

Hot water extractable phosphorus pools as indicators of soil P responses to harvest residue management in an exotic pine plantation of subtropical Australia

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Abstract

Purpose This study evaluated the potential of using hot water extractable phosphorus (P) pools as a method to assess the impacts of harvest residue management on the bioavailability of P in an exotic pine plantation of southeast Queensland, Australia.

Materials and methods This study was carried out under three harvest residue management regimes: (1) residue removal, RR₀; (2) single-level residue retention (operational level), RR₁; and (3) double level of residue retention, RR₂, established immediately following clear-cut harvesting in a randomised complete block experiment. Soil was sampled after 24 months of the residue management regimes applied and analysed for hot water extractable inorganic P (HWEIP), hot water extractable organic P (HWEOP) and total P (HWETP), in relation to hot water extractable organic C (HWEOC) and N (HWEON), calcium chloride extractable P (CaCl₂-P), bicarbonate extractable P (NaHCO₃-P) and fluoride extractable P (Bray1-P).

Results and discussion The HWEIP and CaCl₂-P concentrations showed no significant variations amongst the treatments, while Bray1-P, NaHCO₃-P and the HWEOP P pools were only significantly greater in the RR₂ treatment than the RR₀ treatment. In contrast, the HWETP pool showed highly significant

($p < 0.005$) differences amongst all the treatments. In addition, both the HWEOP and HWETP were significantly related to the HWEOC and the total C, in contrast to the lack of such relationships with soil total P, suggesting their association with the HWEOC released through residue decomposition.

Conclusions This study showed that HWETP is a more sensitive measure of labile soil P and has the potential to be used as an indicator of management practices, particularly in cases where high spatial variations in soil P concentrations might confound P responses.

Keywords Bicarbonate extractable P · Decomposition · Hot water extractable organic C · Hot water extractable organic P · Hot water extractable total P · Residue management

1 Introduction

In the exotic pine plantations of southeast Queensland, Australia, phosphorus (P) deficiency is a major factor limiting plantation establishment and productivity (Xu et al. 1995). Although retaining the harvest residues on site was expected to supply P, soil P availability as a response to harvest residue management has been difficult to establish (Simpson et al. 2003). Difficulties with the assessment of available P, however, are a universal problem due to the complex chemistry and spatial variability of P in soils (Guo et al. 2000; Chen et al. 2008). Quantity-based P analyses such as NaHCO₃ and Bray P may extract inorganic P adsorbed onto solid phases (Mendham et al. 2002) with potential contributions from residual P. On the other hand, calcium chloride (CaCl₂) extractable P which measures P immediately available in soil solution (Rayment and Higginson 1992; Mendham et al. 2002) is prone to leaching (McDowell et al. 2003). Thus, there is a need to identify suitable soil P fractions that could be more sensitive indicators of harvest residue management and P

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availability. Hot water extractable organic C (HWEOC) and hot water extractable total N (HWETN), as labile C and N pools, have been used to assess the impacts of residue management and land use changes on soil quality (Sparling et al. 1998; Ghani et al. 2003; Chen and Xu 2005; Burton et al. 2007; Huang et al. 2008). We hypothesised that since decomposing plant residues are the main source of labile C (Homann and Grigal 1992; Qualls 2000; Xu et al. 2008, 2009), measurements of labile P associated with labile C pools could potentially be suitable indicators of soil P responses to harvest residue management. Therefore, this study assessed the potential of using hot water extractable P pools under different residue management regimes, in relation to common soil P extraction methods and labile C and N pools in an exotic pine plantation of subtropical Australia.

2 Materials and methods

2.1 Site description and experimental design

The study was carried out in a newly logged exotic (slash) pine (*Pinus elliottii* var. *elliottii*) plantation at Toolara State Forest, Maryborough District, in subtropical Queensland, Australia, with an acidic (pH 4.8) loamy sandy soil, which can be waterlogged during the wet season and classified as a soloth (Isbell 1996). In February 2005, immediately following clear-cut harvesting, macro-plots (10×10 m) were established on a section of the plantation in a randomised complete block arrangement with four blocks and three residue management treatments: (1) residue removal (RR₀), (2) single residue retention (RR₁), the operational residue retention level (30–40 t ha⁻¹) and (3) double residue retention, (RR₂).

