

The pre-Colombian footprint on terrestrial nutrient cycling in Costa Rica: insights from phosphorus in a lake sediment record

Gabriel M. Filippelli · Catherine Souch ·
Sally P. Horn · Derrick Newkirk

Received: 11 September 2008 / Accepted: 17 August 2009
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Abstract The impact of pre-Columbian subsistence agriculture on soil nutrient cycling in the American tropics is poorly quantified. Paleolimnological research can address this deficit by documenting the temporal evolution of nutrient cycling in lake watersheds over different time scales. Here we describe our use of a chemical sequential extraction technique adapted from soil fertility research to discern geochemical fractions of phosphorus (P) in lake sediments that serve as proxies for landscape-scale soil nutrient status. These P fractions are mineral P (the original lithic source of bioavailable P), occluded P (mainly bound to soil oxides), and organic P (remains of organic matter production by plants). We applied the P fractionation technique to a lake sediment core from a small lake in southern Costa Rica, Laguna Zoncho. Prior analyses of microfossils and stable carbon isotopes in this core documented an

approximately 3,000 year history of human occupation and agricultural activity in the Zoncho watershed, and shifts in diatom communities in the lake associated both with human impacts and with climate-driven changes in lake level. Our P analyses revealed relatively constant P geochemistry during the first approximately 2,500 years of the record, when other sedimentary proxies reveal forest clearance and maize agriculture of varying intensity. However, the period from approximately 500 to 100 years BP is marked by a drastic shift toward a P geochemistry dominated by occluded forms, with a concomitant decrease in the relative content of both the organic and mineral P forms. This interval coincides with post-Conquest depopulation and forest regeneration at the site, and with an apparent deepening of the lake caused by a shift toward a wetter climate. The dominance of the occluded P fraction during this interval is the opposite of the trend expected with such a climate shift, implicating human dynamics as the principal driver of the changes in soil nutrient status indicated by the P fractions in the Zoncho core. We propose that the entire P geochemical record is dominated by human-induced alteration of the soil nutrient cycles via agriculture and occupation, and that the only interval that reveals the “natural” nutrient status in the region is the short interval when the site is abandoned and surrounding forests regrow. These results for Laguna Zoncho reveal the close connection between even relatively low-technology human activities and soil nutrient status.

G. M. Filippelli (✉) · D. Newkirk
Department of Earth Sciences, Indiana University Purdue
University Indianapolis (IUPUI), Indianapolis, IN 46202,
USA
e-mail: gfilippe@iupui.edu

C. Souch
Department of Research and Education, Royal
Geographical Society, London, UK

S. P. Horn
Department of Geography, University of Tennessee,
Knoxville, TN 37996, USA

Keywords Pre-Columbian populations · Soils · Nutrients · Phosphorus cycling · Costa Rica · Paleoclimate · Lake sediment records

Introduction

The impacts of Late Holocene climate change and prehistoric human activity on soil nutrient cycling in the American tropics are poorly quantified. The centrality of soil to humans and to the development of agriculture gives special importance to the study of how soils and soil nutrients have changed through time, at appropriate temporal resolution, and of the factors that have contributed to these changes. Unfortunately, the nature of soil genesis means that soil characteristics do not provide high-resolution proxies of environmental change. As a soil begins developing on a bare landscape and eventually evolves to a mature state, the later formation processes build upon the earlier ones, and the soil profile that results reflects the current state of the soil but not its status at any particular time in the past. Some temporally specific records of soils do exist when conditions change dramatically, such as during rapid burial or exposure of soil profiles. However, these processes tend to provide only isolated snapshots rather than continuous records, and thus often cannot be reliably tied to the evolution of climate or to human land use histories.

A key to understanding the interplay between soils and biota is examining the evolution of nutrient cycling on landscapes over suitably long time scales. Several studies have investigated changes in soil nutrient status through the use of soil chronosequences (Vitousek et al. 1997; Chadwick et al. 1999). This approach elucidates the progression of soil nutrient geochemistry with time but does not adequately constrain how climatic change and land use affect soil nutrients in a given location. A repository is required that preserves a representative record of soil and soil nutrient conditions as a function of time.

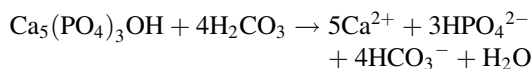
Paleolimnological records derived from the study of lake sediments document past lake conditions, such as temperature, trophic structure, and geochemistry (Oldfield 1977; Gierlowski-Kordesch and Kelts 2000; Dearing et al. 2001; Smol and Last 2003). Sedimentary pollen, plant macrofossils,

charcoal, and allochthonous organic composition provide complementary records of terrestrial ecosystem changes at local and regional scales, driven by both climate change and human impacts (Horn 1993; Northrop and Horn 1996; Lane et al. 2004; Dearing et al. 2008). In lakes where a significant proportion of sediments reaching the lake basin are derived from the contributing watershed, a careful study of these sediments affords a method to document changes in dominant sediments sources and/or sediment delivery.

To understand how soil development and nutrient cycling in southern Central America were affected by Late Holocene climate change and pre-Columbian indigenous land use, we exploited the continuity and preservation potential of lake sediments. Our approach is based on the ability to carefully extract the geochemical characteristics of phosphorus (P), a limiting nutrient on landscapes with relatively predictable behavior during the process of soil development. Changes in the geochemistry of P reveal the nature of soil nutrient cycling in landscapes surrounding the lakes. The nutrient status of soils in turn reflects the impacts of a set of natural processes (e.g., precipitation, temperature, slope stability and erosion) as well as human alteration of the landscape.

