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Water Use Efficiency and Yield of Sweetpotato as Affected by Nitrogen and Potassium Application

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Abstract

The effect of nitrogen and potassium on the yield and water use efficiency of sweetpotato (*Ipomoea batatas* L.) was studied under water stress condition. The treatments consisted of two soil water regimes (30% and 80% of the soil field capacity) and nitrogen and potassium treatments (20, 100, and 200 kg of N ha^{-1}, with a non-limiting potassium supply (160 kg of K ha^{-1}) and 16, 80, and 160 kg of K ha^{-1}, with a non-limiting nitrogen supply (200 kg of N ha^{-1}). The experiment was carried out in complete randomized design with 4 replications. The supply of nitrogen and potassium at 100 kg N ha^{-1} and 160 kg K ha^{-1} produced the highest tuber yields under both well watered and water stressed conditions. A higher nitrogen supply in the soil produced greater leaf area, but increasing soil nitrogen beyond 100 kg N ha^{-1} reduced tuber yields. Leaf area and yields of Lole cultivar were less affected by water stress than were those of Wanmun cultivar. Under water stress conditions, Wanmun cultivar produced lower tuber yields than did Lole cultivar. Plant water use efficiency increased as the potassium supply increased under adequate and water-stressed conditions in both Lole and Wanmun cultivars.

Keywords: leaf area, sweetpotato (*Ipomoea batatas* L.), tuber yield, water stress, water use efficiency

1. Introduction

Sweetpotato is the fifth most important food crop in developing countries after rice, wheat, maize and cassava (FAO, 2002). Among the world's major food crops, sweetpotato is an excellent source of energy (438 kJ 100 g^{-1} edible portion) (Laurie et al., 2012), beta-carotene, in orange and yellow tuber flesh varieties (Van Jaarsveld, 2005; Ofori et al., 2009; Burri, 2011), anthocyanin in purple tuber flesh varieties (Kano, 2005; Lila, 2004), vitamin C, B, minerals (Ca, P, Fe, and K) (Woolfe, 1992). Sweetpotato is source of human food, animal feed and processed products. It is the most important staple food crop which constitutes 80% of rural people's diet in Papua, Eastern Indonesia. Intensive research efforts to enhance production and consumption have been undertaken in recent decades with the aim of increasing recognition of the potential of sweetpotato as a nutritious food for humans and animals (Yamakawa & Yoshimoto, 2002). However, tuber yield of sweetpotato in Papua, Indonesia is low, with an average yield of 10 ton ha^{-1} (Saraswati et al., 2013). Soil moisture is considered amongst the most important factors affecting yield, as it affects root development and hence could impose a significant impact on yields (Yamauchi et al., 1996).

Although sweetpotato is considered as a drought tolerant crop (Hahn & Hozyo, 1984), water plays an important role in its growth and yield. Water deficits reduce leaf water potential and total water use, and subsequently reduce stomatal conductance, leaf area, root mass, total plant mass and tuber yield (Sivan et al., 1996). Drought is a major problem for sweetpotato production in the highland areas of Papua (Schneider et al., 1993; Ballard, 1999). Drought occurs yearly and devastates crops, threatening the lives of the people in the area. Prolonged and severe drought due to the effect of *El Niño* in 1997, resulted in many crops including sweetpotato dying (Prain & Widyastuti, 1998; Ballard, 1999), and many people died of starvation in Papua at this time.

Nitrogen (N), phosphorus (P), and potassium (K) are macronutrients essential for the growth of all plants. They are important for sweetpotato production although sweetpotato has rarely been reported to respond to phosphorus (Norman et al., 1995), probably due to its high phosphorus use efficiency. These elements are not only capable of restoring soil fertility, but they have also been reported to improve osmotic adjustment within plants (Ashraf et al., 2001), hence improving their water use efficiencies.

Nitrogen deficiency may lead to increased stomatal conductance and greater transpiration per unit leaf area due to stomatal opening, thereby resulting in decreased water use efficiency (Morris et al., 1998). In sweetpotato, this was probably a consequence of lower total dry matter production rather than increased total water transpiration per plant (Kelm et al., 2001). Higher yields in maize, on the other hand, can be achieved by supplemental nitrogen primarily because of its vigorous root system (Morris et al., 1998), hence deep root penetration into the soil matrix.

