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The effect of lime on the rhizosphere processes and elemental uptake of white lupin

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ABSTRACT

Acid soils cover 30–40% of the world's arable land and represent one of the major constraints to agricultural production. Lime is routinely added to soil to improve fertility and to reduce the solubility of elements such as aluminum (Al) and cadmium (Cd). White lupin is cultivated globally, however, this is done mainly on acidic soils because of its calcifuge characteristics resulting from its limited ability to compartmentalize calcium (Ca). In abiotic stress conditions, lupins exude organic acids and flavonoids from cluster roots. This can increase the availability of essential soil nutrients to the plant but also exacerbate the uptake of contaminants. We aimed to determine the effect of liming on the rhizosphere processes of white lupin plants in two high-fertility soils, which were treated with seven levels of lime. Nutrient availability and plant uptake was assessed with a pot experiment. Three lime levels have been chosen for a further rhizotron study. Diffusive gradient in thin layers (DGT) gels were applied on selected root zones and then analyzed by laser ablation inductively-coupled plasma mass spectrometry (LA ICP-MS).

The results showed that lime affected the solubility of extractable elements and the plant uptake. In soils treated with different levels of lime, the uptake of nutrients was sufficient to avoid nutrient deficiency. However, analysis of the DGT gels only showed mobilization around the cluster root of the plant grown in the untreated soil. The results indicate that white lupin can be grown at pH as high as 7.50 with 10 wt% lime without suffering from nutrient deficiencies.

1. Introduction

Soil pH is one of the most important chemical parameters influencing element sorption and dissolution processes in soil (Comerford, 2005) and thus the bioavailable fraction to plants. Many authors reported that plant element uptake is highly correlated with pH (Dakora and Phillips, 2002; Hinsinger et al., 2003; Marschner, 1991). The bioavailability of trace element cations such as copper (Cu), zinc (Zn), nickel (Ni), cadmium (Cd) and lead (Pb) and their concentration in plants is significantly reduced at pH > 7.0. Acidic pH can enhance the bioavailability of these elements, as well as essential plant micronutrients, such as iron (Fe), manganese (Mn) and boron (B). However, these benefits can be offset by increased bioavailability of potentially phytotoxic elements such as aluminum (Al^{3+}). Acid soils, covering 30–40% of the world's arable land, represent one of the major constraints in agricultural production due to plant growth inhibition and yield reduction (Marschner, 1991). Several factors could further increase soil acidification, such as large inputs of inorganic fertilizers, high rainfall, acid deposition and greenhouse gases. In addition to toxic concentrations of Al^{3+} and protons (H^+), acid soils can provoke deficiencies in anionic plant nutrients such as molybdate (MoO_4^{2-}) and phosphate (PO_4^{3-}). The ongoing application of PO_4^{3-} containing fertilizers to overcome phosphorus (P) deficiency in acid soils, can lead to the accumulation of Cd (Williams and David, 1976), that exists naturally as an impurity in phosphate rocks, from which phosphate fertilizers are obtained. The entry of toxic metals, such as Cd, from soils into the food

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chain through plant uptake is of primary concern in agricultural production systems because of the potential threats to food quality, crop growth, and environmental health (McLaughlin et al., 2000).

Liming ($CaCO_3$) is routinely used as long-term agricultural practice to improve soil quality by increasing nutrient bioavailability, as well as improving soil structure and increasing rates of infiltration. In addition, liming has been demonstrated to be effective in reducing the solubility of cationic trace elements in soils by increasing the negative charge on oxides, clays, and organic matter (Kirkham, 2006) and/or leading to the pH driven precipitation of mineral phases (Fe, Mn oxides, Ca-phosphates). However, excessive carbonate concentrations may lead to toxic effects besides reducing the plant-available fraction of essential macro- and micronutrients, such as P, Fe, Mn and Zn.

White lupin (*Lupinus albus* L.) is adapted to well drained, light to medium textured soil, can tolerate moderately alkaline soils (up to pH 8.0), provided that the free lime or Ca content of the soil is low (the accepted maximum soil level of $CaCO_3$ is 30–50 g kg^{-1}) (Jansen, 2006), since lupin species are unable to regulate Ca uptake (De Silva et al., 1994). Such typical calcifuge behavior may be related to an insufficient capacity for compartmentation and/or physiological inactivation of Ca (Hawkesford et al., 2011). In addition, an immobilization of P in the tissues of calcifuge plants may occur, since the excessive uptake of Ca may cause precipitation of Ca phosphate in plant tissues (Zohlen and Tyler, 2004). The concentration of carbonate (Brand et al., 2000) and especially the so-called free lime concentration as previously shown in *L. angustifolius* L. (Jessop et al., 1990) is the limiting factor for the plant growth. White lupin is known to cope with abiotic stresses by releasing organic compounds (organic acids and flavonoids) into the rhizosphere (Neumann et al., 1999). However, whether these substances can have beneficial effects increasing the availability of nutrients or might even counteract the liming effect by mobilizing toxic elements needs to be elucidated.

We aimed to determine the effect of lime concentration on the rhizosphere processes of white lupin in two high-fertility soils. Specifically, we sought to measure the bioavailability of nutrients as well as trace elements in selected root zones of the plants, where the release of root exudates is more pronounced. The final objective was to define a so-called "ideal [Ca]/pH zone" where lupin is still able to mobilize nutrients without suffering from Ca toxicity and trace elements such as Cd.

