Fractionation and mobility of phosphorus in a sandy forest soil amended with biosolids

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ABSTRACT

Phosphorus (P) fractionation and testing techniques were used to evaluate the effects of repeated biosolids application on P forms and mobility in a sandy soil in a plantation forest (*Pinus radiata* D. Don). Soil total P and Olsen P in the high biosolids treatment (600 kg N ha^{-1} applied in every three years) had increased significantly ($P<0.05$) in both 0-10 cm and 10-25 cm layers. Mehlich 3 P in soil of the high treatment had increased significantly only at 0-10 cm. Olsen P appeared to be more sensitive than Mehlich 3 P as an indicator of P movement in a soil profile. Phosphorus fractionation revealed that inorganic P (Al/Fe bound P and Ca bound P) and residual P were the main P pools in soil, whereas water soluble P accounted for approximately 70% of total P in biosolids. Little organic P was found in either the soil or biosolids. Concentrations of water soluble P, bioavailable inorganic P ($NaHCO_3$ Pi) and potentially bioavailable inorganic P (NaOH Pi) in both 0-10 and 10-25 cm depths were significantly higher in the high biosolids treatment than in the control. Mass balance calculation indicated that most P applied with biosolids was retained by the top soil (0-25 cm). The standard biosolids treatment (300 kg N ha^{-1}) had no significant effect on concentrations of total P, Mehlich 3 P and Olsen P, and P fractions in soil. It implies that the risk of P losses via leaching in the sandy forest soil because of the repeated biosolids application, particularly at the standard rate, was small.

Keywords: biosolids, forest soil, land application, phosphorus fractionation, sandy soil.

INTRODUCTION

Biosolids, treated sewage sludge suitable for beneficial use, is commonly used as fertilizer and soil amendment to improve soil productivity (Kimberley et al. 2004). Ratios of nitrogen (N) to phosphorus (P) in biosolids are usually narrower than that required by crop growth (O'Connor et al.2004). Land application of biosolids on N-basis generally results in excessive P accumulation in soils, which may increase the risk of P losses to surface or ground water and contribute to water body eutrophication (Chang et al., 1983; Pierzynski et al. 2005).

Phosphorus moves from agricultural land in particulate form via soil erosion and in dissolved form via surface and subsurface runoff (Sheperd and Withers, 2001; Elliott et al. 2005). Substantial vertical movement or leaching of P from crop land regularly receiving animal manure have been documented in recent studies (McDowell and Sharpley, 2001; Nelson et al. 2005).

Phosphorus risk assessment has been undertaken using soil column or field lysimeters to measure runoff P directly (Wither et al. 2001; Elliott et al. 2002, 2005), or using P testing methods to indirectly reveal P distribution and movement in soil profiles (Maguire and Sims. 2002; Bulter and Coale 2005). Many linear or nonlinear relationships have been established between soil P with runoff P, based on which a number of thresholds for soil P index have been set to identify land with high risk of P losses (Heckrath et al. 1995; Sims et al. 2002). However, P leaching potential on waste-amended land is dependent on several factors, such as soil P levels, soil P-retention capacities, hydraulic conditions (e.g., preferential flow pathway), management practices (e.g., rotation), and P sources (Maguire and Sims, 2002a; Djodjic et al. 2004; Schroeder et al. 2004; Kleinman et al. 2003).

Treated biosolids have been applied to *Pinus radiata* D. Don plantation at Rabbit Island near Nelson City, New Zealand, since 1996. Repeated applications to individual forest stands have been made approximately every three years. Responses of tree growth, wood property, and soil and groundwater quality have been monitored regularly (Wang et al. 2004). Biosolids application has resulted in significant improvement in site productivity (Kimberley et al. 2004). Plant available P in soil was found to be higher in biosolids treatments than in the control (Wang et al. 2004).

Most previous studies on P bioavailability and movement were conducted in agricultural and horticultural soils. Phosphorus movement in waste-amended forest soils has received less attention. The objectives of this study were to characterize P forms and investigate their distribution in a sandy soil receiving repeated biosolids application.

