The impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems

Gregory S. Okin
Department of Environmental Sciences
University of Virginia
PO Box 400123
Charlottesville, VA 22904-4123

Natalie Mahowald
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80302

Oliver A. Chadwick
Department of Geography
University of California
Santa Barbara, CA 93106

Paulo Artaxo
Instituto de Fisica
Universidade de Sao Paulo
Rua do Matao, Travessa R, 187
CEP 05508-900, Sao Paulo, Brazil

ABSTRACT

Without significant inputs of plant-available P to the soil from weathering of parent material, leaching and partitioning of P into reservoirs not available to plants can limit the long-term productivity of terrestrial ecosystems. Atmospheric inputs of P delivered on desert dust may be important for the maintenance of productivity for many environments. Here, 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. Our estimates provide a broad understanding of the importance and patterns of aeolian deposition to terrestrial landscapes. Dust source areas are shown to be areas of intense soil P cycling on large scales. While major desert dust source areas are likely too limited by water availability for this rapid cycling to have a major influence on soil 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. Indeed, the prevalence of large dust sources in Africa and Eurasia makes the soils in these areas generally much more dependent on 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, in particular, is seen to be highly dependent on aeolian deposition for the maintenance of long-term productivity. 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 future soil P in the Amazon.
Abstract ................................................................................................................................. 1

Introduction ............................................................................................................................. 4

Methods .................................................................................................................................... 5

Results and Discussion ........................................................................................................... 9

P Cycling in Dust Source Areas ............................................................................................ 11

The Importance of P Deposition to North American Ecosystems ........................................ 12

Hawaii and the Amazon: The Importance of Dust Deposition in Old Soils ......................... 12

Changing P Deposition Through Time in the Amazon Basin ............................................. 15

Summary and Conclusions .................................................................................................. 18
INTRODUCTION

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 the parent material. Weathering of parent material releases P, which then apportions into different pools of varying availability to plants. Losses of P due to leaching, biomass removal through harvesting or fire, or erosion of surface soils, in this view, constitute irreplaceable losses of P from the total P reservoir, thus limiting long-term ecosystem productivity.

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 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 results indicate that inputs of P on dust transported long distances varies depending on 1) the input of P from remote dust sources, and 2) the reservoir of total soil P in downwind ecosystems. Thus, some ecosystems may be highly reliant on input of P from foreign ecosystems for the maintenance of long-term productivity while others may be more dependent on the input of P from weathering of P minerals in the soil.
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

The global loading of desert dust is known to vary on timescales on the order of thousands of years in response to changes in global circulation and regional climate in dust-producing areas (deMenocal et al., 2000; Duce and Tindale, 1991; Mahowald et al., 1999). Some authors (e.g. Tegen and Fung, 1995) 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 may be sensitive to changes in climate and land use in dust source areas.

Here, the importance of P deposited in desert dust to terrestrial ecosystems is analyzed and the consequences of climate change on dust inputs to soils are considered.

METHODS

Pseudo-turnover times of P with respect to dust-borne P inputs, $\square_P$, were calculated for the world’s soils:

$$\square_P = \frac{C_{s,P}}{C_{d,P}D},$$

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). Although soil P is most likely not in steady state and thus the calculated values for $\square_P$ do not represent actual turnover times, pseudo-turnover times do provide a valuable index of the importance of dust-borne P inputs to P cycling in soils.
Estimates of dust deposition, \( D \), are provided by output from the Dust Emission and Deposition (DEAD) module in the Model of Atmospheric Transport and Chemistry (MATCH; Mahowald et al., 1997; Rasch et al., 1997). In DEAD, desert dust in source regions is mobilized when large particles (~75 \( \mu \)m) 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 are 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 2) has been reported and discussed in greater detail elsewhere (Mahowald et al., 1999).

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, as this value encompasses all pools of P in the soil, regardless of their availability to 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 (7 ppm). This approach differs from that of Swap et al. (1992), who used values of $\text{PO}_4^{2-}$ derived from Talbot et al.’s (1990) study of airborne dust over the Amazon during the ABLE-2B experiment. Consideration of $\text{PO}_4^{2-}$, 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. In soils over long time scales, however, primary 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.

Samples of airborne dust collected in the Amazon Basin at Alta Floresta (9°S, 56°W) and analyzed using particle-induced X-ray emission (PIXE), supports 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 is typically very poor in Al but rich in P, biogenic emissions can be assumed to have

**Figure 2.** Plot of P concentration vs. 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 light line corresponds to a P/Al ratio of $6 \times 10^{-3}$. The heavy line corresponds to a P/Al ratio of $1.5 \times 10^{-3}$, atmospheric dust P measured by Talbot et al. (1990) divided by the crustal Al concentration. The crustal P/Al ratio is $8.8 \times 10^{-3}$. 
negligible Al concentrations and high but variable P concentrations. 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 x 10^{-3}, close to the continental P/Al ratio (Figure 2). This result suggests that mineral aerosols in the Amazon Basin have a nearly crustal composition, slightly enriched in Al relative to P. This is consistent with the fact that the majority of material carried long distances by aeolian transport consists of aluminosilicates.

