Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems

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[1] Leaching, biomass removal, and partitioning of phosphorus (P) into reservoirs not available to plants can limit the long-term productivity of terrestrial ecosystems. We evaluate the importance of atmospheric P inputs to the world's soils by estimating the total soil P turnover time with respect to dustborne P additions. Estimated turnover times range from $\sim 10^4$ to $\sim 10^7$ years. Our estimates provide a unique perspective on the importance and patterns of aeolian deposition to terrestrial landscapes. Dust source regions are areas of intense soil P cycling on large scales, but are too water-limited for this rapid cycling to have a major influence on ecosystem dynamics. By contrast, semiarid desert margins receive significant aeolian P from neighboring deserts and are likely influenced by dustborne P additions for the long-term maintenance of productivity. This is particularly true for the semiarid steppes of Africa and Eurasia. The prevalence of large dust sources in Africa and Eurasia indicates that these areas may generally be more influenced by dustborne P additions than soils in the Americas. Significant western hemisphere exceptions to this pattern occur on very old landscapes, such as the forests of the southeastern United States and the Amazon Basin. The Amazon Basin is highly dependent on aeolian deposition for the maintenance of long-term productivity. Dust deposition to terrestrial environments has not been constant with time. Variability in past P deposition related to geologically recent climate change may provide the strongest controls on present and future soil P in the Amazon and elsewhere. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0330 Atmospheric Composition and Structure: Geochemical cycles; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* dust, phosphorus, soil

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1. Introduction

[2] Soil phosphorus is an important plant nutrient that is often limiting in terrestrial environments. Because gaseous inputs of P to the soil pool are negligible, long-term terrestrial ecosystem productivity is often considered to be limited by the soil P reservoir, all of which must be derived from soil parent material. Weathering of parent material releases P, which then apportions into different pools of varying availability to plants [*Walker and Syers*, 1976]. Loss of P due to leaching, biomass removal through harvesting or fire, or erosion of surface soils thus constitutes irreplaceable losses from the total P reservoir, limiting long-term ecosystem productivity.

[3] Recent studies indicate that this view of the soil P pool ignores important inputs of P to terrestrial ecosystems from atmospheric sources, including the deposition of P-rich material derived from fires [*Artaxo et al.*, 2002] as well as dust from upwind erosion and dust emission. Using data from the ABLE-2B experiment, *Swap et al.* [1992] estimated inputs of P to the Amazon Basin from dust originating in North Africa, concluding that over time periods of 500–2000 years, Saharan dust controls soil P dynamics in the Amazon Basin. In studies of a soil chronosequence in Hawaii, *Chadwick et al.* [1999] have concluded that P inputs from dust originating in Asia are important in the maintenance of productivity in Hawaiian ecosystems on million-year timescales. These studies indicate that the importance of dustborne P varies depending on the dust deposition rate and the reservoir of total P in downwind ecosystems. Thus some ecosystems may be highly reliant on input of P from distant ecosystems for the maintenance of long-term productivity, while others may be more dependent on the input of P from weathering of P-bearing minerals in the existing soil substrate.

[4] The global loading of desert dust is known to vary on timescales on the order of thousands of years in response to

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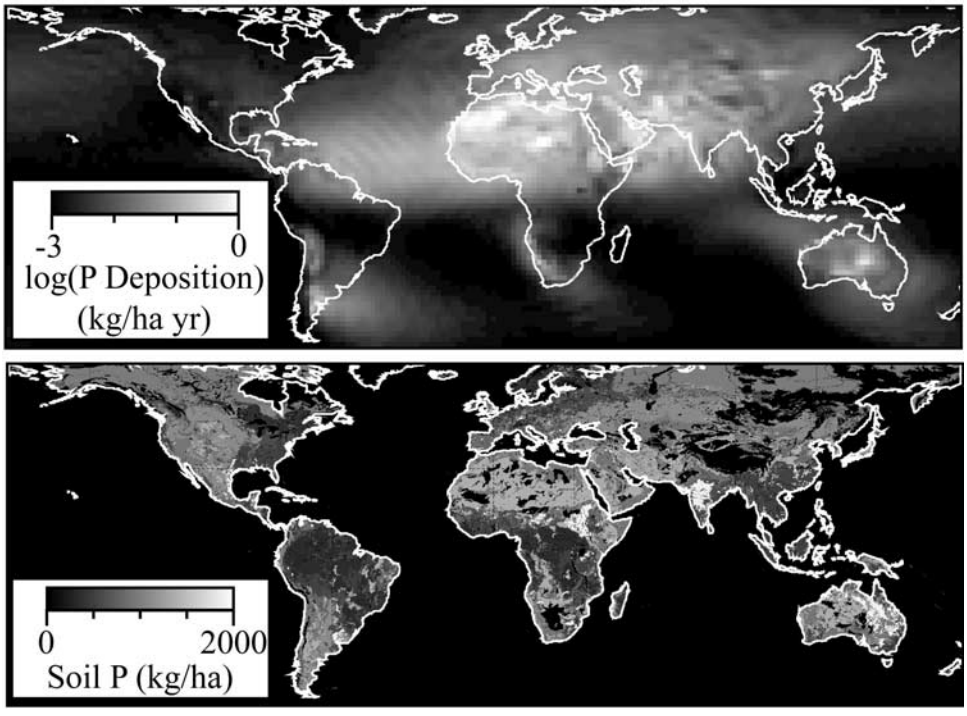

