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Geoderma 130 (2006) 108–123

GEODERMA

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Atmospheric dust in modern soil on aeolian sandstone, Colorado Plateau (USA): Variation with landscape position and contribution to potential plant nutrients

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Received 2 June 2004; received in revised form 30 November 2004; accepted 17 January 2005
Available online 23 February 2005

Abstract

Rock-derived nutrients in soils originate from both local bedrock and atmospheric dust, including dust from far-distant sources. Distinction between fine particles derived from local bedrock and from dust provides better understanding of the landscape-scale distribution and abundance of soil nutrients. Sandy surficial deposits over dominantly sandstone substrates, covering vast upland areas of the central Colorado Plateau, typically contain 5–40% silt plus clay, depending on geomorphic setting and slope (excluding drainages and depressions). Aeolian dust in these deposits is indicated by the presence of titanium-bearing magnetite grains that are absent in the sedimentary rocks of the region. Thus, contents of far-traveled aeolian dust can be estimated from magnetic properties that primarily reflect magnetite content, such as isothermal remanent magnetization (IRM). Isothermal remanent magnetization was measured on bulk sediment samples taken along two transects in surficial sediment down gentle slopes away from sandstone headwalls. One transect was in undisturbed surficial sediment, the other in a setting that was grazed by domestic livestock until 1974.

Calculation of far-traveled dust contents of the surficial deposits is based on measurements of the magnetic properties of rock, surficial deposits, and modern dust using a binary mixing model. At the undisturbed site, IRM-based calculations show a systematic down-slope increase in aeolian dust (ranging from 2% to 18% of the surface soil mass), similar to the down-slope increase in total fines (18–39% of surface soil mass). A combination of winnowing by wind during the past and down-slope movement of sediment likely accounts for the modern distribution of aeolian dust and associated nutrients. At the previously grazed site, dust also increases down slope (5–11%) in sediment with corresponding abundances of 13–25% fines. Estimates of the contributions of aeolian dust to the total soil nutrients range widely, depending on assumptions about grain-size partitioning of potential nutrients in weathered bedrock. Nevertheless, aeolian dust is important for this setting, contributing roughly 40–80% of the rock-derived nutrient stocks (P, K, Na, Mn, Zn, and

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doi:10.1016/j.geoderma.2005.01.012

Fe) in uppermost soil over most of the sampled slope at the undisturbed site, which shows no evidence of recent wind erosion.
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Keywords: Dust; Soil chemistry; Soil texture; Magnetic properties; Nutrients; Colorado Plateau

1. Introduction

Ecosystems acquire their rock-derived soil nutrients from two main sources. One source is the local substrate, such as soil and unconsolidated sediments derived directly from in situ weathering of bedrock or from nearby bedrock. Another source is atmospheric deposition of mineral dust that commonly mixes with the soil and surficial deposits. Distinction between these two sources is important to understanding the geochemical characteristics of soils and the controls over the supply of rock-derived nutrients to plants (Vitousek et al., 1999). The distinction between substrate weathering and mineral-dust inputs can be made by integrating isotopic, mineralogic, textural, and geochemical analyses of soil. For example, dust geochemistry has been used to evaluate the long-term importance of atmospheric mineral-dust additions to the fertility of tropical forests on old, deeply weathered substrates in the Amazon basin (Swap et al., 1992). Similarly, a progressively more important role for atmospheric inputs to ecosystem fertility on progressively older Hawaiian islands is documented by strontium and neodymium isotopes and by the presence of quartz and micas in soil on mantle-derived basalts, which lack these minerals (Chadwick et al., 1999).

Geochemical, isotopic, and mineralogic methods have also been used to identify the presence of aeolian dust in soils and surficial deposits in deserts (e.g., McFadden et al., 1987; Wells et al., 1987; Muhs et al., 1990; Reheis et al., 1995; Shachak and Lovett, 1998). This body of work has improved understanding about interrelated aspects of dust content, soil composition and texture, and soil hydrology. Nevertheless, little is known in detail about the relative contributions of aeolian dust and bedrock weathering to rock-derived nutrient content of most dryland environments, in contrast to recent progress in discerning the disparate sources of soil fertility in the tropics.

The primary purpose of this study is to estimate the abundance of far-traveled mineral dust in modern soil in arid grassland and shrubland on the central Colorado Plateau. From this estimate, we also attempt to determine the relative importance of aeolian dust and weathered local bedrock in providing potential plant nutrients. An important aspect of this study is the finding that the spatial distribution of aeolian dust and its contributed plant nutrients are strongly controlled by position on shallow-gradient slopes. We limited the study to shallow soil (0–10 cm depths) on surficial sandy deposits derived entirely from Permian sedimentary rock, mainly mineralogically simple aeolian sandstone. The approach incorporates magnetic, textural, and geochemical results from samples of soil and rock, as well as atmospheric dust from passive collectors. The basis for applying magnetic methods is the presence of detrital magnetite in the soil and dust, along with its absence in the local bedrock. An earlier study showed that the magnetite, the amount of which can be measured using standard laboratory instruments and the type and size of which can be determined petrographically, must have been deposited as atmospheric mineral dust (Reynolds et al., 2001a). Some nutrients from atmospheric sources can be added to soil as ions dissolved in rainwater and snowmelt. In this study, we do not consider these nutrient sources because of our observations of tight associations between bulk-soil elemental chemistry and magnetite abundance, which is a proxy for mineral-dust addition to the soil.

2. Study sites and sampling

The study area is in Canyonlands National Park in the central part of the Canyonlands physiographic section of the Colorado Plateau (Hunt, 1956; Fig. 1). The Canyonlands region is characterized by nearly flat-lying Paleozoic and Mesozoic sedimentary rocks, and it supports vast expanses of high-elevation (~1500–1900 m), arid grassland and shrubland between deeply incised canyons. Sampling for this study was limited to the Needles district, an area underlain entirely by the Lower Permian Cedar Mesa Sandstone, some of it eroded into spires. The Cedar Mesa Sandstone consists dominantly of white aeolian quartzose sandstone and interbedded red, arkosic beds (redbeds) of sandstone and silty sandstone (Condon, 1997). The redbeds are colored by fine-grained hematite, occurring primarily as translucent rims on silicate grains. Much of the vegetated landscape in the Needles area consists of aprons of sandy surficial deposits that slope gently away from bedrock exposures.

