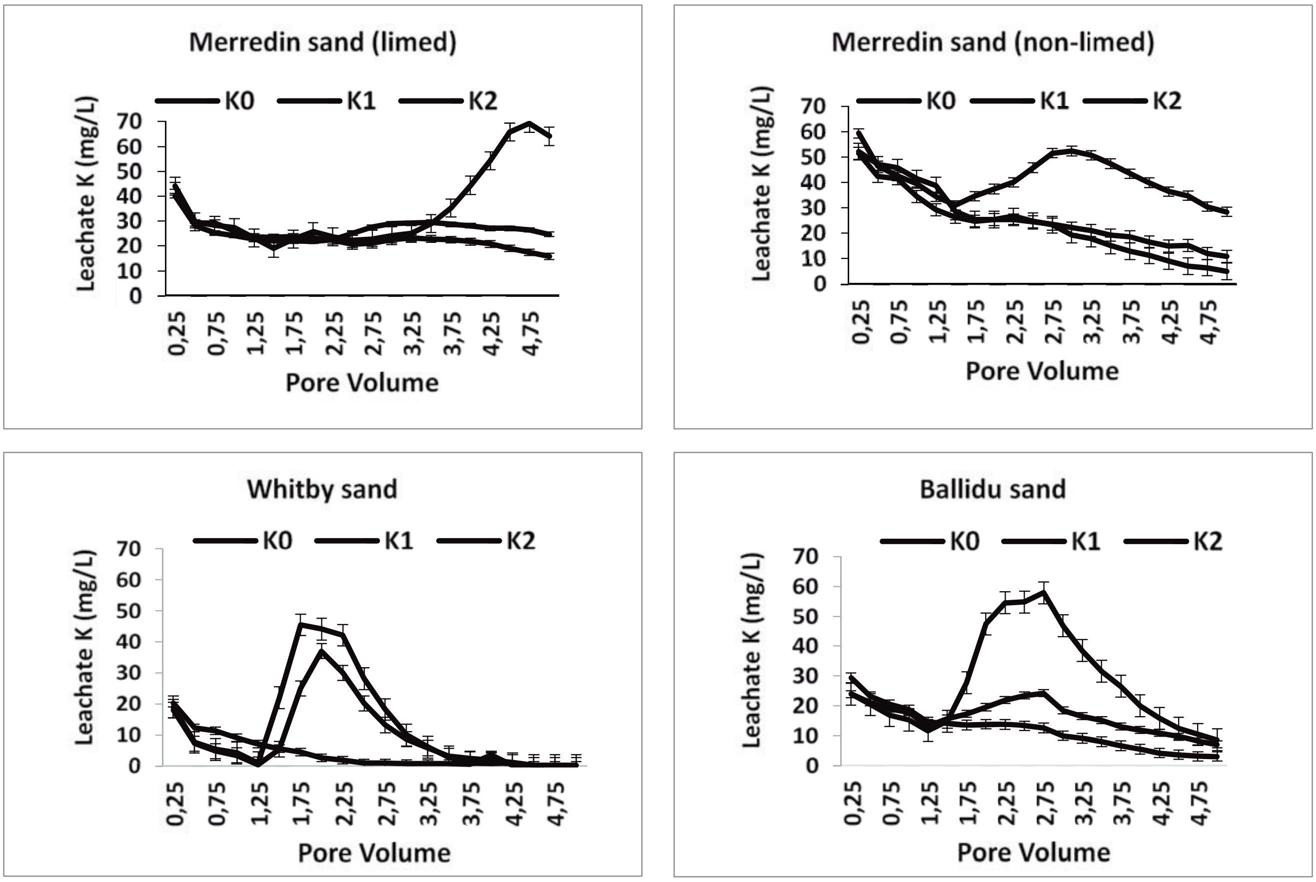

Fig. 2. Changes in leachate K concentrations of continuous 0.25 pore volume drainages from four sandy soils treated with nil K (K0), 20 kg K/ha (K1), and 60 kg K/ha (K2). Values are means of three replicates. (bars represent error bar of the mean).

centrations in the nil K treatment decreased. By contrast, K concentration peaked at 37 and 49 mg/L at 2 PV in the treatments with 20 and 60 kg K/ha respectively, and quickly declined to minimal leachate K concentration at 4 PV (Fig. 2: Whiby sand). The non-limed sands from Ballidu had leachate K concentrations of 25–29 mg/L at 0.25 PV in all K treatments. Thereafter, leachate K concentrations continuously decreased to 3 mg/L at 5 PV in nil K treatment. By contrast, the K in leachate increased at 1.5 PV and reached a peak of 59 mg/L in the 60 kg K/ha soil and 24 mg/L in 20 kg K/ha soil at 2.75 PV, then declined to 8 mg/L at 5 PV (Fig. 2: Ballidu sand).