Figure 1. (top) Phosphorus deposition, $C_{d,P}$, calculated as dust deposition from the MATCH/DEAD/NCEP model multiplied by the continental average P concentration (700 ppm). Note the log scale. (bottom) Soil P in the top 20 cm of the world's soils, $C_{s,P}$. Scale is linear.

changes in global circulation and regional climate in dust-producing areas [*Duce and Tindale*, 1991; *Mahowald et al.*, 1999; *deMenocal et al.*, 2000]. Some authors [e.g., *Tegen and Fung*, 1995; *Mahowald et al.*, 2002; *Mahowald and Luo*, 2003] have also suggested that human alteration of the surface in dust-producing areas can significantly change dust emission on a global scale. On smaller scales, localized disturbance and climate variability can dramatically impact dust emission and downwind deposition [e.g., *Okin and Reheis*, 2002]. Therefore P-cycling in soils with significant dust P inputs is sensitive to changes in climate and land use in dust source areas. Here we estimate the importance of P carried by desert dust to terrestrial ecosystems globally and consider the consequences of climate change on dust inputs to soils.

2. Methods

[5] Pseudo-turnover times of P with respect to dustborne P inputs, τ_P, were calculated for the world's soils,

$$\tau_P = \frac{C_{s,P}}{C_{d,P}D}, \tag{1}$$

where $C_{s,P}$ is the concentration of total P in the top 20 cm of soil (kg/ha), $C_{d,P}$ is the concentration of P in airborne dust, and D is the deposition rate of dust to the soil (kg/ha/yr). Because soil P cannot be assumed to be in steady state, τ_P is termed the "pseudo-turnover time," an index of the importance of dustborne P to the soil P reservoir with units of years.

[6] Estimates of dust deposition, D, are provided by output from the Dust Emission and Deposition (DEAD) module [*Zender et al.*, 2003] in the Model of Atmospheric Transport and Chemistry (MATCH) [*Mahowald et al.*, 1997; *Rasch et al.*, 1997] using winds from the National Center for Environmental Predication/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project for 1979–2000 [*Kalnay et al.*, 1996]. In MATCH/DEAD/NCEP, desert dust in source regions is mobilized when large particles ($\sim$75 μm) begin moving along the surface in the saltation process, forced by strong winds. These large particles mobilize and entrain smaller particles, of which a small fraction are entrained into the atmosphere and transported long distances. Gravitational settling and turbulent dry deposition are included in the model, while wet deposition is included in a simple scavenging coefficient fashion. The dust deposition field used here (Figure 1) has been reported and discussed in detail elsewhere [*Luo et al.*, 2003; *Mahowald et al.*, 2003]. Comparisons to observations suggest that the model does a good job of simulating the climatology of dust concentrations, optical depths, and deposition over several orders of magnitude [*Luo et al.*, 2003], and it can capture individual events as well as interannual variability although there is evidence of overprediction of dust deposition in the Southern Hemisphere [*Luo et al.*, 2003].

[7] In this study, we are primarily concerned with the maintenance of soil P stocks over very long timescales (thousands to millions of years). Thus we have chosen to use literature values for total soil P, which encompass all pools of P in the soil, regardless of their availability to

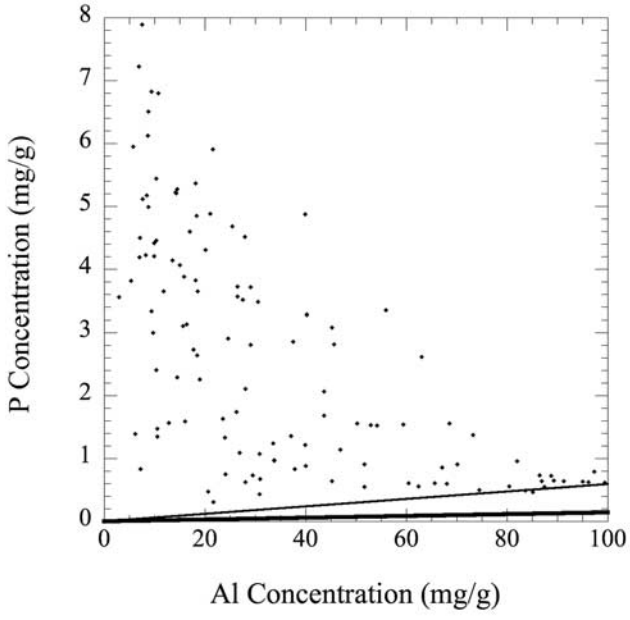

Figure 2. Plot of P concentration versus Al concentration in airborne samples from Alta Floresta, analyzed using PIXE. Samples are mixtures of pyrogenic aerosols (with negligible Al and variable P) and mineral dust. The thin line corresponds to a P/Al ratio of 6×10^{-3}. The thick line corresponds to a P/Al ratio of 1.5×10^{-3}, atmospheric dust P measured by *Talbot et al.* [1986] divided by the crustal Al concentration. The crustal P/Al ratio is 8.8×10^{-3}.