We sampled surficial sediment on slopes at two sites, with focus on a site in Virginia Park, a sheltered basin (~200 ha at 1720 m asl) of vegetated, stabilized sand dunes surrounded on three sides by sandstone walls and bounded on the southwest by a canyon (Figs. 1 and 2). Reheis et al. (in press) described the late Quaternary geomorphic development of the study region and its buried deposits, on the basis of physical properties and optically stimulated luminescence age (OSL) determinations of surficial deposits from auger holes, hand-dug soil pits, and arroyo exposures. The slopes sampled for this study represent the most recent episode of significant aeolian modification of the landscape, including dune formation, that likely ceased by about 2 ka. Because of rugged surrounding topography and lack of water, domestic livestock have never grazed the site; it is referred to here as the never-grazed (NG) site (see Neff et al., in press). Samples were taken from 0 to 10 cm depths from locations, nearly evenly separated by about 20–25 m, along a transect down a gentle (mostly 1°–3°), northwest-facing slope (Fig. 2). The highest-elevation sampling location was near a cliff wall in stabilized dune sand supporting sparse pinyon and juniper, along with native bunchgrass and scattered shrubs. The sampling locations farther down slope traversed mixed plant communities of shrubs (mainly *Ephedra viridis* and *Atriplex canescens*) and native perennial bunchgrass (*Stipa comata*, *Stipa hymenoides*, and *Hillaria jamesii*), with cover by non-native cheatgrass (*Bromus tectorum*) generally increasing down slope in *Hillaria* communities. The spaces among plants are occupied by biologic soil crust (BSC), mainly

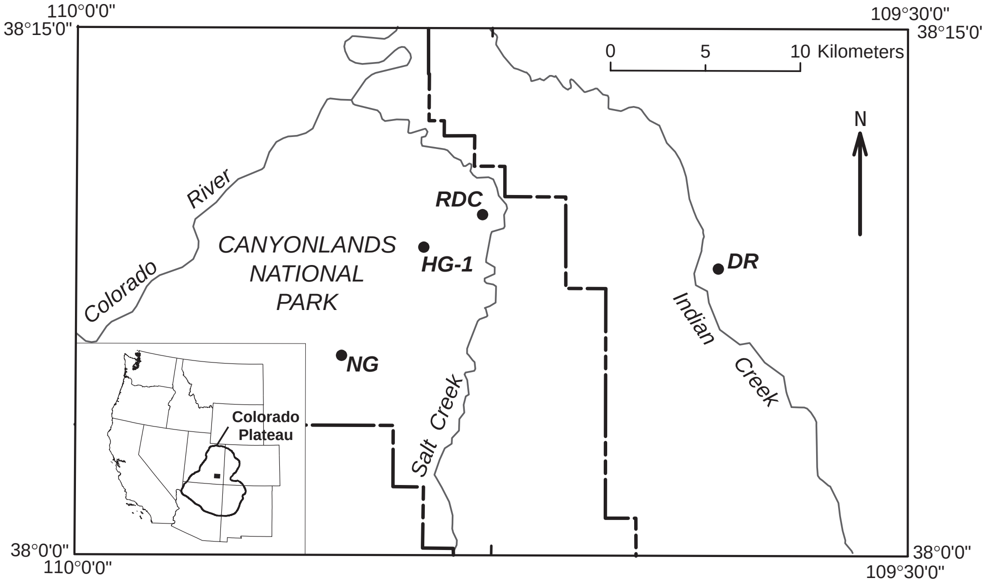

Fig. 1. Map of the study area showing locations of transect sites (NG and HG-1), Dugout Ranch monitoring site (DR), and the dust collection site near HG-1 (RDC). Indian Creek drains the northern Abajo Mountains (south of area of the map).

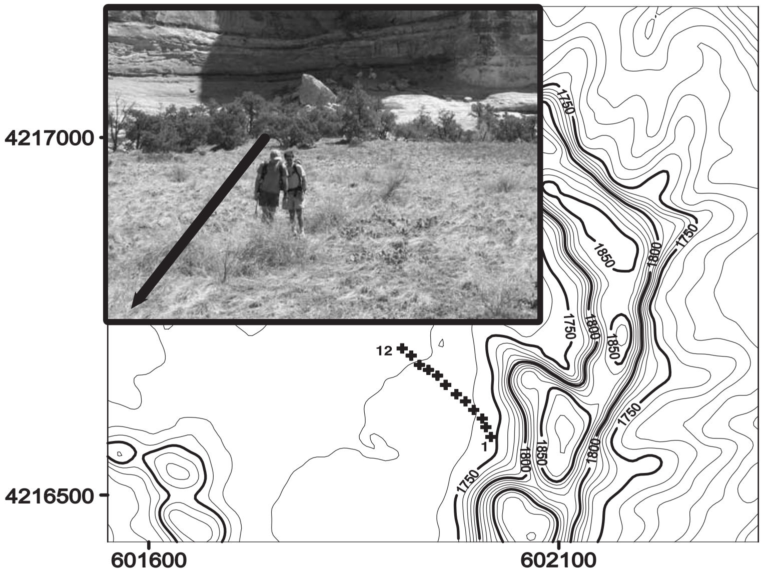

Fig. 2. Topographic and location map of the NG-site area (Virginia Park) based on contoured 30-m DEM grid (Druid Arch 7 1/2′ quadrangle) supplemented by 102 GPS control points calculated with differential correction. Elevations in meters with a 10-m contour interval. Universal Transverse Mercator (UTM, Zone 12N) northing and easting in meters. 1927 North American horizontal datum and 1929 National geodetic vertical datum. Plus (+) symbols mark locations of transect positions from upslope (1) to down slope (12). Inset photograph shows approximate location of the transect (arrow); figures are standing close to position 8.

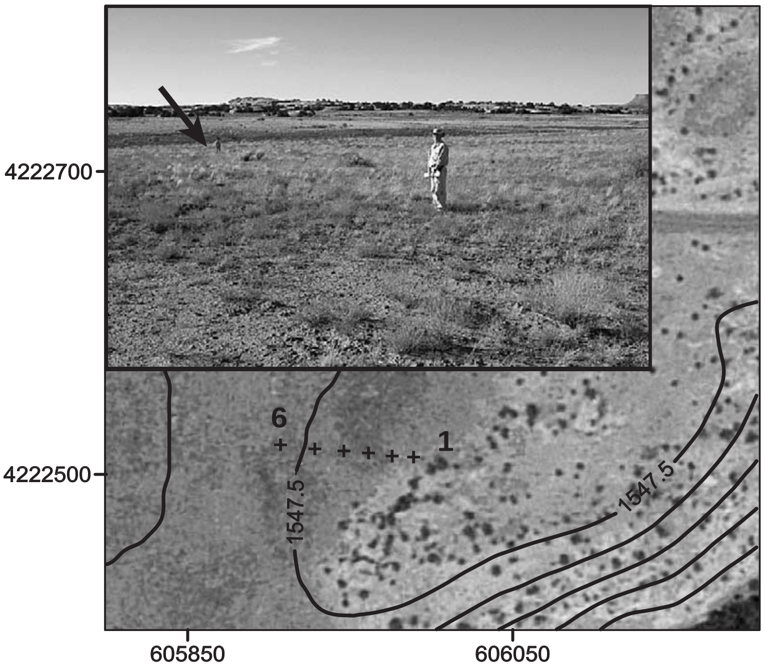

Fig. 3. Topographic and location map of the HG-site area based on contoured 10-m DEM grid (The Loop 7 1/2′ quadrangle). Background image from The Loop digital orthophoto quadrangle. Elevations in meters with a 2.5-m contour interval. UTM convention, as well as horizontal and vertical data, as in Fig. 2. Plus (+) symbols mark locations of transect positions from upslope (1) to down slope (6). Inset photograph shows approximate locations of transect positions 2 (figure in foreground) and 6 (arrow head).

cyanobacteria, lichens, and mosses (see Belnap and Lange, 2001).

