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Granite powder as a source of potassium for plants: a glasshouse bioassay comparing two pasture species

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Abstract

The effect of granite powder (<70 μm) as a K fertilizer was investigated in a glasshouse pot experiment conducted with three acid, sandy topsoils from podzols of South Western Australia and with three fertilizer treatments: a control without K application, a KCl treatment (90 mg K kg^{-1} soil) and a granite treatment (20 g granite kg^{-1} soil, yielding 640 mg K kg^{-1} soil). Subterranean clover (*Trifolium subterraneum*) and ryegrass (*Lolium rigidum*) were cropped in triplicated pots for 7 weeks, harvested and allowed to regrow for another 13 weeks. Clover growth at 7 weeks was in the following order: control < granite < KCl. The growth of ryegrass after 7 weeks was not significantly affected by granite as compared to the control treatment. After another 13 weeks, both species showed a significant growth response to granite application for two of the three soils studied. For both species and all three soils K concentrations in the plant tissue were systematically and significantly higher for KCl relative to granite and for granite relative to control treatment. Minor dissolution of granite occurred during the short duration of the experiment as indicated by changes in soil exchangeable K in uncropped pots (about 1-2% of K applied) and resulted in the increased K concentration in plants and the growth response of subterranean clover after 7 and 20 weeks and ryegrass after 20 weeks of cropping. The possible use of granite powder as a slow-release K fertilizer is discussed.

Résumé

L'effet de granite en poudre (<70 μm) comme fertilisant potassique a été étudié au travers d'essais en pots sous serre conduits sur trois sols sableux acides provenant de l'horizon superficiel de podzols du Sud-Ouest de l'Australie et comparant trois traitements fertilisants: un témoin sans apport de K, un traitement KCl (90 mg K kg^{-1} sol) et un traitement granite (20 g granite kg^{-1} sol, soit 640 mg K kg^{-1} sol). Du trêfle souterrain (*Trifolium subterraneum*) et du ray-grass (*Lolium rigidum*) ont été cultivés à raison de trois répétitions par traitement pendant 7 semaines. Après récolte les repousses ont été récoltés une seconde fois 13 semaines plus tard. Après 7 semaines de culture, la croissance du trêfle augmentait dans l'ordre: témoin < granite < KCl. La croissance du ray-grass après 7 semaines de culture n'était en revanche pas signifcativement affectée par l'apport de granite comparativement au témoin. Après 13 semaines de repousse, les deux espèces montrèrent une réponse à l'apport de granite en terme de croissance, pour deux des trois sols étudiés. Pour les deux espèces et les trois sols étudiés, les teneurs en K des tissus végétaux ont été systématiquement significativement supérieures dans le traitement KCl relativement au traitement granite ainsi que dans le traitement granite relativement au traitement témoin. Une dissolution réduite du granite s'est produite pendant la courte durée de cet essai en pots, ainsi qu'elle a pu être estimée au travers de l'augmentation de la teneur en K échangeable du sol en l'absence de plantes (environ 1-2% du K apporté sous forme de granite). Cette dissolution est toutefois suffisante pour résulter en l'augmentation des teneurs en K des végétaux se manifestant par des réponses en terme de croissance du trêfle souterrain après 7 et 20 semaines de culture et du ray-grass aprés 20 semaines de culture. L'utilisation potentielle du granite en poudre comme fertilisant potassique à dissolution lente est discutée.

Introduction

Rock powders are an abundant by-product of the quarrying industry and may be used as fertilizers or soil conditioners in agriculture (Chesworth et al., 1989; Von Fragstein et al., 1988). The fertilizer effectiveness of granite or feldspars and micas which are some of the major plant nutrient-containing components of granite has however received limited investigation (Hinsinger et al., 1996; Sanz Scovino & Rowell, 1987; Weerasuriya et al., 1993). Nevertheless, the use of silicate rocks and minerals as substitutes for manufactured fertilizers has been recommended for alternative agriculture where chemical fertilizers are not used (Bockman et al., 1990). Some of the very limited scientific literature on this topic reports that granite powder may significantly improve some physical (Kahnt et al., 1986) and/or chemical properties of soils (Hinsinger et al., 1996). However, in most instances (Baerug, 1991a, b; Kahnt et al., 1986), these results had been obtained with unrealistically high rates of application to soils, ranging from a few percent up to a few tens of percent of granite which equate to about tens up to hundreds of tons per hectare. Other authors have concluded that powdered silicate rocks such as granite would hardly affect any soil chemical properties due to the low extent of dissolution of their constitutive minerals (Blum et al., 1989a, b). However Baerug (1991a, b) showed that plant biomass in a pot experiment was increased by the application of 5% granite and that this was due to Mg and K supplied by the granite so that evidently rock powder can function as a fertilizer under some circumstances. Wheat biomass significantly increased with rates of granite application above a threshold of about 2.5 g granite per kg lateritic soil which was probably due to K supplied by the granite (Hinsinger et al., 1996).