plants or the rapidity with which they cycle in the ecosystem. Likewise, when considering the input of P to soils on dust, we have used an estimate of total P in dust. Following *Chadwick et al.* [1999], we have used the continental P concentration (700 ppm). This approach differs from that of *Swap et al.* [1992], who used values of PO_4 derived from *Talbot et al.*'s [1986] study of airborne dust over the Amazon. Consideration of PO_4, the most biologically available and rapidly cycling form of P, versus total P is appropriate for studies interested in only short-term plant uptake or in marine environments in which dust particles settle out of the water column before any weathering of primary P-bearing materials occurs. Over long timescales, however, dustborne P-bearing minerals will weather in the soil profile and all of the P in these fine-grained, high surface area particles will be available.

[8] Samples of airborne dust collected in the Amazon Basin at Alta Floresta (9°S, 56°W) from August 23, 2000, to September 11, 2002, and analyzed using particle-induced X-ray emission (PIXE) support the use of near-continental P concentrations as estimates of total P concentration in desert dust (Figure 2). These samples are most likely mixtures of pyrogenic aerosols and mineral dust. Because biomass in the Amazon Rain Forest is typically very poor in Al but rich in P, biogenic emissions can be assumed to have negligible Al concentrations and high but variable P concentrations. A mixture of pyrogenic and mineral aerosols would thus describe an envelope in Al-P space, the lower limit of which is described by the relative proportions of Al and P in the mineral aerosols. The lower limit of the aerosol samples collected in the Amazon Basin corresponds to P/Al = 6.0×10^{-3}, close to the continental P/Al ratio (Figure 2). This result suggests that mineral aerosols in the Amazon Basin, comprised primarily of aluminosillicates, have a nearly crustal composition, slightly enriched in Al relative to P. Furthermore, the P/Al ratio for the collected aerosol samples displays its minimum values during the summer months, indicating the dominance of desert dust during this time.

[9] Values for soil P concentration were derived by combining a global soil map with information about P concentration in different soils. An order-level global soil map available from the United States Department of Agriculture National Resource Conservation Service based on a global soil map produced by the Food and Agricultural Organization of UNESCO (http://www.nrcs.usda.gov/technical/worldsoils/mapindx/order.html) was combined with total soil P values typical of each soil order (Table 1) to produce a global map of soil P (Figure 1). Reports of total soil P at depths greater than 20 cm are rare in the scientific literature, and global maps of soil depth are also unavailable. As a result, estimation of soil P in the entire soil profile is not possible. However, because cycling of P is most active near the soil surface, we consider utilization of total soil P in the surface horizons an adequate representation of P stocks most important for maintenance of long-term ecosystem productivity [*Jobbagy and Jackson*, 2001].

[10] The values of total soil P used in this study are not intended to be authoritative. In particular, we recognize that the global variability of P stocks within an order may exceed the variability between orders. This is particularly true for P in young soils (Inceptisols and Entisols), the stocks of which are nearly entirely inherited from variable parent material. However, because the soil P concentrations used here span a range ($\sim$300–2000 kg/ha) that is small relative to the range of soil P inputs on dust ($\sim 10^{-3}$–10^{0} kg/ha/yr), we do not anticipate that inaccuracies in soil P stocks will significantly impact the overall patterns of the calculated soil P pseudo-turnover times for most soils.

[11] Geological and geomorphic provinces that have relatively young soils can be expected to have higher

Table 1. Concentration of P in the Top 20 cm of Soils by Order Used in This Study

Soil Order	Total P in Top 20 cm, kg/ha	Source
Alfisol	613	*Cross and Schlesinger* [1995]
Andisol	1039	derived[a]
Aridisol	928	*Cross and Schlesinger* [1995]
Entisol	1369	*Cross and Schlesinger* [1995]
Gelisol	982	*Beyer et al.* [2000]
Histosol	1076	*Schlichting et al.* [2002]
Inceptisol	841	*Cross and Schlesinger* [1995]
Mollisol	1101	*Cross and Schlesinger* [1995]
Oxisol	354	*McGrath et al.* [2001]
Spodosol	410	*Cross and Schlesinger* [1995]
Ultisol	515	*Cross and Schlesinger* [1995]
Vertisol	1906	*Cross and Schlesinger* [1995]

[a]Value for Andisols is derived from total P concentration from Mount St. Helens ejecta, multiplied by a typical Andisol bulk density (0.7 g/cm^3).