A similar slope was sampled at a nearby historically grazed site (HG-1; Figs. 1 and 3) that shares many factors in common with the NG site, including characteristics of bedrock as well as slope angle. Vegetation-species composition is similar to that at site NG but with a higher amount of *Bromus tectorum*, a lower density of native grass species, and a higher density of shrubs, such as blackbrush (*Coleogyne ramosissima*). Cattle had grazed the area of site HG-1 from the late 19th century until about 1974, 10 years following the establishment of Canyonlands National Park. The historically grazed site is characterized by sparse and poorly developed cyanobacteria as the dominant interspace BSC, in contrast to the more densely developed soil crusts at site NG. Neff et al. (in press) attributed some differences in soil texture, composition, and organic-matter dynamics between site NG and two historically grazed sites (including site HG-1) to preferential wind erosion of soil fines from the previously grazed land. Overall, the never-grazed site has more silt, and more total elemental Mg, Na, P, and Mn concentrations. Moreover, site NG has more soil C and N (by 60–70%) than the previously grazed surfaces, leading to higher amounts of chloroform labile C and higher microbial biomass. Monitoring of dust emission at site NG, as well as at nearby currently grazed and previously grazed sites (Reynolds et al., 2003), provides strong support for the interpretation that wind erosion is an important process in producing observed differences in soil texture and chemistry in these settings.

Understanding the mineralogic and geochemical components of the soil required analysis of nearby bedrock and atmospheric dust. Rocks from the Cedar Mesa Sandstone were sampled widely in the Needles area, including locations close to the upper parts of both transects. We analyzed dust captured at two locations—one location at the NG site and the other ~3.5 km from HG-1 (Fig. 1). Each dust trap consists of a cake pan, which contains a layer of marbles suspended on a hardware cloth, mounted at 2 m in height (Reheis and Kihl, 1995). Magnetic properties were determined for dust samples collected in September 2002, having accumulated at both sites over a period of about 6 months.

3. Methods

Magnetic measurements of surficial sediment, dust, and rock samples were made on dried material placed in 3.2-cm^3 plastic containers and normalized for sample mass. Isothermal remanent magnetization (IRM) was measured using an Agico JR-5A 90-Hz spinner magnetometer. Isothermal remanent magnetization imparted in an induction of 0.3 Tesla (T; IRM.3) was taken as a measure for the amount of magnetite sufficiently large (magnetic grain size greater than about 30 nm) to carry remanence (see Thompson and Oldfield, 1986). Hard IRM (HIRM), calculated as (IRM1.2-IRM.3)/2 provided a measure of hematite (King and Channel, 1991). Magnetic susceptibility (MS), a measure of all magnetic material but mainly ferrimagnetic minerals such as magnetite when it is present, was measured in a 0.1 mT induction at a frequency of 600 Hz, using a susceptometer with a sensitivity better than 4×10^{-7} m^3 kg^{-1}.

Magnetic and chemical analyses of surficial sediment were made on bulk samples, sieved to remove particles larger than 2 mm. For the samples obtained from dust collectors, reported IRM was recalculated from original measurements on a sand-free basis to approximate, as closely as possible, values for the dust fraction. The two samples from dust collectors contained abundant sand (46–54%), likely from nearby drainages transported in dust devils. The dust-trap samples were also corrected for amount of organic matter (8–9%, determined by carbon coulometry) to reduce further possible effects of dilution. Particle-size distribution (PSD) for samples of dust and surficial sediment was determined as volume percentage using a laser-light scattering method capable of measuring particles between 0.03 and 2000 μm. For PSD analysis of surficial sediment, organic matter was removed using a 30% solution of hydrogen peroxide and magnesium chloride, and carbonate was removed using a 15% hydrochloric acid solution. Such a treatment also removes any aeolian carbonate dust and detrital calcite, locally derived from calcite cement in the rocks. Major, minor, and trace elements were determined using inductively coupled plasma mass spectroscopy (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES) analyses (Lichte et al.,

1987) of bulk sediment and rock samples and of the <50 μm fraction in dust samples, following pre-existing protocol for these kinds of samples (Reheis et al., 2002).

We examined relevant aspects of the mineralogy of rocks and surficial deposits using petrographic methods. Magnetic minerals were physically isolated (Reynolds et al., 2001b) and then identified in polished grain mounts under reflected light at magnifications to 720×. We also assessed the mineralogic residence of some potential plant nutrients in rocks by examining thin sections of both red and white Cedar Mesa Sandstone.

As described in detail in the following, measurements of the magnetic properties of rock, surficial deposits, and collected dust enable the calculation of dust contents of the surficial deposits from a binary mixing model. The dust content in a soil sample can be factored with particle-size distribution in the sample and with elemental contents determined for the soil sample and for local rock to determine the concentration of a particular element in the dust fraction in the soil sample. The ratio of these amounts to their respective elemental contents in bulk soil then indicates the contribution of dust to potential nutrients.

4. Results

4.1. Mineralogic and geochemical patterns

Strong spatial patterns in physical and chemical properties characterize the surficial deposits. Isothermal remanent magnetization in the NG transect increases overall down slope by a factor of about 8 (~2.6× from position 2; Table 1), reflecting an increase in magnetite content; IRM values level off in the three lowest samples. As described by Reynolds et al. (2001a), magnetic minerals in surficial deposits on sedimentary rocks of Canyonlands consist mainly of strongly magnetic, fine-grained (from <4 μm to ~20 μm) magnetite and titanomagnetite. These minerals, which are commonly intergrown with hematite and a variety of Ti-bearing minerals, could have formed originally only in igneous rocks during initial cooling (Haggerty, 1976). The strongly magnetic minerals are absent in the associated bedrock, and, for the foregoing reasons, the presence of such magnetite and titanomagnetite can only be explained by wind-borne dust. Hematite content (from the HIRM parameter) increases down slope by nearly 3× (Table 1), and, like magnetite, varies little in the

Table 1
Magnetic, textural, and chemical properties of sediments in transects, 0–10 cm depth

Sample	IRM ($Am^2\ kg^{-1}$)	HIRM ($Am^2\ kg^{-1}$)	MS ($m^3\ kg^{-1}$)	Fines (%)	K (%)	Na (%)	Mg (%)	Mn (ppm)	P (%)	Zn (ppm)	Fe (%)	Ti (%)	V (ppm)	Ca (%)
NG-1	2.64E−04	1.31E−04	3.03E−08	18	1.10	0.08	0.43	110	0.02	13	0.61	0.06	11	2.60
NG-2	8.27E−04	2.46E−04	7.72E−08	23	1.40	0.16	0.43	180	0.02	18	0.84	0.10	16	1.00
NG-3	1.00E−03	2.81E−04	1.03E−07	23	1.50	0.17	0.42	160	0.02	18	0.91	0.10	18	2.70
NG-4	9.39E−04	2.07E−04	8.82E−08	27	1.40	0.17	0.36	190	0.02	17	0.85	0.10	15	0.68
NG-5	1.15E−03	1.34E−04	1.19E−07	33	1.60	0.21	0.45	260	0.03	22	0.99	0.11	18	0.82
NG-6	1.40E−03	2.46E−04	1.47E−07	27	1.70	0.26	0.49	300	0.04	24	1.00	0.14	21	0.84
NG-7	1.98E−03	2.34E−04	1.78E−07	39	1.80	0.30	0.59	360	0.06	29	1.10	0.16	24	1.20
NG-8	1.69E−03	2.83E−04	1.95E−07	33	1.80	0.28	0.52	320	0.05	29	1.20	0.15	25	0.88
NG-9	1.94E−03	3.16E−04	1.83E−07	32	1.80	0.29	0.51	330	0.06	27	1.10	0.15	23	0.83
NG-10	2.15E−03	3.62E−04	1.83E−07	33	1.90	0.44	0.83	310	0.05	33	1.40	0.18	34	3.10
NG-11	2.20E−03	4.08E−04	1.90E−07	37	1.80	0.29	0.56	340	0.06	26	1.10	0.14	23	1.10
NG-12	2.14E−03	3.65E−04	1.73E−07	37	1.90	0.30	0.57	390	0.06	27	1.20	0.16	25	0.88
HG-1-1	9.68E−04	1.71E−04	7.70E−08	17	0.98	0.12	0.28	131	0.024	18	0.69	0.06	12.6	2.70
HG-1-2	6.66E−04	1.32E−04	5.61E−08	19	0.87	0.10	0.19	107	0.02	14	0.63	0.047	8.3	1.40
HG-1-3	7.66E−04	1.49E−04	8.22E−08	13	0.94	0.11	0.24	123	0.024	16	0.55	0.049	9.8	2.00
HG-1-4	9.35E−04	1.40E−04	7.94E−08	18	0.97	0.12	0.25	138	0.026	16	0.76	0.059	10.6	1.90
HG-1-5	9.79E−04	1.78E−04	8.51E−08	14	1.00	0.13	0.27	152	0.033	18	0.83	0.066	11.6	1.80
HG-1-6	1.50E−03	2.81E−04	1.32E−07	25	1.40	0.19	0.44	230	0.044	26	0.96	0.094	19.5	2.10

