Science of the Total Environment 521–522 (2015) 326–335

Contents lists available at ScienceDirect

Science of the Total Environment

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

The geochemical transformation of soils by agriculture and its dependence on soil erosion: An application of the geochemical mass balance approach

Kyungsoo Yoo [a],*, Beth Fisher [a], Junling Ji [b], Anthony Aufdenkampe [c], Jonatan Klaminder [d]

[a] University of Minnesota, Dept. of Soil, Water, and Climate, 430 Borlaug Hall, 1991 Upper Buford Circle, St. Paul, MN 55108, United States
[b] University of Delaware, Department of Plant and Soil Sciences, 531 S College Ave. 152 Townsend Hall, Newark, DE 19716-2170, United States
[c] Stroud Water Research Center, 970 Spencer Road, Avondale, PA 19311, United States
[d] Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, SE-90187 Umeå, Sweden

HIGHLIGHTS

- Liming has resulted in soils enriched in Ca relative to their parent materials.
- Fertilization resulted in soils enriched in P relative to their parent materials.
- Agricultural Pb input produced Pb-enriched soils.
- Soil erosion affects enrichments of agriculturally added elements in soils.

ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form 19 March 2015
Accepted 20 March 2015
Available online xxxx

Editor: Charlotte Poschenrieder

Keywords:
Geochemical mass balance
Soil erosion
Anthropocene
Liming
Fertilizer
Chemical weathering
Phosphorous
Calcium

ABSTRACT

Agricultural activities alter elemental budgets of soils and thus their long-term geochemical development and suitability for food production. This study examined the utility of a geochemical mass balance approach that has been frequently used for understanding geochemical aspect of soil formation, but has not previously been applied to agricultural settings. Protected forest served as a reference to quantify the cumulative fluxes of Ca, P, K, and Pb at a nearby tilled crop land. This comparison was made at two sites with contrasting erosional environments: relatively flat Coastal Plain in Delaware vs. hilly Piedmont in Pennsylvania. Mass balance calculations suggested that liming not only replenished the Ca lost prior to agricultural practice but also added substantial surplus at both sites. At the relatively slowly eroding Coastal Plain site, the agricultural soil exhibited enrichment of P and less depletion of K, while both elements were depleted in the forest soil. At the rapidly eroding Piedmont site, erosion inhibited P enrichment. In similar, agricultural Pb contamination appeared to have resulted in Pb enrichment in the relatively slowly eroding Coastal Plain agricultural soil, while not in the rapidly eroding Piedmont soils. We conclude that agricultural practices transform soils into a new geochemical state where current levels of Ca, P, and Pb exceed those provided by the local soil minerals, but such impacts are significantly offset by soil erosion.

1. Introduction

Crop land and pasture together cover ~40% of our planet's land surface (Ramankutty et al., 2008). Agricultural activities promote accelerated nutrient loss as plant biomass is intensively harvested, but elements critical to soil biogeochemical function are also added via fertilizers and amendments. However, the degree that agricultural activities have collectively altered net elemental storage and composition in soil since the agricultural conversion of pre-existing lands is largely unknown, but yet of critical importance from agricultural, ecological, and environmental health perspectives (Richter and Markewitz, 2001).

On time scales that exceed agricultural history, elemental compositions of soils are controlled by pedogenic fluxes of mass addition, loss, transformation, and translocation (Simonson, 1959). Determining these fluxes in the context of soil formation is crucial when considering environmental controls on geochemical diversity of the land surface. One successful method to quantify elemental fluxes is the geochemical mass balance model, which requires normalizing elements of interest relative to a biogeochemically inert element (Amundson, 2004; Chadwick et al., 1999). While this approach can be useful in assessing

---

* Corresponding author.
E-mail address: kyoo@umn.edu (K. Yoo).

http://dx.doi.org/10.1016/j.scitotenv.2015.03.084
0048-9697/

time and management integrated impacts of agricultural soil elemental pools, this potential has not yet been explored.

Our primary goal in this study was to show the utility of the geochemical mass balance model in agricultural settings. We test a hypothesis that agricultural inputs of several key elements such as calcium (Ca), phosphorous (P), potassium (K), and lead (Pb) have replenished the losses of these elements via chemical weathering during pre-agricultural soil formation. The rationale for including a non-nutrient, Pb, in the analysis is that this element was a common contaminant in lead-containing fuel and pesticides before the 1990s (Robinson et al., 2007) and thus had the potential of being added in increased levels due to farming activities. To further assess the significance that soil erosion modifies agricultural soil geochemistry, we examined forest vs. agricultural soils in the flat Mid Atlantic Coastal Plain site with slow soil erosion rates and the hilly Piedmont site with high erosion rates.

2. Methods

2.1. Field sites

Crop and forest soils were compared on both sides of the Fall Line in Delaware and Pennsylvania (Fig. 1). The Fall Line has formed as the hard crystalline sedimentary bedrock in the Piedmont and the soft sediment in the Coastal Plain has different susceptibility to stream incision. The coastal site is located in Newark, Delaware (39°39′55 N 75°44′34 W) at the elevation of 38 m above sea level. The site has little topography and is within 1 km of the fall line (Fig. 1). The second site is a part of the Christina River Basin Critical Zone Observatory and is located in the Appalachian Piedmont in southeastern Pennsylvania (39°51′49″N and 75°46′50″W, 123 m above sea level), north of the Fall Line. The Piedmont site is situated in hilly, convex landscapes and is positioned within watersheds with a history of severe soil erosion (Walter and Merritts, 2008).