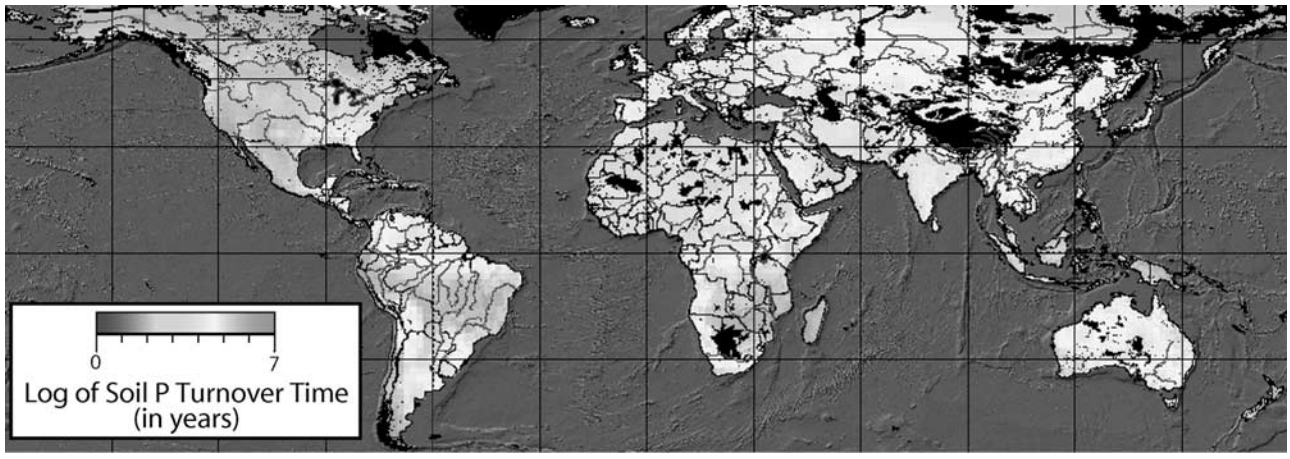

Figure 3. Estimated values of soil P turnover time with respect to inputs of P on desert dust, τ_P. Note log scale. Black areas have little to no soil development: ice, shifting sand, and rock. See color version of this figure at back of this issue.

concentrations of total soil P relative to the more mature soils used here (Table 1). For instance, loess deposits, such as those of the central United States, the Pampas in South America, and the Loess Plateau in China are comprised of P-rich, fine-grained, easily weathered primary minerals. Likewise, P-depleted soil was removed by advancing ice in many areas during the Last Glacial Maximum, including much of northern North America, northern Eurasia, and the valley floors of abundant alpine glaciers. Modern soils that form in these areas date only to the retreat of the ice and are formed on mostly unweathered bedrock and glacial detritus. Finally, in areas of high relief, the constant removal of topsoil on geologic timescales by fluvial erosion and mass wasting ensures constant re-exposure of unweathered material and hence perennially young soils. Erosion and mass wasting of soils in areas of high relief also leads to removal of dust incorporated into the soil, effectively limiting the lifetime of primary mineral P from dust in these soils. Thus, for regions in which the estimated soil P turnover time with respect to aeolian inputs exceeds the timescale for renewal of the surface due to geologic processes, the pseudo-turnover times presented here must be considered simply indices of the importance of modern dust P inputs relative to the modern soil P reservoir.

3. Results and Discussion

[12] Pseudo-turnover times of soil P with respect to inputs of P on deposited dust, τ_P, display a range of values, spanning 5 orders of magnitude from $\sim 10^2$ years to 10^7 years, and indicate that the importance of dust P inputs to soils varies widely depending on (1) the rate of dust deposition and (2) the concentration of P in soils (Figure 3). Geologic processes of surface renewal can operate on timescales shorter than 10^2–10^7 years. In cases where τ_P exceeds the age of the surface, soil P cannot be in steady state and the calculated values for τ_P must be interpreted as an index (with units of years) of the relative importance of modern dustborne P inputs to P cycling in soils.

[13] Initial examination of pseudo-turnover times reveals a sharp contrast between Eurasia and North America, reflecting the differing strength of dust sources in the eastern and western hemispheres. *Prospero et al.* [2002] have discussed the "Dust Belt," a belt of strongly emitting desert dust sources, stretching across North Africa, through Arabia, and into the arid interior of Asia. The western hemisphere, by contrast, lacks large and persistent dust sources of the sort found in the Eurasian Dust Belt. The difference between dust sources in the eastern and western hemispheres is reflected in the significant differences in dust deposition, and hence in the importance of dustborne P in nutrient cycling. In particular, the relatively short dustborne P turnover times for Europe ($\sim 10^3$–10^4 years) contrast sharply with the relatively long turnover times for North America ($>10^5$ years). The well-known red snows of Europe caused by the incorporation North Africa aeolian material into snow-generating air parcels bespeak the importance of aeolian materials to European soils [*Franzen et al.*, 1994; *Mattsson and Nihlen*, 1996].

3.1. P Cycling in Dust Source Areas

[14] The shortest dustborne P turnover times are observed in the Dust Belt itself. This arises from the fact that strongly dust-emitting areas also display the greatest deposition as the coarsest airborne material is redeposited in the near-field, resulting in very rapid nutrient cycling in these deserts. Whereas in highly vegetated regions, nutrient cycling is accomplished through uptake by plants and decomposition of plant material in the soil, the dominance of abiotic transport in arid and semiarid region nutrient cycling is apparent. In particular, Figure 3 highlights the importance of aeolian processes in driving nutrient movement in arid and semiarid regions.

