Agriculture, Ecosystems and Environment 239 (2017) 228–235

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Accumulation and distribution of phosphorus in the soil profile under fertilized grazed pasture

Jihui Tian[a,b,*], Gustavo Boitt[c], Amanda Black[d], Steven Wakelin[e,f], Leo M. Condron[c], Lijun Chen[a]

[a] Institute of Applied Ecology, Chinese Academy of Sciences, P.O. Box 417, Shenyang 11016, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Faculty of Agriculture and Life Sciences, Lincoln University, P.O. Box 85084, Lincoln, 7647, Christchurch, New Zealand
[d] Bio-Protection Research Centre, Lincoln University, P.O. Box 85084, Lincoln, 7647, Christchurch, New Zealand
[e] AgResearch, Lincoln Science Centre, Private Bag 4749, Christchurch 8140, New Zealand
[f] Scion Research, P.O. Box 29237, Christchurch 8540, New Zealand

ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 16 January 2017
Accepted 19 January 2017
Available online 30 January 2017

Keywords:
Leaching
Phosphorus transfer
Long-term fertilization
Winchmore
Soil phosphorus fractionation

ABSTRACT

The fate of phosphorus originating from long-term fertilizer inputs in the soil profile is of great agronomic and environmental concern but remains poorly understood. Sequential fractionation was used to investigate accumulation and distribution of phosphorus in the soil profile to 100 cm (0–7.5, 7.5–15, 15–25, 25–50, 50–75, 75–100 cm) under fertilized and grazed pasture. The trial site had received annual superphosphate fertilizer inputs at different rates (0, 188 and 376 kg superphosphate ha^{-1} $year^{-1}$; control, 188PA and 376PA, respectively) for 57 years. While there was significant accumulation of total phosphorus in the topsoil (0–7.5 cm), no corresponding differences were observed in organic or residual (non-extracted) phosphorus between treatments. However, fractionation data showed that inorganic forms of phosphorus were significantly higher in the 376PA treatment for all soil depths to 50 cm compared with the other treatments. Furthermore, the relative magnitude and significance of differences between the 376PA and other treatments in soil to 50 cm were greater for readily-soluble inorganic phosphorus ($NaHCO_3$ and NaOH I extractable) compared with more recalcitrant inorganic phosphorus (HCl and NaOH II extractable). As such, phosphorus applied in excess of agronomic requirements and soil retention capacity was transferred below the topsoil and root zone by leacing, and most of the transfer of phosphorus was in readily-soluble inorganic forms. This presents an enhanced risk of elevated phosphorus transfer to groundwater with associated adverse impacts on water quality under fertilized and irrigated pastures. Our findings highlight the need to carefully assess and manage fertilizer phosphorus inputs in accordance with agronomic demand and soil retention capacity to minimize downward phosphorus movement and phosphorus transfer to water bodies.

1. Introduction

Phosphorus is one of the major limiting nutrients for plant growth in many agroecosystems, and continuous application of phosphatic fertilizer is required to support agricultural production (Raghothama, 2005). In intensively managed agroecosystems, continuous inputs of phosphatic fertilizer can result in considerable accumulation of phosphorus in the topsoil, posing a long-term environmental hazard of diffuse phosphorus transfer via subsurface flow (leaching) (Frossard et al., 2000; Gburek et al., 2005; Haygarth et al., 2013). Apart from the environmental hazard associated with accelerated phosphorus transfer, the excessive accumulation of phosphorus in the topsoil represents an inefficient use of a finite resource (Schröder et al., 2011). Accordingly, effective management strategies to maintain economically viable levels of production with minimum risk of phosphorus transfer are needed. These will depend not only on the agronomic demand and application rates of fertilizer, but also the patterns of phosphorus accumulation and distribution in the soil profile.

Historically, many investigations have focused on the chemical nature and dynamics of phosphorus in the surface or near surface horizons (Gburek et al., 2005). In contrast, there has been far less

---

* Corresponding author at: Institute of Applied Ecology, Chinese Academy of Sciences, P.O. Box 417, Shenyang 11016, China.
E-mail address: jhtianchina@gmail.com (J. Tian).

http://dx.doi.org/10.1016/j.agee.2017.01.022
0167-8809/

research effort focused towards investigating subsurface accumulation and distribution of phosphorus, due to the general assumption that vertical phosphorus transfer through the soil profile is relatively insignificant as a result of the capacity of most subsoil to fix phosphorus (Gburek et al., 2005). Recent field studies, however, are indicating that phosphorus transfer via subsurface flow (leaching) may be important in circumstances where continuous phosphorus inputs in excess of plant requirements have led to an accumulation of phosphorus, and the risk elevated in soils with a low phosphorus retention capacity or saturation of phosphorus sorption sites (Sims et al., 1998; Szogi et al., 2012). The potential environmental hazard of subsurface phosphorus transfer depends on several factors among which are the application rates of fertilizer and the mobility of bioavailable phosphorus. The potential mobility of phosphorus is controlled by its chemical form, suggesting that it is desirable to determine the amounts and forms of phosphorus in a soil profile rather than in a surface layer.