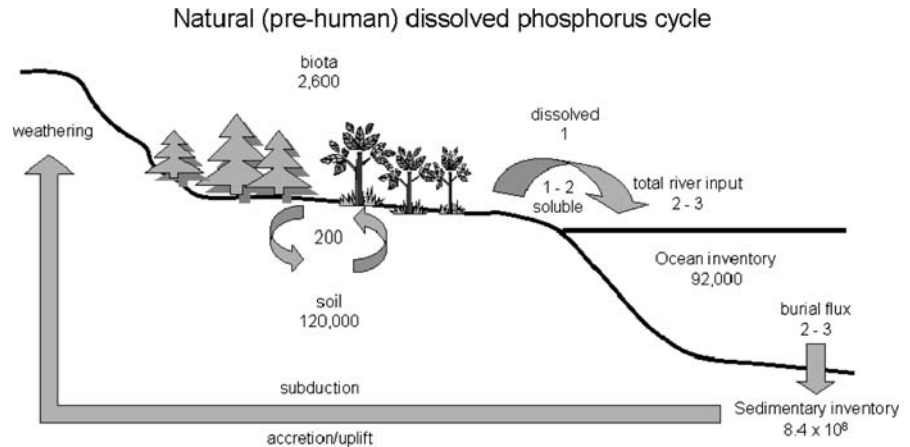
Phosphorus cycling in soils

The cycling of P in soils (Fig. 1) has received much attention, both in terms of fertilization and the natural development of ecosystems. Of the approximately 122,600 Tg P within the soil/biota system on the continents, nearly 98% is held in soils in a variety of forms (Filippelli 2002). The exchange of P between biota and soils is relatively rapid, with an average residence time of 13 years, whereas the average residence time of P in soils is 600 years (Fig. 1). The only significant weathering sources for phosphorus in soils are apatite minerals. These minerals can be congruently weathered as a result of reaction with dissolved carbon dioxide:



In soils, P is released from mineral grains by several processes. First, the reduced pH produced from respiration-related CO₂ in the vicinity of both degrading organic matter and root hairs dissolves P-

Fig. 1 Natural (pre-human) dissolved phosphorus cycle (from Filippelli 2002)



bearing minerals (mainly apatites) and releases P to root pore spaces (Schlesinger 1997). Second, organic acids released by plant roots also can dissolve apatite minerals and release P to soil pore spaces (Jurinak et al. 1986). Much of the available P in soils is in organic matter, which is not directly accessible for plant nutrition. Plants have developed two specific tactics to increase the supply of P to roots. First, plants and soil microbes secrete phosphatase, an enzyme that can release bio-available inorganic P from organic matter (Malcolm 1983; Tarafdar and Claassen 1988). Second, the symbiotic fungi mycorrhizae can coat plant rootlets, excreting phosphatase and organic acids to release P, providing an active uptake site for the rapid diffusion of P from soil pore spaces to the root surface (Antibus et al. 1981). In exchange, the plant provides carbohydrates to the mycorrhizal fungi (Schlesinger 1997).

Phosphorus in soils is present in a variety of forms, and the distribution of P between these forms changes dramatically with time and soil development. The forms of soil P can be grouped into refractory (not readily bio-available) and labile (readily bio-available). The refractory forms include P in apatite minerals and P co-precipitated with and/or adsorbed onto iron and manganese oxyhydroxides (termed “occluded” P). The reducible oxyhydroxides have large binding capacities for phosphate, due to their immense surface area and numerous delocalized positively charged sites (Froelich 1988). The labile forms include P in soil pore spaces (as dissolved phosphate ion) and adsorbed onto soil particle surfaces (these forms are termed “non-

occluded” P), as well as P incorporated in soil organic matter. On a newly-exposed lithic surface, nearly all of the P is present as P in apatite. With time and soil development, however, P is increasingly released from this form and incorporated in the others (Fig. 2). Over time, the total amount of P available in the soil profile decreases, as soil P is lost through surface and subsurface runoff. Eventually, the soil reaches a terminal steady state, when soil P is heavily recycled and any P lost through runoff is slowly replaced by new P weathered from apatites at the base of the soil column.

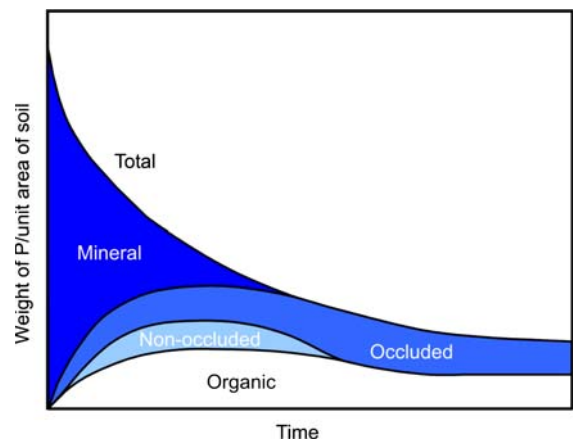


Fig. 2 Conceptual model of change in soil P geochemistry over time (based on Walker and Syers 1976) showing transformation of mineral P into non-occluded and organic forms before eventual dominance of occluded (oxide-bound) and organic forms. Note continual loss of total P from the system

Ecosystem dynamics and soil development

The effects of climate and soil development on P availability have been a focus of several studies (Walker and Syers 1976; Tiessen et al. 1984; Gardner 1990; Crews et al. 1995; Cross and Schlesinger 1995; Vitousek et al. 1997; Schlesinger et al. 1998; Chadwick et al. 1999). For the most part, these studies have used P extraction techniques to determine the biogeochemical forms of P within soils. These techniques differentiate P in similar fractions as displayed in Fig. 2 (Tiessen and Moir 1993). The extraction techniques have been applied to depth and age profiles in soils, to assess the rate of soil P transformations, the role of climate on these processes, the bioavailability of P in these systems, and the limiting controls on plant productivity. As the current geochemical state of a given soil is an integration of all conditions acting since soil development, most efforts have focused on settings in which climate is assumed to have been relatively constant (i.e., tropical settings), and the beginning state of the system and its age are very well known (i.e., soil developing on lava flows). These studies have thus made the classic substitution of space for time, with all the inherent assumptions of constancy in climate and landscape history.

