Short term effects of heating a lateritic podzolic soil on the availability to plants of native and added phosphate

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ABSTRACT

We studied the impact of heating on minerals in a lateritic podzolic soil from Bakers Hill, Western Australia and consequent effects on phosphate availability and plant growth. This forest soil was heated at 250, 350 and 500 °C, which are temperatures attained by topsoil during bushfires. Heating soil caused kaolinite, gibbsite and goethite to dehydroxylate and to partly alter into metakaolinite, amorphous alumina and hematite respectively. Heating increased soil pH, from 4.63 for unheated soil to 4.67, 5.40 and 5.45 for soil heated at 250, 350 and 500 °C respectively. Electrical conductivity (EC) values also increased on heating to 250 °C, although EC then relatively decreased for 350 °C and 500 °C heating. A glasshouse study determined the effect of heating soils on their pH and EC values after cropping and on P uptake by ryegrass. Yield of ryegrass decreased with increasing temperature of heating for unfertilized soil and for heated soils supplied with phosphate (P) fertilizer. The P concentration in ryegrass for each of three harvests ranged from 0.03% to 0.3% and decreased in the same sequence as for yield (i.e. unheated soil > 250 °C > 350 °C > 500 °C heated soil). Clearly heating of soil by bushfires may reduce the availability to plants of native and added phosphate.

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1. Introduction

Wildfire severely impacts ecosystems (FRA, 2010) due to the destruction of vegetation together with degradation of air quality, surface and ground water and soil (Turrión et al., 2010). Fire is also used to remove plant residues in forest and agricultural areas and also for management of natural vegetation (Khanna and Raison, 1986). Forest fires may have significant impacts on physical, chemical, mineralogical and biological properties of soils, thus affecting growth of plants (Certini, 2005; Raison, 1979; Wan et al., 2001). These effects vary depending on several environmental factors that control the combustion process, such as amount and type of fuel, air temperature and humidity, wind speed and topography of the area (Certini, 2005). Fire severity, intensity and soil type also affect soil properties (Mataix-Solera et al., 2011).

Phosphorus (P) is one of the plant nutrients that is most affected by fire cycles (Ferran et al., 2005). There may be a large increase in P in the soil surface shortly after fire due to accumulation of ash (Debano and Klopatek, 1988; Wilbur and Christensen, 1985), but the net long-term loss of P due to burning reduces forest productivity (Romanyà et al., 1994). Fire may lead to the transformation of the chemical bonding of soil nutrients including P. This also includes the alteration of organic forms into inorganic forms with associated changes in availability (Galang et al., 2010). P losses in soluble and particulate forms can increase due to organic matter mineralization and fire-induced soil erosion (Saa et al., 1993). Elemental P may be volatilised (boiling point 280 °C) at temperatures reached in fires and P is also removed in smoke during fire (Cotton and Wilkinson, 1988). Raison et al. (1985) found that P exported to the atmosphere may attain 50% of the total P in the combusted fuels.

The effects of fire on other components of the P cycle are generally poorly known (Debano and Klopatek, 1988; Saa et al., 1993) and in particular little is known of the effects of heating on the transformation of dominant soil minerals and consequent effects on P availability to plants.

Fire affects the nature of soil minerals and presumably their interactions with plant nutrients. Soil temperatures in excess of 500 °C can be reached during fires, which will alter many hydroxylated soil minerals thereby changing their nature and nutrient retention properties. This process may be of particular importance for kaolinite/sesquioxide dominated soils as these minerals are particularly sensitive to dehydroxylation (Ketterings et al., 2000).

Dehydroxylation of kaolinite, gibbsite and goethite by heating produces highly reactive minerals. Dehydroxylation between 500 °C and 700 °C will destroy kaolinite and form metakaolinite (Babuskhin et al., 1985). Gibbsite alters to complex amorphous and crystalline mineral assemblages on heating at about 200 °C (Rooksby, 1972) and goethite transforms to partly ordered hematite at about 300 °C (Cornell and Schwertmann, 1996). The existence and persistence of these reactive dehydroxylated minerals in heated soils are unknown but they have markedly different properties from the precursor minerals. They commonly exhibit greatly reduced

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structural order and increased surface reactivity while retaining their original particle morphology (Babuskhin et al., 1985; Cornell and Schwertmann, 1996; Rooksby, 1972). The interactions of plant nutrients with the reactive minerals present in heated soils clearly require investigation and has not been evaluated by other workers. Most previous work on the effects of fire on soils has focussed on plant nutrients in ash and not on the presence and roles of heated soil minerals. The objective of this glasshouse study was to evaluate the effects of heating soil containing kaolinite, goethite and gibbsite on the availability to plants of native and added phosphate which is known to be strongly sorbed by these minerals. Wild and managed fires affect large areas of soil so that knowledge of the effects of heating on plant nutrient availability is clearly of value.