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

**Table 1.** Concentration of P in the top 20 cm of soils by Order.

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Total P in top 20 cm (kg/ha)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisol</td>
<td>613</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Andisol</td>
<td>1039</td>
<td>?a</td>
</tr>
<tr>
<td>Aridisol</td>
<td>928</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Entisol</td>
<td>1369</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Gelisol</td>
<td>982</td>
<td>Beyer et al. (2000)</td>
</tr>
<tr>
<td>Histosol</td>
<td>1076</td>
<td>Schlichting et al. (2002)</td>
</tr>
<tr>
<td>Inceptisol</td>
<td>841</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Mollisol</td>
<td>1101</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Oxisol</td>
<td>354</td>
<td>McGrath et al. (?????)</td>
</tr>
<tr>
<td>Spodosol</td>
<td>410</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Ultisol</td>
<td>515</td>
<td>Choss et al. (1995)</td>
</tr>
<tr>
<td>Vertisol</td>
<td>1906</td>
<td>Choss et al. (1995)</td>
</tr>
</tbody>
</table>

*aValue for Andisols is derived from total P concentration from Mt. St. Helense ejecta, multiplied by a typical andisol bulk density (0.7 g/cm^3)*
UNESCO was obtained†. Values for $C_s,P$ were derived by combining this soil map 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.

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 (~300 – 2000 kg/ha) that is small relative to the range of soil P inputs on dust ($\sim 10^3 - 10^6$ kg/ha/yr), we do not anticipate that inaccuracies in soil P stocks will significantly impact the overall accuracy of the calculated soil P turnover times.

RESULTS AND DISCUSSION

Estimated turnover times of soil P with respect to inputs of P on deposited dust,$[\square]$, display a range of values, spanning five orders of magnitude from $\sim 10^2$ years to $10^7$ years.

† http://www.nrcs.usda.gov/technical/worldsoils/mapindx/order.html
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

(Figure 3). These results 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.

Initial examination of these results reveals a sharp contrast between Eurasia and North America, reflecting the differing strength of dust sources on the in the eastern and western hemispheres. Prospero et al. (2002) have suggested the existence of a “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, persistent, and connected 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).
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

P Cycling in Dust Source Areas

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. The deserts of the Dust Belt are shown to be regions of very rapid nutrient cycling. 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.

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 important an important differences between North American and Eurasian grassland ecosystems, with Eurasian grasslands highly dependent on the importation of dust from nearby dust-emitting areas and North American grasslands more dependent on P already in the soil.

Okin et al. (2001a; 2001b) have suggested that wind erosion in arid and semiarid environments can be important in redistributing nutrients within landscapes and in the creating of 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 hotspots within ecosystems. Thus,
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

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 on dustborne P from either local or distant sources.

The Importance of P Deposition to North American Ecosystems

In the North American mid-latitudes, a general decrease in dustborne P turnover
times 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
Southeast. 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 dominated by Pleistocene
loess deposits have elevated soil P due to the presence in the soil of largely unweathered,
fine-grained rock flour. The loessal plains of North America, isolated from significant global
dust sources and rich in primary P-bearing minerals, are thus probably among the landscapes
least dependent on dustborne P for the maintenance of long-term productivity.

Hawaii and the Amazon: The Importance of Dust Deposition in Old Soils

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. During the > 4
million years of soil development observed in Hawaii, however, most of the original P is lost
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

and is replaced by P derived from aeolian sources. In particular, Chadwick et al. (1999) have concluded that atmospheric contributions control the soil P pool after a few million years (Figure 4). In our independent estimate 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.

Soil formation on Kauaii, the westernmost and oldest Hawaiian Island, over the past several millions years, has occurred under a relatively consistent local climate. During the past 4 million years the global climate has changed 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. 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.

The timescale for soil formation on Kauaii nearly matches the turnover time of soil P with respect to dustborne input. This observation highlights the interplay between
landscape stability and atmospheric P inputs, and indicates that as long a landscape is stable over the long-term, atmospheric P inputs can become dominant, regardless of the P content of the parent material. In many areas of the globe, recent glaciation, climate change, sedimentation, oceanic regression, and other factors have resulted in young soils. The soils of central Canada, for example, are young due to the retreat of the North American ice sheet since the end of the Pleistocene. The very limited input of dustborne P to the soils in this area, therefore, have had virtually no impact on soil P stocks.

In the Amazon Basin, 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 this ecosystem. Dust deposition derived from the DEAD model displays a good match with nearby deep-sea cores (Mahowald et al., 1999) as well as with in situ data, where available (Figure 5).