MATERIALS AND METHODS

Trial description

A research trial was established in 1997 in a 6-year-old stand of *P. radiata* at Rabbit Island, Nelson, New Zealand, to test the effects of biosolids applications on tree growth and the receiving environment. The mean annual rainfall is 985 mm. The soil consists of coarse coastal dune sands with low N fertility. The soil is classified as a sandy raw soil (Hewitt 1998), which provides free rooting access to the shallow groundwater 2.0 to 4.2 m below the surface.

Three biosolids treatments were applied in a split-plot, randomized block design with four replicates. The treatments consisted of: a control (no biosolids); a standard treatment (target application of 300 kg N ha^{-1}, equivalent to 100 kg N ha^{-1} year^{-1} over 3 years, used in the full scale operation); and a high treatment (double the standard at a target rate of 600 kg N ha^{-1}). The biosolids were applied in October 1997 and re-applied at the same rates to the same plots in November 2000 and October 2003. Details about properties of the biosolids applied and method of application have been given by Wang et al. (2004). In total 900 kg N ha^{-1} and 117 kg P ha^{-1} in the standard treatment, and 1800 kg N ha^{-1} and 234 kg P ha^{-1} in the high treatment were added with these repeated biosolids applications. Soil samples were collected in August 2004 from the trial site at depths of 0-10, 10-25, 25-50, 50-75, and 75-100 cm. Soil samples were air-dried and ground to pass a 2mm sieve. Biosolids samples were collected in 2003 and 2005 and stored under 4°C before analysis.

Characterisation of biosolids and soil

Total solid content in biosolids was determined by oven-drying 50 g of fresh sample at 105˚C. Total P in biosolids were digested following a micro-Kjeldahl digestion (Blakemore et al. 1987), and determined by a Skalar automated segmented flow analyzer using molybdate blue method of Murphy and Riley (1962). The biosolids samples were chemically fractionated following the non-sequential procedure of Sheperd and Withers (2001). Fresh samples were extracted separately by distilled water, 0.5M $NaHCO_3$ (pH 8.2), 0.1M NaOH, and 1.0M HCl. Each extraction was in triplicate.

Soil particle size was analyzed by hydrometer method (ASTM, 1990). Particle analysis of composited soil samples at five depths gave mean values of 95% sand, 3% silt, 2% clay (data not shown). Soil pH was measured with a soil to water ratio of 1:2. Concentrations of total C and N were determined by dry combustion using a Leco CNS 2000.

Soil samples were extracted with Mehlich 3 (M3) solution (0.2M CH_3COOH, 0.25M NH_4NO_3, 0.015M NH_4F, 0.13M HNO_3, and 0.001M EDTA) (Mehlich, 1984). Concentrations of P, Al and Fe in M3 extracts (M3 P, M3 Al and M3 Fe) were analyzed by ICP-OES (Perkin Elmer Optima 3000DV). Phosphorus saturation index (PSI) was calculated as the molar ratio of M3 P to M3 (Al + Fe) in mmol kg^{-1} (Kleinman and Sharpley. 2002). The PSI_{M3} provides insight into a soil's ability to release P to soil solution as well as capacity to bond added P, and PSI calculated from M3 extraction (PSI_{M3}) has been found to be a good indicator in assessing P loss risk (Maguire and Sims 2002b; Sims et al. 2002). Soil P in Olsen solution was determined by the auto-analyzer.