Potassium, an important cation in many physiological and biochemical processes, is required by many plants as much, or even more than nitrogen (Marschner, 1995). The requirement for potassium is higher in sweetpotato than in cereals especially in the harvested roots (O'Sullivan et al., 1997). Potassium has an important effect on photosynthesis, especially carbohydrate and protein synthesis (Pier & Berkowitz, 1987; Robitaille & Lawrence, 1992), and maintains and regulates cell turgor and stomatal movement (Beringer & Nothdurft, 1985; Hsiao & Lauchli, 1986). Potassium influences plant water status and tends to reduce the effect of soil moisture deficiencies (Marschner, 1995; Losch et al., 1992). Plants well supplied with potassium can better regulate their stomatal opening and closing thereby preventing excessive water loss by the plant (Sivan et al., 1996), and providing a drought tolerance mechanism. It is widely known that sweetpotato requires high potassium contents in the soil to promote tuber formation and development (O'Sullivan, 1997). However, the role of potassium in relation to overcoming soil moisture deficits in sweetpotato has rarely been reported. As sweetpotato is often planted in drought-prone areas, potassium from fertilizers could be expected to have beneficial effects not only in increasing tuber yields, but also in improving water use efficiency. An experiment was carried out to study the influence of nitrogen and potassium on water stress and productivity in sweetpotato.

2. Materials and Methods

A pot experiment was conducted in James Cook University, Townsville, Australia. Daily minimum and maximum air temperature and relative humidity were recorded for the period of experiment. The maximum range of temperature was between 29 °C and 32 °C, and relative humidity was between 55% and 73% at 9.00 am and between 45% and 66% at 3.00 am. Two sweetpotato cultivars (drought tolerant Lole and drought sensitive Wanmun) were used as indicator plants and two soil water regimes were applied (30% and 80% of the soil field capacity) with the application of complete and partial nutrients (complete NK level, a partial nitrogen level, and a partial potassium levels). The complete dose level of sweet potato was 100 kg of N ha^{-1}, 80 kg of P ha^{-1}, and 160 kg of K ha^{-1}, and all treatments received the same P level (80 kg P ha^{-1}). Sweetpotato need moderate N, low P, and high K (Hughes et al., 2009). A water content of 30% of soil field capacity was imposed as a water stress treatment that would still be able to support reasonable growth and tuber yields, while another treatment at 80% of the soil field capacity was imposed as a control in which sweetpotato would be expected to produce vigorous growth and maximum tuber yields.

Two separate experiments were carried out using complete randomised designs with 4 replications. The first experiment of 48 pots was a nitrogen fertilizer trial with 3 nitrogen levels, 2 soil water levels, and 2 cultivars, and the second of 48 pots was a potassium fertilizer trial with 3 potassium levels, 2 soil water levels, and 2 cultivars. They were run concurrently using 10 L undrained pots containing 11 kg of clean, washed, coarse sand as the growing medium.

Nitrogen and potassium treatments were applied as follows: (1) The nitrogen treatments consisted of 20, 100, and 200 kg of N ha^{-1} from ammonium nitrate, with a non-limiting potassium supply (160 kg of K ha^{-1}); (2) The potassium treatments consisted of 16, 80, and 160 kg of K ha^{-1} from potassium chloride, with a non-limiting nitrogen supply (200 kg of N ha^{-1}). In this experimental design, treatments 3 and 6 each consisted of the same 16 nutrient applications and one of them was omitted; the results of the remaining treatment were incorporated in both the nitrogen and potassium experiments. The total number of experimental units was, therefore, 80 pots; each pot held one plant.

The N and K inputs were applied to the pots as 4.35 g, 2.15 g, and 0.29 g NH_4NO_3 pot^{-1} which were equivalent to 200 kg N, 100 kg N and 20 kg N ha^{-1}, respectively, and as 1.38 g, 0.69 g, and 0.14 g KCl pot^{-1} which were equivalent to 160 kg K ha^{-1}, 80 kg K ha^{-1} and 16 kg K ha^{-1}, respectively.

Other elements were applied as a basal nutrient dressing using the compounds listed in Table 1. All of the nutrients were applied in a split dose at 1 week (half of the above dose) and again 6 weeks after planting (the remaining half of the above dose). The growing medium was clean, coarse, nutrient free sand, air dried to constant moisture for several weeks. The sand was passed through a 2 mm sieve, washed to remove fine components, dried and its moisture content determined. The amount of water required to bring the soil in the pots to field capacity was calculated using the gravimetric method. The pots and the surface of the growing medium were covered with aluminium foil to minimize evaporation.

