Isotopic exchange kinetics of soil P under *Pinus radiata* and Lucerne Understorey

John Scott[A] and Leo Condron[B]

[A]Landcare Research, Hamilton, New Zealand , Email ScottJ@LandcareResearch.co.nz
[B]Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln, New Zealand, Email Leo.Condron@lincoln.ac.nz

Abstract

Soil inorganic (Pi) dynamics under radiata pine, radiata pine plus lucerne and lucerne alone grown in soil with high and low soil carbon (C) and phosphorus (P) concentrations was investigated. Isotopic exchange kinetics (IEK) analysis revealed that trees and lucerne combined produced a greater decline in recalcitrant forms of Pi ($E_{>3m}$ pool) pool than when they were grown alone, except in the high P, low C soil. In the high P, low C soil, the effect of trees and lucerne combined on $E_{>3m}$ was intermediate between the effect determined for trees and lucerne alone. There was strong evidence of significant redistribution of P from less exchangeable to more readily exchangeable IEK pools. When P and C were very low, trees and lucerne were able to actively deplete all pools and when lucerne was combined with the trees such depletion was enhanced further in the $E_{>1yr}$ pool. The redistributed P in the low P soils appeared to be taken up by plants, whereas in the high P soils the trees, trees with lucerne and lucerne alone increased the available $E_{24h\text{-}3m}$ Pi pool. This study confirmed that changes in soil Pi forms are strongly influenced by interactions between plant species and soil P and C status.

Key Words

Exchangeable inorganic P pools, soil carbon, inorganic P, organic P, nitrogen, mineralisation

Introduction

Silvopastoral systems are a combination of forestry and agriculture with widely spaced trees that enable livestock grazing. It is practiced to achieve production objectives that would not be possible with only one of the contributing species. In New Zealand silvopastoral systems the main tree grown is radiata pine (*Pinus radiata*), with an understorey of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). Pasture production is phosphorus (P) limited in many hill country areas of New Zealand and it is generally uneconomic to apply sufficient fertiliser to remove this P limitation. It is important to elucidate the effect of land use on soil properties with the aim to increase production within fertility constraints.

Condron and Goh (1989) showed that concentrations of organic P (Po) in topsoil increased following the establishment of improved pasture. While, further New Zealand studies have shown that concentrations of organic C and P were significantly lower in mineral soil under plantation forest compared with adjacent grassland (Chen *et al*., 2000). Increased availability of nitrogen (N) can enhance P availability (Zou *et al*., 1995). Furthermore, a clear dependence of soil organic P forms on organic C exists (Tiessen *et al*., 1984). Thus, the effect on P availability in a soil with varying C content and the presence of a N fixing understorey may affect P availability. We (Scott and Condron 2004) reported on Po mineralisation in soils with a range in organic C and total P (TP) concentrations under radiata pine and selected understorey forage species. We found that the specific mineralization rate (SMR - net mineralisation rate i.e. gross mineralisation less microbial and geochemical uptake) and water soluble organic C (WSOC - is an indicator of root exudation and provides, by inference, the contribution of phosphatase enzymes, organic acids and other C compounds that might be available for microbial activity and Po mineralization) were correlated with plant P uptake. We also found radiata pine alone had the highest SMR, with radiata pine grown with lucerne (*Medicago sativa*) having a similar SMR and lucerne and ryegrass the lowest SMR. However, radiata pine plus lucerne produced the greatest biomass and along with trees alone had the greatest P uptake. P uptake under radiata pine plus lucerne was consistently high across all four soils regardless of Pi and Po availability. Consequently, an independent inorganic P dynamic was contributing to this high and consistent P uptake across all soils.

The plant availability of soil P can be characterised by considering the amount of soil solid phase P which could be taken up by a crop (quantity factor), the concentration of phosphate ions in the soil solution (intensity factor), and the ability of a soil to maintain soil solution P concentration (capacity factor) (Frossard and Sinaj 1997). Isotopically exchangeable Pi is the main source of P for most agricultural plants. Isotopic exchange kinetics (IEK) provides a method that incorporates parameters that describe the capacity and intensity factors enabling the effect of time on Pi exchange to be described. Fardeau (1985) developed an IEK model that enables the quantity of soil exchangeable Pi over specified time periods to be determined. Consequently, we determined the IEK of three treatments, radiata pine, radiata pine grown with lucerne, and lucerne alone.