Sample numbers increase down slope. IRM, isothermal remanent magnetization; HIRM, hard IRM; MS, magnetic susceptibility. Fines, silt plus clay fraction (<63 μm).

lower parts of the transect. Hematite occurs in several forms of different origins in these deposits. As a component in aeolian dust, hematite is intergrown with magnetite and other common varieties of iron-titanium oxide minerals. As a component derived from local bedrock, hematite occurs commonly as thin (<5 μm), red translucent rims mainly on sand-sized quartz grains and rarely as particles of specular hematite (both silt and sand sizes). Amounts of silt plus clay (fines) and most potential nutrients (K, Na, Mn, Zn, P, and Fe) also increase down slope (Table 1). Mg increases erratically down slope, and Ca varies greatly. Much of the Ca in these deposits resides in weathered calcite cement from bedrock in both coarse and fine fractions; X-ray diffraction results indicate that minor amounts of Mg may be associated with the calcite cement.

The spatial distribution of magnetite indicates an increasing down-slope accumulation of aeolian dust. The similar down-slope increases in many potential cation nutrients and in fines suggest that some proportion of the nutrients is associated with aeolian dust. Inasmuch as aeolian dust initially falls in nearly uniform amounts across the landscape (except when topographic features interfere with wind), the observed distributions of magnetite, nutrients, and fines must be related to surficial processes that concentrate fines down slope. Such processes might include local redistribution by wind, by which fines were winnowed out of deposits in high-energy, upper slope settings and perhaps deposited lower on the landscape. Surfaces at NG are stable today with no evidence for significant wind-driven redistribution of sediment, on the basis of (1) dense BSC cover, (2) absence of mobile sand, and (3) wind-erosion monitoring there since 1998 (Reynolds et al., 2003). If the distribution of aeolian dust has been strongly modified by wind, this modification would have occurred mostly in the past when dunes formed in the basin (see Reheis et al., in press). The preceding evidence from geomorphic and BSC studies suggests that the modern surface has been stabilized by vegetation and BSC for at least several centuries. Down-slope transport of fines by water is another possibility. Conditions that promote or retard runoff on sandy surfaces covered by BSC are described by Yair (1990), Verrecchia et al. (1995), and Kidron and Yair (1997). On a surface mostly covered by BSC, intermittently exposed sediment or loose dust may be transported by sheet wash over the crusted surface (see Shachak and Lovett, 1998). The down-slope increases in magnetite (8×) relative to fines (2×) suggest that the finest particles (expected to be aeolian dust) are preferentially concentrated down slope. This inference is corroborated by particle-size analysis that shows a down-slope increase in the fine-silt (4–20 μm) fraction relative to coarser silt fractions. Similarly, abundances of magnetite and potential nutrients increase gradually over the lower five transect positions at site HG-1. Amounts of fines are erratic and decrease slightly overall, however, except for a sharp increase in fines in the lowest toe-slope position (Table 1).

In the following section, we examine the connections among the abundances of magnetite, nutrients, and fines, in attempting to estimate the extents to which dust and weathered bedrock are responsible for rock-derived nutrient content.

4.2. Abundance of aeolian dust in surficial deposits

The mass proportion of dust (dustf) in each sample is calculated using a binary mixing relation, where the IRM of the dust and rock components (IRMdust and IRMrock, respectively) and mixture concentrations (IRMsoil) are known (Albarède, 1995):

$$\text{dustf} = (\text{IRMsoil} - \text{IRMrock})/(\text{IRMdust} - \text{IRMrock}). \quad (1)$$

The value for IRMrock (3.87×10^{-5} Am^2 kg^{-1}) was the geometric mean of 19 samples of Cedar Mesa Sandstone. Samples of both white (13) and red (6) rock were analyzed to approximate the proportion of these lithic varieties in the study area. The IRM of white sandstone (geometric mean, 2.71×10^{-5} Am^2 kg^{-1}; range, $0.84–7.03\times10^{-5}$ Am^2 kg^{-1}) is less than the IRM of the red facies (geometric mean, 8.40×10^{-5} Am^2 kg^{-1}; range 0.14–7.67 10^{-4} Am^2 kg^{-1}) because of the presence of hematite in the redbeds. The IRMrock value is far below IRM values for soil (Table 1) and dust (Table 2); excluding the rock component would have little effect on calculated dust content in this analysis. Iron oxide minerals responsible for IRM of rock might include very small

Table 2
Magnetic and chemical results from dust-trap samples

Sample	IRM original	IRM corrected	Fines (%)	OM (%)	K (%)	Na (%)	Mg (%)	Mn (ppm)	P (%)	Zn (ppm)	Fe (%)	Ti (%)	V (ppm)
CM2-5/01					2.0	2.1	1.1	414	1.80	703	2.0	0.32	48
CM2-4/02					2.3	1.2	1.3	441	0.60	862	2.1	0.22	47
CM2-9/02	0.00554	0.01241	54	9.1	2.1	1.2	1.4	538	0.63	1070	2.3	0.26	56
CM3-9/02	0.00512	0.01377	46	8.2	2.2	1.1	1.4	467	0.45	478	1.8	0.26	54

Sample, CM-2 denotes samples from the trap at site NG, followed by month/year of collection; CM-3 from the trap at site RDC (Fig. 1). IRM values in $Am^2\ kg^{-1}$. IRM original refers to results on bulk samples. IRM corrected refers to the IRM adjusted for amounts of sand and organic matter (OM; see text). Fines, amount of silt plus clay. Chemical results obtained on the <50 μm fraction.

amounts of magnetite inclusions in sand-sized quartz grains, in addition to hematite. The values for the dust samples are 1.24×10^{-2} $Am^2\ kg^{-1}$ and 1.37×10^{-2} $Am^2\ kg^{-1}$ for the NG site and the collector close to HG-1 site, respectively, on sand-free and organic matter-free bases (Table 2).