Pastoral agriculture is the predominant form of land use in New Zealand, and the continuous application of phosphatic fertilizer has been an important factor in the development and expansion of pastoral farming for a long time (Condron, 1986). For example in the Canterbury region, there is approximately 200,000 ha of grazed pasture that are extensively fertilized (Toor et al., 2004). Much of this pastoral farming, particularly in the South Island lowlands, has occurred on stony alluvial soils that are extensively irrigated (Carrick et al., 2013). It is recognized that many of these irrigated, stony soils have a high vulnerability to phosphorus leaching i.e., low phosphorus retention capacity, rapid permeability and low water holding capacity (Carrick et al., 2013). In the absence of direct field measurement, many studies have used a mass balance approach to account for phosphorus transfer within the soil-plant-water system. For instance, both Nguyen and Goh (1992) and Williams and Haynes (1992) indicated that an unknown quantity of phosphorus was being lost via outwash and phosphorus leaching. Furthermore, the unaccounted (or lost) phosphorus was markedly greater in the high phosphorus fertilization treatment compared with the lower one (Nguyen and Goh, 1992). However, while a mass balance approach may infer fertilizer efficiency and potential phosphorus transfer within the systems, it does not give any insight into the forms of phosphorus in soils. For example, which forms of phosphorus are most readily transferred via subsurface flow (leaching) in heavily fertilized soil, and how these forms are distributed in the soil profile?

Many studies have also investigated the amounts and forms of phosphorus leaching using intact lysimeters in the fertilized and irrigated pasture. For instance, both Toor et al. (2003) and Toor et al. (2005) suggested greater proportion of phosphorus transferred through the soil profile was present in unreactive phosphorus forms (mainly as organic phosphorus; 84–89%) compared with the reactive phosphorus forms (mainly as inorganic phosphorus; 11–16%), due to the greater mobility of unreactive phosphorus as monoesters and diesters. In comparison, reactive phosphorus (mainly as inorganic phosphorus) could also be susceptible to leaching in circumstances where the phosphorus sorption capacity is relatively more saturated (Siemens et al., 2004). Nevertheless, data from short-term lysimeter experiments can't reveal the in situ distribution and potential transfer of phosphorus in the soil profile, particularly in sites where fertilizer and irrigation have been applied for long periods. Therefore, data on soil phosphorus accumulation and distribution in the soil profile may shed light on the patterns of potential phosphorus transfer through soil and, on the effective management of long-term applications of fertilizer with minimum phosphorus losses in the intensively managed agroecosystems.

The objective of this study was therefore to assess the accumulation, distribution and potential leaching (as indicated by the degree of phosphorus saturation) of phosphorus in the soil profile subject to long-term application of phosphatic fertilizer. It was hypothesized that the continuous inputs of phosphatic fertilizer would have resulted in significant accumulation of phosphorus in the soil profile, and that the potential of phosphorus transfer via leaching would thereby be enhanced.

2. Materials and methods

2.1. Study site and experimental design

The long-term fertilizer trial is located on the Winchmore Irrigation Research Station (171° 48′ E, 43° 47′ S) in Canterbury, New Zealand. The soil is classified as a shallow, free-draining Lismore-series stony silt loam (Orthic Brown, New Zealand; Typic Dystrustept, USDA; Endoskeletic Cambisol, IUSS Working Group, 2006), formed from moderately weathered greywacke loess over gravels. The A horizon is approximately 180 mm deep with an average stone concentration of 5 g kg^{-1}; the total soil depth varied between 300 and 400 mm (Schipper et al., 2013).

The trial, initiated in 1952, was designed to investigate effects of different rates of superphosphate applications on pasture production. Full details of the trial history and establishment have been reported in Rickard and Moss (2012). The trial has four replicates of five treatments arranged in separately fenced and irrigated 0.09 ha plots (borders) in a randomized complete block design. The treatments selected for this study were the nil fertilizer (control), 188 kg superphosphate ha^{-1} $year^{-1}$ (188PA), and 376 kg superphosphate ha^{-1} $year^{-1}$ (376PA). All treatment plots received rainfall (740 mm) plus an average of 4.3 flood irrigation events (100 mm) per year (total c. 1150 mm $year^{-1}$). Lime was applied at establishment (5 t ha^{-1}), and again in 1972 (4.4 t ha^{-1}), to maintain soil pH above 6. Each treatment was rotationally-grazed by a separate flock of sheep to avoid nutrient transfer between treatments. Stocking rates were designed and adjusted to maintain the optimal pasture utilization.

2.2. Soil sampling

Soil samples were collected in April 2009, 57 years after the treatments were applied. Conventional sampling using a soil corer was not practicable due to the stony nature of the soil. As such, pits at the same relative locations within each plot, and approximately 1 m wide by 2 m long, were excavated to a depth of 1.5 m using a mechanical backhoe. Along each pit profile, soils and stones were collected from six depth-intervals (0–7.5, 7.5-15, 15–25, 25–50, 50–75 and 75–100 cm) using a $40 \times 40 \times 25$ cm^3 (0.04 m^3) steel frame. Samples were separated into soils and stones by sieving from 10 cm to 2 mm, and the two fractions weighted. The determined quantity of soil was used to calculate the amounts of phosphorus for each depth increment, and also the total soil profile phosphorus. Sub-samples, excluding stones, were taken from each depth increment for analysis, and the remainder was returned to the pit before refilling.

2.3. Soil phosphorus fractionation and soil property analysis

Soil phosphorus fractionation was carried out according the scheme described by Condron et al. (1996). Forms of inorganic phosphorus (P_i) and organic phosphorus (P_o) were determined by sequential extraction of 0.5 g samples of soil (<2 mm). The extractions used 1 M ammonium chloride (NH_4Cl, discarded-this step is essential to remove exchangeable cations that may affect the subsequent solubility of soil phosphorus (Condron and Newman, 2011)), 0.5 M sodium bicarbonate (pH 8.5; $NaHCO_3$-P_i, $NaHCO_3$-P_o), 0.1 M sodium hydroxide (NaOH I-P_i, NaOH I-P_o), 1 M