2.2 Soil sampling and processing

Five soil cores (ca 7.5 cm diameter) were systematically sampled within each plot at 0–10 cm depth after 24 months of establishing the experiment and bulked into a composite sample, passed through a 2.0-mm sieve before sub-sampled for microbial biomass C (MBC) and chemical analyses. Sub-

samples for MBC analysis were stored at 4.0 °C and analysed within a week, while sub-samples for chemical analyses were air-dried and ground to powder.

2.3 Chemical analyses

Soil total P was determined by the ascorbic acid method (Murphy and Riley 1962) following 5:2 nitric/perchloric (HNO₃/HClO₄) acid digestion (Sparks 1996). Hot water extractable inorganic P (HWEIP) was determined following the extraction method similar to that for HWEOC (Sparling et al. 1998; Chen and Xu 2005). In this method, 8.0 g (oven-dried equivalent) of air-dried soil was incubated at 70 °C for 18 h in 40.0 ml of deionised water, shaken end-over-end for 5 min, and the extract passed through a 0.45-µm filter membrane. Hot water extractable total P (HWETP) was determined after 5:2 HNO₃/HClO₄ acid digestion of 10 ml of the hot water extracts. Hot water extractable organic P (HWEOP) was the difference between P determined in undigested and that of digested hot water extracts. Other inorganic P pools, bicarbonate extractable P (NaHCO₃_P), fluoride extractable P (Bray1_P) and calcium chloride extractable P (CaCl₂_P), were extracted according to Rayment and Higginson (1992), except that NaHCO₃_P was extracted in a soil to a solution ratio of 1:20 (Bekunda et al. 1990). All soil extracts were determined for P by a UV Spectrophotometer at 880 nm using the ascorbic acid method (Murphy and Riley 1962).

Soil total C was determined by a Eurovector 3000 elemental analyser (Milan, Italy) coupled to a GVI Isoprime mass spectrometer (Manchester, UK) while labile C and N as HWEOC and HWETN, respectively, were determined in the same hot water extracts described above by a Shimadzu TOC-VCSH/CSN TOC/N analyser. Hot water extractable organic N (HWEON) was the difference between the HWETN and the inorganic N (NH₄⁺-N and NO_x-N) of the same extracts as determined by a SmartChem 200 discrete chemistry analyser (DCA) (Westco Scientific Instruments). The Shimadzu TOC analyser was used to determine the MBC following extraction by the fumigation–extraction method (Vance et al. 1987; Chen and Xu 2005).

Table 1 Soil total P, hot water extractable inorganic P (HWEIP), organic P (HWEOP) and total P (HWETP), fluoride extractable P (Bray1_P), calcium chloride extractable P (CaCl₂_P) and bicarbonate extractable P

(NaHCO₃_P) under the residue removal (RR₀), single residue retention (RR₁) and double residue retention (RR₂) residue management treatments after 24 months following clear-cut harvesting

Treatments	Total P (mg kg ⁻¹)	HWEIP (mg kg ⁻¹)	HWEOP (mg kg ⁻¹)	HWETP (mg kg ⁻¹)	Bray1_P (mg kg ⁻¹)	CaCl ₂ _P (µg kg ⁻¹)	NaHCO ₃ _P (mg kg ⁻¹)
RR ₀	33.88a	1.54a	0.57b	2.11c	1.74b	213a	1.87b
RR ₁	42.19a	2.39a	1.18ab	3.36b	1.84b	378a	3.21ab
RR ₂	44.95a	2.46a	1.92a	4.38a	2.81a	265a	3.62a

Figures with the same letter in each column are not significantly different at $p < 0.05$

Table 2 Hot water extractable organic C (HWEOC), organic N (HWEON) and total N (HWETN), and microbial biomass C (MBC) under different residue management regimes after 24 months following clear-cutting of an exotic pine plantation in southeast Queensland

Treatments	Total C (%)	HWEOC (mg kg ⁻¹)	HWETN (mg kg ⁻¹)	HWEON (mg kg ⁻¹)	MBC (mg kg ⁻¹)
Residue removal	0.87b	246b	11.91a	8.66b	87.32a
Single residue retention	1.29a	246b	12.84a	10.23b	50.44b
Double residue retention	1.33a	354a	16.40a	13.07a	61.35b

Figures with the same letter in each column are not significantly different at $p < 0.05$

2.4 Statistical analyses

Analyses of variance were carried out on all measured parameters, and where there was a significant treatment effect at $p < 0.05$, the data were subjected to the least significant difference (LSD) test. Correlation and regression analyses of labile C and P pools were also carried out to establish their relationships.