Table 1. Nutrient application rates, adjusted from Asher et al. (2002)

Element	Application rate ($kg \cdot ha^{-1}$)	Compound	Rate of compound	
			($kg \cdot ha^{-1}$)	($g \cdot pot^{-1}$)
N	200	NH_4NO_3	572	4.347
P	30	$NaH_2PO_4.2H_2O$	173	1.588
K	160	KCl	161	1.375
Ca	35	$CaCl_2$	98	0.510
Mg	30	$MgCl_2 \cdot 6H_2O$	250	3.315
S	25	Na_2SO_4	111	0.654
Fe	5	Fe Na EDTA	32.9	0.058
B	2	H_3BO_3	11.4	0.007
Mn	5	$MnCl_2 \cdot 4H_2O$	16.35	0.014
Zn	4	$ZnCl_2$	8.34	0.004
Cu	3	$CuCl_2 \cdot 2H_2O$	8.04	0.003
Mo	0.4	$[NH_4]_6 MoO_{24} \cdot 4H_2O$	5.15	0.003

Shoot tip cuttings of sweetpotato stems, 25 cm long were planted into non-draining 10 L pots containing 11 kg of air-dried sand that had been watered to field capacity. Water was then withheld for 1 week until the soil moisture content reached 80% for the control (with non-limiting water conditions), and for 3 weeks until 30% field capacity for the water stressed treatments. The plants were then watered to the nominated percentage of field capacity every second day, based on the weight lost from the pots by transpiration.

The plants were harvested 5 months after planting. Each plant was separated into leaf blades and tubers. At harvest, tuber fresh weight and total leaf area per plant were recorded. Leaves were dried at 70 ºC and the dry masses were recorded. To quantify water use efficiency, transpiration was recorded as the weight losses from the pots every second day. Water use efficiency is the ratio of dry matter produced (g of total dry biomass) to the amount of water used in transpiration (kg of water applied per plant) during the whole growth period (Taiz & Zeiger, 2002; Da Matta et al., 2003).

Analyses of variance based on factorial experiments in complete randomized designs were conducted to test the significance of each treatment effect and their interactions at a 5% ($P < 0.05$) significance level. The Duncan Multiple Range Test was used to determine whether the effects of the treatments on plant growth parameters were significant.

3. Results and Discussion

Nitrogen additions had a significant positive effect on the leaf area of both cultivars under both water regimes (Figure 1). Bourke (1985) found that nitrogen fertilizer increased leaf number, and as a consequence increased leaf area and growth rates. On the other hand, potassium additions produced a significant deleterious effect to leaf area in both cultivars under both soil water regimes (Figure 1). The greater leaf areas produced by lower potassium supply were attributed to the presence of non-limiting nitrogen contents in the soil.

