Aeolian dust in Colorado Plateau soils: Nutrient inputs and recent change in source

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Aeolian dust (windblown silt and clay) is an important component in arid-land ecosystems because it may contribute to soil formation and furnish essential nutrients. Few geologic surfaces, however, have been characterized with respect to dust-accumulation history and resultant nutrient enrichment. We have developed a combination of methods to identify the presence of aeolian dust in arid regions and to evaluate the roles of this dust in ecosystem processes. Unconsolidated sandy sediment on isolated surfaces in the Canyonlands region of the Colorado Plateau differs greatly in mineralogical and chemical composition from associated bedrock, mainly aeolian sandstone. Detrital magnetite in the surficial deposits produces moderately high values of magnetic susceptibility, but magnetite is absent in nearby bedrock. A component of the surficial deposits must be aeolian to account for the abundance of magnetite, which formed originally in far-distant igneous rocks. Particle-size analysis suggests that the aeolian dust component is typically as much as 20–30%. Dust inputs have enriched the sediments in many elements, including P, Mg, Na, K, and Mo, as well as Ca, at sites where bedrock lacks calcite cement. Soil-surface biologic crusts are effective dust traps that apparently record a change in dust sources over the past several decades. Some of the recently fallen dust may result from human disturbance of land surfaces that are far from the Canyonlands, such as the Mojave Desert. Some land-use practices in the study area have the potential to deplete soil fertility by means of wind-erosion removal of aeolian silt.

Many studies have addressed the presence of aeolian dust in soils and surficial deposits in deserts to provide important geologic and ecologic information bearing on landscape dynamics (1–16). From this body of work, we have improved understanding about: (*i*) current and past sources and flux of dust, hence changing conditions of dust emission; (*ii*) the genesis of desert soils; (*iii*) the influences of aeolian silt and clay on water-infiltration rates in soil; (*iv*) the evolution of desert surfaces (such as desert pavement) relevant to surface stability, as well as the distribution of surface and subsurface water; and (*v*) interrelations among aeolian dust, distribution of plants and soil crust, rain-water runoff, and productivity. Nevertheless, we lack fundamental knowledge about the accumulation history of aeolian dust on most landscapes and about how to discriminate between contributions from parent material and aeolian dust to the biotic system.

Although many different methods provide clear evidence for aeolian input into soils (4, 6, 8, 9, 11, 13, 17, 18), ecosystem studies would benefit from rapid assessment of aeolian components in soils. Here we demonstrate that magnetic methods, which characterize the type and distribution of iron oxide minerals, can be applied to detect the presence of aeolian dust in young surficial sediments and soils over large arid-land areas. The magnetic results, combined with geochemical and textural analyses, form a basis for understanding the influence of fine-grained aeolian inputs on soil fertility of the central Colorado Plateau, Utah.

Geologic and Ecologic Setting

The Canyonlands physiographic section of the central Colorado Plateau (Fig. 1) is characterized by high-elevation sedimentary rocks that have undergone little tectonic deformation. Benches, mesa tops, slickrock buttes of resistant sandstone, and upland grass and shrub steppe, all isolated from alluvial and colluvial sedimentation, commonly are mantled by a thin layer of fine-grained sediment that supports much of the productivity of the region. Sedimentary rocks in the study area are dominantly Permian to Jurassic sandstone, with lesser exposure of interbedded siltstone, mudstone, and limestone. Igneous rocks occupy only small areas of the central Plateau (19). The western and southwestern margins are covered by thick sequences of Tertiary lavas, dominantly basaltic (20). In contrast, geologic-physiographic provinces surrounding the Plateau contain vast areas of more felsic (silicic) igneous rocks.

The Canyonlands area is largely a cool, semiarid desert. Annual precipitation in the study area (south of Moab, Utah) averages 216 mm, with about 35% falling during summer. When undisturbed, the uppermost soil layer is covered by biological soil crust (BSC). These crusts are a dominant source of nitrogen (21), increase water infiltration (22), and reduce soil erosion (23) in this region. Organisms in the BSC excrete a sticky polysaccharide material that traps sediment and glues soil particles together, forming a cohesive surface crust. In Canyonlands, the kinds and density of BSC components give an indication of disturbance history and surface stability. The BSC at our sites is composed of >20% lichens and mosses. The combination of the lichen *Collema*, a cyanobacterial symbiont, with the cyanobacteria *Microcoleus vaginatus* and *Scytonema nostoc* represents a mature association, indicating stability of the surface over many decades, on the order of at least 50–70 years. A recovery rate for *Collema* alone is estimated at a minimum of 45 years (24).