At the Coastal site, parent material includes stream deposits of fine and medium sands and gravels that were eroded from upstream Piedmont where our second site is located. The bedrock in the Piedmont erosional setting is largely metamorphosed sedimentary rocks such as gneiss, schist, quartzite, and marble (Woodruff and Thompson, 1972). Quartzite is the parent material at the Piedmont site. At both sites, XRD showed little difference in the mineral species and their abundances between the parent materials under the two different land uses (data not shown). The coastal site receives mean annual precipitation (MAP) of 1143 mm, and the mean annual temperature (MAT) is 12 °C (Office of Delaware State Climatologist, accessed 22 Feb., 2012). These climate records are similar to MAP of 1095 mm and MAT of 12 °C at our Piedmont site (Pennsylvania State Climatologist, accessed 27 April, 2014).

The two sites offer an opportunity to examine the agricultural impact on soil elemental budgets in eroding hilly Piedmont upland vs. relatively slowly-eroding Coastal Plain lands with similar climates. The sites also differ in their soil parent materials; stream sediment in the Coastal Plain vs. meta-sedimentary bedrock in the Piedmont site. Still the parent materials share similar mineralogy because the Coastal stream sediment parent material originated from the Piedmont. Information regarding crop rotations, farming practices, and fertilizer and amendment application rates at the study sites were acquired by personal communication with the farm managers. Below we provide a more detailed description of each site.

2.1.1. Coastal Plain site

We examined a forest soil and an agricultural soil that are about 300 m apart and underlain by visually identical stream deposits. The forest site has been protected as University of Delaware's ecological research forest. Most of the forest is ~150 year old second growth forest. The agricultural land is owned by the University of Delaware and has been annually tilled with chisel plow, subsoil shank three-point plow, offset disk, and field cultivator. Soil mixing induced by plowing is substantial at the site and the upper 30 cm of the soil is estimated to be completely mixed within a few decades (Yoo et al., 2011). During the four years prior to this study, the crops included soybeans, corns, potatoes, baby lima beans, pumpkins, watermelon, and cantaloupes.

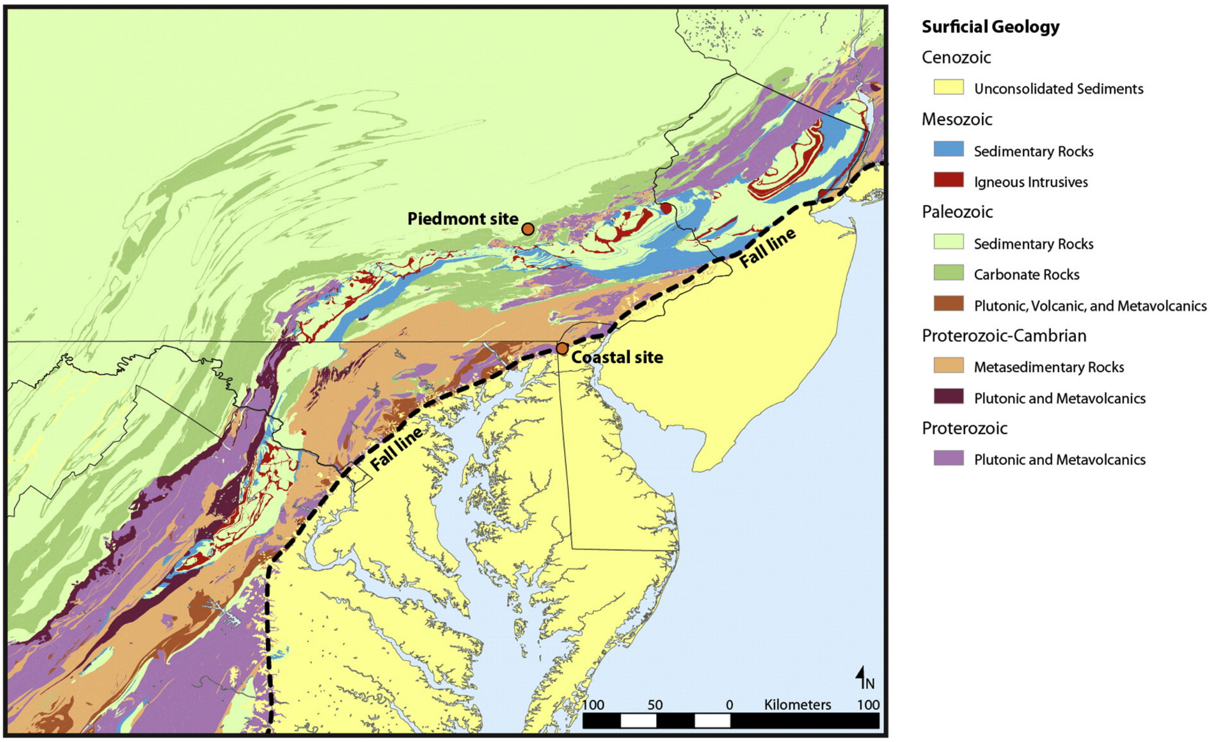

Fig. 1. Study site locations. The two study sites are on the opposite sides of the Fall Line. The flat coastal site is underlain by stream sediments eroded from the Piedmont. The Piedmont site is characterized by hilly landscapes with metamorphosed sedimentary bedrock geology.