Another approach to assessing terrestrial P cycling is by examining P geochemistry in lake sediments, using the same extraction techniques as the soil studies. This technique adds several dimensions to the soil work outlined above. First, lake sediment records allow us to examine an integrated record of watershed-scale processes associated with P cycling on the landscape. Second, it allows discrete temporal resolution at a given site, providing an actual record of local processes including landscape stability, soil development, and ecosystem development. Past studies (Filippelli and Souch 1999; Filippelli et al. 2006) have focused on oligotrophic headwater lakes dominated by allochthonous sediment production, with the philosophy that in such settings lake sediments are usually largely unaffected by diagenetic processes related to sedimentary decomposition of organic matter, and hence have a P geochemistry that is relatively stable after deposition. In this paper, we focus on a lake that is likely mesotrophic through its history; as we discuss in the results section, we do not feel that this significantly alters the P sedimentary

geochemistry from the lake core, as the proportion of reducible P (termed occluded from a soil science perspective) is extremely high compared to other settings that we have studied. This serves as evidence that whatever suboxia has occurred in the sediments due to organic matter degradation was not severe enough to reduce this form of P, which is extremely susceptible to suboxic dissolution in other settings (Filippelli et al. 2003).

Conceptual model of phosphorus geochemical changes: landscape disturbance, and forest regrowth

Several modern studies of soil P transformations under disturbance and regrowth scenarios provide a useful conceptual model into which to place the historical record. Grossmann and Mladenoff (2008) observed that agricultural fields that laid fallow and were allowed to regrow forests exhibited higher organic P content and lowered mineral P content (the latter partly due to high acidity of forest soils). In a review paper, Chen et al. (2008) found the same decrease in mineral P content of soils that transitioned from grassland to forests. Garcia-Montiel et al. (2000) reported on soil P geochemical transformations in response to the reverse of this process—namely, forest clearance for pasture in the Amazon. In this case, deforestation caused a decrease in occluded P content and an increase in organic P content. These studies may be graphically portrayed using the soil development model of Fig. 2. In this case, forest growth is an ecological succession that influences the soil P composition by shifting toward the right of the diagram (i.e., lower proportion of mineral P and relatively higher proportion of occluded and organic P; Filippelli and Souch 1999; Filippelli et al. 2006), and landscape and soil disturbance a process reversing natural soil P development and shifting P composition to the left of the diagram.

Study area and history

To examine human, as well as possible climatic, influences on soil nutrient cycles, we analyzed P fractions in the sediments of a small lake in southern Costa Rica, using a sediment core spanning the last three millennia. In a review paper on sediment-based

records of Holocene environmental history in Mexico and Central America, Bradbury (1982) noted that the long history of agricultural land use in this area would complicate efforts to reconstruct paleoclimate from sediment records, because the impacts of agriculture might mimic or mask evidence of climate change. Untangling signals of climate change and human impacts in sediment records from Mexico and Central America has indeed proven difficult, but progress is being made through the use of multi-proxy and multi-site approaches investigating stable isotopes, sediment geochemistry, and other proxies in lake and marine sediments (Leyden 2002; Brenner et al. 2002). Moreover, the evidence of human impacts in lake sediment records is increasingly viewed not simply as a ‘compromising factor’ (Bradbury 1982) for paleoclimatic reconstruction, but also as possible evidence of human responses to climate variability and change (Brenner et al. 2002; deMenocal 2001).

Once regarded as stable, Holocene climates in the circum-Caribbean region appear to have been characterized by considerable variability (Fritz et al. 2001, Grimm et al. 2001, Horn 2007), with potentially important consequences for pre-Columbian agriculture and population dynamics. Oxygen isotopes and trace element cycling within lake cores studied from the Yucatan Peninsula, and trace element data from sediment cores from the Cariaco Basin, show evidence for several drying events during the Holocene (Hodell et al. 1995; Curtis et al. 1996; Haug et al. 2001, 2003; deMenocal 2001; Brenner et al. 2002). The most significant signal from the Yucatan Peninsula sites occurs during the latest Holocene, where shifts in isotopic indicators and geochemistry reveal an aridification event that is likely closely tied to the collapse of the Classic Mayan civilization approximately 1100 year BP. This event is also recorded in Ti concentrations in Cariaco basin sediments (Haug et al. 2003).

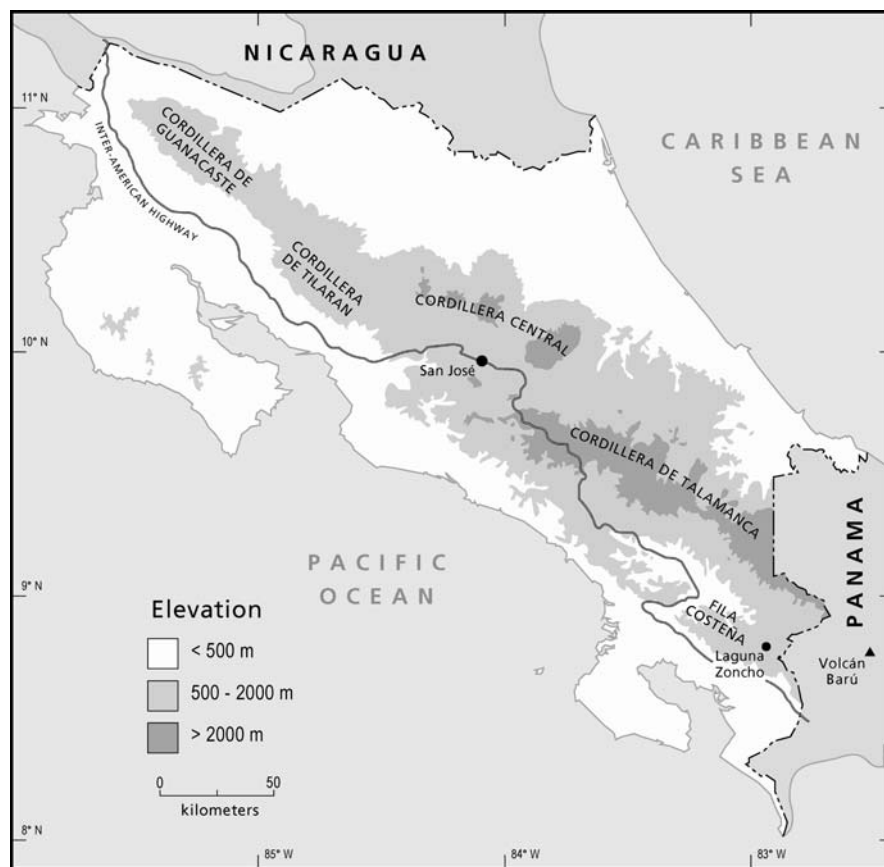
Additionally, a significant amount of attention has recently been paid to the impacts that early civilizations had on their environment. The concept of “the noble savage” living in harmony with the land and having a negligible environmental footprint has been called into question based on evidence for substantial alteration of landscapes due to subsistence agriculture and hunting practices (Denevan 1992; Wilmshurst 1997; Kirch 2005; O’Connor 2005; Guthrie 2006).