Methods

Surficial sediments covered by BSCs were sampled at nine sites (Fig. 1; Table 1, which is published as supplemental data on the PNAS web site, www.pnas.org) that included grassland, small depressions (potholes) in sandstone, and mesa tops. The BSC represents the youngest sediment in these short profiles, but deeper samples may not record a successively older depositional sequence because of possible bioturbation. None of the sites currently receive alluvial or colluvial sediment, except potholes receiving sediment, mainly sand, from immediately adjacent bare-rock catchments (typically 3–8 m in diameter). The sampling sites are associated with exposures of the Entrada, Navajo, Kayenta, or Cedar Mesa (Cutler Group) formations consisting mainly of gray aeolian sandstone or red beds (dominantly sandstone with fine-grained interstitial hematite) deposited in mixed fluvial and aeolian environments. One site (7U-11) lies on a mesa capped by sandstone and a thin limestone bed. Rocks at these sites are not weathered deeply.

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Abbreviations: BSC, biologic soil crust; MS, magnetic susceptibility.

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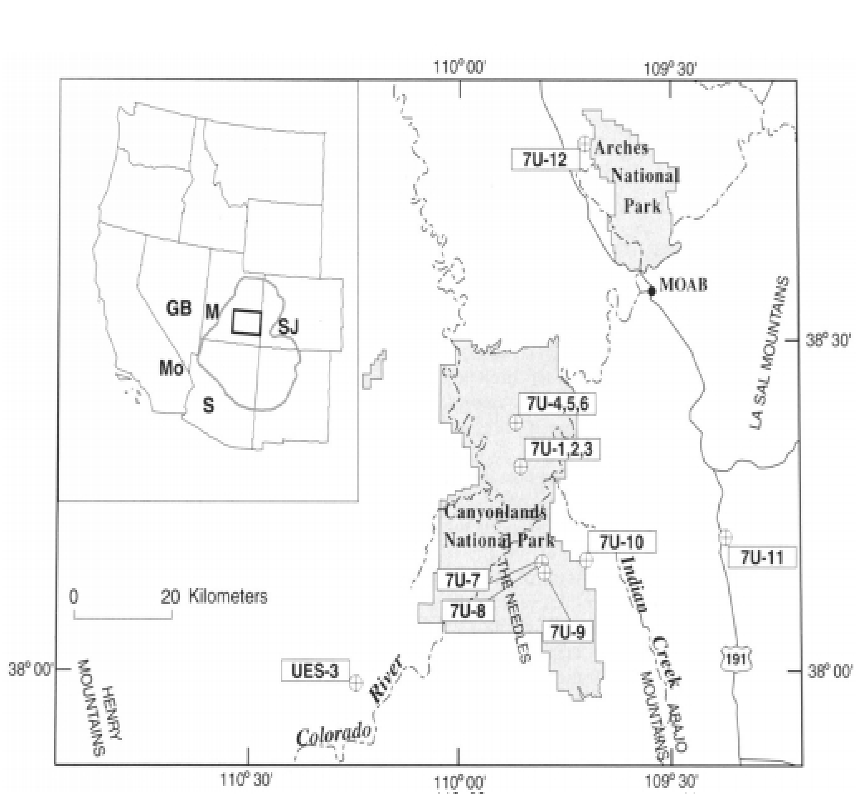

Fig. 1. Location map of sampling sites and inset map of western U.S. Boundary of the Colorado Plateau surrounds rectangle indicating the area of the site-location map. GB, Great Basin; Mo; Mojave Desert; S, Sonoran Desert; M, Marysvale volcanic field; SJ, San Juan volcanic field.

At most sites, soil cores (3 cm in diameter) were collected in increments of 0–0.5 cm, 0.5–2 cm, 2–5 cm with multiple samples from a depth interval combined into bulk samples weighing 50–100 g. At site UES-1, the BSC was sampled at 0–0.5 cm and underlying sediment at 1–10 cm. At each site, nearby rock outcrops were sampled. We used a combination of magnetic (refs. 25 and 26; *Supplemental Methods*, which is published as supplemental data on the PNAS web site) and reflected-light petrographic methods to determine the types, amounts, and origins of magnetic minerals. Magnetic property measurements included (*i*) magnetic susceptibility (MS), a measure of all magnetic material but dominantly magnetite, when present; (*ii*) frequency-dependent MS (from measurements at 600 and 6,000 Hz), a measure of the amount of superparamagnetic (<30 nm) magnetite; and (*iii*) hard isothermal remanent magnetization, a measure of the amount of hematite. Major, minor, and trace elements were determined by using a combination of energy-dispersive x-ray fluorescence and inductively coupled plasma-emission spectroscopy.