[15] While the deposition of P-rich material in arid areas that are the strongest sources of desert dust may have limited impact on the vegetation of these highly water-limited environments, our results indicate the potential importance of dust-emitting deserts on the long-term maintenance of productivity in semiarid desert margins. In particular, the

grasslands of the Sahel and Central Asia display very short soil P turnover times with respect to aeolian inputs ($\sim 10^2$–10^4 years). This result indicates an important difference between North American and Eurasian grassland ecosystems. We conclude that in Eurasian grasslands, soil P is mainly dust-derived and has a constant depositional source. In North American grasslands, by contrast, soil P appears to be derived mainly from parent material with insignificant atmospheric deposition. The consequences of this difference for ecosystem function and dynamics in North American and Eurasian grasslands has, to our knowledge, never been investigated or commented upon in the literature, but may be an interesting area for future study.

[16] *Okin et al.* [2001b, 2001a] have suggested that wind erosion in arid and semiarid environments can be important in redistributing nutrients within landscapes and in creating islands of fertility. Windborne dust, therefore, must be considered not only an important contributor to the regional biogeochemical cycling of P, but aeolian processes themselves are likely important determinants of P-rich hot spots within ecosystems. Thus even in environments that are, in aggregate, not highly dependent on dustborne P for the maintenance of long-term productivity, loci within a landscape may be relatively P-poor and therefore beholden to dustborne P from either local or distant sources.

3.2. Importance of P Deposition to North American Ecosystems

[17] In the North American midlatitudes, a general decrease in dustborne P turnover times from $\sim 10^{4.5}$ to $\sim 10^6$ is observed from west to east, with the greatest dependence of soil P on dust inputs observed in the southeastern United States. This trend accompanies a general increase in podzolization processes, and P leaching, from west to east and north to south in North America, indicated by the prevalence of Ultisols underlying the deciduous forests of the southeastern United States. These results indicate that in eastern North American forests, long-term productivity and P availability is largely mediated by inputs of P from desert dust originating in North Africa. In contrast, areas of the central United States experience much less P deposition in desert dust and are therefore much less dependent on P for the maintenance of soil productivity. In fact, the dominance of glacially deposited material (i.e., loess, moraines, etc.) or glacially exposed bedrock in much of the central United States and Canada probably indicates that the turnover time of P with respect to dust inputs is much longer in these ecosystems than indicated in Figure 3.

3.3. Importance of Dust Deposition for Old Soils in Humid Environments: Hawaii, the Amazon, and the Congo

[18] During the >4 million years of soil development observed in the Hawaiian Islands, *Chadwick et al.* [1999] have concluded that atmospheric contributions control the soil P pool after a few million years. Hawaii, located in the tropical Pacific, is among the least dusty areas of the globe, displaying approximately 10^{-3} kg/ha/yr P deposition. The parent material for Hawaiian soils, likewise, is extremely P-rich (~4000 kg/ha in the youngest soils, from *Crews et al.* [1995]), being originally derived directly from mantle-derived ocean island basalt. In our independent estimate here of the turnover time of soil P in Hawaiian soils with respect to dustborne P inputs for Hawaii, we estimate a pseudo-turnover time of a few million years. Thus geochemical estimates of the importance of soil P from Chadwick et al. corroborate our estimate of the times required for aeolian P to dominate the P reservoir in Hawaiian soils.

[19] Soil formation on Kauaii, the westernmost and oldest Hawaiian Island, over the past several millions years, has occurred under moderately variable local climate [*Hotchkiss et al.*, 2000]. By contrast, global climate has changed far more drastically. In particular, some authors have indicated dramatically higher dust deposition in the Pacific during the Pleistocene caused by increased aridity in some areas of the globe and the greater availability of fine-grained glacial till during glacial periods [*Patterson et al.*, 1999]. The similarity between the estimates of *Chadwick et al.* [1999] from Hawaiian soils, which comprise an integration of climatic changes over the past 4 million years, with those presented here, based on present inputs of P, indicates that the present-day importation of P on dust to Hawaiian soils is close to the average value for the central Pacific for the past several million years.

[20] In the Amazon and Congo Basins, by contrast, additions of P on dust from the Sahara are large enough relative to soil P concentration to have replenished the soil P many times since the evolution of these ecosystems. By contrast, relatively high soil P concentrations in the young volcanic soils of the tropical forests of Central America, the Philippines, and Indonesia, coupled with low dust deposition rates in these areas, results in long turnover times.

[21] The short turnover times in the Amazon and Congo tropical rain forests, the shortest outside of the dust producing regions themselves, indicate a strong dependence of their respective soil P pools on Saharan dust, a result consistent with the conclusion of *Swap et al.* [1992] for the Amazon. While our estimates for the dust deposition in the Amazon are an order of magnitude less than those of Swap et al., the use here of total P concentration in dust instead of dustborne phosphate from *Talbot et al.* [1986] results in very similar estimates of dustborne P deposition in the Amazon Basin.

3.4. Changing P Deposition Through Time in the Amazon Basin

[22] The short turnover times of dustborne P in Amazonian soils indicates that soil P in the Amazon Basin may be dependent on changing dust deposition due to changing Saharan climate and global circulation patterns that have affected land cover in the Sahara source areas. *deMenocal et al.* [2000] have reported the changing deposition of Saharan dust to the Atlantic over the past 25 kyr. The material deposited off the western coast of North Africa and recorded in cores analyzed by deMenocal et al. belongs to the same plume of material that is deposited in the Amazon Basin [*Talbot et al.*, 1986; *Swap et al.*, 1992]. Thus Atlantic core data can be used to estimate the amount of material deposited in the Amazon Basin in the past.