3 Results

3.1 Variations in labile P pools across treatments

Residue management had no significant impact on the soil total P (Table 1). Similarly, HWEIP and CaCl₂_P also showed no significant variation amongst the treatments, in contrast to the NaHCO₃_P and Bray1_P, which were significantly greater in the RR₂ treatment compared to the RR₀ treatment (see Table 1). However, the HWEOP was significantly greater in the RR₂ treatment than in the RR₀ treatment, while the HWETP pool showed highly significant ($p < 0.005$) variations amongst the treatments (see Table 1). The HWETP was twice the magnitude in the RR₂ treatment than in the RR₀ treatment. In addition, HWEIP, which is the labile inorganic P pool, was greater than the HWEOP pool in all treatments.

Table 3 Pearson’s correlations between soil total P, fluoride extractable P (Bray1_P), calcium chloride extractable P (CaCl₂_P), bicarbonate extractable P (NaHCO₃_P), hot water extractable inorganic P (HWEIP),

	Bray1_P	CaCl ₂ _P	NaHCO ₃ _P	HWEIP	HWEOP	HWETP
CaCl ₂ _P	0.00 (ns)					
NaHCO ₃ _P	0.49 (ns)	0.50 (ns)				
HWEIP	0.37 (ns)	0.85***	0.61*			
HWEOP	0.40 (ns)	-0.26 (ns)	0.29 (ns)	-0.16 (ns)		
HWETP	0.58*	0.59*	0.72**	0.78**	0.49 (ns)	
Total P	0.35 (ns)	-0.65*	-0.06 (ns)	-0.52 (ns)	0.55 (ns)	-0.11 (ns)

ns not significant ($p > 0.05$)

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (significant)

3.2 Variations in labile C pools across treatments

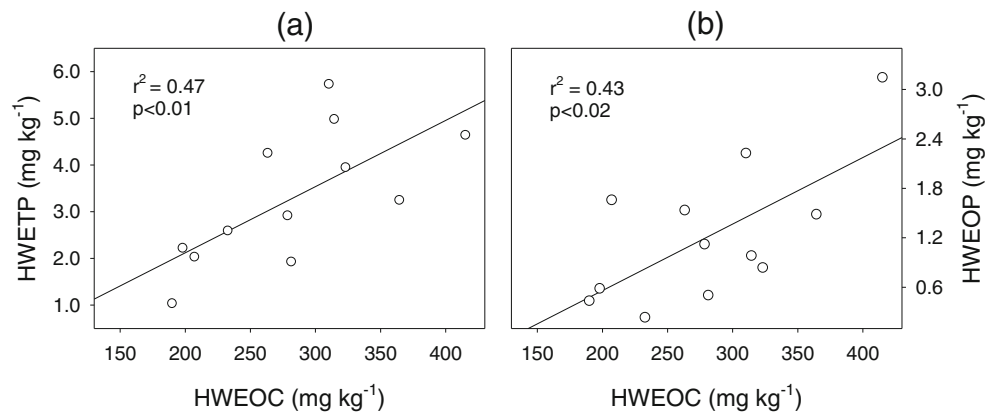
Soil total C was significantly greater in both the RR₁ and RR₂ treatments compared to the RR₀ treatment (Table 2), in contrast to the soil total P. Similarly, the HWEOC and HWEON were significantly greater in the RR₂ treatment than in the RR₀ treatment. The HWETN, however, showed no significant variations among the treatments. In contrast to the HWEOC, the MBC was significantly greater in the RR₀ treatment compared to both the RR₁ and RR₂ treatments.

3.3 Correlations between labile C and P pools

Pearson correlation analyses of P pools showed no significant correlations between total soil P and the hot water extractable P pools (Table 3). The HWEIP was highly significantly correlated to the CaCl₂_P ($p < 0.001$) and to some extent, the NaHCO₃_P ($p < 0.05$). The HWETP, however, was significantly correlated to the CaCl₂_P, Bray1_P and NaHCO₃_P (see Table 2). Regression analyses between the labile P pools and the C and N pools showed that HWETP and HWEOP were significantly related to both HWEOC (Fig. 1) and soil total C (Fig. 2), in contrast to the lack of such relationship with soil total P (data not presented). There were also significant relationships between the hot water extractable organic and total N and P pools (Fig. 3). No significant correlation between soil total C and soil total P was observed.

organic P (HWEOP) and total P (HWETP) under different harvest residue management regimes after 24 months following clear-cut harvesting of an exotic pine plantation in southeast Queensland ($n = 12$)