Particle size was determined as volume percentage by using a laser-light scattering method capable of measuring particles between 0.03 and 2,000 μm. Sediment and sandstone samples were treated similarly for optimal comparison. Organic matter was removed by using a 30% (vol/vol) solution of hydrogen peroxide and magnesium chloride where needed. Carbonate was removed by using a 15% (vol/vol) hydrochloric acid solution to eliminate calcite cement in the rock and any pedogenic carbonate (not observed visually) in the surficial sediment. Such a treatment also removes from the sediment any aeolian carbonate dust and detrital calcite derived locally from calcite cement in the rocks. The surficial sediment contains low organic carbon and low inorganic carbon (most <1 wt %, from 36 analyses). Thus, calcite content of surficial sediments calculated from inorganic carbon content is commonly <10 wt %.

Evidence for Aeolian Dust Input

Magnetic data (Table 2, which is published as supplemental data on the PNAS web site) and petrographic observations show that magnetic minerals in the surficial sediments differ greatly from those in nearby bedrock. MS values of sediment (2.1 to 27.3 $\times 10^{-8}$ m^3 kg^{-1}) reflect the presence of magnetite, as confirmed petrographically, and are much greater than values of associated bedrock (-1.7×10^{-9} m^3 kg^{-1} to 1.1×10^{-8} m^3 kg^{-1}; Fig. 2*a*) that are typical of the sedimentary rocks of the region. Highest MS values are in the BSC (Fig. 2*a*). Similarly, hematite content (hard isothermal remanent magnetization parameter in Fig. 2*b*) is much greater in surficial sediment than in bedrock, even in redbeds.

Petrographic observations provide information on the type and origin of the magnetic minerals. Magnetic minerals in surficial sediments consist primarily of strongly magnetic, silt-size (typically 4–20 μm) magnetite and titanomagnetite, commonly intergrown with hematite, ilmenite, pseudobrookite, and ilmenorutile. Such Fe–Ti oxide minerals could have formed only originally in igneous rocks during initial cooling (27). These strongly magnetic minerals are absent in the associated bedrock, and thus residual concentration of magnetic minerals from the rocks cannot account for the magnetic and petrographic results. BSCs at most sites also contain fly ash produced by means of coal combustion, as revealed by spherical silt-size (<20 μm) magnetic particles, mostly consisting of magnetite and silicates in metallographic textures (28). These magnetic particles are absent in underlying sediment and bedrock, but their small numbers cannot account for the higher MS values in the BSC compared with underlying sediment. Some Fe–Ti oxides, such as large (80–160 μm) specular hematite, have been reworked from bedrock, especially redbeds, into overlying sediment.

Two kinds of analyses indicate that ultrafine, superparamagnetic magnetic minerals, which may form via pedogenesis in

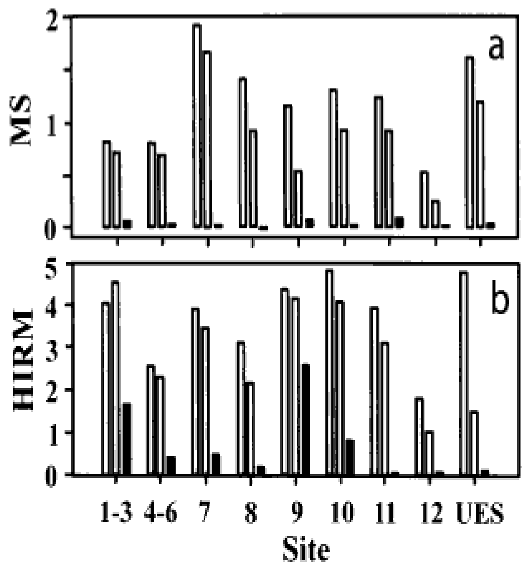

Fig. 2. Plots of MS (in 10^{-7} m^3 kg^{-1}) (*a*) and hard isothermal remanent magnetization (in 10^{-4} Am^2 kg^{-1}) (*b*). For each site or average for a group of sites (site nos. 1–3 and 4–6), the left-hand bar represents BSC (0–0.5 cm in depth); the middle bar represents underlying surficial sediment (0.5–5 cm in depth); and the right-hand bar represents bedrock. At site UES, the middle bar represents a depth of 1–10 cm. For both parameters, 46 samples from the BSC, 45 from underlying sediment, and 16 from bedrock are represented.