[23] In order to identify the effect of changing dust deposition on the Amazon Basin soil P reservoir, ocean

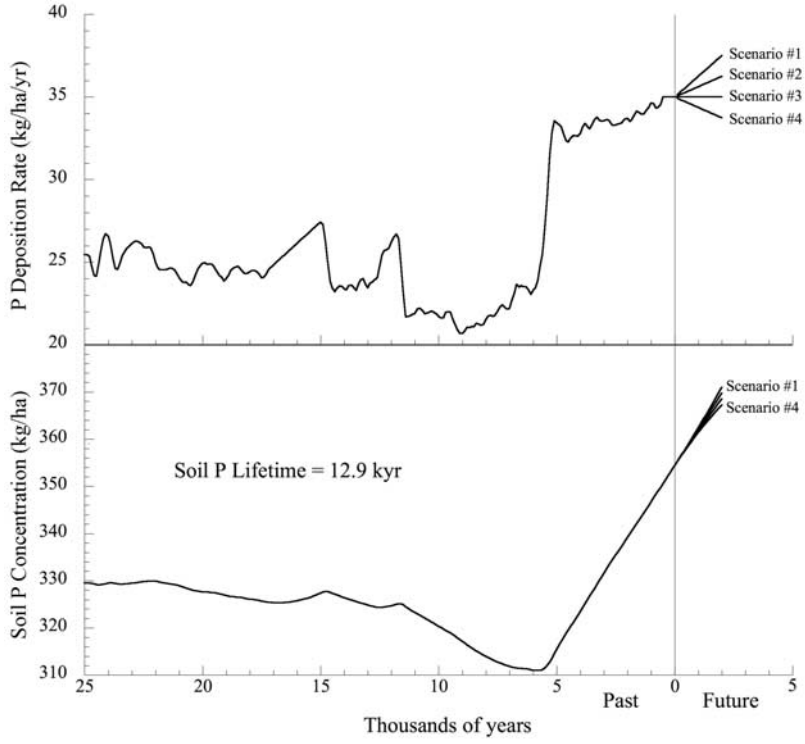

Figure 4. (top) Estimates of past dust deposition to the central Amazon Basin based on sediment core deposition rates reported by *deMenocal et al.* [2000]. (bottom) Estimates of soil P concentration for Oxisols in the central Amazon Basin, assuming an initial steady-state concentration. Four future scenarios are considered: Scenario 1, deposition rate increases to twice the rate of increase observed from 4 ka to present; Scenario 2, deposition rate same as the rate of increase observed from 4ka to present; Scenario 3, deposition rate remains at current level (35 kg/ha/yr); and Scenario 4, deposition rate decreases at a rate equal to the rate of increase observed from 4 ka to present.

sediment core values for terrigenous material deposition from *deMenocal et al.* [2000] were interpolated to 100-year spacing and resulting values were smoothed with a 300-year running average filter. The smoothed data were then divided by the youngest dust deposition value (11.7 g/cm^2/kyr) and multiplied by modern-day P deposition in the central Amazon (35 kg/ha/yr), essentially normalizing the data to modern deposition. This approach accounts for the reduction in dust deposition downwind of the dust source area, but does not accommodate changes in atmospheric circulation over the past 25 kyr.

[24] The variability of dustborne P delivery to the Amazon Basin in the past 25 kyr, and particularly the general increase over the past 4 kyr, suggests that soil P concentrations are not in steady state in the Amazon Basin. Therefore the resulting estimates of past deposition of P to Amazon soils (Figure 4) were used to construct a nonsteady state model of soil P concentrations that includes an exponential decay term and a time-variable deposition term,

$$\frac{dP(t)}{dt} = -\lambda P(t) + D_P(t), \tag{2}$$

where $P(t)$ is the soil P concentration in the top 20 cm, $D_P(t)$ is the aeolian P deposition rate, and $\lambda = \tau^{-1}$, where τ is the lifetime of P in the soil and is different from the pseudo-steady state lifetimes, τ_P, reported in Figure 3.

[25] The nonsteady state model of soil P has three degrees of freedom: (1) the concentration of soil P at 25 kyr B.P. (P(25ka)), (2) the lifetime of P in soils, τ, and (3) the time-dependent rate of P deposition, $D_P(t)$ (Figure 4). If soil P concentration is assumed to be in steady state at 25 kyr B.P., meaning that P(25ka) = D_P(25ka)/τ, then constraining the present-day value of soil P for Amazon Basin Oxisols (354 kg/ha; see Table 1) dictates values of τ and P(25ka) of 12.9 kyr and 330 kg/ha, respectively. Soil P concentration for Oxisols in the central Amazon Basin over the past 25 kyr using these values is presented in Figure 4.