Furthermore, there is even some suggestion that humans have had a global impact on climate since the early Holocene (Ruddiman 2003). Exploring the extent to which early humans impacted the environment helps place current human disturbance in context.

Our examination of the impacts of human activity and possible shift in climate on soil development (and thus agricultural potential) in the circum-Caribbean region focused on P fraction evidence of soil nutrient status in association with other proxy data in the sediments of Laguna Zoncho (8.813°N, 82.963°W, 1,190 m elevation), a small (0.75 ha) lake in southern Pacific Costa Rica (Fig. 3). Analyses of various proxies in a core recovered from near the center of the lake in 1997 documented marked shifts in watershed vegetation, land use, and aquatic communities. Clement and Horn (2001) analyzed pollen and microscopic charcoal in the core, identifying five pollen zones showing varying levels of human impact in the watershed. Lane et al. (2004) later examined stable carbon isotope signatures in the sediments as an additional proxy for forest clearance and maize agriculture, and Haberyan and Horn (2005) documented shifts in diatom assemblages.

Laguna Zoncho is located on the eastern end of the Fila Costeña, overlooking the Coto Brus Valley near the town of San Vito, Costa Rica. The Fila Costeña is a complex range composed primarily of folded and faulted deepwater sedimentary rocks. Tertiary volcanic rocks outcrop near the lake but the only active Quaternary volcano in the region is Volcan Barú in western Panama, located 45 km east of the lake. The basin occupied by Laguna Zoncho formed due to mass wasting, faulting, or both. The lake was 2.3 m deep when cored in March 1997; in July 2007, it was 3 m deep, circum-neutral (pH 7.37), and fresh (conductivity 16 $\mu\text{S cm}^{-1}$; alkalinity 12 mg l^{-1}) (Haberyan et al. 2003). The available topographic map (Cañas Gordas 1:50,000 sheet) is at too small of a scale to accurately delineate the lake’s small watershed, but we estimate it to be no larger than about 7 ha, or 9–10 times the size of the lake. The lake has no outflow and no permanent inlets. Modern land cover in the region consists of cattle pastures, coffee and other agricultural fields, and remnant pre-montane rain forest, the largest tract of which is located at the Organization for Tropical Studies’ Las Cruces Biological Station, located 2 km south of the lake. Daily et al. (2001)

Fig. 3 Location of Laguna Zoncho in the Fila Costeña of southern Costa Rica



mapped modern land use (forest vs. non-forest) in the area using a 1994 Landsat image; Laguna Zoncho is within 0.5 km of Site SV-1 in their Fig. 3. Archaeological sites and phases were summarized for the region by Anchukaitis and Horn (2005). The Laguna Zoncho area has an estimated mean annual temperature of 20–21°C, and receives on the order of 3,000–4,000 mm precipitation annually (Coen 1983). Precipitation is lowest from December to March, but the dry season is less strongly felt than on the central and northern Pacific slopes of Costa Rica or farther to the north in western Central America.

A 6.0 m long sediment core reaching mineral regolith was recovered from near the center of the lake using a plastic tube fitted with a rubber piston for the near-surface sediments, and a 5-cm diameter Colinviaux-Vohnout (C–V) locking piston corer (Colinviaux et al. 1999) for the deeper sediments. This study of P geochemistry as well as previous paleoecological analyses focused on the upper lacustrine section (0–290 cm) of the core, which is composed of water-lain

sediments with organic contents ranging from 20–80% dry mass based on loss on ignition at 550°C, and includes a layer of tephra (99–100.5 cm) from the most recent eruption of Volcán Barú (Clement and Horn 2001), dated at 500 ± 60 year BP by (Behling 2000; Anchukaitis and Horn 2005). Clement and Horn (2001) obtained three AMS C^{14} dates on organic macrofossils in the lacustrine unit of the core; these dates indicate that the modern lake formed ~ 3200 cal year BP.

Methods

A sequential extraction technique (Ruttenberg 1992), similar to that of Tiessen and Moir (1993), was used to geochemically distinguish pools of P related to mineral material (the ultimate source of P in ecosystems), an occluded fraction (related to soil oxyhydroxides), and an organic fraction. This technique involved (1) a citrate-dithionite-bicarbonate reducing

agent and magnesium chloride (occluded fraction), (2) dissolutions with sodium acetate + acetic acid solution and hydrochloric acid (mineral fraction), and (3) ashing followed by dissolution with hydrochloric acid (organic fraction). Twenty-nine samples were selected and analyzed. Approximately 0.2 g of each sample was weighed into new 15-ml polyethylene centrifuge tubes. Samples with reagents were shaken on an orbital shaker for the recommended amount of time depending on the protocol for each extraction step, and then centrifuged for 10 min. All supernatants were decanted into acid cleaned polyethylene bottles, and saved for analysis. A Shimadzu scanning UV–visible spectrophotometer was used for the determination of P concentrations for steps II–IV from the sequential P extraction using the molybdate blue technique for color development (Strickland and Parsons 1975). Dithionite-extractable P concentrations were determined by ICP-AES because the CDB solution interferes with the standard color development. Randomly-chosen replicates were analyzed with an agreement within 6%.