At site NG, the estimated amount of dust in the soil samples ranges from 2% at the top of the transect to 18% at the lowest three positions (Fig. 4). The abundance of fines in these samples ranges from 18% to 39% (Fig. 4; Table 1). At site HG-1, the estimated amount of dust is 5–11% in samples with corresponding abundance of 13–25% fines (Fig. 5; Table 1).

Using magnetic susceptibility instead of IRM as the proxy for aeolian magnetite yields identical patterns of dust abundance, but slightly larger estimates (by about 3%, at most, for samples having dust amounts >15%). Isothermal remanent magnetization is chosen over MS to estimate the abundance of far-traveled dust in this setting, primarily because MS values of bedrock show higher variability than IRM. This variability is caused in part by strong diamagnetism in some sandstone samples.

4.3. Nutrients in aeolian dust—contribution to total pool of soil nutrients

The estimated concentration of a particular element in the dust fraction (dustE) of a bulk soil sample can be calculated by the expression that the total soil pool for a particular element (soilE pool, as measured directly by ICP methods; Table 1) is the sum of the elemental concentrations in the dust fraction (dustf*-dustE) and in the fraction locally derived from bedrock (rockf*rockE):

$$\text{soilE pool} = \left(\text{dustf}^{*}\text{dustE}\right) + \left(\text{rockf}^{*}\text{rockE}\right). \quad (2)$$

Dustf is provided for any transect sample from Eq. (1). The parameter rockE is the average value for

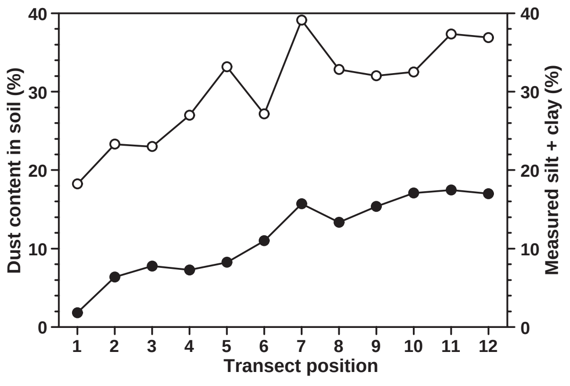

Fig. 4. Plots of the abundances of aeolian dust (●) and measured fines (silt plus clay fractions (○)) with position in the transect (sample numbers increase down slope) at site NG.

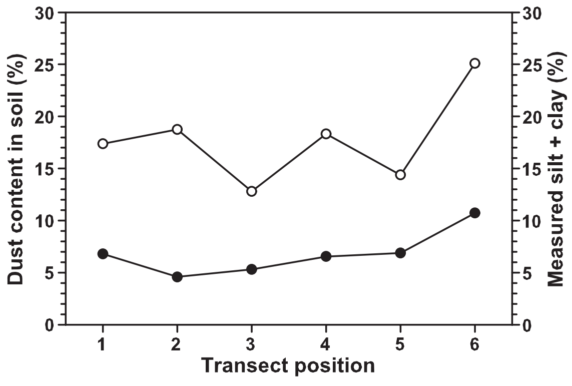

Fig. 5. Plots of the abundances of aeolian dust (●) and measured fines (silt plus clay fractions (○)) with position in the transect (sample numbers increase down slope) at site HG-1.

a particular element from geochemical results on 18 samples (13 white and five red) of Cedar Mesa Sandstone distributed widely in the Needles area (Table 3). The parameter rockf represents the mass proportion of the rock-derived sediment, most simply taken as 1−dustf. This case would be valid if all rock-derived nutrients were evenly distributed through all particle sizes derived from the local bedrock.

The potential importance of aeolian dust to landscape fertility at any location along a transect may be expressed for a particular element as the proportion of elemental abundance in the dust fraction (dustf*dustE) to the bulk-soil elemental abundance (soilE pool). Assuming that bedrock-derived nutrients are evenly distributed through all bedrock-derived particle sizes, the contribution from dust at the NG site is mostly >20% to ~80% for most elements (except Mg) over most of the transect (Fig. 6a, b). The contribution of dust to Na, P, Mn, Zn, and Fe is greater than 40% over most the transect. For most nutrient elements, contributions increase systematically down slope over the middle part of the transect, perhaps reflecting the increasing down-slope accumulation of aeolian dust relative to weathered rock. Similar patterns are found for chemically immobile elements in this setting (Ti and V). The very tight correspondence among Fe, Ti, and V is consistent with a strong aeolian dust input of these elements having mineralogic residence dominantly in Fe–Ti oxide minerals, such as titaniferous magnetite, in which small amounts of V are ubiquitous. The contributions from dust to soil Na, P, Zn, Fe, Ti, and V at HG-1 (~20–65%) are close to the ranges found for the NG site (Fig. 7a, b). At the NG site, the calculated contribution of Mn in the uppermost transect position is negative. As this result is not possible, it indicates that the assumption of broad particle-size distribution of bedrock-derived nutrients is not fully applicable, at least for Mn. As with Mn at site NG, values derived for Mg, Mn, and K are negative in several samples from the upper part of the transect at site HG-1.

Because of the negative contributions noted above, we also considered the opposite end-member case that all rock-derived nutrients are limited to the soil fines (Figs. 6c, d and 7c, d). In this scenario, the parameter rockf is estimated as the difference between the fine fraction in a transect sample and the mass proportion of dust in that sample (measured fines−dustf). This scenario sets upper bounds on the contribution of dust to soil fertility, but it is not fully acceptable, because it produces dustE values for site NG that are unreasonably high (the summed

Table 3
Chemical results of rock samples from the Cedar Mesa Sandstone in the study area

Sample	K (%)	Na (%)	Mg (%)	Mn (ppm)	P (%)	Zn (ppm)	Fe (%)	Ti (%)	V (ppm)	Ca (%)
01U 1-1r	1.20	0.27	0.35	240	0.01	6	0.27	0.02	10	4.0
01U 2-1w	1.10	0.04	0.09	69	0.01	4	0.1	0.02	4	2.8
01U 2-2r	1.70	0.05	0.25	26	0.04	20	0.76	0.09	10	0.3
Salt Creek 1w	0.81	0.2	0.76	220	0.02	9	0.31	0.02	6	8.5
Salt Creek 2w	1.00	0.04	0.09	130	0.02	10	0.33	0.04	6	9.8
Salt Creek 3w	1.30	0.05	0.10	200	0.02	24	0.62	0.05	7	12.0
8U-2-4w	0.88	0.03	0.17	43	0.02	6	0.35	0.05	10	3.4
8U-5-3w	0.91	0.08	0.71	200	0.01	13	0.43	0.02	5	6.5
8U-19-4r	1.50	0.05	0.14	110	0.03	14	0.67	0.09	14	4.9
8U-19-5w	0.78	0.03	0.08	150	0.02	8	0.41	0.06	6	7.8
CM-MPw	0.68	0.02	0.063	27	0.004	4.2	0.28	0.014	2.3	0.23
CM-MPr	1.50	0.037	3.20	503	0.018	34.1	1.2	0.035	8.3	6.5
CM-VPw	0.83	0.023	0.44	46	0.0094	7.7	0.19	0.034	6.8	1.2
CM-SFw	0.51	0.013	0.035	4.2	0.004	6.9	0.086	0.018	3.2	0.05
CM-CPw	0.71	0.14	0.12	378	0.007	3	0.22	0.017	6.6	11.4
CM-Ches w	0.88	0.023	0.047	26	0.0079	4.9	0.18	0.022	4.7	1.5
7U-7-7w	0.75	0.03	0.07	100	0.009	9	0.41	0.03	5	7.9
7U-7-9r	1.40	0.04	0.08	22	0.01	8	0.76	0.07	12	0.46

Color of samples (w=white, red=red) denoted in sample identifiers.