Fig. 1 The relationships between hot water extractable total P (HWETP) and hot water extractable organic C (HWEOC) (a), and hot water extractable organic P (HWEOP) and HWEOC (b) under different residue management regimes in an exotic pine plantation of southeast Queensland



4 Discussion

This study showed that hot water could extract a relatively large quantity of soil P, as demonstrated by the large differences between the hot water extracted P and the dilute CaCl_2 extracted P (see Table 1), probably through the same mechanism that increased the solubility of labile C and N pools through hot water extraction (Ghani et al. 2003; Chen and Xu 2005). While no significant variations in HWEIP among the treatments were observed, HWEIP is a substantial P pool comparable to the Bray1_P and NaHCO_3 _P, in magnitude (see Table 1). The highly significant correlation between CaCl_2 _P and HWEIP (see Table 2) suggests that these P pools may be similar. The CaCl_2 _P is regarded as the P immediately available in soil solution (Mendham et al. 2002), and we expected this to reflect the inorganic P immediately released from the residues (Palviainen et al. 2004). However, the lack of a significant variation of the CaCl_2 _P among the treatments may be due to the high-leaching potential of this P pool (McDowell et al. 2003) especially in the sandy soil. Considering the relationship between CaCl_2 _P and HWEIP, we would speculate that the lack of a significant variation of HWEIP among the treatments could also be due to uneven leaching losses.

The significant variations in HWEOP and HWETP (see Table 1) under different residue management regimes were consistent with the measurements of NaHCO_3 extractable organic and inorganic P following clear-cutting and residue retention in a *Pinus radiata* plantation in South Australia (Bekunda et al. 1990). It also parallels those of HWEOC and HWETN employed to assess residue management impacts and land use changes on soil quality (Ghani et al. 2003; Chen et al. 2004; Chen and Xu 2005). The greater proportion of inorganic P (HWEIP) relative to HWEOP was consistent with the study of P in sandy soils (Turner et al. 2002), probably due to the low organic matter content characteristic of sandy soils and high mineralisation rates. The highly significant variations in HWETP amongst the treatments, compared to the other extraction methods or P pools, suggest that HWETP probably encompassed both the inorganic and organic P released from the residues. Further assessment of HWETP is therefore recommended to ascertain its potential as an indicator of management practices and plant growth.

The lack of a significant relationship between soil total P and HWEOP or HWETP (see Table 2) indicated the spatial variations in the soil total P and therefore the inconsistencies in P response to residue management in the past (Simpson et al. 2003). In contrast, the significant relationships amongst

Fig. 2 The relationships between hot water extractable organic P (HWEOP) and soil total C (a), and between HWEOP and hot water extractable organic C (HWEOC) (b) under three different residue management regimes in an exotic pine plantation of southeast Queensland

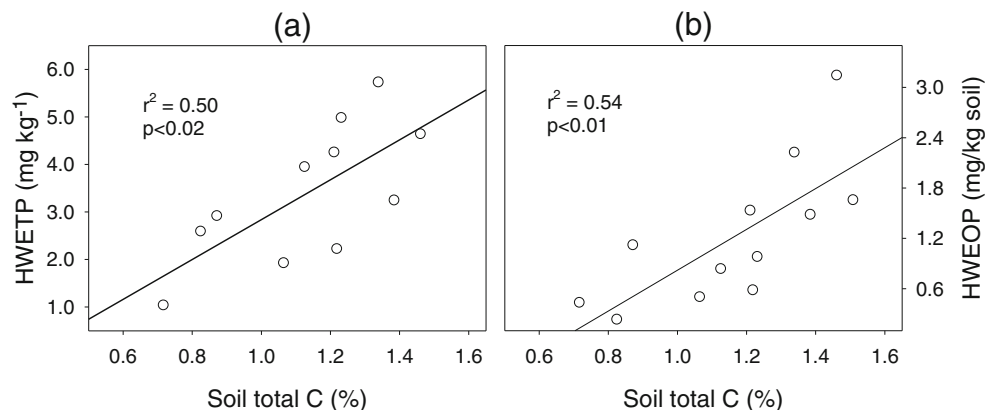
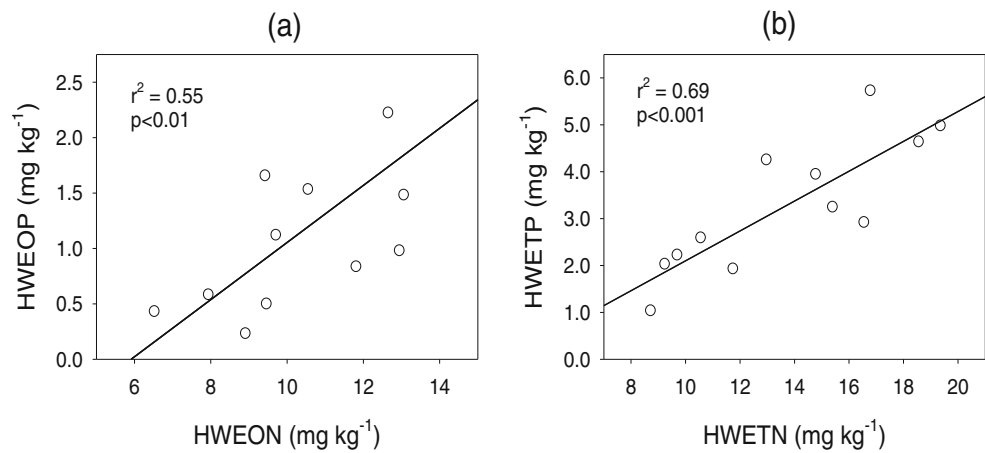