The aim of the present work was to investigate the hypothesis that the stimulation of plant growth due to granite application is indeed a K response. It involved a pot experiment where plant growth and K content were measured for two pasture species grown on three sandy, acid podzol materials for three K treatments: (i) a control treatment without any application of K, (ii) a granite treatment and (iii) a KCl treatment.

Materials and methods

Granite and soil properties

The granite used in the present experiment was obtained from Pioneer Quarry (Pioneer Concrete Pty Ltd, Western Australia) at Herne Hill in the Darling Scarp, Western Australia. This quite coarse material (about 50% coarser than 1 mm) was dried, dry ground and sieved to less than 70 μm. The chemical composition of the fine powder which was used in the present experiment is given in Table 1.

Three sandy, acid podzols were collected from near Waroona, about 120 km south of Perth, Western Australia. The three soils belong to the Bassendean Dune system which consists of low hills with iron podzols in the well-drained sites and humus podzols in the intervening swampy swale areas (McArthur, 1991). Soil 1 was sampled near the site of the reference soil SCP 11 (Swan Coastal Plain, see McArthur, 1991) and consisted of an iron podzol developed at the upper slope of a low ridge. Soil 2 was sampled near the site of reference soil SCP 12 (McArthur, 1991) which is a humus podzol developed in a poorly drained area. Soil 3 was sampled in a humus-iron podzol at a poorly drained site, four kilometres west of SCP 11. Only the topsoil (roughly the top 10 cm) was used after having been air-dried and sieved to pass through a 2 mm sieve. Some physical and chemical properties of these three soils are given in Table 2. As these soils developed from a siliceous sand they are deficient in most nutrients, including K.

Cropping technique

For each of the three soils, pots were prepared by mixing 1.4 kg of air-dried soil with solutions of basal nutrients so as to yield the following application rates: 23 mg N kg^{-1}, 20 mg P kg^{-1}, 40 mg Ca kg^{-1}, 2 mg Mg kg^{-1}, 0.54 mg Cu kg^{-1}, 1 mg Zn kg^{-1}, 5 mg Mn kg^{-1}, 0.07 mg Co kg^{-1}, 0.07 mg Mo kg^{-1} and 0.12 mg B kg^{-1}. The amended soils were left to dry in plastic buckets lined with plastic bags to form non-leaching pots. When the soils had dried, they were thoroughly mixed in each bag so as to incorporate the basal nutrients. Three treatments representing different sources of K were then imposed. A control treatment ('Control') which did not receive anything other than the basal nutrients, i.e. all nutrients but K. A KCl treatment ('KCl') in which K was applied as dissolved potassium chloride at a rate of 90 mg K kg^{-1} soil simultaneously with the basal nutrients. This rate of

Table 1. Chemical composition of the <70 μ m granite powder; all values are in g kg^{-1}

SiO_2	Al_2O_3	TiO_2	$Fe_2O_3^a$	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	LOI[b]
748	131	1.1	16.8	0.2	7.9	5.1	38.5	40.3	0.3	0.1	10.7

[a]All iron was assumed to be ferric iron,
[b]LOI stands for loss on ignition at 1200 °C.

Table 2. Selected physical and chemical properties of the three soils

Soil No	Sand[a]	Silt[a]	Clay[a]	Org. C	Electr. Cond. (1:5 soil:water)	pH(H_2O)	pH($CaCl_2$)	CEC	exch. Ca	exch. Mg	exch. Na	exch. K
	(g kg^{-1} soil)				(μS cm^{-1})			($cmol_{c(+)}$ kg^{-1} soil)				
1	980	10	10	50	18	5.9	4.7	0.57	0.61	0.17	0.05	0.04
2	960	20	20	56	48	5.3	3.8	2.18	0.56	0.36	0.05	0.05
3	950	20	30	63	77	6.5	5.9	4.19	1.65	0.65	0.29	0.05