some settings (29), do not contribute significantly to the MS of the sediments and BSCs. First, the tight correlation ($R^2 = 0.95$; 73 specimens) of MS with isothermal remanent magnetization of surficial sediment reveals that magnetite particles (>30 nm) capable of holding a permanent magnetization dominate the MS at these sites. Second, the uniformly low values of frequency-dependent MS (most $<3 \times 10^{-9}$ m^3 kg^{-1}; Table 2) indicate a very small contribution from superparamagnetic particles, whether formed *in situ* or incorporated in aeolian material.

Contrasts in magnetic properties and mineralogy are unequivocal evidence that aeolian dust is present at the sampled sites, especially considering their isolation from alluvial or colluvial input. The presence of detrital silt-sized magnetite and titanomagnetite, abundant in the sediments and soils but absent in nearby sedimentary rocks, can be explained only by wind-borne dust. The oxide minerals indicate sources from igneous rocks, whether from surfaces and drainage areas close to the igneous-rock terrain or from drainage courses far from these terrains. Fly-ash magnetite, found only in the BSCs, is further evidence for long-distance aeolian input, because the closest coal-fired power plant is more than 100 km from the study site.

The analyzed sediments atop bedrock consist of sand (64–500-μm particle size) and a silt-plus-clay (fines) fraction that averages 33% in the BSC and 40% in the sediments under the BSC. Fines in the sediment are much higher than those in associated bedrock (averaging 10% fines). The BSC and underlying surficial sediment have the same average silt content (23%) and similar sand content (67% and 60%, respectively), with 47% of the total coarse clay and silt (1–63 μm) <10 μm in size. In contrast, 2–7% of the fines in bedrock samples are <10 μm. Fine fractions in the sediments provide only a crude estimate of aeolian dust in the sandy sediments, inasmuch as some silt and clay likely are derived from local bedrock. The results suggest that as much as about 20–30% of the surficial deposits is aeolian dust. The very high proportion of small particles in the surficial sediments suggests distant sources for much of the dust, inasmuch as particles <20 μm are known to travel hundreds of kilometers (1, 3, 30) and those <4 μm are characteristic of trans-Atlantic transport from North Africa (31).

Historical Changes in Dust Composition

The magnetic and x-ray fluorescence geochemical (Table 3, which is published as supplemental data on the PNAS web site) patterns strongly imply a shift in dust source during the past few decades. The consistently higher MS of the BSC (Fig. 2*a*), relative to that of the underlying sediment, parallels the distribution of Zr (Fig. 3). MS and Zr are correlated at all depths combined ($R^2 = 0.62$; $P < 0.05$). Zr and Ti usually vary together in sediments, because they are chemically immobile proxies for detrital-heavy minerals (32, 33). We observed a difference in the relative abundance of Zr and Ti when the BSC was compared with underlying sediment (Fig. 3). Such a difference is a powerful indicator of a change in the source area for the dust in these deposits, or it is the result of physical sorting. The presence of well developed BSCs at these sites, reflecting a very stable soil environment over the past several decades, argues against post-depositional physical separation of Ti-bearing from Zr-bearing minerals. Variations in particle size cannot explain the pattern of magnetic and chemical properties. The average MS of the BSC samples is 14% higher than that of underlying sediment, despite the identical average silt content for the BSC layer and the underlying sediment layer. In addition to magnetite and Zr, the