Results and discussion

Analysis of pollen and microscopic charcoal in the upper lacustrine unit of the Laguna Zoncho core led Clement and Horn (2001; Table 1) to identify five different intervals of activity in the watershed, each corresponding to a “zone.” The lowest interval (Zone 5; ~3240–2770 cal year BP or 1290–820 BC) indicates fairly major forest disturbance and agricultural activity, including the earliest maize cultivation documented in the region. More limited agriculture occurred during a subsequent interval (Zone 4; 2770–1770 cal year BP or 820 BC to AD 180) characterized by forest regeneration and fewer fires; the human population in the watershed may have been lower at this time. Zone 3 (1770–460 cal year BP or AD 180–1490) marks a period of more intensive agricultural activity that may have included the establishment of maize fields that were cropped permanently, rather than in rotation. A sharp decline in human activity and disturbance in the watershed occurs at the beginning of Zone 2 (460 cal year BP or AD 1490) at the time of the Spanish Conquest and shortly after the eruption of Volcán Barú (Clement and Horn 2001). This interval saw an increase in forest taxa and

Table 1 Inorganic content and charcoal:pollen ratios of Laguna Zoncho core samples

Depth (cm)	% Inorganic content	Charcoal:pollen
0	73.3	2.1
9	72.1	2.9
19	63.6	1.0
28	43.0	0.2
38	34.3	0.2
47	42.7	0.2
56	18.0	0.2
66	49.7	0.3
75	38.1	0.3
85	49.3	0.5
92	75.4	2.0
94	75.9	0.9
103	80.4	2.1
106	70.4	4.9
120	72.5	5.4
136	78.0	7.6
152	80.1	4.6
168	79.5	11.4
184	78.1	6.8
192	77.4	7.3
200	77.4	10.3
216	74.8	7.0
222	71.9	3.0
239	58.1	2.2
247	58.4	3.2
255	69.3	2.0
271	55.9	5.7
272	74.4	8.5
287	72.3	5.6
288	80.1	4.4

Charcoal:pollen ratios provide estimates of fire frequency that are unaffected by variations in sedimentation rate. See Clement and Horn (2001) for additional charcoal indices

decrease in fires as forests regrew and agricultural activity lessened. However, small amounts of maize pollen in the sediments indicate that some indigenous agriculture persisted in the watershed during the post-Contact period, with some maize cultivation evident also in the uppermost sediments (Zone 1), associated with the development of an Italian expatriate colony in the 1950s.

Later analysis of diatom assemblages in the Zoncho sediments revealed shifts that reflected

long-term climate change as well as human impacts on the lake (Haberyan and Horn 2005). Of particular importance for the current analysis is evidence of a deepening of the lake in Zone 2, the interval of post-Conquest forest recovery in the Zoncho watershed.

Our goal here was to test how subsistence-level agriculture affects soil nutrient status, and to look for indications of possible climate shifts in the P data that may be masked in other proxies by the heavy human impact at the site. We were specifically interested in the climatic context of the Spanish Conquest (Zone 2). Depopulation of the region resulting from the Spanish Conquest likely played a large role in the

near abandonment of the site during Zone 2, with the eruption of Volcán Barú possibly providing an additional impetus for site abandonment by people whose numbers were already reduced by contact-era disease, warfare, and enslavement (Clement and Horn 2001). However, data from some locations in the circum-Caribbean point indicate a shift toward a drier regional climate at this time, which may also have influenced population dynamics at Zoncho. A record of Ti content from Cariaco Basin shows the most dramatic decrease in concentration from 400 to 200 cal year BP. This has been interpreted as the result of a decrease in precipitation and runoff of

Table 2 Phosphorus geochemistry and relative phosphorus contents for occluded, mineral, and organic phosphorus fractions from Laguna Zoncho

Depth (cm)	Occluded P ($\mu\text{mol/g}$)	Mineral P ($\mu\text{mol/g}$)	Organic P ($\mu\text{mol/g}$)	Total P ($\mu\text{mol/g}$)	Occluded P (%)	Mineral P (%)	Organic P (%)
0.0	9.1	8.9	16.7	34.7	26.1	25.7	48.2
9.0	7.9	8.8	17.2	33.8	23.3	25.9	50.8
19.0	19.6	14.9	20.4	55.0	35.7	27.1	37.2
28.0	16.3	5.1	19.6	41.0	39.6	12.5	47.9
38.0	20.3	3.5	18.8	42.6	47.7	8.2	44.1
47.0	23.1	4.3	18.5	45.8	50.4	9.3	40.3
56.0	28.5	8.8	20.7	58.0	49.2	15.1	35.7
66.0	30.0	7.1	18.0	55.1	54.4	13.0	32.6
75.0	30.9	6.7	16.6	54.2	57.1	12.3	30.6
85.0	27.8	8.1	17.0	52.9	52.5	15.4	32.1
93.5	8.4	15.2	10.7	34.2	24.4	44.4	31.2
94.0	12.7	13.0	11.1	36.8	34.5	35.4	30.1
103.0	8.4	12.4	9.2	30.0	27.9	41.3	30.8
107.5	6.0	11.9	16.1	34.1	17.7	35.0	47.3
121.5	5.0	14.2	18.1	37.3	13.5	37.9	48.6
137.5	5.7	12.2	14.3	32.2	17.7	37.9	44.4
153.5	2.8	9.0	11.9	23.8	11.9	37.8	50.3
169.5	3.0	7.6	9.6	20.2	15.0	37.8	47.2
185.5	4.4	8.5	10.2	23.1	19.1	37.0	44.0
193.5	3.0	9.1	11.4	23.5	12.9	38.7	48.5
201.5	2.8	17.7	16.7	37.3	7.5	47.6	44.9
217.5	4.9	25.6	18.8	49.3	9.9	52.0	38.1
223.5	3.8	10.5	12.3	26.5	14.2	39.6	46.2
251.0	8.1	23.2	16.2	47.5	17.0	48.9	34.1
256.5	11.3	27.6	18.2	57.0	19.8	48.3	31.9
272.5	3.7	8.6	8.4	20.7	18.0	41.4	40.5
273.5	6.7	18.8	15.6	41.1	16.4	45.7	38.0
288.5	8.9	16.4	15.2	40.5	22.0	40.5	37.5
289.5	7.2	17.1	13.6	37.9	19.0	45.1	35.9