[a]Particle size was determined after organic matter digestion. Sand, silt and clay contents are thus given on an organic C-free basis.

application was selected as a realistic rate of application compared with common agricultural practices and was expected to yield a growth response in these low K status soils. A granite treatment ('Granite') in which 20 g of granite powder was added per kilogram of soil and thoroughly mixed through the soil: this application provided 640 mg K kg^{-1} soil. This rate of application was chosen accordingly to the rate used in a previous experiment (Hinsinger et al., 1996). This experiment showed with some other K responsive soils that a dissolution of about 5% of applied granite might occur which would represent about 32 mg K kg^{-1} soil in the present case. A larger release of K from granite might be expected in the present experiment due to plant removal of dissolved K. In order to investigate a realistic rate of application (equivalent to about 20 tons granite ha^{-1}) it was thus decided not to use a larger rate of application of granite. All pots for the three treatments were then watered to field capacity and the wet soils were left to equilibrate in the glasshouse for 26 days before sowing. The water used throughout the experiment was reverse osmosis deionised water (MilliQ water).

Two pasture species were compared: ryegrass (*Lolium rigidum* cv Standard) and subterranean clover (*Trifolium subterraneum* cv Trikkala). A third treatment ('Blank') was left unplanted throughout the experiment. Thirty and fifteen pregerminated seeds were sown for ryegrass and clover respectively. After eight days seedlings were thinned so as to keep 20 seedlings of ryegrass and 10 of clover per pot. For all treatments, soil was maintained at about 95% field capacity by watering to weight at least every second day. All nutrients except K and N were added a second time after 5 weeks of growth. In addition, during the course of the experiment, N was applied fortnightly as NH_4NO_3 at a rate of 23 mg N kg^{-1} soil. Pots were mulched with plastic beads, hand weeded and rerandomised regularly. The experiment was conducted in a glasshouse between April and August 1994. All treatments were triplicated.

Harvest and analyses

Plants were harvested at the soil level seven weeks after sowing. Plants were allowed to regrow until a second harvest was taken 13 weeks after the first harvest, i.e. 20 weeks after sowing. The regrowth of plants was more variable for clover than for ryegrass. After each harvest the shoots were oven-dried at 70°C for three days and weighed. To extract K from plant tissue a 200 mg subsample of ground plant material was placed in a vial with 25 mL of 0.2 *M* HCl and the vials were shaken overnight at 25 °C on a reciprocal shaker at 200 rpm. The digests were filtered with ashless filter paper (Whatman 42) before being assayed by flame photometry.

At the time of the first harvest, some soil was sampled in the pots of all treatments with a borer (diameter = 1 cm). Three core samples were taken to the base of the pots, air-dried and thoroughly mixed with one another. Soil pH and electrical conductivity were measured in a suspension of 1 g soil per 5 mL deionised water, after shaking the suspensions for one hour at 150 rpm and 25 °C. Another 1 g subsample of soil was placed into a centrifuge tube with 9 mL 0.02 *M* NH_4Cl

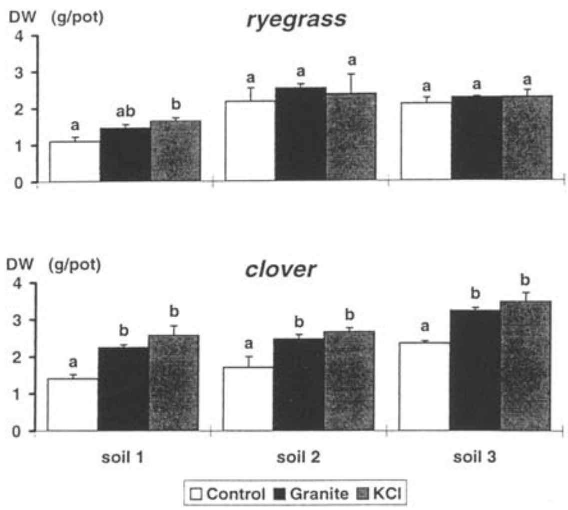

Figure 1. Plant growth for control, granite and KCl treatments expressed as shoot dry weight at first harvest, after 7 weeks of growth (mean value of three replicates). The bars indicate the standard deviations calculated among the three replicates. For each soil and species fertilizer treatments yielding a significantly different shoot dry weight according to a Fisher test (at $p<0.01$) are indicated by a different letter.