Potassium accumulative concentrations (PAC) or total K losses during the period of 5 PV leaching at 60 kg K/ha were 107.5 mM in the limed soil (Fig. 3: Merredin sand limed) and 127.4 mM in the non-limed soils (Fig. 3: Merredin sand non-limed), compared with 41,85 mM in the non-limed Whitby and Ballidu soils, respectively (Fig. 3: Whitby sand, Ballidu sand). The PAC values at nil or 20 kg K/ha were significantly lower than that at 60 kg K/ha in all tested soils, except for Whitby soil which showed similar K leaching between the treatments of 20 and 60 kg K/ha.

Leachate NO_3 concentrations decreased from 200 mg/L at 0.25 PV to 50 mg/L at 1 PV, and thereafter declined to about 40 mg/L at 5 PV regardless of K treatments in the limed Merredin soil (Fig. 4: Merredin sand limed). Leachate in non-limed Merredin soil also showed a sharp decrease in NO_3 concentrations at 0.25–0.5 PV, but then increased to peaks of about 100 mg/L at 1.25–1.5 PV in all three K treatments (Fig. 4: Merredin sand non-limed). In the non-limed Whitby and Ballidu soils, leachate NO_3 concentrations were also similar between K treatments during the period of 5 PV leaching (Figs. 4: Whitby and Ballidu sands). Consistently, soil K treatments had little effect on NO_3 accumulative concentrations or total NO_3 losses by leaching in all tested soils (Figs. 5).

Leachate pH and EC

The first pH peak at 1.75 PV corresponded with the peak in NO_3 drainage (Fig. 6: Merredin sand limed), and the second pH peak at 2.5 PV corresponded with K leaching. At 5 PV, the leachate pH was the same for nil, 20 and 60 kg K/ha treatments. There were significant interactions between K and lime on leachate pH. Both lime and K application in the Merredin soil caused a decrease NO_3/K molar ratio. In the non-limed Merredin soil, there was no changes in NO_3/K molar ratio with K addition (Fig. 6). In contrast, K application decreased NO_3/K