[26] Results from the nonsteady state model indicate that over the past 25 kyr, a total of approximately 602 kg/ha have been removed from Amazonian Oxisols. The average soil P concentration for the past 25 kyr for these soils is 325 kg/ha (Figure 4). We conclude that the entire soil P pool in the Amazon has been replenished roughly twice by dustborne P addition during this time, indicating that soil P stocks and long-term productivity in the Amazon is highly dependent on Saharan dust despite its variability in the past.

[27] If the assumption of steady state concentration at 25 kyr B.P. is abandoned and a reasonable range of initial P

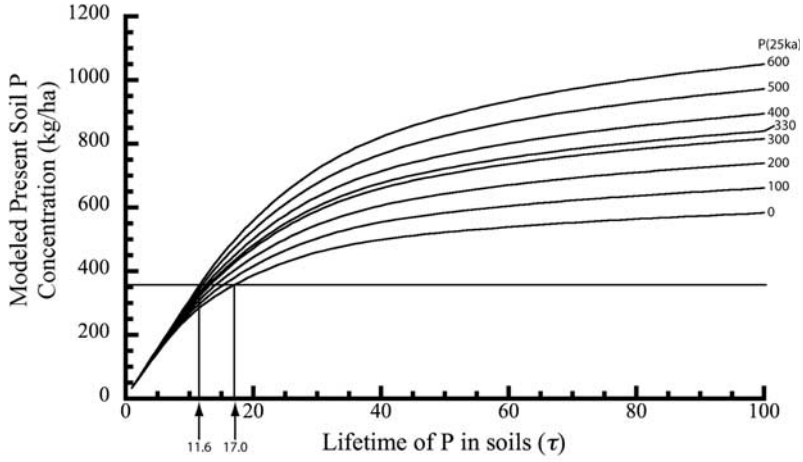

Figure 5. Modeled present soil P concentration versus lifetime of P in soils for several different starting soil P concentrations, P(25ka) in kg/ha. Modern Amazon Oxisol soil P (horizontal line) can be explained by a relatively narrow range of lifetimes for a wide range of initial P concentrations.

soil concentration is considered, then a range of estimates for τ results (Figure 5). The range of estimates obtained in this way is remarkably narrow, indicating that the lifetime of P in Amazon soils lies between 10 and 20 kyr. This estimate is highly consistent with the pseudo-steady state turnover time estimated for the central Amazon of a few tens of thousands of years (Figure 3). Thus it would be simple to conclude that future climate change would have a dramatic impact on soil P concentrations in the Amazon over the next few thousand years.

[28] However, the abrupt termination of the African Humid Period and consequent jump in dust emission from Africa at 5 kyr B.P. [*deMenocal et al.*, 2000] has resulted in present-day soil P concentrations in the Amazon that may be significantly below steady state values (the steady state P concentration given D_p = 35 kg/ha/yr and τ = 12.9 kyr is approximately 450 kg/ha). As a result, soil P concentrations in the Amazon can be expected to rise over the next several thousand years, regardless of trends in African dust emission and transport.

[29] To show this, we modeled future central Amazon soil P concentrations for four different scenarios (Figure 4): in Scenario 1, dustborne P deposition increases at a rate twice that of the rate of increase observed over the past 4 kyr ($+1.3 \times 10^{-3}$ kg/ha yr^2); in Scenario 2, dustborne P deposition increases at a rate equal to the rate of increase observed over the past 4 kyr ($+6.3 \times 10^{-4}$ kg/ha yr^2); in Scenario 3, dustborne P deposition remains constant at present levels, and in Scenario 4, dustborne P deposition decreases at a rate equal to the rate of increase observed over the past 4 kyr (-6.3×10^{-4} kg/ha yr^2).

[30] Scenarios 2 and 3 represent the control case, with no change in P deposition or changes commensurate with recent trends in deposition associated with the continuing aridification of North Africa. Scenario 1 represents the case in which anthropogenic disturbance and/or climate change results in dramatic changes to North African soils and/or the regional hydrological cycle. Scenario 4 represents a case where a warmer climate results in increased precipitation in North Africa and suppression of dust emission from the continent.

[31] In all four scenarios, modeled soil P concentrations increase for the next several thousand years. Although Scenario 4 does result in the lowest future soil P concentration increases in the Amazon Basin, the differences between the scenarios are minor, suggesting that the far-from-equilibrium soil P concentration in the present-day Amazon will dominate the trends in long-term P dynamics in the near future. Land use and climate change in North Africa, in other words, are likely to have an insignificant impact on P cycling and productivity in the Amazon. Furthermore, due to its similarities with the Amazon in terms of the age of the ecosystem and the amount of dust deposited there, we conclude that the Congo will also be unaffected by changes in surface conditions in North Africa.