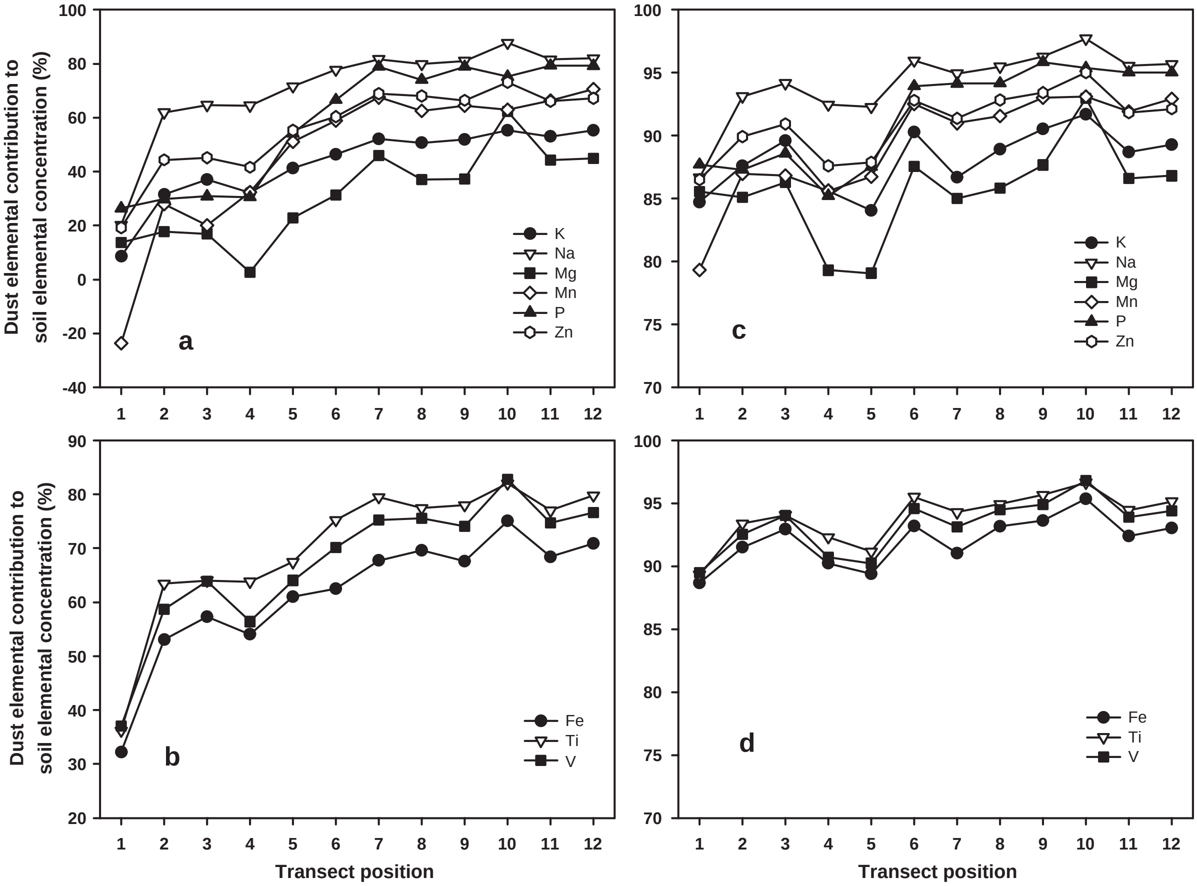

Fig. 6. Plots of contributions of dust to elemental concentrations in samples from the NG transect (sample numbers increase down slope). Plots a and b illustrate the case in which rock-derived nutrients are assumed to be evenly distributed through all particle sizes. Plots c and d illustrate the case in which rock-derived nutrients are assumed to be limited to soil fines.

abundances of K, Na, Mg, P are >10%, much higher than modern dust values; Table 2).

5. Discussion

5.1. Contributions of dust to soil nutrient pools

The preceding results indicate that aeolian dust is a major contributor to surface soil mass and to rock-derived nutrients in soil and surficial deposits on Cedar Mesa Sandstone. For several reasons, it is difficult to make accurate determinations of the contribution of dust to surface-sediment elemental content. No universal correction can be applied to account for the grain-size distributions of potential nutrients from bedrock because these nutrients have different mineralogic residences and thus variable grain sizes. For example, the presence of dominantly sand-sized alkali feldspar in Cedar Mesa redbeds indicates that rock may deliver some K and Na to the coarse fraction of derived sediment and soil. Petrographic observations indicate that micas (muscovite and biotite) in the Cedar Mesa Sandstone may deliver some K, Na, and Mg to both the coarse and fine fraction in soil. In contrast, geochemical results on weathered Cedar Mesa Sandstone, separated into fine (<63 μm) and coarse fractions, indicate a higher proportion of some potential nutrients in the bedrock fines (Neff et al., in press): 67 (±4)% of K, 73 (±7)% of Mg, 79 (±6)% of Mn, and 79 (±2)% of P. We conclude from this set of observations that the