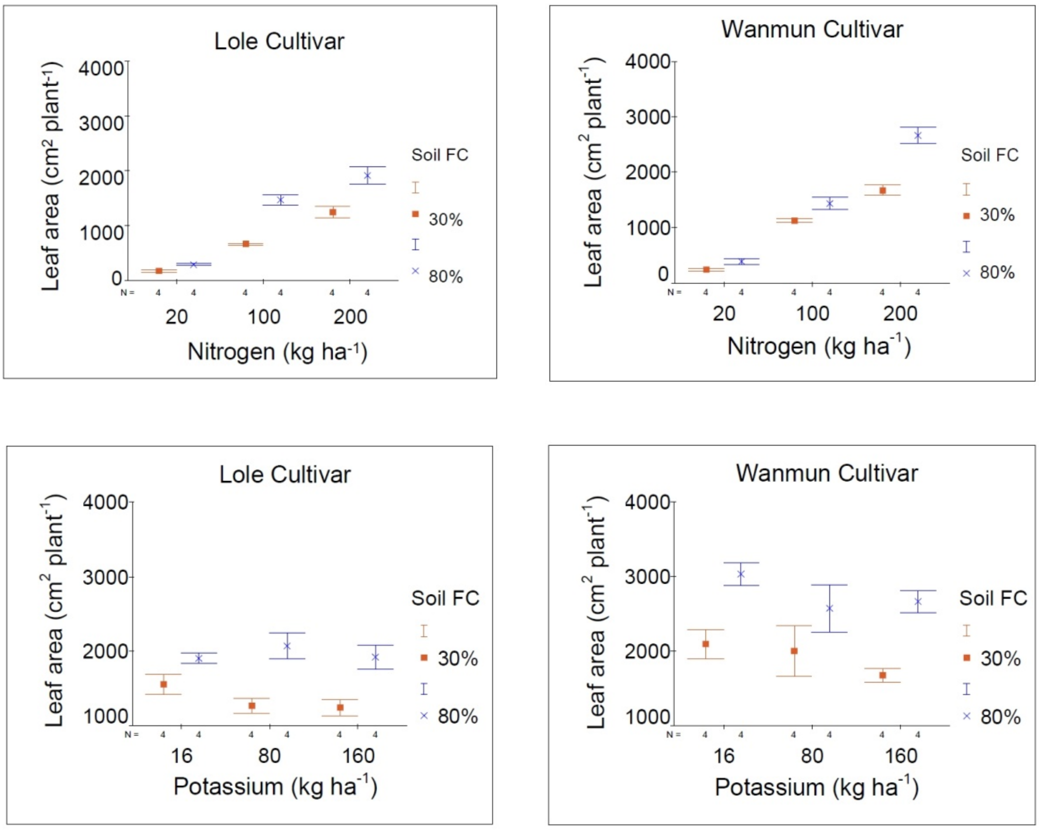

Figure 1. The effect of N and K on the leaf area of Lole and Wanmun sweetpotato cultivars grown under 30 and 80% soil field capacity

Note. Error bars represent standard errors of means with 4 replications. (The nitrogen responses are shown for the non-limiting K trial, and the potassium responses for the non-limiting N trial).

Tuber yield was significantly affected by the nutrient addition treatments and their interactions. The effect of nitrogen on tuber yield under well-watered conditions was greater in Wanmun (870 g plant^{-1}) than in Lole (644 g plant^{-1}) when supplied with 100 kg of N ha^{-1} (Figure 2). Under water stressed conditions, however, the greater nitrogen supplies produced greater tuber yields. Tuber yield was optimal (391 g plant^{-1} from Wanmun and 411 g plant^{-1} from Lole) at a nitrogen application of 100 kg ha^{-1} (Figure 2).

Under water stress conditions, tuber yields increased when potassium application rates were increased, but the yields were much lower than those of the well watered plants when grown in soils with the same level of potassium. Under such conditions, the cultivars produced their greatest yields of tubers (Lole: 426 g plant^{-1}; Wanmun: 403 g plant^{-1}, respectively) with the application of 200 kg ha^{-1} of N and 160 kg of K ha^{-1} (Figure 2).