We earlier (Scott and Condron, 2004) hypothesized that the effect of conifers and understorey forage species on soil P form and availability is influenced by soil conditions (organic C, and Pi and Po concentration), which, in turn, are determined by land use history. Here we extend our earlier reported work on short term effects of radiata pine and selected pasture species on soil organic phosphorus mineralisation by reporting on the transformation of isotopically exchangeable Pi pools under radiata pine and lucerne grown in 4 combinations of high and low C and P.

Methods

Scott and Condron (2004) explained experimental details and analyses methods other than IEK. Nevertheless, briefly, radiata pine and lucerne seedlings were grown individually and in combination in 4 examples of a Templeton silt loam soil (Immature Pallic Soils (Hewitt, 1998), USDA Udic Haplustepts) containing the 4 combinations of high and low C and P for 36 weeks. The chemical, physical, and P status of the four soils are shown in Table 1. For comparison between soils, L_PL_C will be referred to as the low P low C soil, L_PH_C low P high C, H_PH_C high P high C and H_PL_C as high P low C. An equal amount of soil for each treatment (100 g) was placed in containers. Four replicates of 3 treatments imposed on each soil are reported here. Radiata pine trees only (T), trees and lucerne grown together (T+L), lucerne grown alone (L). After planting, the pots were placed on a capillary mat in a glasshouse in a split plot randomised block design. During the experiment, lucerne was sequentially harvested at growth stages suitable for grazing.

Isotopically exchangeable P

Isotopic exchange kinetic parameters and Pi pools were determined for tree and lucerne combinations following the method described by Fardeau *et al.* (1985) and Frossard and Sinaj (1997).

After the addition of carrier-free ^{33}P to a soil-water suspension at steady state, the radioactivity decreases with time (Fardeau *et al.*, 1985; Frossard and Sinaj, 1997) such that:

$$r_{(t)}/R = \{r_{(1)}/R\} * \{t + [r_{(1)}/R]^{1/n}\}^{-n} + r_{(\infty)}/R \qquad (1)$$

Where R is the total introduced radioactivity (MBq); $r_{(1)}$ and $r_{(\infty)}$ are respectively the radioactivity remaining in the solution after 1 minute and infinity, and *n* is a parameter representing the disappearance rate of the tracer from the solution after one minute. The parameter, *n*, is the slope of the linear regression between log $[r_{(t)}/R]$ and log(t). The maximum dilution of ^{33}P, $r_{(\infty)}/R$, is estimated by the water soluble P (C_P) to total soil inorganic P (P_T) ratio :

$$r_{(\infty)}/R = 10 * C_P/P_T \qquad (2)$$

An isotope exchange experimental procedure involves a 1:10 soil:solution ratio therefore $10{*}C_P$ is equivalent to the water soluble P in the soil.

Isotopically exchangeable P at time t ($E_{(t)}$) can be calculated assuming:

(i) $^{31}PO_4$ and $^{33}PO_4$ ions have the same fate in the system and

(ii) whatever the time, t, the specific activity of the phosphate ions in the soil solution is equivalent to the isotopically exchanged ions in the whole system.

R/r_1 is the ratio of total introduced radioactivity to radioactivity remaining in solution after 1 minute. It is considered an estimate of the P sorbing capacity of the soil (Frossard and Sinaj 1997).

Three factors can be used to characterise Pi availability in soil. Firstly, the intensity factor represented by P concentration in the soil solution (C_P), Secondly, the quantity factor can be explained by the P content of the pool of free ions (E_{1min}) and the quantity of isotopically exchangeable P ($E_{(t)}$). Thirdly, the capacity factor which represents the soils fixation capacity can be described by R/r_1 and *n*.

The quantities of P calculated in the pools of Fardeau *et al.* (1993) multicompartmental model are:

(i) *The pool of free ions (E_{1min})*

The phosphate in this pool is immediately available for plant uptake. The P ions are in the soil solution or if adsorbed, have the same kinetic properties as those in solution. Exchange between other pools is possible.