Phosphorus fractionation

Soil P was sequentially extracted according the procedure of Sui et al (1999), a modified procedure from Hedley's method (Hedley et al. 1982). Two grams of soil was sequentially extracted by end-to-end shaking with 30 mL of distilled water, 0.5M $NaHCO_3$ (pH 8.2), 0.1M NaOH, and 1.0M HCl each for 16h. P concentrations in the above extracts were determined directly by auto-analyzer and regarded as inorganic P. Total P in $NaHCO_3$ and NaOH extracts were determined following a micro-Kjeldahl procedure of APHA (1998). Organic P in $NaHCO_3$ and NaOH extracts were calculated as the difference of total P and inorganic P. Phosphorus concentrations in residual soil were determined using the same method as for concentration of the total P in biosolids. Based on this sequential procedure, soil P fractions were sequentially referred to as water soluble P (WSP), bioavailable inorganic P ($NaHCO_3$ Pi), readily mineralizable organic P ($NaHCO_3$ Po), amorphous and some crystalline Al and Fe inorganic P (NaOH Pi), potentially bioavailable organic P (NaOH Po), relatively stable Ca-bound P (HCl P), and residual P (Zhang et al. 2002; Sharpley et al. 2004). Soil total P (TP) was the sum of all above P fractions.

Statistical Analysis

Analysis of variance (ANOVA) and least significant difference (LSD) tests were used to determine the statistical significance of the biosolids treatment effects using the SAS GLM procedure (SAS Institute Inc., 2000). Regression analysis was performed using the SAS REG procedure.

RESULTS AND DISCUSSIONS

Fractionation of phosphorus in biosolids

Biosolids contained only 2.0% and 1.0% of total solids in 2003 and 2005 samples, respectively. Concentrations of the total P were 1.32% in 2003 sample and 1.85% in 2005 sample.

Non-sequential fractionation results indicated that the solubility of P in biosolids was high and most P was in the inorganic P forms (Figure 1). Water soluble P dominated the total biosolids P, suggesting a greater potential for rapid P release after biosolids application. There was little NaOH extractable P (Al/Fe bound P) in biosolids, indicating no addition of metal salts during the waste water treatment process.

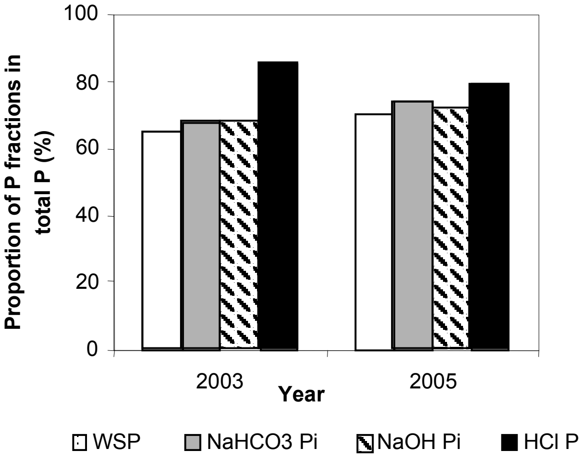

Figure 1. Solubility of P fractions in biosolids.

The amounts of P fractions varied widely from sources of liquid digested sludge. Shepherd and Withers (2001) reported on an average 18% of the total P was water extractable, 33% $NaHCO_3$ extractable, 23% NaOH extractable and 72% HCl extractable. Withers et al. (2001) reported that water, $NaHCO_3$, NaOH and HCl could extract 8%, 35%, 30% and 94% of the total P, respectively, in anaerobically digested liquid sludge**.** Biosolids in our study contained apparently more water soluble P and less HCl P than that in previous studies (Figure 1), but our study agreed with them on that inorganic P dominated total P in liquid digested sludge.

Effect of biosolids application on soil acidity, carbon and phosphorus availability

There was a significant ($P<0.05$) increase of total organic C in the surface soil (0-10 cm) of the plots with high biosolids application. Soil pH in the surface soil (0-10 cm) in the high biosolids treatment was significantly lower than in the control. The standard biosolids treatment had no significant effect on either pH or concentration of total organic C (Table 1).

The high biosolids treatment had a significant effect on Mehlich 3 extractable P (M3 P) concentration in surface soil (0-10 cm). M3 P concentrations in the deeper soil layer (10-25 cm) at both standard and high biosolids treatments were higher than that in the control, but the increases were not statistically significant (Table 1). There was little difference in M3 P among treatments below 25 cm, indicating little M3 P movement in the lower soil layers (25-100 cm).