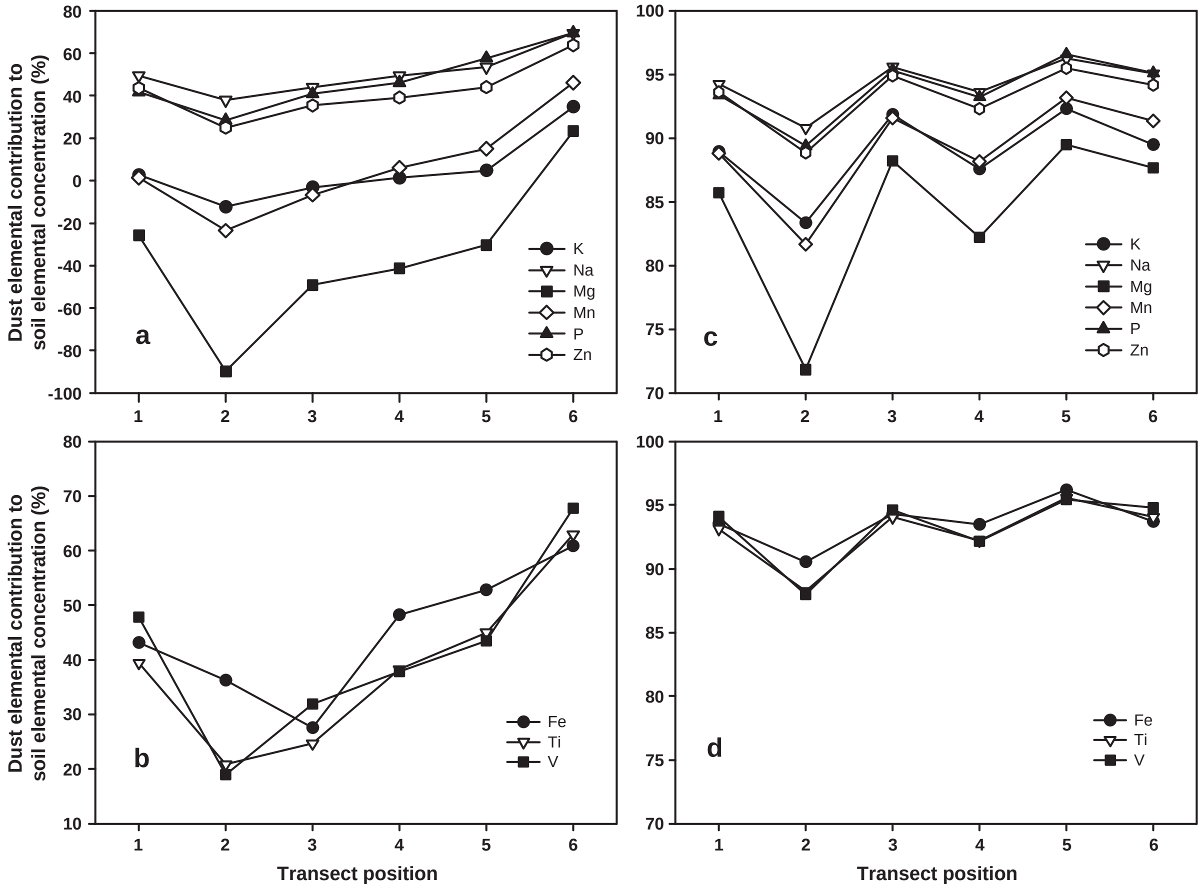

Fig. 7. Plots of contributions of dust to elemental concentrations in samples from the HG-1 transect (sample numbers increase down slope). Plots a and b illustrate the case in which rock-derived nutrients are assumed to be evenly distributed through all particle sizes. Plots c and d illustrate the case in which rock-derived nutrients are assumed to be limited to soil fines.

estimated contributions of dust to soil fertility at these sites fall between values from the two end-member cases (Figs. 6 and 7).

The role of aeolian dust in ecosystem nutrient dynamics in these semi-arid ecosystems is likely to be significant. Phosphorus can co-limit productivity (with N) in semi-arid environments (Guevara et al., 2000; Snyman, 2002), particularly when water availability is high. Despite uncertainty regarding the total contribution of dust to surface P, our results show that this contribution is significant. Although desert environments are not as poor in rock-derived nutrients as tropical systems where the role of dust in nutrient cycling has been more extensively studied (e.g., Chadwick et al., 1999), there is a wide variation in P content across arid and semi-arid ecosystems (Lajtha and Schlesinger, 1988; Neff, unpublished data). In soils such as those derived from Cedar Mesa Sandstone, it is likely that aeolian dust inputs represent an important input of P to ecosystems. The more specific roles of these inputs, including their availability to biotic systems, remain unknown.

Similar approaches reveal the importance of aeolian dust to dryland soil nutrient pools in other geologic settings. Using a two-component mixing model, McFadden et al. (1998) evaluated the development and compositions of vesicular A soil horizons (Av horizons) on mid-Holocene and late Pleistocene geomorphic surfaces in the Mojave Desert, California. The Av horizon forms largely by the accumulation of aeolian dust, as summarized by McFadden et al. (1998). Abundances of SiO_2 in regional dust, soil parent material, and the Av horizon were factored to estimate the relative fractions of dust and parent material in a particular soil sample. Among the important observations from this study was the recognition of chemical alteration in the Av horizon that resulted in variable distributions of some nutrients, especially highly soluble Na, as a function of depth and age of surface. The method also revealed an anomalous distribution of P in some soils that was attributed to changes in phosphate availability to regional dust as dust sources varied during the late Quaternary. Although the investigation by McFadden et al. (1998) and the current one differ with respect to climate, geomorphic setting, as well as soil type, age, and depth, these studies illustrate the value of physical and chemical properties of substrates, parent material, and dust for understanding the nutrient status of dryland soil.

5.2. Sources of uncertainty

A source of uncertainty in calculating the mass proportion of dust (dustf) is the IRM value for modern dust. The value used in this study is based on only one sample from each collector acquired over a 6-month period and may not fully represent the IRM of dust that accumulated in the upper 10 cm of the surfaces over decades or, at site NG, even centuries. The nearly identical IRM values of the two dust samples, though, imply that these values at least adequately represent modern dust. Although magnetic results from modern dust are limited, they are consistent with a longer-term record of magnetite-bearing dust in the study region. A previous study showed the presence of abundant magnetite in sediment-filled potholes on high, isolated surfaces of a variety of rock types, none of which contain magnetite (Reynolds et al., 2001a). The age of the pothole-filling sediment is poorly known but exceeds many centuries on the basis of the composition and inferred age of the biologic soil crust associated with each site.

An uncertainty regarding the contribution of far-traveled dust, as estimated here, to soil fertility stems from the possibility of dust from sources that lack magnetite. The magnetics approach, exploiting IRM as a proxy for aeolian magnetite abundance, cannot detect dust contributions that are not associated with magnetite. If this contribution were significant, then the determination of dust abundance based on IRM would underestimate all dust and would overestimate the contribution of magnetite-associated dust to the soil nutrient pool. Regardless of the difficulty in quantifying a contribution from dust that may be unassociated with magnetite, the results show that dust inputs must provide a large proportion of potential nutrients to the soil. The soil nutrient pool over most of the transect samples is large compared to potential contributions from locally derived Cedar Mesa Sandstone, and the difference must come from dust.

One way to evaluate the importance of dust from different sources (sources associated with magnetite vis-à-vis those that lack magnetite) is to compare IRM and HIRM with a nutrient index. The nutrient index here is the sum of normalized values of K, Na, P, Mn, and Zn in each sample. (Magnesium was not used because some of it may be associated with rock-derived calcite.) HIRM values record hematite-bearing inputs from several sources: (1) local bedrock, (2) dust with associated magnetite, and (3) possibly dust without magnetite, such as the weathered products of extensive redbeds in the region that are relatively high in potential nutrients (Neff, unpublished data). If any of these inputs make significant contributions, we would expect to find close correspondences between HIRM and elemental abundances. At site NG, HIRM and nutrient abundances are poorly correlated, in contrast to highly correlated IRM and nutrient abundances (Fig. 8). At site HG-1, hematite and nutrient abundance show a moderately tight correlation, but it is not as strong as the correspondence between IRM and the nutrient index. Thus, hematitic sources may contribute to, but do not dominate, nutrient-rich dust inputs on Cedar Mesa substrates. Another possibility–dust from sources lacking both magnetite and hematite associations with potential nutrients–remains untested. This possibility is not considered important, because the estimated contribution of dust to Fe, Ti, and V is very high and closely approximates the contribution to rock-derived nutrients, especially Na, P, and Zn.