Fig. 3 The relationships between hot water extractable organic P (HWEOP) and hot water extractable organic N (HWEON) (a), and between hot water extractable total P (HWETP) and total N (HWETN) (b) under different residue management regimes in an exotic pine plantation of southeast Queensland



the HWEOP, HWETP, HWEOP and total C (see Figs. 1 and 2), and the greater concentrations under the residue treatments (see Table 1 and Table 3), supported our hypothesis that labile P fractions were associated with the labile C fractions, which most likely originated from the residues (Kumar and Goh 2000; Chen and Xu 2005). These observations were supported by past ^{31}P and ^{13}C NMR studies showing P release being closely associated with the loss of the O-alkyl C, the labile C fraction of decomposing residues (Gressel et al. 1996; Ha et al. 2007), consistent with our ^{13}C NMR study of the aboveground harvest residues as decomposition progressed (data not presented). Mathers and Xu (2003) have also indicated the relationship between the O-alkyl C fraction of SOM and inorganic P. The established relationship between O-alkyl C and HWEOP (Huang et al. 2008) and therefore soil P suggested that the mineralisation of HWEOP could have been the source of organic and inorganic P in soil solutions. In addition, the significant relationship between HWEOP and HWEON (see Fig. 3) points to the close association of N and P bound to the labile C compounds.

Hot water extraction has been used to quantify P in aquatic ecosystems (Miyata and Hattori 1986), probably P bound by tissues of microscopic marine organisms. Similarly in the soil, hot water extraction has been suggested to release labile C mostly of microbial origin (Sparling et al. 1998). However, the apparent decreasing MBC and increasing HWEOP as the residue-loading rate increased (see Table 3) indicated that the contribution of soil microbes to the HWEOP pool might be negligible in comparison to the contribution of the residues to the HWEOP pool. Likewise, the HWEOP and HWETP could have largely originated from the residues.

We acknowledged that a limitation of this study is the sampling intensity of only five cores (7.5 cm diameter) per plot and that the study was conducted in a single site. While we contend that such a sampling intensity was sufficient for a 10×10 m plot, it might explain the insignificant differences in soil total P even though the total P concentration was more than

30% greater in the RR_2 treatment than in the RR_0 treatment (see Table 1). Nonetheless, the study demonstrated that even with such a sampling intensity in a situation of large spatial variations in total P concentrations, other P pools are more sensitive indicators of bioavailable P as a response to forest management. We suggest further work is carried out with a more intensive sampling regime, and in more than one site, for a broader understanding of the usefulness of hot water extractable P pools.

5 Conclusions

This study showed that HWETP pool was a more sensitive indicator of soil P responses to harvest residue management compared to total P and traditional measures of available P such as Bray1_P , NaHCO_3_P and CaCl_2_P . This was because HWETP and HWEOP are closely associated with the labile C fractions released from the decomposing residues. Thus, measurement of HWETP is a potentially appropriate method for understanding and quantifying soil P responses directly related to organic residue retentions in soil conditions, where large spatial variations in P concentrations are a problem. Nonetheless, the potential of HWETP or HWEOP as indicators of forest management needs to be further explored with a greater sampling intensity than the one in this study, and in more than one site, for a broader understanding.

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