2. Material and methods

2.1. Soil and glasshouse experiment

The top soil (0–10 cm) of the Yalanbee, lateritic podzolic soil which is an Alfisol (USDA, 2010) was collected from a virgin eucalypt forest site at Bakers Hill, 73 km east of Perth, Western Australia at 31°46′34.21″S latitude and 116°28′31.81″E longitude. These soils have been developed from colluvium derived from lateritised granite. The landscape consists of laterite-capped uplands and colluvium mantled moderate slopes, where the samples originated (McArthur, 1991). The average annual rainfall is 552 mm with an average of 64 rain days each year for Bakers Hill with most rain in the May–September period and highest monthly rainfall during June and July (Bureau of Meteorology, 2011). The same sandy, highly P deficient soil had been used in a study of the P fertilizer value of chicken litter ash by Yusiharni et al. (2007) so that its P-response characteristics and basal nutrient requirements are known. The sampled soils are very gravely sandy earths derived from laterite colluvium. The soil was passed through a <2 mm sieve for use in the glasshouse experiment and for chemical analysis. Soil properties are listed in Table 1. To prepare heated soils under conditions that resemble heating of soils in a wildfire, subsamples of soil were heated under oxidising conditions in shallow trays for 1 h at 250 (BH250), 350 (BH350) and 500 °C (BH500) which are temperatures reached by top soils in bush fires (Raison, 1979). These particular temperatures are above and below dehydroxylation maxima of the major hydroxylated minerals in the soil (Babuskhin et al., 1985; Cornell and Schwertmann, 1996; Grim, 1968) and the dehydroxylation reactions are largely completed within 1 h.

Phosphate (P) as monocalcium phosphate (MCP) (zero, 1.66, 3.33, 6.66 and 13.33 mg of P/kg) was mixed with 200 g of <2 mm original and 3 preheated soil samples in a plastic bag and placed in a non draining plastic pot. Basal fertilizer excluding P was applied to all pots, the soil was then mixed thoroughly and incubated at field capacity for 4 days before seeding with ryegrass. Twenty pregerminated seeds of annual ryegrass (*Lolium rigidum* Gaud) were placed in the pots at 1 cm depth and thinned to 10 plants per pot at the two-leaf-stage of growth. This is a commonly used bioassay species for P fertilizer studies as the nutrient requirement and glasshouse culture procedures for ryegrass are well established (Snars et al., 2004). The treatments were replicated three times, the location of pots on the glasshouse table was randomised every week and pots were maintained at constant weight with deionised water. Plants were harvested 3 times at 4-week intervals by cutting the tops at about 1 cm above the soil surface. Plant material was dried at 60 °C until constant weight occurred then ground and analysed.

2.2. Soil and plant analysis techniques

XRD analysis of unheated and heated soil samples was carried out using two techniques. Conventional XRD analysis was conducted with a Philips PW3020 diffractometer and synchrotron XRD (SXRD) analysis was performed at the Australian Synchrotron. Samples of soil for scanning electron microscopy and energy dispersive X-ray spectrometry (EDS) using a JEOL 6400 instrument were placed on metal stubs. Total carbon and nitrogen were determined on an Elementar CNS (Vario Macro) analyzer.

Soil samples were analysed for pH and electrical conductivity (EC) (1:5 H_2O) and available P (Bic P) using 0.01 M sodium bicarbonate extractant at pH 8.5 followed by colorimetric determination of dissolved P (Colwell, 1963). To determine poorly ordered minerals in heated soils, extractable forms of (iron) Fe, aluminium (Al) and silicon (Si) in the soil were dissolved in dithionite–citrate–bicarbonate (DCB), ammonium oxalate (Ox) and sodium pyrophosphate (SP) solutions (Rayment and Higginson, 1992) and elements were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) (Perkin-Elmer, Norwalk, CT, USA). Soils were analysed before planting and after the last harvest.

The harvested plant tops were digested in perchloric acid and analysed for P, calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), sulphur (S) and trace elements by inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin-Elmer, Norwalk, CT, USA) (Rayment and Higginson, 1992).

Replicate (3) plant data were averaged and statistically analysed including fitting of internal efficiency curves. An analysis of variance followed by Tukey's Honestly Significant Differences test were performed to identify the different levels of P added and heating treatments using SAS (SAS Institute, 1999). Differences for levels of P added in pH, EC and available P after the last harvest were assessed using one way-ANOVA. All results are presented as significant differences at $p < 0.05$.

3. Results and discussions

3.1. XRD and SEM

Conventional and synchrotron XRD patterns of heated and unheated Yalanbee soil show the effect of heating on soil mineralogical properties (Fig. 1). The SXRD patterns had much better sensitivity and peak to background discrimination than conventional XRD. Both techniques showed that the main crystalline compounds of unheated soils are quartz and kaolinite together with minor amounts of gibbsite and goethite, which were more clearly revealed by conventional XRD

Table 1
Properties of original and heated Bakers Hill (BH) soil samples (n = 1).

Properties	Unheated BH Soil	BH 250 °C	BH 350 °C	BH 500 °C
pH (1:5 H_2O)	4.63	4.67	5.40	5.45
EC (1:5 H_2O) µS/cm	39.9	119.1	91.8	77.1
Total P (mg/kg)	54	45	46	51
Bic P (mg/kg)	1.55	2.17	3.27	1.93
Total N (%)	0.080	0.078	0.072	0.023
Total C (%)	1.64	1.56	0.75	0.015
Total Ca (mg/kg)	471			
Total Mg (mg/kg)	437			
Total K (mg/kg)	498			
Total Na (mg/kg)	53			
Total S (mg/kg)	56			
Total Fe (mg/kg)	9115			
Total Ni (mg/kg)	7			
Total Pb (mg/kg)	20			
Total Cu (mg/kg)	2			
Total Mn (mg/kg)	55			
Total Zn (mg/kg)	7			
Total Al (mg/kg)	39,840			
Total Ba (mg/kg)	40			
Clay percentage (%)	4			
Silt percentage (%)	6			
Sand percentage (%)	90			