![Figure 5](#)

**Figure 5.** Comparison between surface dust concentration measured during the ABLE-2B experiment (solid line) and with DEAD model results from the same period (dashed line). ABLE-2B data from [Natalie?](#)

The short turnover times in the Amazon Basin—the shortest outside of the dust producing regions themselves—indicate a strong dependence of the soil P pool in the Basin on Saharan dust, a result consistent with the conclusion of Swap *et al.* (1992). 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. (1990) results in very similar estimates of dustborne P deposition in the Basin.

### Changing P Deposition Through Time in the Amazon Basin

The short turnover times of dustborne P in Amazonian soils indicates that soil P in the Basin may be dependent on changing dust deposition due to changing Saharan climate. 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 (Swap et al., 1992; Talbot et al., 1990). Thus, Atlantic core data can be used to estimate the amount of material deposited in the Amazon Basin in the past using the following methodology: 1) ocean sediment core values for terrigenous material deposition were interpolated to 100-yr spacing and resulting values were smoothed with a 300-yr running average filter, 2) the smoothed data were then divided by the youngest

![Figure 6](image)

**Figure 6.** Top: Estimates of past P 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 4 ka to present  
Scenario #3: Deposition rate remains at current level (35 kg/ha/yr)  
Scenario #4: Deposition rate decreases at a rate equal to the rate of increase observed from 4 ka to present.
dust deposition value (11.7 g/cm²/kyr) and multiplied by modern-day P deposition in the central Amazon (35 kg/ha/yr).

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 Basin. Therefore, the resulting estimates of past deposition of P to Amazon soils (Figure 6), were used to construction a non-steady state model of soil P concentrations that includes an exponential decay term and a time-variable deposition term:

\[
\frac{dP(t)}{dt} = -\tau P(t) + D_P(t),
\]

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

The non-steady 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, \(\tau\) and 3) the time-dependent rate of P deposition, \(D_P(t)\), given in Figure 6. If soil P concentration is assumed to be in steady state at 25 kyr B.P.—meaning that \(P(25ka)=D_P(25ka)/\tau\)—then constraining the present day value of soil P for Amazon Basin Oxisols (354 kg/ha, see Table 1) dictates values of \(\tau\) and \(P(25ka)\) of 12.9 kyr and 330 kg/ha, respectively. Soil P

---

**Figure 7.** Modeled present soil P concentration vs. 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.
concentration in the central Amazon Basin over the past 25 kyr using these values is presented in Figure 6.

Results from the non-steady 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 6). We conclude that the entire soil P pool in the Amazon has been replenished 1.85 times by dustborne P addition during this time. We conclude that the maintenance of soil P stocks and long-term productivity in the Amazon is highly dependent on Saharan dust.

If the assumption of steady state concentration at 25 kyr B.P. is abandoned and a reasonable range of initial P soil concentration is considered, then a range of estimates for results (Figure 7). The range of estimates obtained in this way is remarkably narrow, indicating that the lifetime of P in Amazon soils lies between 10 – 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 climate change would have a dramatic impact on soil P concentrations in the Amazon.

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 \( D_p = 35 \text{ kg/ha/yr} \) and \( t = 12.9 \text{ kyr} \) 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.

To show this, we modeled future central Amazon soil P concentrations for four different scenarios (Figure 6):
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

**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$^2$),

**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$^2$),

**Scenario #3:** Dustborne P deposition remains constant at present levels, and

**Scenario #4:** Dustborne P deposition decreases at a rate equal to the rate of increase observed over the past 4 kyr ($-6.3 \times 10^{-4}$ kg/ha yr$^2$).

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 result in dramatic changes to North African soils and/or the regional hydrological cycle. Scenario #4 represents the case where a warmer climate results in increased precipitation in North Africa and suppression of dust emission from the continent.

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. These results suggest 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.

**SUMMARY AND CONCLUSIONS**

Estimates of the turnover time of soil P with respect to aeolian P inputs provides broad understanding of 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, reflects the prevalence of large
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

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 areas
are seen to be areas of intense soil P cycling on large scales through aeolian emission,
transport, and deposition. While deserts of the Dust Belt are likely too limited by water
availability for this rapid cycling to have a major influence on soil 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.

For old humid ecosystems such as the western Hawaiian Islands and the Amazon
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. A brief consideration of soil P concentration in the Amazon Basin
indicates that soils in least parts of the Basin are not in equilibrium with respect to dustborne
P deposition.

Of course, anthropogenic changes to landscapes throughout the globe are resulting
in changes that will influence 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. However, in areas with increased topsoil erosion due to human activities
such as logging and deforestation, aeolian deposition of P will become increasingly
important in the regeneration of long-term productive potential.
The influence of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems
Okin, Mahowald, Chadwick, and Artaxo

CITED REFERENCES