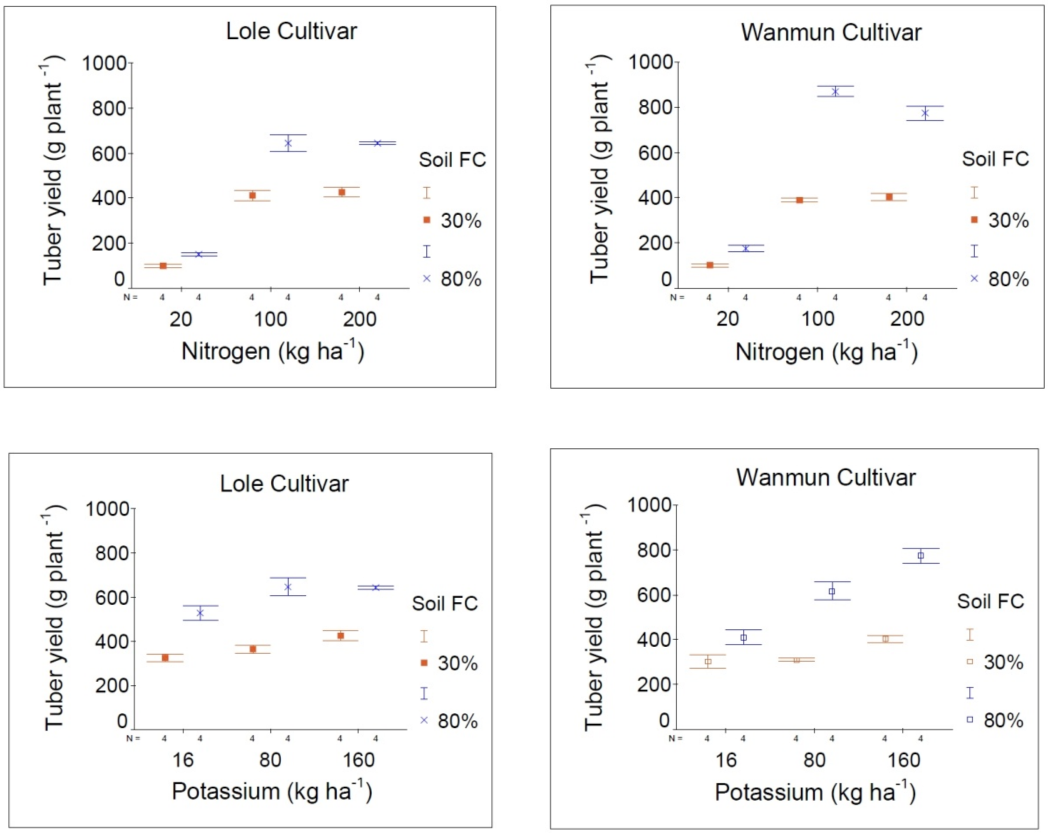

Figure 2. The effects of nitrogen and potassium on tuber yields of Lole and Wanmun cultivars grown under 30% and 80% of soil field capacity

Note. Error bars represent standard errors of means with 4 replications. (The nitrogen responses are shown for the non-limiting K trial, and the potassium responses for the non-limiting N trial).

The effects of potassium on tuber yields were significant. Non-limiting water and moderate N applications (160 kg N ha^{-1}) produced the greatest yields of 774 g plant^{-1} in Wanmun and 643 g plant^{-1} in Lole (Figure 2). The tuber yields of Wanmun declined when the application rate of potassium was reduced to 80 kg of K ha^{-1}. Increasing potassium rate to 80 and 160 kg K ha^{-1} increased the tuber yield in Lole to 647 g plant^{-1}, and 643 g plant^{-1}, respectively. Hence, 160 kg ha^{-1} of K is needed to ensure optimal tuber yields from Wanmun.

These results show that, although there was a lack of response to potassium in root development in both cultivars and a much smaller response in shoot growth, the potassium content of the soil may limit tuber yield even when no effect is seen in leaf growth. This result was supported by Jian-wei (2001) and Bourke (2005) that K fertilizer significantly increased sweetpotato yield. Greater nitrogen applications to infertile growing media promoted the growth of the vegetative parts of the Lole and Wanmun cultivars. The lack of increase in tuber production with soil nitrogen levels greater than 100 kg N ha^{-1} may be attributed to the influence of nitrogen on tuber growth and development. Kelm et al. (2001) showed that tuber initiation was delayed with high nitrogen supply in two sweetpotato genotypes. Hartemink et al. (2000) and Hughes et al. (2009) also found that nitrogen fertilizer negatively affected tuber yield of sweetpotato by promoting vine growth, as was evident in the present trial.

Taufatofua and Fukai (1996) reported faster sweetpotato growth and greater tuber yields by increasing the soil nitrogen content under irrigation. They also observed that, in the absence of a nitrogen fertilizer, the yield of tubers was still high, but this was associated with adequate supplies of soil nitrogen. Hence, the responses of sweetpotato to applications of nitrogen depend on the cultivar, soil type, and climatic conditions (O'Sullivan et al., 1997).

A greater potassium supply promoted greater tuber yields in both cultivars under both water regimes. This result agrees with that of Bourke (1985) who also found that potassium fertilization up to a rate of 375 kg K/ha increased sweetpotato tuber yields in the Papua New Guinea highlands. Such a response was attributed to the role of potassium in starch synthesis, leading to tuber growth and development through the accelerated translocation of photosynthates from leaves to tubers (Mukhopadhyay et al., 1992). In *Colocasia esculenta*, an increase in both soil nitrogen and potassium contents increased growth and tuber yields, due to the greater assimilate translocation and accumulation rates of the plants grown in enhanced soils (Vasudevan et al., 1996). Similarly, George et al. (2002) also reported that a yield increase in sweetpotato as a result of potassium application, was mainly due to an increase in storage root to shoot ratio, which led to a greater amounts of photosynthetic translocation to the tuber. Higher contents of potassium in the soil, according to Hahn (1977) prevented excessive leaf growth, resulting in higher tuber yield. Wang et al. (1995) demonstrated that a decrease of stem and leaf yields, and consequent reduced transpiration, was caused by the application of potassium; the associated increase in overall yield of tubers was consistent with the results of the present experiment where increased levels of soil potassium also reduced the leaf area and increased tuber yields.