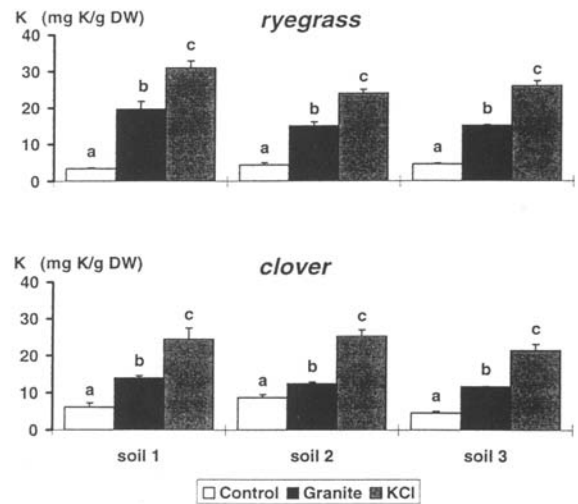

Figure 2. Potassium concentration in plant tissue for control, granite and KCl treatments at first harvest, after 7 weeks of growth (mean value of three replicates). The bars indicate the standard deviations calculated among the three replicates. For each soil and species, fertilizer treatments yielding a significantly different K concentration according to a Fisher $p<0.01$) are indicated by a different letter.

for extracting the exchangeable cations. After one hour shaking at 150 rpm and 25 °C, the suspensions were centrifuged. The supernatant was then filtered with an ashless filter paper (Whatman 42). Two further extractions were subsequently made for each sample and the three filtered supernatants were combined for K and Na assay by flame emission photometry and for Ca and Mg assay by atomic absorption spectrometry.

Results

Plant growth

For all three soils the dry weight of ryegrass shoots at 7 weeks was systematically higher for the Granite and KCl treatments as compared to the Control treatment (Figure 1). However, the three treatments did not yield significantly different dry weights, according to a Fisher test (at $p<0.01$). Conversely for clover at 7 weeks, the dry weights for the Granite and KCl treatments were significantly higher (at $p<0.01$) than for the Control treatment for all three soils. Though the KCl treatment systematically yielded the highest dry weights, these were never significantly different to those for the Granite treatment. The yield increase due to granite application as compared to the Control ranged between 37% for soil 3 and 60% for soil 1.

For the second harvest at 20 weeks, dry weights were again systematically higher for Granite than for Control treatment (Table 3). The difference between these two treatments was significant (at $p<0.05$) for both species and all soils but soil 3. For clover only 1 or 2 out of 10 plants regrew in some pots after the first harvest, leading to a large variability in dry weights within treatments, and notably for soil 3. Although the differences were not significant (at $p<0.05$), dry weights at the second harvest were systematically higher for Granite than for KCl for both species and all three soils.

Potassium nutrition

For the three soils and both species, K concentration in the plant tissue was systematically ranked as follows: Control < Granite < KCl. The three treatments being significantly different (at $p<0.01$) after 7 weeks (Fig 2) and after another 13 weeks in all cases but one (at $p<0.05$, Table 4). According to Reuter & Robinson (1986), K concentrations of 15 mg g^{-1} for clover and 10 mg g^{-1} for ryegrass are to be considered as critical concentrations below which plants are K deficient. After 7 weeks, K concentrations in clover shoots were below this critical level for both Control and Granite treatments whereas only Control plants were K deficient for ryegrass (Figure 2). Typic symp-

Table 3. Dry weight of shoots at the second harvest (DW_2) and cumulative weights for the two harvests (DW_{1+2}: mean ± standard deviation. For each soil and species, means with different letters are significantly different according to a Fisher test (at $p<0.05$). All values are in mg pot^{-1}

		Soil 1		Soil 2		Soil 3	
		DW_2	DW_{1+2}	DW_2	DW_{1+2}	DW_2	DW_{1+2}
Ryegrass	Control	999±47^a	2099±152^a	1572±210^a	3749±576^a	1541±311^a	3641±432^a
	Granite	1877±147^b	3234±247^b	2354±224^b	4894±144^b	1714±89^a	3990±104^a
	KCl	1747±133^b	3395±157^b	2086±167^b	4459±377^{ab}	1537±179^a	3814±12^a
Clover	Control	73±62^a	1482±48^a	568±263^a	2280±485^a	1431±421^a	3798±416^a
	Granite	1141±393^b	3390±354^b	1201±137^b	3682±198^b	3497±732^a	6746±696^b
	KCl	1064±135^b	3633±319^b	1205±32^b	3871±81^b	2870±2231^a	6365±2413^{ab}