(ii) *P exchangeable between 1 minute and 24 hours ($E_{1min\text{-}24h}$)*

This pool represents P which can be exchanged during the time of active P uptake by a single root or root hair.

(iii) *P exchangeable between 24 hours and 3 months ($E_{24h\text{-}3m}$)*

This pool represents P which can be exchanged during the time of active P uptake by the entire root system of an annual crop.

(iv) *P exchangeable between 3 months and a year ($E_{3m\text{-}1yr}$)*

This pool represents the P which can be exchanged after the main period of active P uptake of an annual crop until the end of the agricultural year.

(v) *P which cannot be exchanged within a year ($E_{>1yr}$)*

This pool is determined as the difference between total inorganic P and the sum of the other exchangeable pools described above. The total inorganic P used was determined by the difference between total P determined by digestion and organic P.

Statistical analysis

A split plot analysis of variance was performed using Genstat 5th edition release 4·2 for Windows™ (VSN International Ltd, Oxford, UK) and an unrestricted least significant difference (LSD, P = 0.05) was determined to compare treatment means.

Results

Table 1. Chemical and physical properties determined for the soils prior to planting.

Soil	depth (cm)	pH	C %	N %	C/N	TP µg g^{-1}	Clay <2µm	Silt 2-63µm	Sand >63µm
							-----	% volume	-----
L_PL_C	15-20	5·3	2·5	0·21	12	320	18	54	28
L_PH_C	1-5	5·2	5·1	0·40	13	524	12	47	40
H_PH_C	1-5	6·0	4·0	0·34	12	768	18	66	16
H_PL_C	0-5	6·2	2·4	0·20	12	721	13	50	36

Table 2. Isotopic exchange kinetic parameters and Pi pools determined for the soils prior to planting.

Soil	Cp (mg L^{-1})	R/r$_1$	*n*	E_{1min}	$E_{1min\text{-}24h}$	$E_{24h\text{-}3m}$	$E_{3m\text{-}1yr}$	$E_{>1yr}$	Inorganic P	Organic P
				-----	-----	-----	(µg g^{-1})	-----	-----	-----
L_PL_C	0·05	1·95	0·41	1·0	18·1	49·4	17·5	49·2	135	185
L_PH_C	0·29	1·41	0·32	4·0	30·9	61·2	23·4	92·3	212	312
H_PH_C	0·26	2·07	0·33	5·3	44·7	93·5	36·2	137·9	318	450
H_PL_C	0·16	2·15	0·32	3·5	29·7	75·1	36·4	206·0	351	370

Table 3. Effects of plant treatments and soils on differences in IEK parameters Cp, R/r$_1$ and *n* and Pi pools (µg P g^{-1} - E_{1min}, $E_{1min\text{-}24h}$, $E_{24h\text{-}3m}$, $E_{3m\text{-}1yr}$, $E_{>1yr}$) calculated between the original soils and soils after 36 weeks growth.

Soil	Cp (mg L^{-1})			R/r$_1$			*n*		
	T	**T+L**	**L**	**T**	**T+L**	**L**	**T**	**T+L**	**L**
L_PL_C	0·003	-0·019	-0·007	0·61	0·76	-0·07	0·028	0·055	0·025
L_PH_C	-0·152	-0·155	-0·119	0·31	0·16	0·07	0·062	0·082	0·050
H_PH_C	-0·128	-0·109	-0·099	0·26	-0·07	-0·03	0·065	0·092	0·057
H_PL_C	-0·026	-0·072	-0·083	0·33	-0·18	0·21	0·018	0·089	0·101
LSD	*0·033*			*0·37*			*0·062*		
cf≡soil	*0·034*			*0·33*			*0·052*		