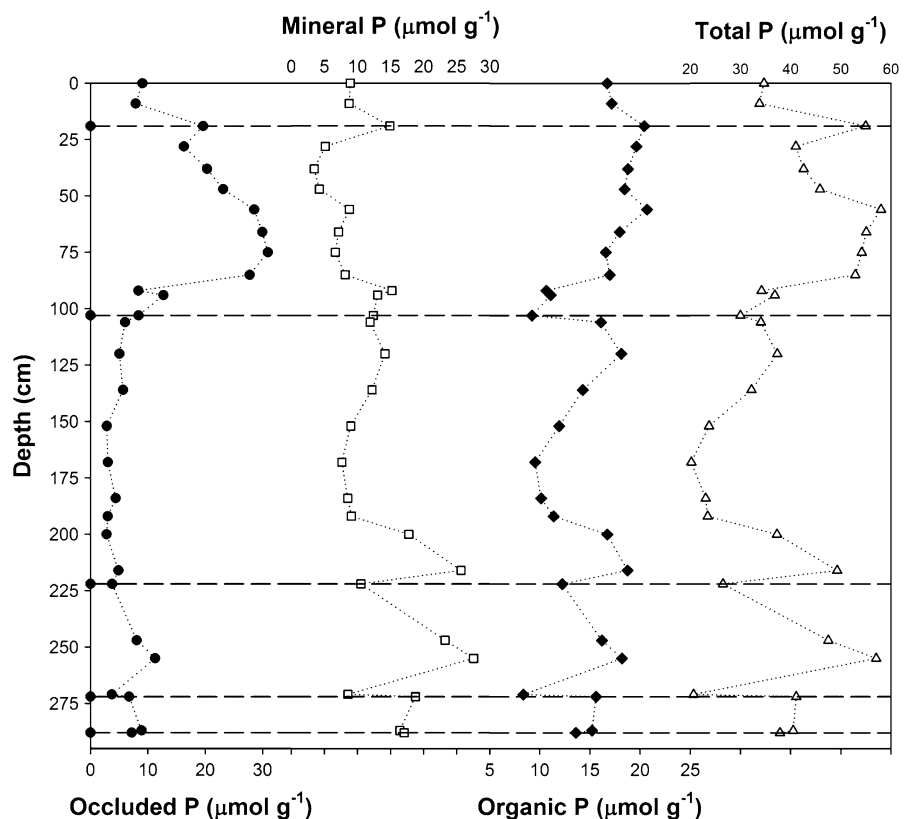
terrestrially-derived Ti from northern Venezuela, perhaps the result of the ITCZ being displaced further southward than normal (Haug et al. 2003). How such a change would affect southern Pacific Costa Rica is uncertain, but the Cariaco record suggests that drought deserves at least some consideration as a third possible impetus for site abandonment at Zoncho, where indigenous inhabitants depended on rain-fed maize agriculture. In contrast to this regional record, the local diatom record from Laguna Zoncho suggests deepening of the lake during this interval (Haberyan and Horn 2005), presumably in response to higher precipitation and runoff. We conjectured that the nutrient status of the watershed soils might also shed light on this apparent contradiction.

The P geochemical record from this site (Table 2; Fig. 4) is significantly different from that found in earlier studies. This site has significantly more organic P and occluded P than other lake sediments studied by the authors previously (Fig. 5), although most of these were in temperate alpine settings. Based on the P geochemical model presented earlier

(Fig. 2), this P composition indicates a relatively well-developed soil nutrient status. This is predictable, as the high temperature and high precipitation in the tropical setting of southern Costa Rica lead to more completely developed soil profiles.

The temporal record of P geochemistry shows some variability in the lower portion of the record, particularly with several concomitant peaks in mineral P and organic P in Zone 4 and the base of Zone 3, driving peaks in the total P concentrations (Fig. 4). Both are intervals of human occupation, and Zone 3 is a time of significant human disturbance. These peaks may be due to charcoal and some fragments of soil lithic material high in P that resulted from human activities. Most of Zone 3 is marked by more constant P fraction geochemistry, with a slight increase in organic P. The most dramatic change in the record occurs in the lower portion of Zone 2, where the organic P fraction decreases sharply (by about 50%), followed by an event somewhat after the tephra layer (and volcanic explosion) in which the occluded P content increases roughly fivefold, the mineral P content decreases, and the organic P content returns

Fig. 4 Total P concentration and P concentrations for each P-bearing fraction ($\mu\text{mol P g}^{-1}$) as a function of depth, with age control points on the left axis and Zones delineated by dashed lines. The largest sustained variation in the P records occurs in Zone 2, characterized by abandonment of the Laguna Zoncho site and forest regrowth under conditions of low or no human disturbance