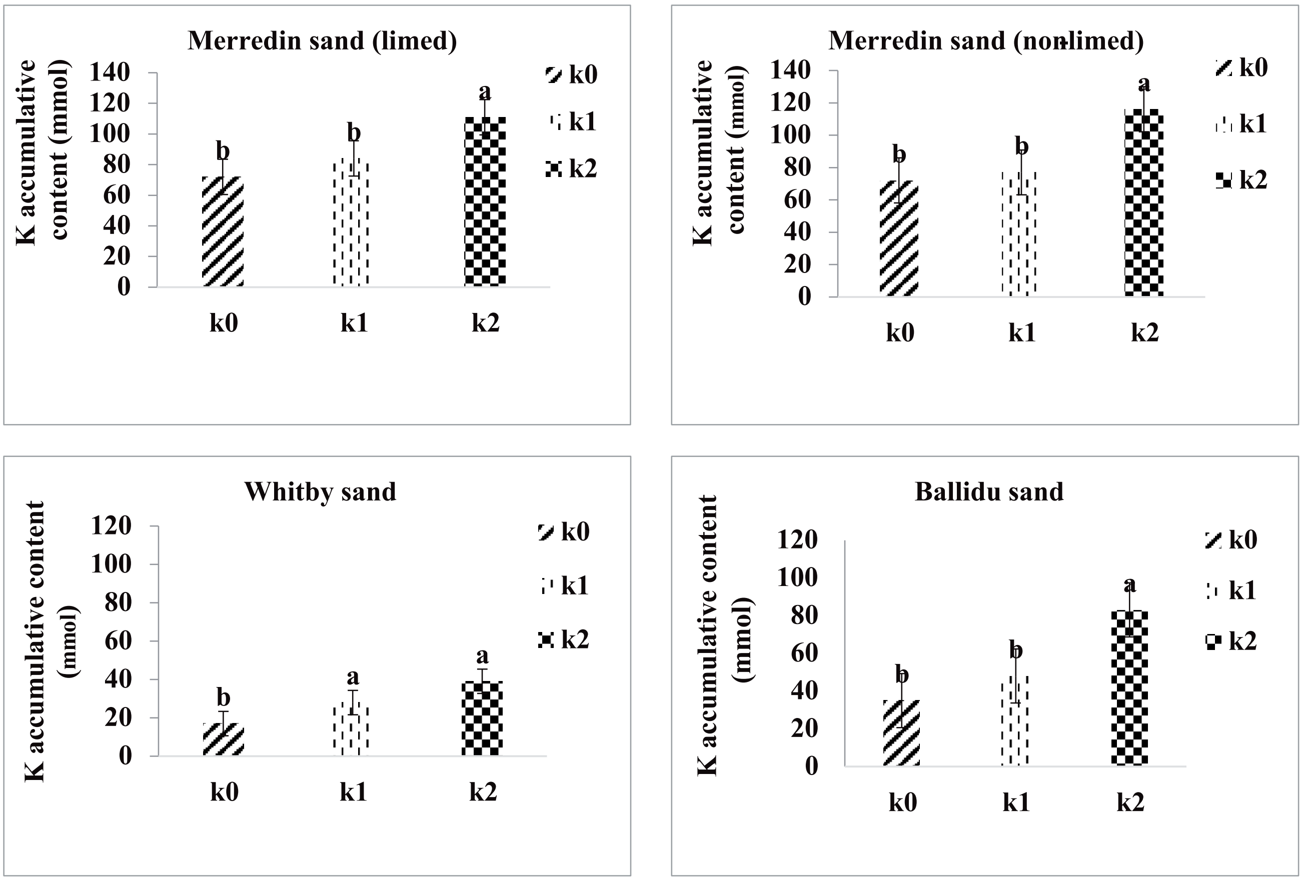

Fig. 3. Potassium accumulative content (mmol, n = 3) over 5 pore volume leaching period of four sandy soils treated with the equivalent of nil K (K0), 20 kg K/ha (K1) and 60 kg K/ha (K2) and 50 kg N/ha. (bars represent error bar of the mean).

molar ratio in the Whitby and Ballidu soils. Moreover, K treatments had greater effect on NO_3/K molar ratio in Whitby soil than other three soils (Fig. 2).

With K and urea fertilizers, maximum leachate pH was 7.4 at 1.75 to 2.5 PV in the 20 kg K/ha treatment of limed Merredin sand and reduced to 6.0–6.2 at 1.75 to 2.5 PV in the 20 and 60 kg K/ha treatments of non-limed Merredin sand (Fig. 7). The leachate pH increased by one unit in the limed compared to non-limed Merredin soil. However, the leachate pH was 4.2–4.5 in Whitby soil and 6.6–6.8 in Ballidu soil with little evidence of K effect during the period of 5 PV leaching (Fig. 7).

Application of K and urea application increased leachate EC in the limed Merredin soil. The 60 kg K/ha treatment showed two peaks in leachate EC (Fig. 8: Merredin sand limed): the first peak of 1.46 dS/m at 2 PV was attributed to NO_3 leachate and the second peak of 1.4 dS/m at 3.25 PV to K leachate. The leachate EC in all three K treatments declined with the progress of leaching and remained stable from 3.75 PV onwards. In the non-limed Merredin soil, the highest EC value was 1.3 dS/m at 1.75–2.25 PV in 60 kg K/ha treatment and the lowest EC value was 0.8 dS/m at 1.75 PV in the nil K treatment (Fig. 8: Merredin sand non-limed). Both Whitby and Ballidu soils had a small peak value of 1.65 dS/m at 1.5 PV and 1.8 dS/m at 1.75 PV, respectively in the treatment of 60 kg K/ha, while the leachate EC remained 1.1–1.2 dS/m in the treatments of nil, 20 kg K/ha during the period of 5 PV leaching (Fig. 8: Whitby and Ballidu sands).

Discussion

Although fertilizer K is susceptible to leaching by rainfall or irrigation in light-textured soils, the present study has shown that the loss of applied K from leaching on sandy and acidic soils can be ameliorated by lime application through delaying the peak of K leaching and reducing the total amount of K leached. For example, with 60 kg K/ha applied, the peak of K leaching was at 4.75 PV for the limed soil compared to 3 PV for the non-limed soil (Fig. 2). Moreover, liming significantly reduced leachate NO_3 concentrations compared with the non-limed treatment. The findings have clearly demonstrated the beneficial role of liming in soil nutrient retention and crop N and K nutrition on sandy and acidic soils. In the agricultural lands of Western Australia, liming has been widely used to ameliorate extensive soil acidification, particularly in the subsoils, that restricts crop roots from growing into the deep soils for access to moisture and nutrients (Dolling et al., 1991).

