Geoderma 332 (2018) 45–59

Contents lists available at ScienceDirect

Geoderma

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

Does soil erosion rejuvenate the soil phosphorus inventory?

Andre Eger[a,*], Kyungsoo Yoo[b], Peter C. Almond[c], Gustavo Boitt[c], Isaac J. Larsen[d], Leo M. Condron[c], Xiang Wang[b], Simon M. Mudd[e]

[a] Landcare Research, Department Soil and Landscapes, Gerald St, Lincoln 7608, New Zealand
[b] University of Minnesota, Department of Soil, Water, and Climate, 439 Borlaug Hall, 1991 Upper Buford Circle, St. Paul, MN 55108-6028, USA
[c] Lincoln University, Department of Soil and Physical Sciences, PO Box 85084, Lincoln 7647, New Zealand
[d] University of Massachusetts, Department of Geosciences, 627 North Pleasant Street, 233 Morrill Science Center, Amherst, MA 01003-9297, USA
[e] University of Edinburgh, School of GeoSciences, Geography Building, Drummond Street, Edinburgh EH8 9XP, UK

ARTICLE INFO

Handling Editor: M. Vepraskas

Keywords:
Soil phosphorus
Phosphorus fractionation
Soil residence time
Soil age
Soil erosion
Hillslopes
Soil chronosequences
Soil parent material

ABSTRACT

Phosphorus (P) is an essential nutrient for life. Deficits in soil P reduce primary production and alter biodiversity. A soil P paradigm based on studies of soils that form on flat topography, where erosion rates are minimal, indicates P is supplied to soil mainly as apatite from the underlying parent material and over time is lost via weathering or transformed into labile and less-bioavailable secondary forms. However, little is systematically known about P transformation and bioavailability on eroding hillslopes, which make up the majority of Earth's surface. By linking soil residence time to P fractions in soils and parent material, we show that the traditional concept of P transformation as a function of time has limited applicability to hillslope soils of the western Southern Alps (New Zealand) and Northern Sierra Nevada (USA). Instead, the P inventory of eroding soils at these sites is dominated by secondary P forms across a range of soil residence times, an observation consistent with previously published soil P data. The findings for hillslope soils contrast with those from minimally eroding soils used in chronosequence studies, where the soil P paradigm originated, because chronosequences are often located on landforms where parent materials are less chemically altered and therefore richer in apatite P compared to soils on hillslopes, which are generally underlain by pre-weathered parent material (e.g., saprolite). The geomorphic history of the soil parent material is the likely cause of soil P inventory differences for eroding hillslope soils versus geomorphically stable chronosequence soils. Additionally, plants and dust seem to play an important role in vertically redistributing P in hillslope soils. Given the dominance of secondary soil P in hillslope soils, limits to ecosystem development caused by an undersupply of bio-available P may be more relevant to hillslopes than previously thought.

1. Introduction

Phosphorus (P) is an essential element for all life on Earth through its role in forming ATP and as a structural component of DNA (Nelson et al., 2008). Consequently, the P cycle in terrestrial and marine environments has been studied extensively (Filippelli, 2002; Paytan and McLaughlin, 2007; Turner and Condron, 2013; Walker and Syers, 1976). Ecological research has shown that P fertility of terrestrial ecosystems is strongly linked to the weathering trajectory of soils with time: on geomorphically stable landforms, increasingly chemically altered soils lead to a declining pool of plant-available P, which can cause a decline of primary production and biomass, and strongly influence species and functional diversity (Crews et al., 1995; Eger et al., 2013b; Peltzer et al., 2010; Zemunik et al., 2015). The depletion of plant-available P, however, is not simply a result of P weathering loss but also due to intensive biochemical transformations and recycling (Frossard et al., 2000).