Table 4. Potassium concentration of shoots at the second harvest (13 weeks after the first harvest): mean ± standard deviation. For each soil and species, mean values with different letters are significantly different according to a Fisher test (at $p<0.05$). All values are in mg g^{-1}

		Soil 1	Soil 2	Soil 3
Ryegrass	Control	1.60±0.22^a	1.79±0.18^a	1.65±0.18^a
	Granite	5.04±0.38^b	4.02±0.25^b	4.98±0.24^b
	KCl	8.88±2.19^c	7.23±0.20^c	10.00±0.39^c
Clover	Control	4.35±0.36^a	2.94±0.11^a	1.75±0.34^a
	Granite	7.37±0.89^b	6.23±0.45^b	3.52±0.47^a
	KCl	14.42±0.22^c	10.27±0.97^c	9.10±4.05^b

toms of K deficiency were consistently recorded for clover (Snowball & Robinson, 1993) for the Control and, to a lesser extent for the Granite treatment whereas no symptoms were present for the KCl treatment. For ryegrass, a yellowing of leaf tips was commonly present especially for the Control treatment and, to a lesser degree for the Granite and KCl treatments. After another 13 weeks of growth the K concentration in shoot tissue was below the critical level for both clover and ryegrass for all treatments, suggesting that all plants were K deficient (Table 4); the most K deficient plants were for the Control treatment and the least deficient were for the KCl treatment.

The K content of shoots as calculated from the K concentration and dry weight of shoots ranks similarly to K concentration, both after 7 and 20 weeks (data not shown): Control < Granite < KCl. For all three soils and both species, the three fertilizer treatments were significantly different after 7 weeks (at $p<0.01$) and after another 13 weeks (at $p<0.05$). For the Granite treatment, the cumulative K content for the two harvests amounted to 37-43 mg K per pot for ryegrass and 38-50 mg K per pot for clover that is about 3-4% of the total K applied as granite. For the KCl treatment it amounted to 66-75 mg K per pot for ryegrass and 78-98 mg K per pot for clover, that is 53-59% and 62-77% of K applied as KCl, respectively. Presumably the roots of the plants would also have contained K but these were not analysed.

Soil chemical properties upon application of granite and after 7 weeks of plant growth.

Electrical conductivity of the 1:5 soil:water extract did not change due to granite application in most instances (data not shown), whereas soil pH was affected, though slightly, by granite application (Table 5). Although no significant pH change was encountered immediately after granite application (see ≪initial≫ values in Table 5), pH after incubation (see ≪blank≫ treatment) systematically increased for the granite treated soils as compared to the control. This increase remained below 0.3 pH units for all three soils. Values of soil pH for soils from the clover and ryegrass treatments were similar to corresponding values for the blank and initial pH in most cases. Although soil pH appeared to be system-

Table 5. Soil pH measured immediately after incorporation of the fertilizers (initial) and at first harvest (after 26 days of incubation plus 7 weeks of growth). Blank values were obtained from uncropped pots. All values except initial ones are mean values of 6 replicated measurements. For each soil and treatment, means with different letters indicate pH values which are significantly different according to a Fisher test (at p<0.05).

	Soil 1				Soil 2				Soil 3			
	Initial	Blank	Ryegrass	Clover	Initial	Blank	Ryegrass	Clover	Initial	Blank	Ryegrass	Clover
Control	5.46	5.66^{b}	5.25^{b}	5.30^{b}	4.87	5.06^{a}	4.94^{b}	5.28^{c}	6.66	7.06^{a}	7.16^{a}	6.62^{a}
Granite	5.45	5.79^{c}	5.58^{c}	5.26^{b}	4.88	5.35^{b}	4.67^{a}	4.82^{b}	6.51	7.20^{b}	7.11^{a}	7.29^{c}
KCl	5.34	5.49^{a}	5.14^{a}	4.97^{a}	5.36	5.23^{b}	4.67^{a}	4.60^{a}	6.56	7.06^{a}	7.09^{a}	6.96^{b}

Table 6. Exchangeable cations measured immediately after incorporation of the fertilizers (initial) and at first harvest (after 26 days of incubation plus 7 weeks of growth). Blank values were obtained from uncropped pots. All values except for the initial ones are mean values of 6 replicated measurements. For each soil and treatment, means with different letters indicate fertilizer treatments which are significantly different according to a Fisher test (at p<0.05). All values are in $cmol_{c(+)} kg^{-1}$ soil.