Soil	E_{1min}			$E_{1min-24h}$			E_{24h-3m}			E_{3m-1yr}			$E_{>1yr}$		
	T	**T+L**	**L**	**T**	**T+L**	**L**	**T**	**T+L**	**L**	**T**	**T+L**	**L**	**T**	**T+L**	**L**
L_PL_C	0·2	-0·1	-0·2	7·1	5·6	-0·4	-10·3	-2·9	-9·7	-8·5	-6·2	-5·9	-18·9	-27·4	-22·1
L_PH_C	-1·7	-2·0	-1·5	-1·8	-0·9	-2·4	-9·8	-7·8	-7·7	-8·2	-8·5	-5·6	-44·8	-49·4	-22·8
H_PH_C	-2·2	-2·3	-1·9	-0·6	5·7	-1·9	11·0	20·7	1·3	-0·4	-2·3	-4·8	-43·0	-67·2	-53·7
H_PL_C	-0·1	-1·7	-1·6	3·6	2·0	5·2	7·6	18·0	24·3	-0·6	-0·8	0·02	-43·6	-87·8	-109·8
LSD	*0·6*			*8·2*			*19·3*			*6·8*			*40·1*		
cf≡soil	*0·6*			*9·0*			*16·5*			*6·1*			*37·8*		

cf≡soil indicates the LSD (P=0.05) for comparing treatment means for the same soil.

A significant redistribution of P from less exchangeable to more exchangeable fractions and IEK pools occurred.

Conclusion

IEK analysis revealed that trees and lucerne combined produced a greater decline in recalcitrant forms of Pi ($E_{>3m}$ pool) pool than when they were grown alone (except in the high P, low C soil (H_PL_C)). In the high P, low C soil (H_PL_C), the effect of trees and lucerne combined on $E_{>3m}$ was intermediate between the effect determined for trees and lucerne alone. The enhanced depletion of recalcitrant Pi under trees and lucerne may be related to increased N availability.

There was strong evidence of significant redistribution of P from less exchangeable to more readily exchangeable IEK pools. When P and C were very low (L_PL_C), trees and lucerne were able to actively deplete all pools and when lucerne was combined with the trees such depletion was enhanced further in the $E_{>1yr}$ pool. The redistributed P in the low P soils (L_PL_C, L_PH_C) appeared to be taken up by plants, whereas in the high P soils (H_PH_C, H_PL_C) the trees, trees with lucerne and lucerne alone increased the available E_{24h-3m} Pi pool.

In conjunction with the work by Scott and Condron (2004) it appeared that radiata pine was better able to utilize all forms of P when soil P and C status were low, but not in the low P, high C soil. Because the low C soils showed greater SMR and lower resin Po than the high C soils this suggests a degree of protection afforded Po by the high C, well structured soils and the possible influence of different C forms. The findings of this study confirm that changes in soil P forms are strongly influenced by interactions between plant species and soil P and C status.

References

Chen CR, Condron LM, Davis MR, Sherlock RR (2000) Effects of afforestation on phosphorus dynamics and biological properties in a New Zealand grassland soil. *Plant Soil* **220**, 151-163.

Condron L M and Goh K M 1989 Effects of long-term phosphatic fertilizer applications on amounts and forms of phosphorus in soils under irrigated pasture in New Zealand. J. Soil Sci. 40, 383-395.

Fardeau JC, Morel C, Jappé J (1985) Cinétigue d'échange des ions phosphate dans les systémes sol: solution. Vérification experimentale de l'équation theorique. Paris: C.R. Seances Academy Sciences. T. 300, III 8, 371-376.

Fardeau JC, Morel C, Oberson A (1993) Phosphore, matiére organiqueset eutrophisation des écosystems. In Decroux J. and Ignazi J.C. Eds., Matiéres Organiques et Agricultures. BLOIS, France: NDT.

Frossard E, Sinaj S (1997) The isotopic exchange technique: A method to describe the availability of inorganic nutrients. Applications to K, PO_4, SO_4 and Zn. *Isotopes in Environmental and Health Studies* **33**, 61-77.

Scott JT, Condron LM (2004) Short term effects of radiata pine and selected pasture species on soil organic phosphorus mineralisation. *Plant and Soil* **266**, 153-163.

Tiessen H, Stewart J W B and Cole C V 1984 Pathways of phosphorus transformations in soils of differing pedogenesis. *Soil Science* **48**, 853-858.

Zou X, Binkley D, Caldwell BA (1995) Effects of dinitrogen-fixing trees on phosphorus biogeochemical cycling in contrasting forests. *Soil Science* **59**, 1452-1458.