5.3. Sources of magnetite-bearing dust

The presence of magnetite does not yield information about specific sources of dust. As discussed

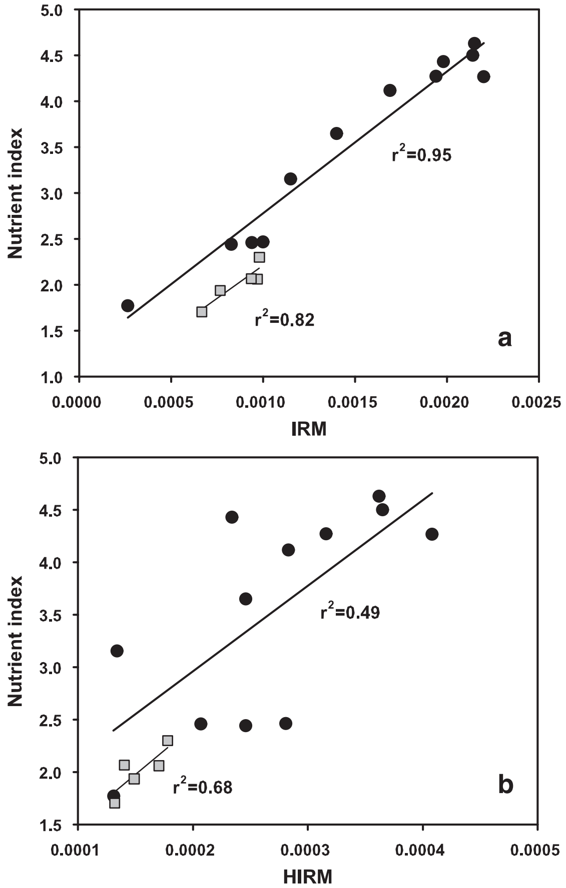

Fig 8. Plot of nutrient index vs. IRM in Am^2 kg^{-1} (a) and HIRM in Am^2 kg^{-1} (b) for samples from the NG (●) and the HG-1 (□) sites. The nutrient index is the sum of normalized abundances of K, Na, P, Mn, and Zn. The lowest sample (in the toe-slope) position that is illustrated in other figures is not shown for site HG-1, because there is no equivalent geomorphically situated sample at site NG.

by Reynolds et al. (2001a), many different magnetite-bearing sources may contribute dust from both within and beyond the Colorado Plateau. Small variations in chemical and magnetic properties from BSC and underlying sediment in potholes in the study area suggest changes in dust sources over the past 100–150 years. One likely source is the Mojave Desert, a highly favorable region for producing magnetite-bearing dust (Reynolds et al., 2003). Monitoring of modern dust emission in the Mojave Desert shows that dust can reach the Colorado Plateau during large wind events (Chavez et al., 2002). Within the Colorado Plateau, magnetite-bearing, middle Tertiary intrusive rocks (Friedman and Huffman, 1998), which form the cores of small mountain ranges, contribute sediment to terrace gravels, alluvial fans, and drainage courses. Of these, the Abajo Mountains and two of its drainages, Salt Creek and Indian Creek that flow intermittently northward from this range (Fig. 1), represent the closest sources of magnetite. Magnetite abundances at upland-soil and sediment-filled pothole sites widely distributed over the study area (Fig. 1; Reynolds et al., 2001a,b; Reynolds, unpublished data), as well as in dust-trap samples, are not associated with proximity to magnetite-bearing drainages, indicating that these drainages are not dominant, recent sources of dust in the sandy surficial deposits described in this report.

5.4. Effects of disturbance on dust abundance and nutrient patterns

A notable difference between the sites is in the patterns of dust abundance relative to amount of fines. Magnetite abundance (dust abundance) at NG increases down slope along with increasing amounts of fines (Fig. 4). Dust abundance at HG-1 also increases generally down slope but in a pattern unrelated to variable amounts of fines (Fig. 5). We have interpreted the lower overall amounts of magnetite at the grazed site to its depletion by wind erosion (Neff et al., in press). The impact of grazing at site HG-1 is further manifested in the presence of thin, immature cynaobacterial BSC in plant interspaces that is interpreted as regenerated, recovering BSC after grazing ceased in 1974. These interpretations are supported by our observations of ongoing surface sediment depletion by wind erosion at several sites, including a currently grazed site on nearby Dugout Ranch (Fig. 1; Reynolds et al., 2003).

6. Conclusions

The approach applied here uses magnetic methods to estimate mass proportions of dust in surficial deposits derived mainly from nutrient-poor sandstones and to assess the contribution of dust to soil nutrients. In this Colorado Plateau setting, IRM is a proxy for aeolian magnetite abundance. The magnetic approach would be inapplicable in settings where bedrock contained more magnetite than that present in ambient aeolian dust. The approach may also be problematic in settings in which large amounts of local bedrock-derived hematite might contribute greatly to total IRM relative to aeolian magnetite, if very sparse. Nevertheless, large areas of arid lands underlain by sedimentary rocks having mostly uniform lithology (much of the Colorado Plateau) or by some kinds of metamorphic rocks are amenable to this approach. Other parts of the Colorado Plateau, however, are underlain by bedrock characterized by more highly variable lithologies (having a high proportion of fine-grained sediment and relatively high content of potential nutrients) than the sites on Cedar Mesa Sandstone reported here. In settings with these finer-grained substrates, aeolian dust would have lesser importance for soil fertility than we report for the sites on the Cedar Mesa.

Comparison of results from the two settings suggests that the disturbed site is relatively depleted in dust, fines, and many nutrients over geomorphically equivalent central parts of the transects (excluding the upper, dominantly sandy parts in pinyon–juniper settings and the lowermost toe slopes; Figs. 4 and 5; Table 1). At site NG, abundance of dust ranges 7–17% corresponding with 27–39% fines, whereas at site HG-1 abundance of dust ranges 5–7% corresponding with 13–19% fines. We attribute the lower amounts of dust and fines at site HG-1 to the effects of past grazing (see also Neff et al., in press; Belnap and Gillette, 1998). If so, we can address an important question about aeolian replenishment of nutrients in formerly grazed surfaces: What conditions and time spans are required for dust- and nutrient-depleted areas to approach the current dust-derived, soil nutrient levels of similar but ungrazed surfaces? If we greatly oversimplify and assume that the surface at site HG-1 was fully depleted in dust and that it has regained in 25–30 years about half of the dust as now present at site NG, then site HG-1 might contain dust levels similar to those at site NG after about 50–60 years. Under more likely scenarios that not all dust was eroded from site HG-1, longer time spans approaching a century would be required for dust-level (and presumably nutrient) recovery after grazing ceased. Such a time span is on the same order as that estimated for the recolonization of these surfaces by a mature population of BSC after disturbance (Belnap and Eldridge, 2001; Belnap and Warren, 2002). An effective way in which to rebuild mineral-derived nutrient pools in these previously grazed settings, which lack dense vegetation cover especially during common periods of drought, is through the trapping of fines by well-developed BSC, particularly that which produces rough, uneven surfaces (see Danin and Ganor, 1991). For these reasons, a well-developed BSC, or some other kind of trap, likely provides critical antecedent conditions for rebuilding nutrient status in these kinds of dryland soils that are vulnerable to wind erosion.

Finally, the approach described here can provide a framework for examining past changes in dust inputs over time, with possible effects on ecosystem productivity. Our preliminary magnetic, chemical, and geochronologic examination of deeper sediments at the NG site suggests that dust inputs here varied over the last ~20 ky with an overall increase in rock-derived nutrients during the past 10 ky, illustrating the importance of the Quaternary history of dust inputs to understanding processes of modern nutrient cycling.

Acknowledgments

We grateful acknowledge H. Goldstein, E. Fisher, I. Casteñeda, Y. Axford, and G. Skipp for assistance in the laboratory; D. van Sistine for preparing the location figure; J. Yount for field work and preparation of site maps; J. Belnap for insightful discussions; and M. Miller, C. Bern, and two anonymous referees for excellent reviews. J. Belnap was instrumental in the design of the study. This work was supported by the Earth Surface Dynamics Program of the U.S. Geological Survey.

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