	Soil 1				Soil 2				Soil 3			
	Initial	Blank	Ryegrass	Clover	Initial	Blank	Ryegrass	Clover	Initial	Blank	Ryegrass	Clover
K												
Control	0.03	0.03^{a}	0.01^{a}	0.01^{a}	0.06	0.06^{a}	0.03^{ab}	0.02^{a}	0.05	0.04^{a}	0.02^{a}	0.02^{a}
Granite	0.04	0.05^{b}	0.03^{b}	0.02^{b}	0.07	0.09^{b}	0.03^{a}	0.04^{b}	0.05	0.06^{b}	0.03^{a}	0.03^{b}
KCl	0.27	0.14^{c}	0.04^{c}	0.03^{b}	0.29	0.20^{c}	0.04^{b}	0.04^{b}	0.26	0.22^{c}	0.07^{b}	0.04^{c}
Na												
Control	0.02	0.04^{a}	0.02^{a}	0.01^{a}	0.08	0.06^{a}	0.04^{a}	0.01^{a}	0.27	0.20^{a}	0.11^{a}	0.07^{b}
Granite	0.04	0.04^{a}	0.03^{a}	0.02^{a}	0.07	0.11^{b}	0.04^{a}	0.07^{b}	0.21	0.21^{a}	0.16^{a}	0.04^{a}
KCl	0.03	0.05^{a}	0.03^{a}	0.02^{a}	0.07	0.05^{a}	0.04^{a}	0.01^{a}	0.19	0.24^{b}	0.21^{a}	0.15^{c}
Ca												
Control	0.52	0.60^{a}	0.64^{a}	0.61^{a}	0.96	–	1.06^{b}	1.24^{b}	1.71	1.86^{a}	1.84^{a}	1.84^{b}
Granite	0.47	0.58^{a}	0.61^{a}	0.64^{a}	0.80	–	0.79^{a}	1.88^{c}	1.21	1.80^{a}	1.78^{a}	0.92^{a}
KCl	0.52	0.58^{a}	0.60^{a}	0.62^{a}	0.93	–	1.02^{b}	0.81^{a}	1.35	1.98^{a}	1.82^{a}	1.92^{b}
Mg												
Control	0.16	0.18^{a}	0.12^{a}	0.12^{a}	0.51	0.40^{a}	0.45^{b}	0.45^{b}	0.70	0.60^{ab}	0.52^{a}	0.51^{a}
Granite	0.14	0.17^{a}	0.13^{a}	0.11^{a}	0.46	0.47^{b}	0.36^{a}	0.56^{c}	0.45	0.56^{a}	0.54^{a}	0.47^{a}
KCl	0.13	0.15^{a}	0.11^{a}	0.10^{a}	0.52	0.40^{a}	0.43^{ab}	0.37^{a}	0.25	0.61^{b}	0.56^{a}	0.56^{b}

atically affected by the fertilizer treatment, especially for clover, no clear trend (i.e. liming effect of granite) was evident for the three soils and two plant species. Compared with the control, the KCl treated soils 1 and 2 exhibited a significant decrease in pH after plant growth whereas a pH increase occurred for soil 3 (Table 5).

Exchangeable K was not affected by granite application immediately after incorporation (see initial ≪values≫ in Table 6) whereas it became about an order of magnitude larger due to KCl application. After incubation, exchangeable K for granite-treated soils was significantly higher than for the control (at p<0.05) for the three soils (Table 6). The corresponding increase amounted to 0.02-0.03 cmol K kg^{-1} soil. In all cases but one exchangeable K remained larger for the granite treated soil than for the control after 7 weeks of plant growth (Table 6). Although exchangeable K for the KCl treatment was significantly larger than for granite and control treatments for all cases but two (clover soils 1 and 2), it decreased substantially throughout the course of the experiment. It decreased during incubation prior to cropping, as indicated by comparing blank and initial values for the three soils and notably for soil 1 for which it was halved. It further decreased after 7 weeks of cropping, reaching a level of exchangeable K close to the initial value for the control and was only slightly higher than for the other treatments. In most cases, exchangeable Na, Ca and Mg were not significantly affected by the application of granite and KCl (Table 6).