Our current understanding of long-term P transformations is largely based on soil chronosequence studies; a study concept that takes advantage of a set of landforms that formed at different but known times in the past that have been minimally rejuvenated by erosion or deposition. In this framework, all other soil forming factors since cessation of erosion or deposition are assumed to have been similar between sites, allowing for isolation of the influence of time on soil development. Synthesising multiple soil chronosequences in New Zealand, Walker and Syers (1976) established the seminal soil P development concept: with increasing time, bio-available P declines as a result of leaching and the transformation of primary, rock-derived apatite P into less directly bio-available P forms such as organic P and P adsorbed to or occluded into secondary oxides. Whereas apatite P can be made directly bio-

* Corresponding author.
E-mail address: egera@landcareresearch.co.nz (A. Eger).

https://doi.org/10.1016/j.geoderma.2018.06.021
Received 27 November 2017; Received in revised form 20 April 2018; Accepted 25 June 2018

available as PO_4^{3-} through mineral dissolution in an acidic soil environment, the physically occluded P fraction, in particular, comprises P forms that are highly stabilized (Smeck, 1985) and hence not readily accessible by biota as a result of physical protection in mineral structures (primary or secondary silicate minerals, oxides, oxyhydroxides), organic matter and soil micro-aggregates (Blake et al., 2003; Guo and Yost, 1998). The Walker and Syers paradigm of P development has been found to be generally valid for a range of soils in different climatic and lithologic settings (Crews et al., 1995; Eger et al., 2011; Selmants and Hart, 2010; Turner and Laliberté, 2015).

However, the nominally non-eroding setting of a chronosequence is a special case, as most of Earth's surface undergoes either net erosion (Larsen et al., 2014b) or deposition. Hillslopes are predominantly erosional landforms, where gravity and physical disturbances facilitated by water or bioturbation drive the downslope movement of soil, which is then delivered to fluvial systems or deposited on convergent sections of slopes or at slope-valley transitions. As mass is physically and chemically lost from a soil profile on an eroding hillslope, soil cover is maintained over time by the counterbalancing process of soil production (Gilbert, 1877; Heimsath et al., 1997), the conversion of parent material to soil. Soil production is regarded as a natural rejuvenator of soil nutrients by the replacement of weathered, nutrient-poor material with unweathered substrate (Amundson et al., 2015; Porder and Hilley, 2011; Porder et al., 2007b; Vitousek et al., 2003). The 'fertilisation' through soil production on slopes could be especially significant for soil P because in most terrestrial settings P is supplied to the biogeochemical cycle by weathering of the P-bearing mineral apatite and hence is delivered to the base of the soil by the parent material, unless there are external sources of P, such as atmospheric input. Dust has a major impact on soil P budgets in sufficiently P-depleted soils and/or where dust deposition rates are high (e.g., Chadwick et al., 1999; Eger et al., 2013a). Atmospheric input may even play an important role in P cycling at younger stages of ecosystem development in some locations (Arvin et al., 2017; Boyle et al., 2013).

The role of hillslope topography and soil erosion processes need to be considered when evaluating soil P pools and fractionation as it will affect the time soil material is residing on the slope before removal by chemical or physical processes (Agbenin and Tiessen, 1994; Amundson et al., 2015; Porder and Hilley, 2011; Porder et al., 2007b; Vitousek et al., 2003). For example, in Hawaii lower proportions of occluded P but more organic P were found on a hillslope in comparison to the geomorphically stable shield surface, indicating rejuvenation via slope dynamics (erosion and deposition) (Vitousek et al., 2003). However, no clear trends of P fractionation existed across the hillslope itself, from the shoulder (younger soils) to the toeslope (older soils). P fractionation data from ridge-slope-valley transects in Puerto Rico demonstrated the dominant control on the spatial distribution of more labile P forms was topography; labile P was lowest on the ridge and generally increased downslope toward the valley (Mage and Porder, 2013). In contrast, parent material was the main control on occluded and total P, with the highest values in the valleys, and apatite P (< 5% of total P in all soils) was unrelated to either topography or parent material (Mage and Porder, 2013). Selected soil P fractions (total P, apatite P, labile P and occluded P at 0–20 cm depth) on ridgetops in Puerto Rico were not significantly controlled by erosion rates or soil residence time, however, erosion rates and residence times varied little between sites (McClintock et al., 2015). Data from slope transects in Brazil showed that young upper slope soils (Entisols) have higher apatite P and lower labile P concentrations than Inceptisols in mid and lower slope positions (Agbenin and Tiessen, 1994). Differences in relative soil residence times induced by erosion were deemed the likely reason for the behaviour of apatite P. With only the study from Brazil adhering to the P-development concept derived from chronosequences, the relationship between P fractions and the relative soil age on slopes is less clear.