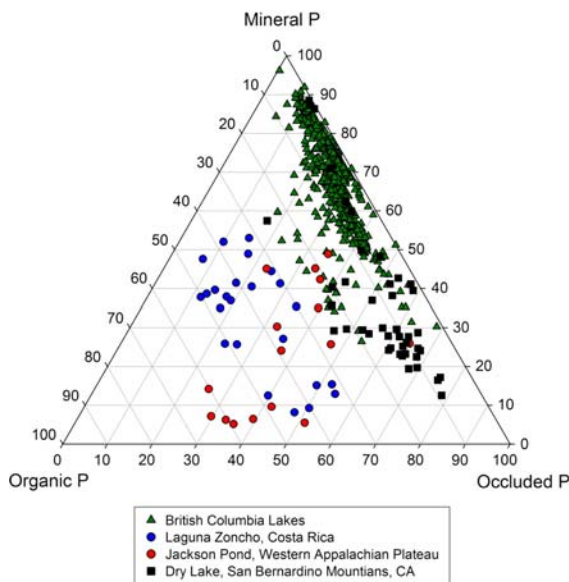


Fig. 5 Percentage of total P found for lakes from different geographical environments. This constitutes our global database of lake sediment P distribution to date, with examples from the glaciated alpine Coast Mountains of British Columbia with high mineral P content related to steep slopes, high erosion, and continual exposure of fresh mineral material (Filippelli et al. 2006); the alpine Dry Lake in the arid San Bernardino Mountains of southern California with high occluded P associated with the build-up of soil oxides under conditions of low precipitation (Filippelli and Souch 1999); the temperate Jackson Pond on the Appalachian Plateau with a relatively stable erosion history under a lower relief setting resulting in relatively mature soil nutrient distribution (Filippelli and Souch 1999); and Laguna Zoncho (this study), with high organic and occluded components for much of the record related to tropical setting and relatively low relief leading to a soil nutrient distribution similar to the Appalachian Plateau example

to levels occurring in Zone 3 (Fig. 4). After this event, occluded P slowly declines back to previous levels by Zone 1, while the other fractions exhibit only gradual shifts (Fig. 4).

This temporal record is intriguing, particularly when viewed against several of the other indicators in the lake sediment core and from the perspective of the percent of total P represented by each P fraction (Fig. 6). Collectively, these records reveal only subtle change from Zone 5 through Zone 3, an approximately 2500 year interval marked by relatively high charcoal abundance, high inorganic sediment content, and P fractional percentages exhibiting ranges of about 10–20% occluded P, 35–50% mineral P and 30–50% organic P. Some indication of a gradual

increase in the percentage of organic P is present in the profile, perhaps related to the maturation of the lake itself and the development of some internal lake P cycling (Schlesinger 1997). The most dramatic change that occurs in these records begins at the base of Zone 2 at 103 cm core depth, corresponding to an interpolated date of AD 1490 (Clement and Horn 2001). At this time, roughly coincident with the deposition of the tephra layer, the percent occluded P increases rapidly and reaches a peak of 50% of total P by 75 cm core depth, or roughly AD 1630. After this peak, occluded P remains high but steadily decreases to the top of Zone 2 (Fig. 6). As a consequence of the increase in the occluded P concentration (which then drives this occluded P fraction increase), the percent mineral P in the lake core is low through this interval, and the percent organic P starts low but increases steadily.

Zone 2 of the Zoncho core shows very low microscopic charcoal content, indicating few fires in the watershed or region, and lower inorganic content (Table 1). Clement and Horn (2001) interpreted this interval to represent a sharp reduction in agriculture and regrowth of the forest, an interpretation supported by the near disappearance of maize and weedy herb pollen and an upsurge in tree pollen. Later analyses by Lane et al. (2004) showed a concomitant shift in stable carbon isotope values in the Zoncho sediments, corresponding to a shift from C_4 to C_3 vegetation in the watershed as forests replaced agricultural fields. These changes in proxy indicators in the Zoncho core document population decline in the watershed and region. The observed changes in P geochemistry also reveal a significant alteration of P cycling in the landscape during this interval. The proportion of mineral P decreases in concert with the decrease in inorganic sediment fraction, reflecting a decrease in runoff-related erosion of soils in this region. The diatom record, however, suggests deeper lake levels and presumably higher runoff (Haberyan and Horn 2005). It is likely that the reduced erosion is related to forest regrowth and reduced use of agricultural footpaths (Ziegler et al. 2001), and the re-establishment of “normal” soil profiles during weathering.

Using an assumption of relatively stable climate throughout this interval, what process could lead to somewhat constant P nutrient status in the watershed interrupted by a transient shift in P cycling during