Table 1. Effects of biosolids application on soil pH, organic carbon, M3 extractable elements, PSI_{M3} and Olsen P*.

Treatment	pH	C	M3 P	M3 Al	M3 Fe	M3 Ca	PSI_{M3}	Olsen P
		%	mg kg^{-1}				%	mg kg^{-1}
				0-10 cm				
Control	4.92a	1.09a	84a	575a	547a	325a	8.7a	20.2a
Standard	4.77a	1.42a	146ab	557a	499a	378a	16.5ab	33.6a
High	4.45b	2.12b	220b	606a	538a	363a	22.0b	57.5b
				10-25 cm				
Control	5.44a	0.37a	113a	634ab	466a	248a	11.3a	19.4a
Standard	5.29a	0.48a	134a	614a	444a	229a	14.4a	24.7ab
High	5.12a	0.47a	154a	707b	453a	239a	14.4a	31.0b
				25-50 cm				
Control	5.82a	0.20a	89a	512a	325a	180a	11.4a	13.2a
Standard	5.90a	0.30a	80a	505a	308a	197a	10.5a	14.4a
High	5.61a	0.24a	94a	558a	328a	205a	11.4a	17.5a
				50-75 cm				
Control	6.03a	0.11a	46a	389a	233a	131a	8.1a	7.2a
Standard	6.07a	0.15a	46a	388a	233a	147a	7.9a	8.3a
High	5.98a	0.14a	52a	386a	220a	142a	9.2a	9.2a
				75-100 cm				
Control	6.29a	0.09a	30a	326a	185a	104a	6.2a	4.0a
Standard	6.32a	0.14b	27a	340a	186a	144a	5.5a	4.7a
High	6.11a	0.10a	31a	336a	178a	124a	6.3a	4.9a

*Values with the same letter in a column at the same depth are not significantly different ($P>0.05$).

Sims et al. (2002) suggested 51-100 mg kg^{-1} of M3 P in soil as agronomical optimum. Concentrations of M3 P in soils at top 50 cm in the control treatment in the current study were all higher than 50 mg kg^{-1} (Table 1), indicating the soil has sufficient P to support plant growth. Sims et al. (2002) also suggested 150 mg M3 P kg^{-1} as a threshold above which improved P management was required for environmental concern, because these excessive P may lead to an increased potential of P losses via surface or subsurface runoff. Concentrations of soil M3 P in the surface and subsurface soils in our study had been higher than this environmental threshold in the high biosolids treatment (220 and 154 mg kg^{-1}), and near the threshold under standard treatment (146 and 134 mg kg^{-1}) (Table 1). There is little potential for overland runoff in our trial site because of the high hydraulic conductivity and infiltration rate in this sandy soil. The most likely pathway for P to enter waterway is through leaching to the shallow groundwater. Our soil profile data indicated that minimal downward movement of M3 P to soil layers below 25 cm.

Concentration of Olsen P in plots of the high biosolids treatment was significantly ($P<0.05$) higher than those of the control and the standard treatments in the top soil (0-10 cm), and than that of the control treatment in the subsurface soil (10-25 cm) (Table 1). It was apparent that Olsen P concentration in the biosolids treatments was higher than that of the control in deeper soil layers, although these differences were not statistically significant. Heckrath et al. (1995) suggested 60 mg Olsen P kg^{-1} as environmental change point above which rapid release of P to drainage would happen. All our Olsen P concentrations were well-below that point and P should be absorbed in high energy soil sites.

Regression analysis also showed highly significantly linear relationship between Olsen P and M3 P tests (R^2=0.83**, n=60) (**, significant at the 0.05 levels of probability). There was a consistent distribution pattern of Olsen P with M3 P, with an average recovery of 18% for Olsen P to M3 P.