Discussion

Effect of granite application on soil chemical properties

Among the soil chemical properties which were investigated, only exchangeable K was consistently and significantly affected by granite application for the blank treatment relative to the value for control (Table 6). This confirms the results obtained by Hinsinger et al. (1996) in a laboratory incubation experiment on a range of soils from Western Australia. The increase in exchangeable K for the granite treated soils with respect to the control treatment ranged between 45 and 62%. However, as these soils initially contained little exchangeable K (Table 2), this increase represents only minor dissolution of the granite (about 1 to 2%). These figures are consistent with the previous results of Hinsinger et al. (1996) which show that granite dissolution as assessed by the increase of exchangeable K did not exceed 5% of the applied granite after 2 months incubation. As a comparison, the application of KCl, at a rate of K application which was about one seventh that of the granite treatment, yielded a 5 to 9-fold increase in exchangeable K immediately after incorporation (see ≪initial≫ values in Table 6). The increase of exchangeable K for KCl treated soils with respect to control soils amounted to 115-131 mg K per pot which is close to the amount of K applied (126 mg K per pot). This indicates that upon incorporation of KCl into the three soils, all the applied K was recovered as exchangeable K. However, after incubation (blank treatment) exchangeable K had substantially decreased in the KCl treated soils: as compared to the initial values, this decrease ranged from 22 to 71 mg K per pot. Thus in spite of their mineralogy being dominated by quartz and kaolinite (McArthur, 1991), these sandy soils have a substantial K fixation capacity. Indeed, during the course of the experiment 17 to 56% of the K applied as KCl was fixed by the soils. Such a K fixation capacity is likely to be due to the occurrence of discrete, residual 2:1 clay layers within kaolinite crystals, as indicated by Singh & Gilkes (1991) and Delvaux et al. (1990a, b). The occurrence of K fixation indicates that a fraction of K dissolved from granite may also have not been recovered as exchangeable K. Thus estimates of granite dissolution solely based on changes in exchangeable K may underestimate the true extent of dissolution. Since no consistent change in exchangeable Na, Ca and Mg was encountered for granite treated soil (Table 6), it can be concluded that incongruent dissolution of granite occurred during the experiment with preferential relase of K which corresponded to a minimum of 1 to 2% of the applied granite. This result may indicate a loss of K by exchange from interlayer sites in mica which was not accompanied by losses of other ions as would occur for congruent dissolution of mica and the other minerals in granite. Significant changes in exchangeable Ca and Mg in soils due to silicate rock application have been described, though for much larger rates of application of a crushed basalt rock (Gillman, 1980) but this difference may reflect the much more rapid weathering (dissolution) of mafic rocks relative to felsic rocks (Nahon, 1991). The present dissolution results for granite powder are in good agreement with those previously obtained by Hinsinger et al. (1996) for a larger range of soils from Western Australia. In addition, they confirm that only minor liming effect can occur due to granite application considering the slight pH change obtained for blank treatment relative to the value for control (Table 5).

Effect of granite application on potassium nutrition and plant growth

The release of K due to granite dissolution as shown here can explain the systematic and significant increase of K concentration in the plant tissue for both species, grown on granite treated soils as compared to control soils (Figure 2). Although plant K concentrations indicate that both species responded positively to granite, only clover exhibited a systematic and significant growth response to granite application after 7 weeks (Figure 1). After another 13 weeks, both species showed a systematic growth response to granite application which was significant only for soils 1 and 2 (Table 3). The consistent increases of shoot dry weight and K concentration in the shoot tissue of both species relative to control are probably a response to K applied. Since the dry weights of shoots for granite and KCl are not significantly different for 7 or 20 weeks of growth (Figure 1, Table 3), one might be tempted to conclude that granite was as efficient as KCl as a K fertilizer. This is definitely not the case as is demonstrated by considering the K status of the plants. The KCl treated soils systematically yielded much higher K concentrations in shoots relative to granite treated soils (Figure 2, Table 4). Taking into account that the rates of K application were very different on a unit K basis (90 mg K kg^{-1} soil as KCl versus 640 mg K kg^{-1} soil as granite), granite was thus much less efficient than KCl as a K fertilizer. The relative effectiveness or substitution value of granite versus soluble fertilizer such as KCl can only be determined by comparison of complete response curves (Barrow, 1985) and thus requires additional investigation.