4. Summary and Conclusions

[32] Estimates of the turnover time of soil P with respect to aeolian P inputs provides a unique perspective on the importance and patterns of aeolian deposition to terrestrial landscapes. Differences between the eastern and western hemispheres, with the eastern hemisphere displaying significantly lower P turnover times, reflect the prevalence of large and persistent dust sources in the eastern hemisphere and indicates that there may be important ecological differences in P-limited ecosystems in the two hemispheres. Dust source regions are areas of intense soil P cycling on large scales through aeolian emission, transport, and deposition. While deserts of the Dust Belt are too water-limited for this rapid cycling to have a major influence on ecosystem dynamics in these regions, semiarid desert margins, which receive significant aeolian P from the neighboring deserts, are likely dependent on dustborne P for the long-term maintenance of productivity. This is particularly true for the semiarid steppes of Africa and Eurasia. Semiarid regions at the margins of dust-producing deserts are continental-scale sinks for dustborne P and can thus be expected to be

highly productive in the long term under conditions of sufficient soil moisture and N concentrations. We conjecture that under more mesic conditions, however, highly winnowed P-depleted areas in dust-producing deserts will remain unproductive areas underlain by sandy soils.

[33] For old humid ecosystems such as the western Hawaiian Islands, the Amazon Basin, and the Congo Basin, dustborne P may be the primary controller of soil P concentration, and therefore maintenance of long-term productivity. However, for these ecosystems, variability in past P deposition, particularly in light of the geologically recent end of the glacial period and the subsequent changes to the global climate, may provide the strongest controls on present as well as future soil P. Consideration of soil P concentration in the Amazon Basin indicates that soils are probably not in equilibrium with respect to dustborne P deposition.

[34] Our finding that soil P concentrations are highly variable even in old, highly weathered ecosystems such as the Amazon and the Congo provides an important contribution to our understanding of the function of these ecosystems over long timescales. In particular, our findings suggest that these ecosystems are currently net P sinks and that reasonable anthropogenic or climatic perturbations to global dust dynamics will have little effect on soil P concentrations. Indeed, soil P in old equatorial forests is likely to rise even under severely altered climate. Only a nearly complete cessation of the dust cycle such as that conjectured during the African Humid Period is likely to have an impact on P concentrations in tropical ecosystems.

[35] In light of the dramatic anthropogenic changes to these ecosystems, the expected increase in soil P concentrations in the Amazon and the Congo in distant future is difficult to predict. On a millennial timescale, our findings imply that soil fertility lost as the result of land use is not necessarily permanent, particularly in the northern reaches of these tropical ecosystems where dust deposition is most significant: The soil P reservoir is likely to be replenished by dustborne P inputs. For regions that are spared significant anthropogenic alteration and that do not undergo significant climate change, our results indicate a likely long-term increase in productivity [*Davidson et al.*, 2004]. This increase in productivity may be accompanied by an increase in biomass resulting in increased sequestration of atmospheric CO_2.

[36] Of course, the importance of dustborne P to an ecosystem also depends on the soil P reservoir. Anthropogenic activities throughout the globe are resulting in changes to P cycling that impact the importance of dustborne P to soils. Fertilizer additions of P in many parts of the globe, particularly the developed world, dwarf additions to soils by aeolian deposition, obviating the impact of dustborne P on the local P cycle. In areas with increased topsoil erosion due to human activities such as agriculture and deforestation, on the other hand, aeolian redistribution of P at multiple scales will become increasingly important in the preservation or regeneration of long-term productive potential.

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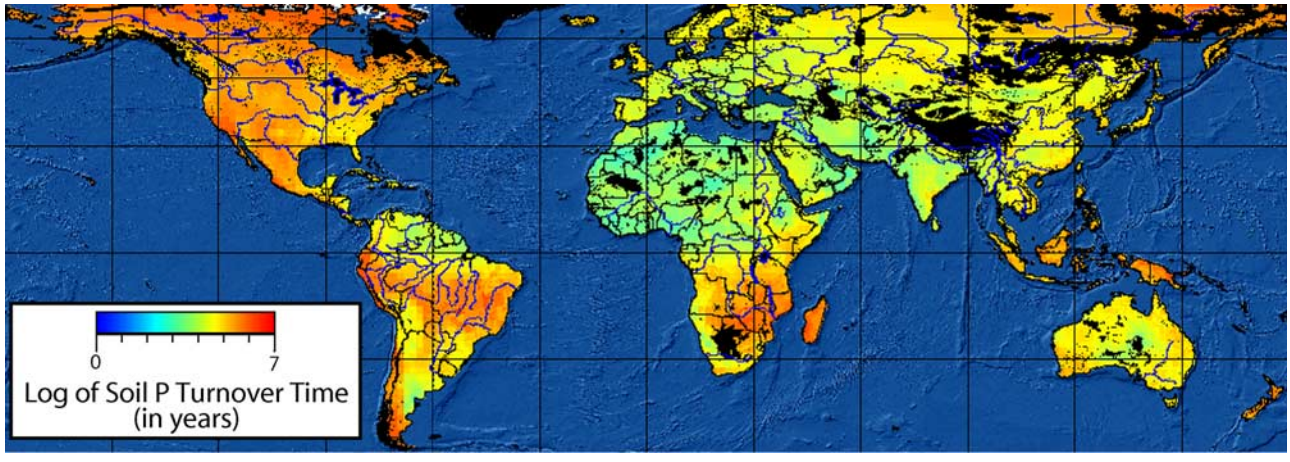

Figure 3. Estimated values of soil P turnover time with respect to inputs of P on desert dust, τ_P. Note log scale. Black areas have little to no soil development: ice, shifting sand, and rock.