Phosphorus saturation index (PSI)

Phosphorus saturation index describes the degree to which the potential P sorption sites were saturated with P. PSI_{M3} in the top soil (0-10 cm) of the high biosolids treatment was 153% higher and significantly ($P<0.05$) greater than that in the control. Although PSI_{M3} in the standard treatment was 90% higher than that in the control in the top soil, there was no significant difference in PSI_{M3} between the standard and the control treatments. The PSI_{M3} values in both high and standard biosolids treatments in the subsurface soil (10-25 cm) were 27% higher than that in the control (Table 1). Sims et al. (2002) suggested 15% of PSI_{M3} as environmental threshold for soils with moderately acidity and low OM in mid-Atlantic region of the USA. In our study PSI_{M3} values in the top soil (0-10 cm) of both standard and high biosolids treatments were greater than the threshold, indicating an increasing potential for P to migrate to deeper soil layers. The PSI_{M3} values at other depths in all treatments were below that environmental point, implying that the subsoil had a great potential to retain P.

There was a highly linear relationship (R^2=0.99**, n=60) between PSI_{M3} and M3 P/M3 Al, another PSI introduced by Khiari et al. (2000). Similar relationship was also reported by Kleinman and Sharpley (2002). We found that PSI_{M3} was a more accurate PSI than M3 P/M3 Al in our soil because M3 Fe represented a greater part of P sorption capacity (M3 (Al+Fe)) in our study (about 40%) than previous studies, which were 12% and 7% reported by Khiari et al. (2002) and Sims et al. (2002), respectively.

Sequential fractionation of soil phosphorus

Effects of biosolids application on P fractions were greater in upper two soil layers (0-10 cm and 10-25cm) than in deeper soils. The high biosolids treatment had a greater effect on P fractions than the standard rate of biosolids application did. Concentrations of WSP, $NaHCO_3$ Pi, NaOH Pi in the surface and subsurface soils had increased significantly ($P<0.05$) in the high biosolids treatment. However, biosolids treatments had no significant effect on concentrations of HCl P and residual P. There were no significant changes of P fractions in soil layers below 25 cm, except NaOH Po in soil layer of 25-50 cm in the standard treatment (Table 2).

Concentrations of organic P extracted by $NaHCO_3$ and NaOH ($NaHCO_3$ Po and NaOH Po) were relatively low because of the low organic matter in soil. This implied that any movement of organic P in this soil was unlikely to be significant, although organic P might contribute greatly to runoff P in other soils (Chang et al. 1983; Eghball et al. 1996).

Concentration of soil total P had increased significantly ($P<0.05$) in the upper two layers (0-25 cm) of the high biosolids treatment. The standard biosolids treatment has no significant effect on total P concentration in soil (Table 2).

Table 2. Concentrations of soil P fractions at different depths*.

Treatments	WSP	$NaHCO_3$ Pi	$NaHCO_3$ Po	NaOH Pi	NaOH Po	HCl P	Residual P	TP
				mg kg^{-1}				
				0-10 cm				
Control	5.0a	25.6a	8.7a	67.4a	5.4a	45.7a	57.8a	215.5a
Standard	12.4a	39.8a	10.0a	82.9ab	12.0b	42.6a	59.5a	259.2ab
High	25.8b	58.7b	11.6a	110.6b	5.5a	48.8a	60.1a	321.1b
				10-25 cm				
Control	3.5a	30.8a	2.4ab	94.4a	0.0a	75.8a	65.1a	272.0a
Standard	5.8ab	38.4ab	1.2a	96.3a	0.5a	68.7a	63.4a	274.4ab
High	6.4b	42.2b	4.5b	110.6b	1.3a	65.9a	66.1a	296.9b
				25-50 cm				
Control	2.9a	23.4a	0.6a	67.1a	0.2a	110.9a	61.4a	266.5a
Standard	3.2a	22.2a	1.6a	62.1a	2.8b	105.5a	60.6a	258.0a
High	3.7a	28.0a	0.4a	73.7a	0.4a	108.2a	62.0a	276.3a
				50-75 cm				
Control	1.6a	10.1a	0.9a	35.2a	1.6a	121.8a	36.5a	207.7a
Standard	1.9a	10.8a	0.3a	36.8a	1.9a	118.0a	39.3a	208.9a
High	1.8a	11.6a	0.5a	36.5a	1.9a	110.7a	33.4a	196.4a
				75-100 cm				
Control	1.0a	6.2a	1.1a	19.9a	3.0a	126.8a	34.6a	192.5a
Standard	1.2a	6.8a	0.3a	23.2a	2.8a	119.8a	36.6a	190.7a
High	1.0a	6.8a	0.1a	23.2a	2.3a	139.6a	33.8a	206.9a

*Values with the same letter in a column at the same depth are not significantly different (P>0.05).