The present results demonstrate that granite and KCl show quite different behaviors upon incorporation into the soil. The soluble KCl fertilizer was completely dissolved upon incorporation and all K applied was initially recoverable as exchangeable K. Subsequently, a substantial proportion of this K was fixed by the soil. Under field conditions for sandy soils such as those employed in the present experiment it is likely that a large part of applied K would have leached out of the topsoil (Gillman et al., 1989; Wong et al., 1992) and, possibly to below the part of the soil which is colonized by plant roots. This K would become non-available to the crop as has been shown to occur under intensive cropping systems (Pieri & Oliver 1986.) Conversely only a minor fraction of granite dissolved in the soil so that most K would remain in the topsoil suggesting that such a K fertilizer might be less sensitive to leaching than a soluble fertilizer such as KCl. A more appropriate comparison of granite and KCl to assess their relative effectiveness as K fertilizers under leaching conditions would have been obtained in draining rather than the non-draining pots employed in the present experiment. Due to their differing kinetics of K release and to the possible occurrence of other fertilizer-soil reactions, the long term relative effects of these two sources of K need to be more appropriately assessed before these glasshouse results can be extrapolated to field conditions.

Table 7 compares the amounts of K recovered in the shoots after 7 weeks of growth with the change of exchangeable K (ΔK_{soil}) in cropped pots versus uncropped pots (blank treatment). This table indicates different behaviors for granite and KCl. Indeed, for both control and KCl treatments the amount of K in the shoots was systematically close to or lower than the reduction in exchangeable K in the soil K (ΔK_{soil} in Table 7). Since the amount of K in the shoots is an underestimate of K uptake by whole plants (roots were not included), it is not possible to conclude if the difference between the two sets of data correspond either to K stored in the roots or to additional fixation of K in cropped relative to uncropped pots. These results suggest that K requirements of clover and ryegrass were largely supplied by exchangeable K for both control and KCl treatments. Conversely, for granite treated soils, the amount of K in the shoots systematically exceeded ΔK_{soil}, being up to 2 to 3-fold larger for soils 1 and 3 (Table 7). This suggests that both species met a large part of their K requirements from nonexchangeable K originating from the granite. The granite used in the present experiment contains substantial amounts of biotite, a trioctahedral mica. The nonexchangeable interlayer K of trioctahedral micas has been shown to be released as a consequence of plant uptake (Mortland et al., 1956). Gilkes & Young (1974) showed that clover was able to remove K from biotite and Hinsinger et al. (1992) and Hinsinger & Jaillard (1993) showed that Italian ryegrass removed K from phlogopite. This release of nonexchangeable K is due to rhizosphere processes induced by roots acting as a sink for K. In the present experiment, it is not possible to clearly establish that plants removed K from granite or if they simply benefited from the supply of nonexchangeable K due to soil-mediated dissolution of granite. The present results suggest that the exchangeable K content of the soil is not a suitable criterion of the ability of granite to supply K to plants as exchangeable K values do not provide any indication of rhizosphere dissolution of granite.

The present work clearly indicates that granite acts as a K fertilizer. It should be kept in mind that according to calculations made by Fragstein et al. (1988) and Hinsinger et al. (1996), granite powder is unlikely to become an economic alternative to soluble fertilizers such as KCl for conventional agriculture. However it might be recommended for use in alternative agricultures where use of chemical fertilizers is forbidden or in circumstances where chemical fertilizers are unavailable such as in some developing countries. The assessment of rock powders for such uses requires further studies over a longer term, including draining pot experiments and field experiments. Finally some consideration must be given to identifying those soil properties that promote dissolution of rock powders. Unlike water soluble fertilizers such as KCl it is probable that factors other than water content will influence the extent and rate of dissolution of rock powders. This has been demonstrated for phosphate rock fertilizers where dissolution for a range of soils from Western Australia is related to the exchange acidity of the soil (Hughes & Gilkes, 1994).

Table 7. Potassium content of shoots at the first harvest (K_{shoot}) and reduction in exchangeable K in the soil during plant growth (i.e. $\Delta K_{soil} = (K_{blank} - K_{plant})$, with plant=ryegrass or clover). All values are in mg pot^{-1}.

		Soil 1		Soil 2		Soil 3	
		K_{shoot}	ΔK_{soil}	K_{shoot}	ΔK_{soil}	K_{shoot}	ΔK_{soil}
Ryegrass	Control	4	11	10	16	10	11
	Granite	28	11	38	33	34	16
	KCl	51	55	57	87	59	82
Clover	Control	9	11	15	22	11	11
	Granite	31	16	31	27	38	16
	KCl	63	60	68	87	75	98

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