The supply of nitrogen and potassium fertilizers at 100 kg N ha^{-1} and 160 kg K ha^{-1} produced the highest tuber yields under both well watered and water stressed conditions. A higher nitrogen supply in the soil produced greater leaf area, but increasing soil nitrogen availability beyond 100 kg N ha^{-1} reduced tuber yields. Low nitrogen and potassium supplies in the soil reduced plant growth and yields that are both characteristics of poor water use efficiency. The sweetpotato cultivars Lole and Wanmun, grown under 30% of the soil field capacity, consistently produced stunted plants and low tuber yields. However under water stress conditions, Wanmun producing lower tuber yields than Lole. Thus the nutrient levels required to produce optimal growth in the present study demonstrate the necessity to apply reasonable doses of nitrogen and potassium to sweetpotato plants. It also demonstrates that the balance of nitrogen and potassium is important in determining tuber yield in sweetpotato. Reducing nitrogen inputs to levels below the optimal level (100 kg N ha^{-1}) with the addition of potassium had no effect on tuber yields. For this reason, an imbalance of nutrients between nitrogen and potassium should be avoided. On the other hand, tuber yields under water stress conditions increased under greater nitrogen and potassium supplies. This may be attributed to the fact that nitrogen and potassium are essential plant nutrients, which are widely reported to increase osmotic adjustment of plant cells under drought conditions (Ashraf et al., 2001). Hence, a greater nitrogen supply balanced with a greater potassium supply, produced greater tuber yields under water stress conditions. However, the nutrient requirement may depend on the cultivar, soil type, and climatic conditions (O'Sullivan et al., 1997; George et al., 2002).

There were statistically significant differences between the water use efficiency responses of the plants grown under different nitrogen and potassium fertilizer inputs (Figure. 3). The Lole cultivar had significantly greater water use efficiency than Wanmun at each corresponding fertilizer input level. The greatest water use efficiency of Lole was obtained under the supply of 100 kg N ha^{-1} which was not statistically different from its water use efficiency under 200 kg N ha^{-1} for both cultivars under both water regimes, and it was driven by lower dry matter production. The water use efficiency of both cultivars was significantly greater under the low soil water treatments in the nitrogen experiment and, although not strongly significant, tended to be higher in low soil water treatments in the potassium experiment (Figure 3). The lowest water use efficiency was produced by plants growing under low nutrient inputs, and was a consequence of poor growth and low transpiration rates.