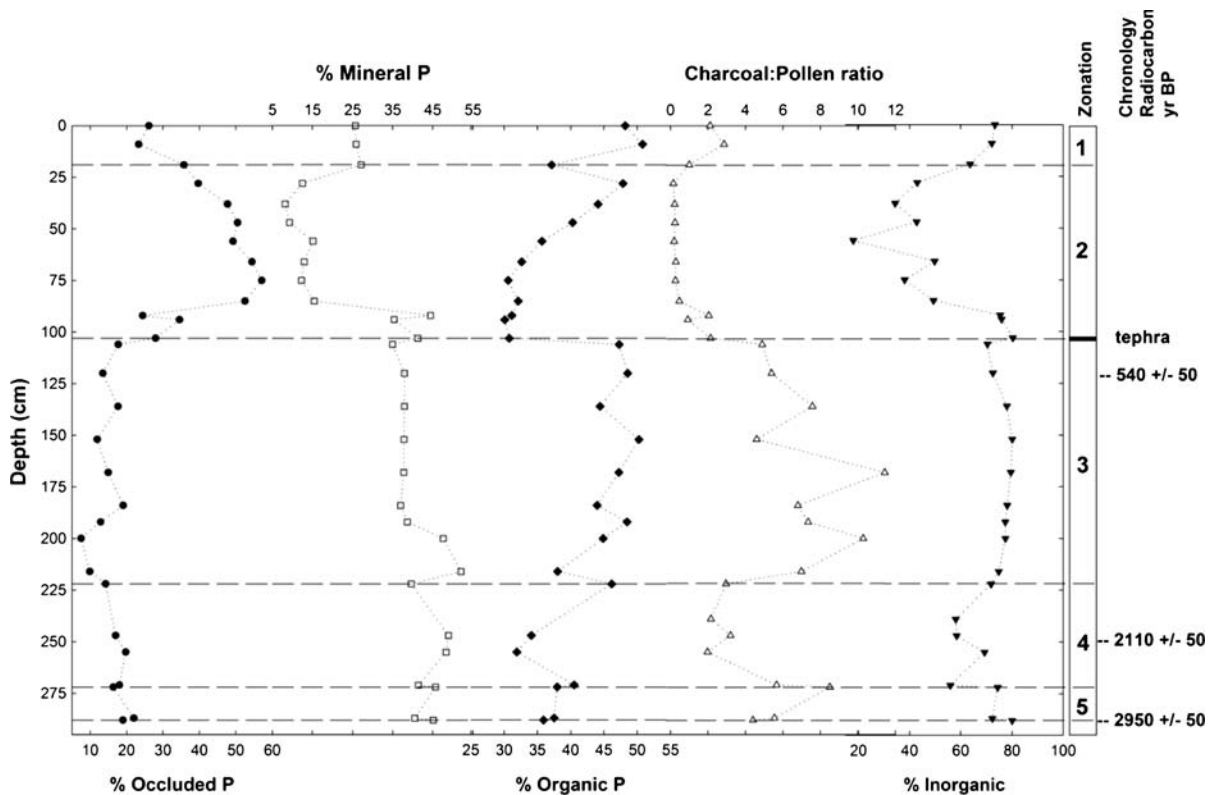


Fig. 6 Summary diagram of the percentage of total P represented by various P-fractions over time (this study), along with a record of inorganic content and charcoal: pollen ratios (from Clement and Horn 2001). Based on Clement and Horn (2001), *Zone 1* is the interval of Italian colonization; *Zone 2* is marked by the presence of maize pollen indicating continued human occupation at the site, but a decline of herbaceous disturbance taxa and the increase in forest taxa indicating lower population levels and less intense agricultural activity; *Zone 3* pollen assemblages indicate intense agricultural activity, with higher percentages of disturbance taxa, lower forest taxa, and

increased abundance of charcoal. Permanent fields may have existed near the lake; *Zone 4* is marked by an increase in pollen of forest taxa, signaling some forest regrowth. The presence of maize pollen indicates continued human disturbance; and *Zone 5* has high percentages of disturbance taxa and abundant charcoal present, indicating heavy human impact. Note the large deviation during *Zone 2* of all of the factors examined, with the dominance in iron-bound (occluded) P corresponding to low levels of charcoal input as this site was abandoned by humans

Zone 2? One possibility is that, other than the interval in *Zone 2*, the entire record reflects the impacts of humans on soil nutrient cycling in this region. As stated earlier, the pollen and charcoal record at this site reflects nearly continuous human alteration of the landscape in this area, with sometimes heavy disturbance related to maize agriculture. In this scenario, the relative balance between occluded, mineral, and organic P fractions seen in *Zones 5–3* and *1* is the product of agricultural and occupation impacts on soil development and soil nutrient status. Agricultural burning is reflected in the charcoal profile, and the high inorganic contents in sediments reflect enhanced

denudation as a function of soil disturbance. It is only during *Zone 2*, when the site experiences a major decline in population and human-related impacts, that soils are allowed to return to pre-human impact status as forests regrow, although there is a similar but less dramatic shift in P geochemistry during *Zone 4*, characterized by some forest regrowth. This scenario is supported by the decrease in inorganic content in lake sediments (a function of lower denudation rates in the catchment) and the decrease in mineral P component (Fig. 6). Of course, this does not explain adequately the high occluded P component in *Zone 2* (both as a fraction of total and as actual

concentration); perhaps the more extensively weathered volcanic soils in the region have a high proportion of oxides which act to occlude a substantial proportion of the total soil P when undisturbed by human activities. If an inverse assumption can be made, this finding can be supported by a modern analog. Garcia-Montiel et al. (2000) found that deforestation leads to lower occluded P and higher organic P, and thus reforestation of a disturbed site may lead to the conditions observed at Laguna Zoncho. Additionally, Garcia-Montiel et al. (2000) noted that this transition can occur much more rapidly in a disturbed setting than is usual for the relatively slow transformations of soil P during succession.

The high occluded P content is not likely driven by geochemical characteristics within the lake or the surface lake sediments. The paleolimnological record suggests a deepening of the lake and thus a relative reduction in oxygen content in lower lake waters if all conditions remained constant. This lowering in oxygen would act to decrease occluded P via the dissolution of redox-sensitive oxides that contain this P fraction. Together with the lake level data itself, we see little evidence of a shift to a more arid environment at this time, at least at Laguna Zoncho. Thus, a more likely scenario is that the P geochemical record does not reflect internal processes to the lake, but rather a watershed-scale change in soil nutrient status as the region became less disturbed by human activity.

If robust, this “disturbance model” of soil P cycling would indicate a rather profound impact of non-industrialized humans on soil resources, arguing (by extension from the Zoncho results) for a potentially much more lengthy record of human impacts on the environment than has been popularized in the past. We have initial evidence of such an effect from the Maori of New Zealand, where sediment records from Poverty Bay reveal the impact that the hunting practices of the Maori—burning lowland shrubs to concentrate wildlife into concentrated hunting regions—had on soil erosion, carbon dynamics, and soil nutrient geochemistry (Gomez et al. 2001). And as noted earlier, we are increasingly aware of even early human footprints on the environment. Although both the Costa Rica and New Zealand findings are preliminary, they may support the growing body of literature finding significant pre-Industrial impacts by humans on the global environment.

Conclusion

We present a “disturbance model” to explain observed changes over a >2000-year, lake-sediment record of soil nutrient status from Laguna Zoncho in Costa Rica. This model argues that the near-continuous human occupation of the fertile watershed surrounding this lake had a profound effect on soil nutrients, with a short window of abandonment allowing soils to recover to pre-human states. If this model is accurate, then evidence exists for a rather profound impact of non-industrialized humans on soil nutrient resources over a very long time period, which may in turn have impacted societal development and the Holocene evolution of global biogeochemical cycles (Ruddiman 2003).

Acknowledgments Support from this research came from the National Science Foundation (BCS-9911526 to GF and CS; OCE-0452428 to GF). We thank Jennifer Latimer and Sara Slater-Atwater for laboratory assistance. Sediment coring at Laguna Zoncho and prior radiocarbon and microfossil analyses were funded by a grant to S. Horn and R. L. Sanford, Jr., from The A. W. Mellon Foundation.

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