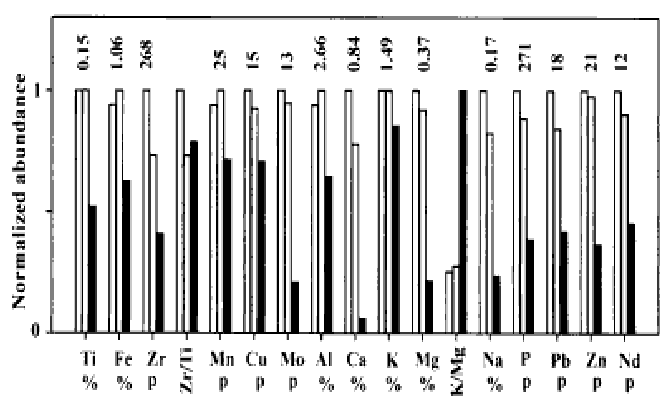

Fig. 3. Plots of elemental contents as well as Zr/Ti and K/Mg, normalized to highest value, shown at the top of bar sets. Plots represent averaged values from all sites, except the Ca plot, which shows results from site 12 where bedrock contains little calcite cement. Values are in ppm (p) or wt %. Bars represent depths and bedrock as in Fig. 2. Results are from energy-dispersive x-ray fluorescence for Ti, Fe, Zr, Mn, Cu, Mo, and Zn, and are from inductively coupled plasma–atomic emission spectroscopy for the others.

BSC is enriched in other components, such as Na, Ca, Ce, Cr, Mg, and Pb, relative to underlying sediment.

The combination of higher magnetite and Zr/Ti along with nearly constant Ti and Fe contents in the BSC, compared with underlying sediment, implies that the inferred shift in dust source has been from relatively mafic sources (the dominant igneous type on the Colorado Plateau) toward more felsic (e.g., rhyolitic or granitic) sources (34). There are numerous possible dust sources, past and present. The Colorado River, which is deeply incised into the study area, drains areas of igneous rock; thus, riverbank deposits may be a local source of some aeolian magnetic material. Such deposits, however, are deep within canyons, and widespread transport of dust from them is therefore unlikely. Recent dust contributions from intrusive centers (the Henry, Abajo, and La Sal Mountains) and their drainages within the Colorado Plateau (ref. 19; Fig. 1) are also possible. Areas of igneous rock terrain, and their drainages, that might produce felsic aeolian dust at the margins of the Colorado Plateau include the San Juan volcanic field in southwestern Colorado (35) and the Marysvale volcanic field in southwestern Utah (36). Regional felsic sources outside the plateau include the Mojave, Sonoran, and Great Basin deserts, which are generally upwind from the study area (ref. 37; Fig. 1).

A change in dust source over the past several decades may result from the increasing disturbance of southwestern desert surfaces by human activities that include urbanization, agriculture, livestock grazing, off-road vehicle use, use of dirt roads, water diversion from lakes, and military training. These activities increase dust emission from previously stable desert surfaces (23, 38, 39). Muhs (4) showed that present-day dust fall on the California Channel Islands comes from areas of intensive human activity in the western Mojave Desert during periods of high easterly Santa Ana winds, although westerly winds dominate the wind field in the Mojave otherwise. Satellite images have captured recent movement of dust plumes from the central Mojave Desert onto the Colorado Plateau (P. Chavez, Jr., and D. MacKinnon, written communication). These and other observations (40, 41) document that the southwestern deserts are dust sources, and that the dust can travel hundreds of kilometers during a single wind event.

Effects of Aeolian Dust on Soil Fertility of the Colorado Plateau

Dust input into these deposits is reflected strongly by their geochemical properties (Tables 3–5, which are published as supplemental data on the PNAS web site). At all sites, surficial sediments are enriched strongly in many elements, including plant-essential macronutrients and micronutrients, compared with associated bedrock (Fig. 3). Enriched nutrients include P (2×), K (1.2×), Mg (4.4×), Na (3.8×), Ca (10.5×, excluding comparisons to calcite-cemented sandstone), Fe (1.6×), Cu (1.4×), Mn (2.1×), and Mo (5×).