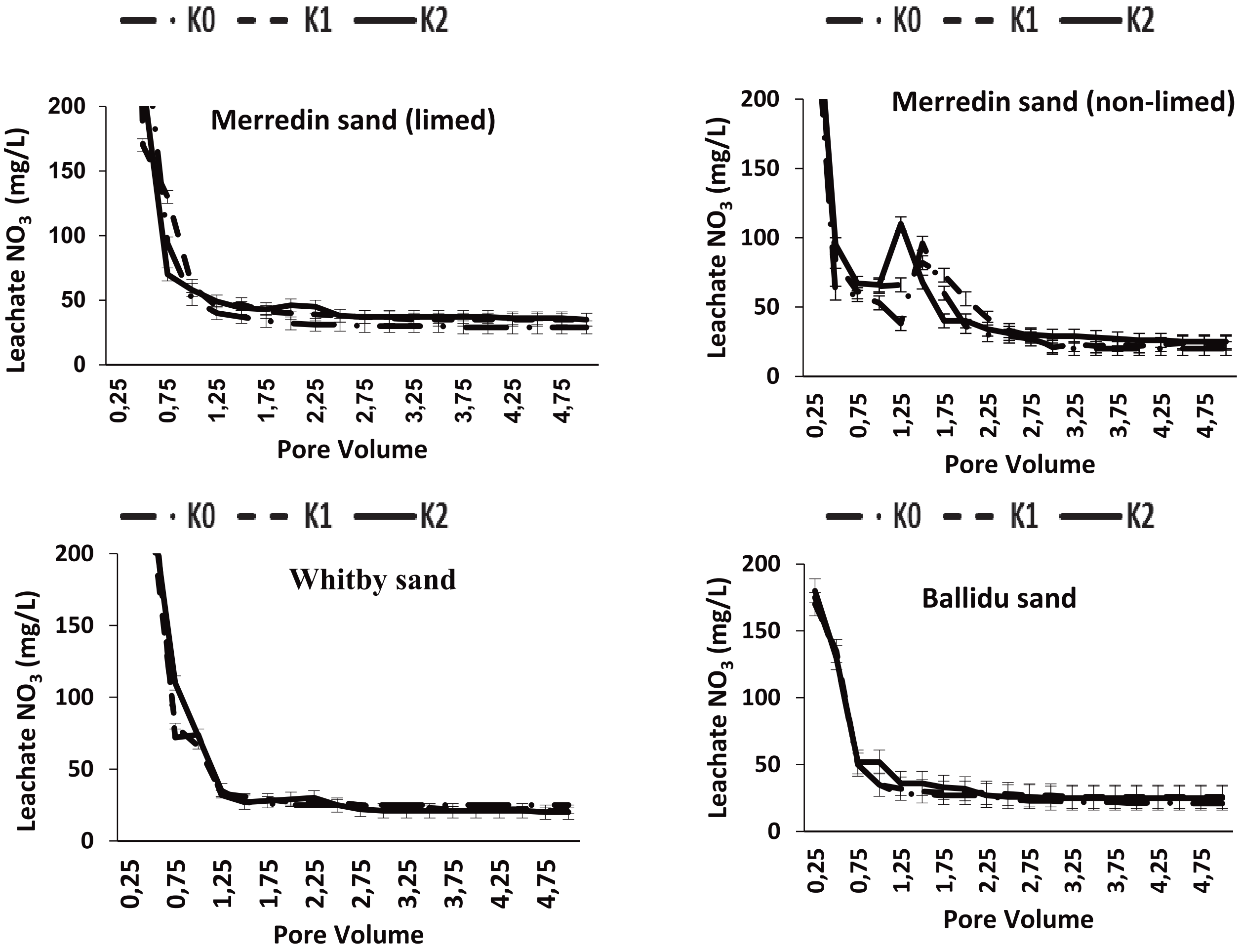

Fig. 4. Changes in leachate nitrate concentration from 0.25 pore volume drainages of four sands treated with nil K (K0), 20 kg K/ha (K1) and 60 kg K/ha (K2). Values are means of three replicates. (bars represent error bar of the mean).

The lime-induced changes in the pattern and intensity of soil K leaching were most likely related to changes in soil chemical properties after lime application, which increased pH (4.5 to 6.2), CEC (2.67 to 5.11 cmol/kg) and exchangeable Ca (1.55 to 4.31 cmol/kg) (Table 1). The pH of soil solution can influence the availability of nutrients to plants, and soil pH is also important for CEC because an increase in pH increases the number of negative charges on the colloids, thereby increasing CEC (Dolling et al., 1991; Sposito, 1989). As a consequence liming would increase soil K absorption, making the applied K less susceptible to leaching. This study also showed that liming clearly caused a delay in K leaching from the soil profile particularly at high K rate (Fig. 2), compared with high cumulative K value in the leachate of the non-limed soil. In contrast, previous studies showed that liming increased the amount of Ca and Mg leaching from soils and uptake by plants (Barik & Aydin, 2013) and gypsum application led to increase in the rate of exchangeable Ca and decrease in the ratio of Al/Ca (Black & Cameron, 1984). All these findings show that liming can play a significant role in soil and plant nutrition.