2. Materials and methods

2.1. Soils

We selected two high-fertility soils with contrasting chemical–physical characteristics (Table 1), referred to as "Pukekohe" and "Levin" soils. Both soils were slightly acidic (Pukekohe pH 5.45; Levin pH 6.46), rich in macro- and micronutrients meeting plant requirements for an optimal growth. Seven different lime ($CaCO_3$, Thermo Fischer Scientific NZ Ltd.) treatments (T1–T7) were applied to both soils, as follows T1: 0 wt%, T2: 0.31 wt%, T3: 0.61 wt%, T4: 1.25 wt%, T5: 2.50 wt%, T6: 5.00 wt%, T7: 10.00 wt%. The $CaCO_3$ amended soils were well mixed in buckets and then transferred into pots. For each treatment five replicates consisting of 250 g of soil were used. After filling, pots were moved to a greenhouse, watered to field capacity and left there for a week in order to allow the lime to react with soil.

2.2. Pot experiment

White lupin seeds (*L. albus* L.), were soaked for 24 h in ASTM Type I ultrapure water and then transferred to the pots containing the different soil treatments. Subsequently, plants were grown in a greenhouse for 6 weeks, watered every two days with tap water and weeds were carefully removed every week. After 6 weeks, plants were harvested and the above ground biomass was assessed. The above-ground biomass of the plants was thereby cut 3 cm above the soil level and it was carefully washed with deionised water. Plants were dried at 60 °C for one week until constant weight was reached and then ground for subsequent elemental analyses. Rhizosphere samples were obtained from each pot by gently uprooting the plants and by removing the soil adhering to the roots by shaking and brushing. These samples were oven dried, ground and sieved using a 2 mm sieve. All sample processing was carried out ensuring that there was minimal metal contamination.

Table 1
Chemical–physical characteristics of Pukekohe and Levin soils; LOD = limit of detection.

	Pukekohe	Levin
Parameter		
pH (H_2O)[a]	5.95 ± 0.04	6.46 ± 0.06
CEC (me/100g)[b]	22.00	15
Base saturation [%][c]	70.00	88
C [%][d]	2.10	1
N [%][e]	0.23	0.13
Olsen P [me/100g][f]	290.00	229
N available [kg/ha][g]	50.00	53
Total P [mg/kg][h]	3414 ± 26	2247 ± 20
Total S [mg/kg][h]	491 ± 6	296.46 ± 1.32
Total Ca [mg/kg][h]	4147 ± 117	7008 ± 99
Total Mg [mg/kg][h]	2400 ± 95	2873 ± 43
Total K [mg/kg][h]	1951 ± 59	2242 ± 54
Total B [mg/kg][h]	<LOD	8.89 ± 0.15
Total Cd [mg/kg][h]	1.45 ± 0.03	0.47 ± 0.01
Total Cu [mg/kg][h]	65 ± 0.46	20 ± 0.20
Total Mo [mg/kg][h]	<LOD	<LOD
Total Mn [mg/kg][h]	1266 ± 12	387 ± 6
Total Zn [mg/kg][h]	173.21 ± 1.06	66.52 ± 0.72
Total Fe [mg/kg][h]	44606 ± 96	22729 ± 1527
Total Pb [mg/kg][h]	61.02 ± 0.76	13.08 ± 0.18
Cd $Ca(NO_3)_2$-extractable [mg/kg]	0.015 ± 0.002	0.008 ± 0.002
Cu $Ca(NO_3)_2$-extractable [mg/kg]	0.13 ± 0.015	0.123 ± 0.006
Mn $Ca(NO_3)_2$-extractable [mg/kg]	39.75 ± 4.17	8.58 ± 0.25
Zn $Ca(NO_3)_2$-extractable [mg/kg]	0.37 ± 0.06	0.177 ± 0.017
Fe $Ca(NO_3)_2$-extractable [mg/kg]	0.654 ± 0.195	0.511 ± 0.036

[a] 1:2 (v/v) Soil:water slurry followed by potentiometric determination of pH.
[b] Summation of extractable cations (K, Ca, Mg, Na) and extractable acidity.
[c] Calculated from extractable cations and cation exchange capacity.
[d] Determined by NIR, calibration based on total carbon by Dumas combustion.
[e] Determined by NIR, calibration based on Total Nitrogen by Dumas combustion.
[f] Olsen extraction followed by molybdenum blue colorimetry.
[g] Anaerobic incubation followed by extraction using 2 M KCl followed by Berthelot colorimetry.
[h] Pseudo total elemental concentration in the soil, determined by microwave digestion of 0.5 g sieved (2 mm) soil sample with 5 mL conc. HNO_3 and 1 mL H_2O_2.

2.3. Soil and plant analysis

Following microwave-assisted digestion (CEM MARS Xpress, CEM Corporation, NC, USA) of samples (0.3 g each) in concentrated 65% HNO_3 and 30% H_2O_2, the total elemental concentrations in plants were determined by inductively coupled plasma–optical emission spectroscopy (ICP-OES) (Varian 720-ES; Varian, Mulgrave, Australia). Wageningen Evaluating Programs for Analytical Labs (WEPAL) plant was used as reference material. The recoveries for Cd, Fe and Zn were 94%, 94.5% and 91.7% respectively. Soil pH was determined by adding 25 mL of deionised water to 10 g of oven dried soil. Samples were stirred and left to equilibrate overnight. Subsequently the pH was measured in the supernatant.

The plant available element fraction was obtained by extracting soils with 0.05 M $Ca(NO_3)_2$ in a ratio of 1:6 (w/v) for 2 h on an