Proportions of P fractions in total P can reveal the effect of biosolids application on the relative changes of P fractions in the receiving soil. Most changes resulting from biosolids application occurred in the surface soil, where proportions of WSP, $NaHCO_3$ Pi in soil increased and those of HCl P and residual P decreased after repeated application of biosolids (Table 3). Although concentration of NaOH Pi increased significantly in the high biosolids treatment (Table 2), the proportion of this P fraction had not increased significantly (Table 3). In layer of 10-25cm, changes in proportions of soil P fractions maintained in a similar pattern as in surface soil, but the magnitude of these changes was much smaller. No responses of P proportions to biosolids treatments were observed in soil layers below 25 cm.

Both concentration and proportion values of P fractions indicated that inorganic P (Al/Fe P and Ca P) was the main soil P form, followed by residual P and HCl P in the upper layers of the soil (0-25 cm). As soil depth increased, Ca P (HCl P) became the dominant part of total P (Table 3). This shift was related to soil pH increases with soil depth (Table 1), thus the shift of dominance from Al/Fe P to Ca P (Table 3). However, concentration of M3 Ca decreased with soil depth (Table 1).

Correlation analysis showed significantly negative linear relationships between HCl P and M3 Ca (R^2=0.59**, n=60). Similar significantly negative relationship were also observed between soil pH and M3 Ca (R^2=0.0.74**, n=60). These results imply that M3 Ca may not be a good indicator of availability of soil Ca for P binding. Some Ca compounds with relatively low solubility (e.g., $CaCO_3$) have large capacity to retain P.

Table 3. Proportion of soil P fractions at different depths (%)*.

Treatment	WSP	$NaHCO_3$ Pi	$NaHCO_3$ Po	NaOH Pi	NaOH Po	HCl	Residual P
%							
0-10 cm							
Control	2.3a	11.9a	4.0a	31.1a	2.5a	25.2a	27.1a
Standard	4.8a	15.3b	3.9a	31.8a	4.7b	16.5b	23.2ab
High	7.8b	18.1c	3.7a	34.4a	1.8a	15.2b	19.1b
10-25 cm							
Control	1.3a	11.3a	0.9a	34.7a	0.0a	27.8a	24.0a
Standard	2.1a	14.0a	0.5a	35.1a	0.2a	25.1ab	23.1a
High	2.2a	14.2a	1.5a	37.2a	0.4a	22.2b	22.3a
25-50 cm							
Control	1.1a	8.7a	0.3a	25.1a	0.1a	41.6a	23.1a
Standard	1.2a	8.5a	0.7a	23.8a	1.2b	41.0a	23.6a
High	1.3a	10.1a	0.2a	26.6a	0.2a	39.1a	22.5a
50-75 cm							
Control	0.8a	4.9a	0.4a	17.0a	0.8a	58.9a	17.3a
Standard	0.9a	5.2a	0.1a	17.6a	1.0a	56.4a	18.8a
High	0.9a	5.9a	0.3a	18.4a	1.0a	56.7a	16.9a
75-100 cm							
Control	0.5a	3.2a	0.6a	10.4a	1.5a	65.8a	18.1a
Standard	0.6a	3.5a	0.2a	12.1a	1.6a	62.3a	19.7a
High	0.5a	3.3a	0.1a	11.2a	1.2a	67.0a	16.5a

*Values with the same letter in a column at the same depth are not significantly different ($P>0.05$).