The effects of the rate of K-fertilizer on K leaching may also differ between soil textures. An annual application of up to 150 kg K/ha in the tropics resulted in 16–52% loss of the fertilizer K by leaching in sandy clay loam, but much less K leaching occurred in clay soil at the depth below 1 m (Rosolem & Steiner, 2017). Due to high leaching potential in the tropics, split K application can minimize K losses and improve K use efficiency in tropical soils with low clay contents (Sitthaphanit et al., 2009). Less K leaching and lower K concentration in deeper layers (< 0.05 mmol L^{-1}) could be attributed to the increase in CEC of variable charge sites in the upper layers after liming increases soil solution ionic strength and pH (Sposito, 1989) and plant K uptake (Caires et al., 2005). In this study, liming significantly decreased total K and nitrate leaching, and also delayed NO_3 leaching with the peak occurring at 1.25 PV (Fig. 4). Liming was also reported to reduce P leaching from the columns of clayey and sandy soils by 49 and 51%, respectively (Andersson et al., 2016). With different N and drainage treatments on a hillslope grassland, Alfaro et al. (2004) found that K leaching over time showed two phases, firstly a rapid initial decrease with preferential flow at the beginning of

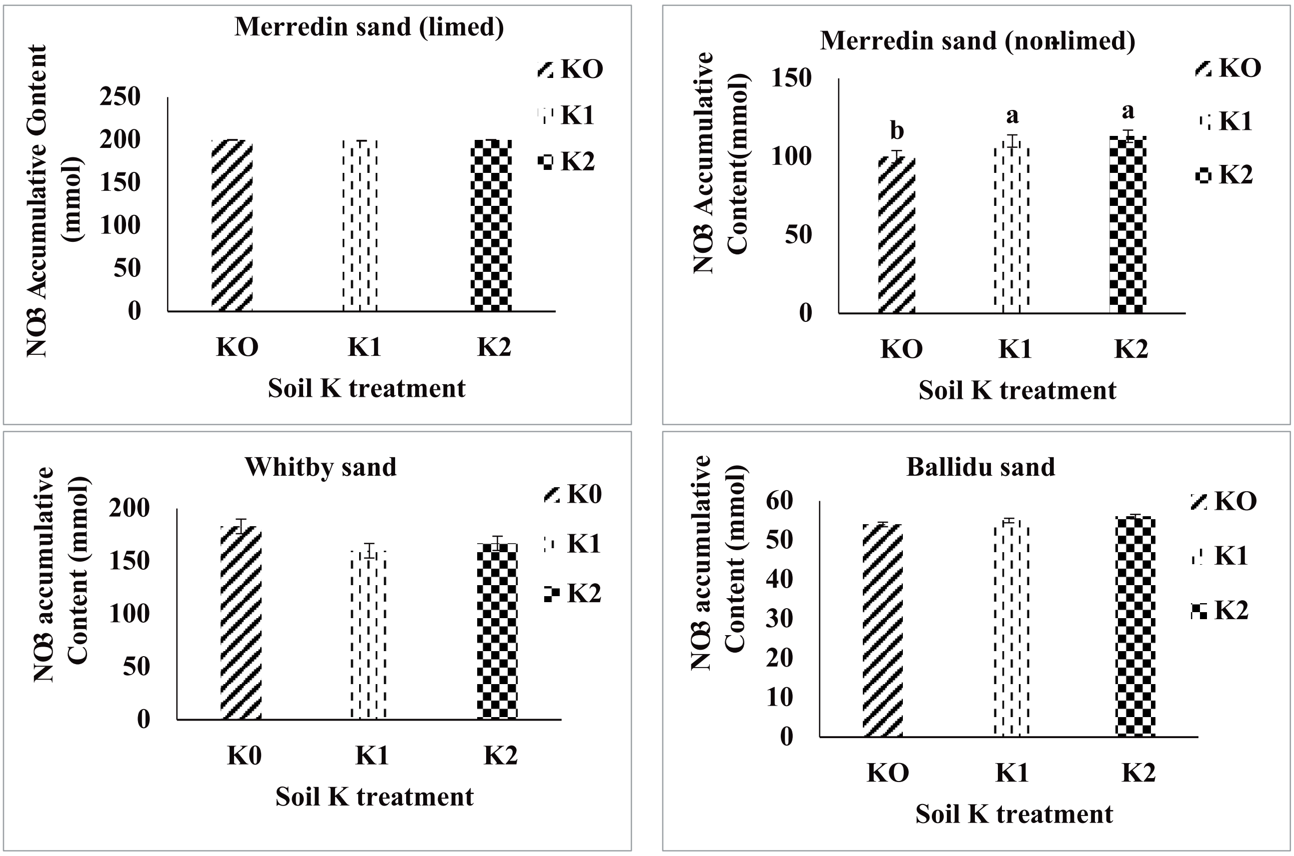

Fig. 5. Nitrate accumulative content leachate (millimole, n = 3) over 5 pore volume leaching period of four sandy soils treated with the equivalent of nil K (K0), 20 kg K/ha (K1) and 60 kg K/ha (K2) and 50 kg N/ha. (bars represent error bar of the mean).

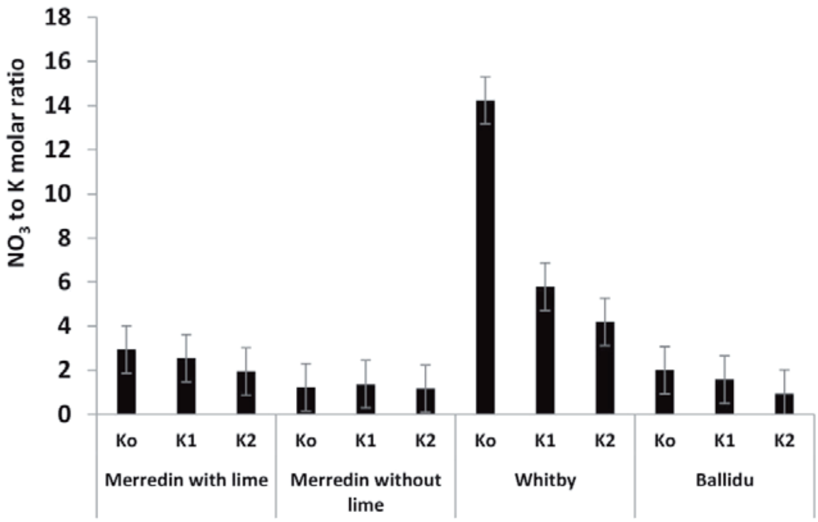

Fig. 6. The NO_3/K molar ratio of four sandy soils (limed and non-limed Merredin sands, non-limed Whitby and Ballidu sands) treated with the equivalent of nil K (K0), 20 kg K/ha (K1) and 60 kg K/ha (K2) and 50 kg N/ha. (bars represent error bar of the mean).

the drainage period, followed by a slower phase dominated by matrix flow, and soil N addition reduced the amount of K leaching during the drainage period. In contrast, ANDERSSON et al. (1994) found that liming intensified nitrification and nitrate production, and according to the study by MKHONZA et al. (2020) liming increased the dissolution of P, Ca-P and nitrate and would increase the risk of nitrate leaching in the absence of plant roots.

Nitrate leaching from agricultural soils can represent a substantial loss of fertilizer N, but a large variation in losses has been reported. Leachable NO_3 was higher in agriculture soils than in non-agricultural soils (GARG et