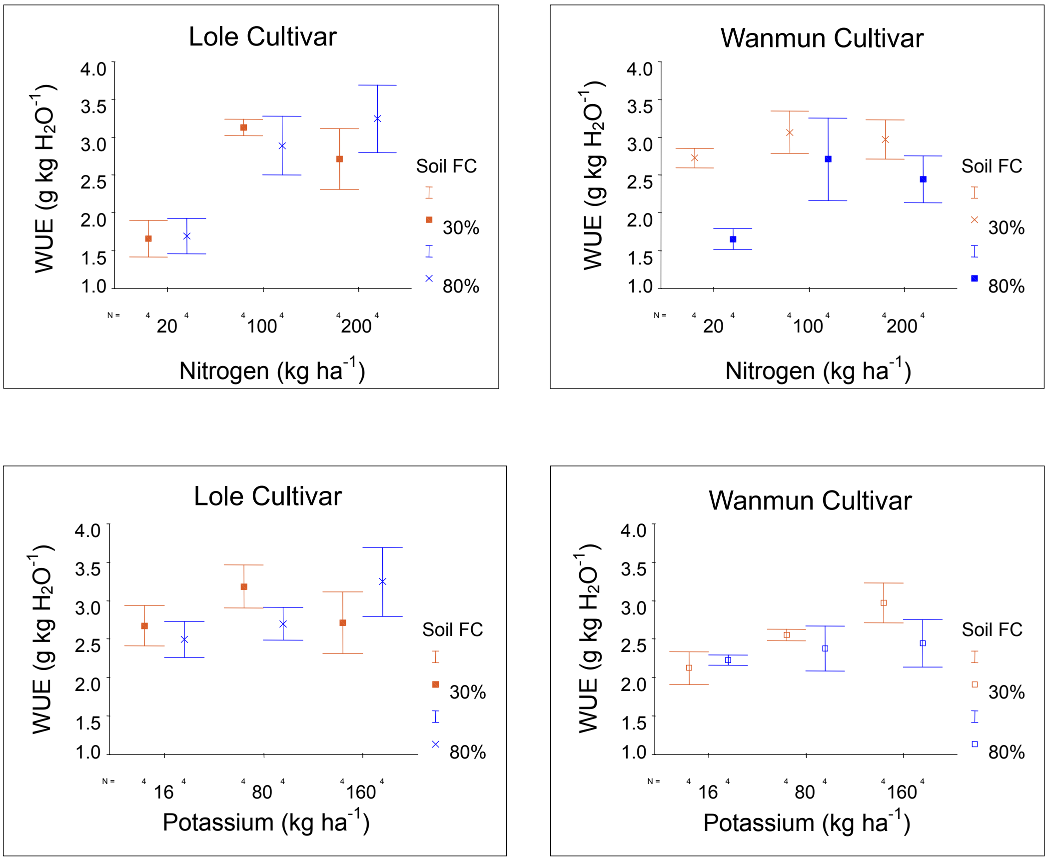

Figure 3. Effects of nitrogen and potassium inputs on the water use efficiency of Lole and Wanmun cultivars grown under 30 and 80% of the soil field capacity (Soil FC)

Note. Error bars represent standard errors of means with 4 replications. (The nitrogen responses are shown for the non-limiting K trial, and the potassium responses for the non-limiting N trial).

Plant water use efficiency increased as the potassium supply also increased. Under well-watered conditions, plant growth with the addition of 160 kg K ha^{-1} produced high water use efficiency in both cultivars. This suggests that potassium has a beneficial effect in improving water use efficiency in sweetpotatoes. Similarly the water use efficiency increased under water stress conditions when greater amounts of potassium were supplied to both cultivars.

The overall effect of nitrogen and potassium on water use efficiency showed that optimal soil nitrogen contents (100 kg N ha^{-1}), with high potassium applications (160 kg K ha^{-1}), increased water use efficiency in both cultivars under both soil water regimes. Potassium at this rate particularly contributed to improved water use efficiency under water stress conditions. Potassium influences plant water status and tends to overcome the effects of soil moisture deficiencies (Marschner, 1995; Losch et al., 1992). Plants well supplied with potassium can better regulate their stomatal opening and closing thereby preventing excessive water loss by the plant (Sivan, et al., 1996), and providing a drought tolerance mechanism.

4. Conclusions

The amount of nitrogen is important in regulating the balance between vegetative and tuber growth. The lack of nitrogen, on the other hand, resulted in stunted growth and affected overall plant growth and tuber yield. Greater potassium availability enhanced tuber yields when the soil was also supplied with basal amounts of the other plant nutrients; the potassium applications increased tuber yield but did not enhance growth of the vegetative parts of the sweetpotato.

The significance of greater water use efficiency of Lole under water stressed conditions was attributed to its relatively low transpiration rates. The Wanmun cultivar consistently produced a greater mass of tubers than Lole under well watered conditions. When the soil water content was restricted, however, Lole supplied with 100 kg

N ha^{-1} and 160 kg K ha^{-1} produced its greatest tuber mass.

The extent of the reduction of growth and yields varied between the drought tolerant Lole and drought sensitive Wanmun cultivars. The leaf growth and yields of Lole were less affected by water stress than were those of Wanmun, despite Wanmun produced greater tuber yield. Plant water use efficiency increased as the potassium supply also increased under well and stressed water condition in both Lole and Wanmun cultivars. Thus, the use of 100 kg N ha^{-1} and 160 kg K ha^{-1}, applied as ammonium nitrate and potassium chloride respectively, was found to be the best combination of nutrients to sustain sweetpotato growth under well watered and water stressed conditions encountered in the present experiment.

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