Fate of biosolids-derived phosphorus

Kleinman et al. (2003) pointed out that using soil profile data to assess potential risk of P leaching may not be reliable in some soils because P can be leached through preferential flow. To understand the fate of biosolids-derived P, we calculated mass balance of biosolids-derived P accumulated in top 25 cm soil under the high treatment, because no significant TP changes were observed below 25 cm and only the high rate of biosolids application had an significant effect on soil TP. Accumulation of TP in 0-25 cm soil layer was 189 kg ha^{-1} in the high treatment, accounting for 81% of total P loaded by biosolids. The remaining biosolids-derived P (approximately 45 kg P) was most likely taken up by vegetation. In a previous study on the same site, significantly larger trees grown in plots receiving biosoilds application were reported (Wang et al. 2004). Although there was no significant increase in foliage P concentrations, more P and nutrients had been taken up by the larger trees in the biosolids treatments. Therefore, P added to this sandy soil during repeated biosolids applications were either retained by top 25 cm soil or utilised by the tree crop. This implies that little biosolids-derived P would have been leached to groundwater.

Fractionation of biosolids P showed that P fractions loaded by biosolids followed the order: WSP>>HCl P>$NaHCO_3$ Pi, NaOH Pi. Mass balance calculation of each P fraction showed that P accumulated in the soil was in the following order: $NaHCO_3$ Pi>NaOH Pi>WSP at the standard treatment, and NaOH Pi>$NaHCO_3$ Pi >WSP at the high treatment. Despite the plant uptake of WSP, WSP accumulated in soils was far less than that loaded by biosolids, which might imply that a considerable part of WSP was transformed into less labile forms ($NaHCO_3$ Pi, NaOH Pi) after biosolids was applied to soils. Concentrations of HCl P in soils were not affected by biosolids application, which might result from HCl P in biosolids being dissolved and transformed into $NaHCO_3$ Pi and NaOH Pi after application. This was in agreement with the study of Sui et al. (1999) who reported that HCl P in biosolids could be dissolved and transformed into other P fractions once applied to soils, especially WSP and $NaHCO_3$ Pi.

CONCLUSIONS

Phosphorus fractionation revealed that WSP was the dominant P form in the aerobically digested liquid biosolids. Biosolids application had a greater effect on P forms and accumulation in the top soil layers (0-10cm and 10-25 cm) than it did in lower soil layers within the sandy forest soil profile. After repeated biosolids application, soil Olsen P increased at the top two layers (0-25 cm) in the high biosolids treatment, whereas M3 P and PSI_{M3} significantly increased only in the surface soil (0-10 cm). Our study demonstrated that Olsen P is more sensitive than M3 P as an indicator of P movement.

Sequential fractionation showed that inorganic P (Al/Fe P and Ca P) and residual P were the main P fractions, whereas organic P contributed little to total P. Concentrations of WSP, $NaHCO_3$ Pi, NaOH Pi and total P in the top soil layers (0-25 cm) increased significantly in the high biosolids treatment. However, concentrations of HCl P were not affected by biosolids application. Unlike biosolids, only small proportion of soil P fraction was WSP. This suggested that WSP from biosolids was transformed into less labile forms ($NaHCO_3$ Pi, NaOH Pi) when biosolids were applied to the soils.

Concentration of M3 P in the high biosolids treatments, and PSI_{M3} in both standard and high biosolids treatments had been higher than some suggested environmental thresholds. However, P distribution data and mass balance calculation indicated that almost all biosolids-derived P was either retained by the top soil (0-25 cm) or taken up by the tree crop, and no significant downward movement of biosolids-derived P in the soil profile was observed. Therefore, the risk of leaching loss of biosolids-derived P to groundwater is minimal. In particular, when the biosolids are applied at the standard rate, equivalent to 300 kg N ha^{-1} in every 3 years and used at full-scale operation, to the coarse sandy soil with minimal overland runoff or preferential flow during leaching process, the risk of biosolids-derived P to cause offsite water body eutrophication is low.

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