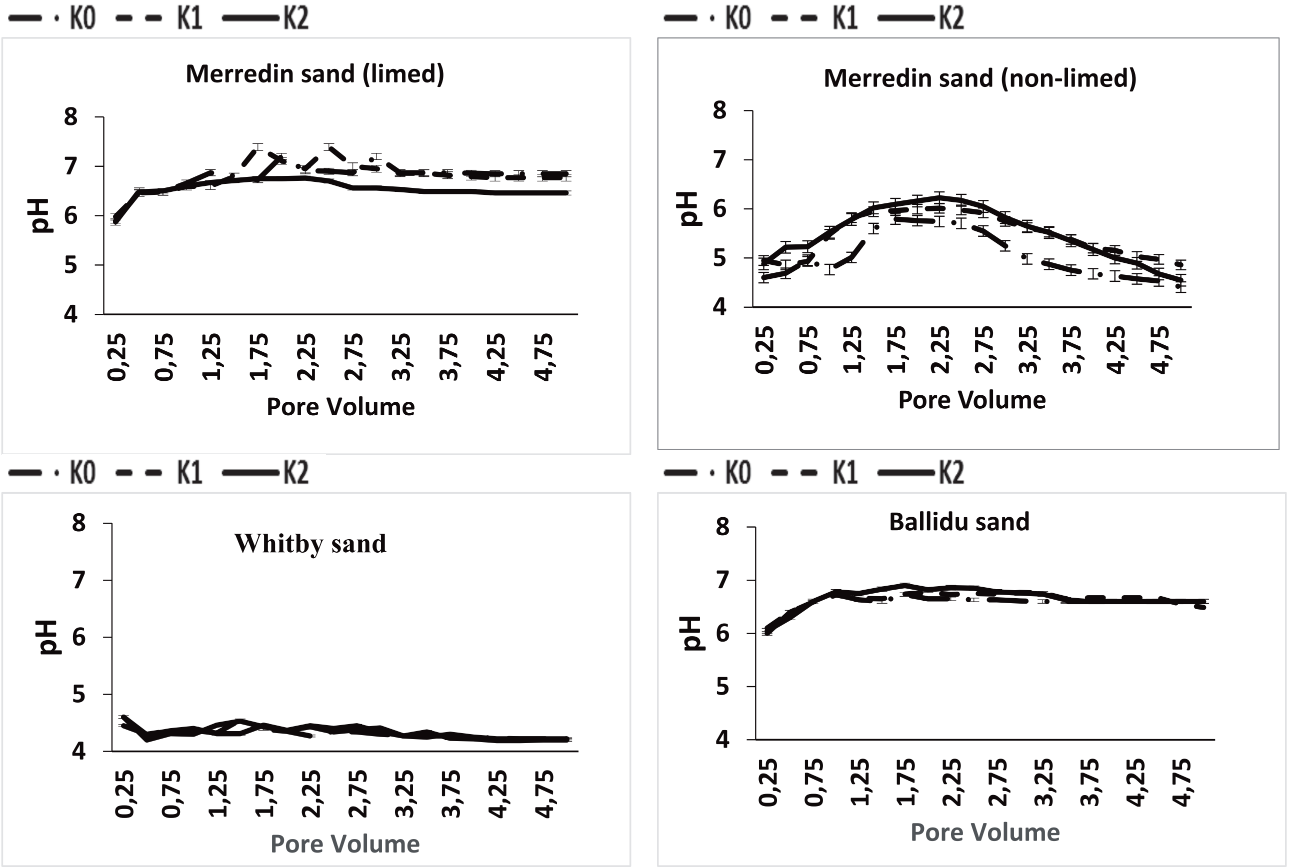

Fig. 7. Changes in pH from 0.25 pore volume drainages of four sands treated with nil K (K0), 20 kg K/ha (K1) and 60 kg K/ha (K2). Values are means of three replicates. (bars represent error bar of the mean).

al., 2014). Urea is widely used in agriculture soils of the arid and semi-arid regions. The hydrolysis of urea to ammonium carbonate followed by the nitrification of NH_4, is rapid (Prakash et al., 1999). In carbonate-bearing soil, the acid produced by nitrification causes an increase in Ca and Mg concentrations in soil solution. These cations can exchange with soil K and thus application of manure and urea may increase both nitrate and K^+ leaching. This study found that the amount of leached NO_3 from nil K soils was greater than from the K treated soils, and K leaching was significantly reduced by liming. Lime application improves soil properties (Moreira & Fageria, 2010) and is able to preserve macro nutrients in soils and reduce environmental pollution (Kolahchi & Jalali, 2007).

Soil pH and EC in the drainage water were significantly affected by lime and K treatments. Liming increased soil pH, and the change in pH can influence soil nutrient retention and leaching. In the limed soil the highest EC of 1.4 dS/m occurred at 3.25 PV, compared with 1.32 dS/m at 2 PV in non-limed soil, indicating the delay in nutrient leaching. Differences in some soil physical and chemical properties could also affect K leaching. For example, non-limed Merredin sand had more acidic pH, lower CEC and higher concentration of exchangeable Al than the limed Merredin sand (Table 1), despite the same particle texture (85% sand, 8% silt, 7% clay). The change in pH and CEC would contribute to varying K leaching between the two soils (Fig. 2). Slight difference in soil bulk density was observed between the limed and non-limed soils.

The NO_3^-/K molar ratio was also affected by K application. Among the four studied soils, the highest ratio was observed in Whitby soil with nil K application. The intensified nitrate leaching of this soil may be partially due to light texture and low CEC (1.56 Cmolc kg^{-1}). Very acidic pH (4.6) of this soil would also intensify the dissolution and availability of NO_3 and increase its leaching potential. Soil pH is the most important factor affecting soil processes and nutrient bioavailability (Neina, 2019). Moreover, higher organic carbon content (12 g kg^{-1}) of Whitby soil than other three soils would likely increase soil sorption and desorption processes. Nevertheless, applying K had reduced the NO_3^-/K molar ratio in all studied soils (Fig. 6).