The divergence in P fractionation on eroding slopes relative to what is predicted from chronosequence studies highlights the need to reconcile the apparently different behaviour of P observed in different topographic settings. We suggest that comparing these findings in the context of soil P evolution as proposed by Walker and Syers (1976) is the most promising approach. Amundson et al. (2015) proposed a unifying concept in which temporal shifts from N to P nutrient limitation in terrestrial ecosystems are related to the continuum of residence times of minerals within the soil. The concept of Amundson et al. (2015) builds on new appreciation of tectonic uplift as a driver of erosion and thus P supply in the otherwise P-depleted tropical soils (Porder et al., 2007b). Uplift is typically associated with tectonic plate margins and a major control of erosion rates that are inversely related to soil residence times. Soil residence time in these studies is defined as the length of time that is required for soil material to be removed by erosion and replaced by soil production, and during which soil particles experience physical and biogeochemical conditions at the top of the weathering profile (Almond et al., 2007; Dere et al., 2013; McClintock et al., 2015). Compared to chronosequences developed in flat landforms, Amundson et al. (2015) suggested that residence times for most hillslope soils in temperate climates give rise to neither N nor P limitation. In other words, soils on eroding hillslopes are not too young to have N limitation or too old to be depleted in mineral P.

Whether eroding hillslope soils indeed occupy an optimal residence time window with respect to P limitation remains to be tested. There are few data that directly link individual P fractions to absolute soil residence times (McClintock et al., 2015). Additionally, previous studies of soil P on eroding hillslopes are largely limited to tropical landscapes (Abekoe and Tiessen, 1998; Agbenin and Tiessen, 1994; Araújo et al., 2004; Mage and Porder, 2013; McClintock et al., 2015; Porder and Hilley, 2011; Porder et al., 2007b; Vitousek et al., 2003). In these actively eroding tropical systems, deep chemical alteration of bedrock causes soils to be depleted in apatite P, which provides the first indication that the optimal window hypothesis may not be applicable globally. However, the applicability of these studies from tropical landscapes to extra-tropical regions may also be limited. In contrast to temperate climate regions, in the tropics, deep and more completely weathered profiles prevail, mineralisation rates of organic matter are higher, low-reactivity clays and pedogenic oxide/hydroxides increasingly dominate the residual soils, and the legacy of glacial/periglacial conditions during the Pleistocene is largely absent.

Here we present new P fractionation data quantitatively linked to hillslope soil residence times across two gradients of erosion rates in temperate ecosystems and compare them to published results regarding patterns and rates of P transformation. We initially hypothesised, based on the proposal by Amundson et al. (2015), that higher soil production and erosion rates and hence shorter residence times result in high total soil P concentrations and high proportions of primary mineral P as expected for immature soils, whereas lower erosion rates and longer residence times result in low total soil P due to the intensive weathering of older soil particles, and a high proportion of secondary P forms as expected in more mature soils. However, our data do not support this hypothesis and instead, somewhat distinct from the conceptual framework laid out in Walker and Syers (1976), highlight the significance of weathering below the base of the soil in temperate climates, biological uptake of P and potential dust accretion.

2. Methods

2.1. *Definition of mean soil particle age, residence time, turnover time and comparison with soil age*

We first require a consistent framework for the measure of time for our soils. As we will show, soil residence time and soil age provide consistent temporal references to which soil P dynamics from geomorphically active and stable landscapes can be compared. We conceptualize that the mass balance of a hillslope soil (Fig. 1) is largely determined by the difference between the mass losses via physical and