The results of this study form a basis for understanding the influence of fine-grained aeolian deposits on ecosystem processes of the central Colorado Plateau. Dust inputs can alter soil fertility significantly and thus affect many ecosystem properties, including plant-community composition and productivity. As soils age, the supply of soil nutrients from minerals declines unless replaced by other inputs, such as dust (42). Dust may contain not only many plant-essential nutrients (e.g., Na, P, K, and Mg), but also substances that affect the availability of these nutrients (e.g., carbonates). P, which is commonly a limiting nutrient in desert soils, can govern plant productivity as well as affect carbon and nitrogen mineralization rates in deserts (43). K and Mg may strongly influence plant-community composition in semiarid areas (44). Even small increases in the proportion of fine particles, or in some nutrients, may increase invasibility by exotic annual plants (16, 45). Our results show that aeolian inputs have increased most plant-essential nutrients in surficial sediments relative to bedrock values. Dust inputs have doubled soil P. P derived from dust is critical for plant growth in these soils, inasmuch as plants in the study area are relatively P-deficient (J.B., unpublished data). Carbonates, which diminish P bioavailability in high-pH soils, are abundant (typically 4–10%). Mo, known to limit N fixation in terrestrial systems (46), is elevated 5× by means of dust inputs. Both Mo and P are essential to the N-fixation process. Because BSCs are the dominant source of fixed N in this ecosystem (21), and because lichens lack roots and thus are unable to tap nearby soil for nutrients, the addition of Mo and P by means of dust may be essential for continued N-fixation activities in the crusts. Moreover, the high K/Mg ratios (≈16) observed in bedrock are similar to those that favor annual plants over perennial plants (44). With dust additions, the much lower soil K/Mg ratios (≈5) in the overlying sediment are those shown to favor perennial over annual plants (ref. 44; J.B., unpublished data). Thus, the current plant-community composition likely would be much different in the absence of dust-derived nutrients.

We have not measured the fraction of plant-available nutrients in the surficial sediments, but relevant data are provided by an investigation of P fractions in shallow (0–10 cm) soil (having well developed BSCs) in undisturbed grassland within the study area (K. Gonzales, R. L. Sanford, M.R., and R.R., unpublished data). Correlation of MS with silt content confirms aeolian dust inputs into the shallow soil. Both labile and refractory P contents increase with increasing silt content, indicating that dust inputs recently have supplied plant-available P to the ecosystem. In addition, analyses of atmospheric dust obtained in 2000 from passive collectors at monitored sites in the study area show high amounts of labile P (R. L. Sanford and M.R., unpublished data).

Whereas dust deposition can enrich soils (42), erosion of aeolian-deposited fines can remove valuable nutrients (e.g., ref. 47). Replenishment of the nutrient-rich aeolian material then would depend on future aeolian input. Existing climatic and landscape conditions, however, differ substantially from past conditions of dust input. For example, modern forests occupy the Colorado Plateau at elevations between 1,600–3,500 m (48). During full glacial (22,000–15,000 years B.P.) and late glacial (15,000–11,000 years B.P.) times, however, high-elevation landscapes (>2,600 m) supported alpine vegetation related to colder climatic conditions than those at present (49, 50). Open-vegetation communities, characterized by *Artemisia*, extended at least another 100 m lower in elevation (51). Sparse vegetation may have rendered the high-elevation landscapes on the Colorado Plateau, including much of the basaltic High Plateaus on its western margin, more vulnerable to dust emission than today. The area between 2,500–3,500 m in elevation is 10% of the land surface of the entire plateau and thus minimally represents the expanded, high-elevation surface area most likely exposed to direct wind erosion between about 11,000–25,000 years B.P. than that which was exposed afterward, as forests moved to higher elevations (48, 49). In addition, many of the arid basins west of the Colorado Plateau held large pluvial lakes during the late Pleistocene. Desiccation and deflation of these lake beds during the Pleistocene–Holocene transition (12,000–8,000 years B.P.) are recorded clearly by the rapid formation of fine-grained shallow-soil horizons on uppermost Pleistocene and lower Holocene deposits in areas surrounding the former lakes (13, 52). This deflation likely produced far more dust than is generated currently from this region. Studies of the composition and ages of older silty deposits on the central Colorado Plateau will yield information about dust sources, the timing of dust input, and the roles of these older deposits in past and current ecosystem function.

Our monitoring of wind erosion in the study area, using particle-impact sensors placed 5 cm above the surface, reveals much greater soil loss from a grazed grassland surface than from two nearby undisturbed but otherwise similar surfaces stabilized by BSC (53). Initial measurements of dust fall, obtained in the passive collectors at 2 m above the surface, show little difference in dust inputs at the sites. Moreover, preliminary textural and magnetic results from shallow (0–10 cm) soil in previously grazed settings are consistent with loss of both silt and magnetite relative to an ungrazed but otherwise similar setting. If these results apply widely, they imply that some current land-use activities may deplete soil fertility in this remote region faster than nutrients can be replaced by means of aeolian deposition. The future nutrient load in the soils of the central Colorado Plateau thus depends on the balance of nutrients lost and regained, as well as composition of future dust inputs, all of which will be influenced by climatic variability and human activity as they modify southwestern landscapes.

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