Conclusion

This study has demonstrated that lime application can increase CEC and reduce K and NO_3 leaching on sandy soils, and thus may make significant contribution to K and N nutrition and improve crop productivity on sandy, low-K and acidic soils.

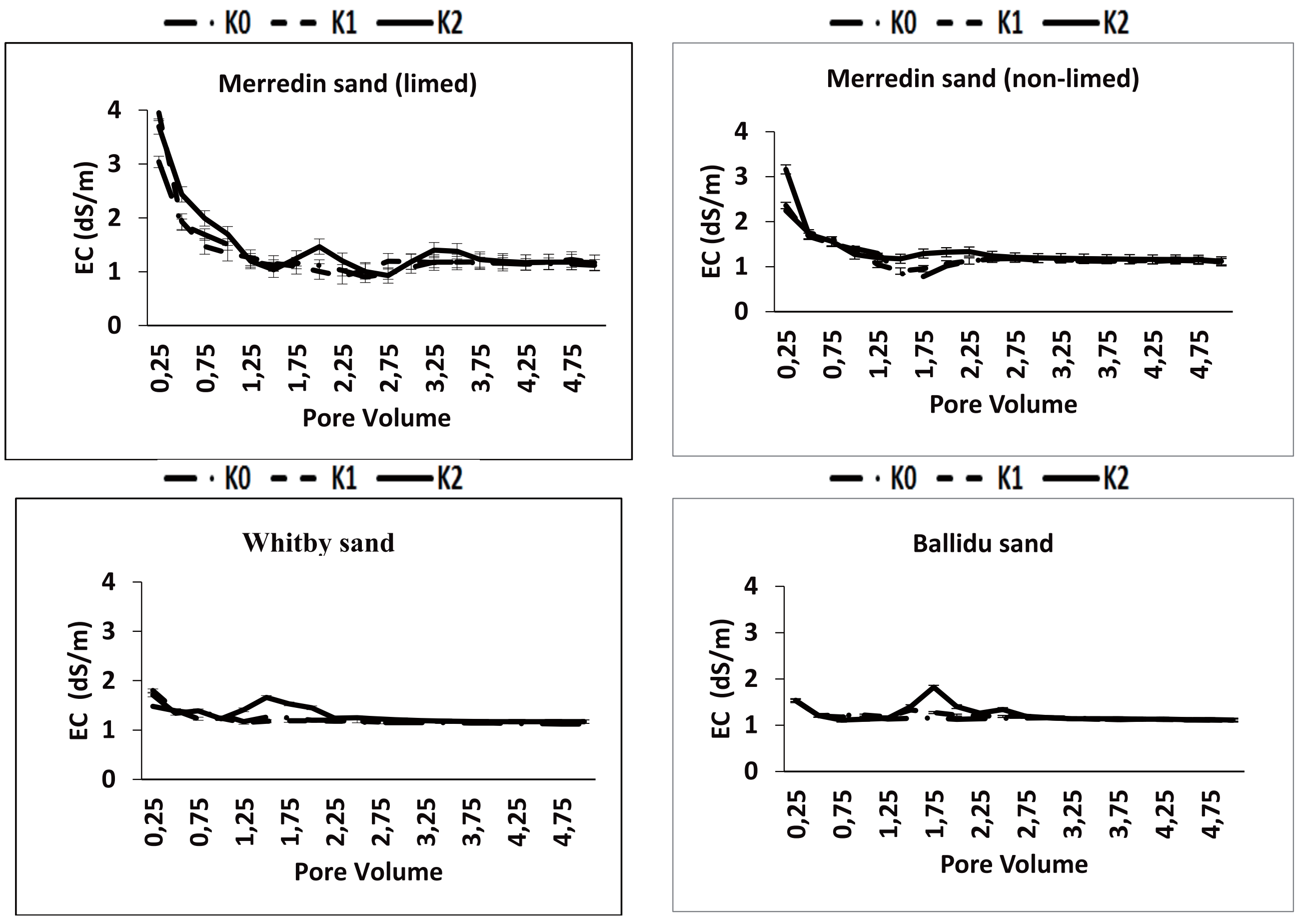

Fig. 8. Changes in EC from 0.25 pore volume drainages of four sands treated with nil K (K0), 20 kg K/ha (K1) and 60 kg K/ha (K2). Values are means of three replicates. (bars represent error bar of the mean).

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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