Recent Seasonal Variations in Arid Landscape Cover and Aeolian Sand Mobility, Navajo Nation, Southwestern United States

Amy E. Draut

U.S. Geological Survey, Santa Cruz, California, USA

Margaret Hiza Redsteer and Lee Amoroso

U.S. Geological Survey, Flagstaff, Arizona, USA

The socioeconomic impacts of climate change pose problems not only in developing countries but also to residents of arid lands in the United States among marginalized societies with limited economic means. In the Navajo Nation, warming temperatures and recent drought have increased aeolian sediment mobility such that large, migrating sand dunes affect grazing lands, housing, and road access. Dust derived from this region also affects albedo and longevity of the Rocky Mountains snowpack, located downwind. We present initial results from a study that monitors sand transport and vegetation within a 0.2 km^2 site in the Navajo lands, measuring the effects of drought on landscape stability since 2009. Sand mobility decreased substantially as 1 year with near-normal monsoon rainfall (2010) somewhat abated a decade-long drought, temporarily doubling vegetation cover. Vegetation that grew during 2010, with adequate rain, died off rapidly during dry conditions in 2011. Short-term increases in rainfall that promote annual, but not perennial, plant growth will not improve landscape stability in the long term. Climate projections suggest that a warmer, drier climate and potentially enhanced sediment supply from ephemeral washes will further increase aeolian sand transport and dune activity, worsening the present challenges to people living in this region. Connections among climate, vegetation, and aeolian sediment erodibility in this region are highly relevant to other areas of the world with similar environmental problems.

1. INTRODUCTION

Human communities most vulnerable to the effects of climate change are those with limited natural resources for subsistence, limited economic means, and rapid population growth. Although such conditions are more commonly associated with developing countries, even within some of the wealthiest nations there are societies whose environmental and socioeconomic resources render them particularly vulnerable to twenty-first century climate change. The Navajo Nation is the largest tribal reservation within the United States, and its location is presently restricted to arid and semiarid lands within the Navajo ancestral homeland. These lands are stressed by drought, land-use practices, and a population that grew rapidly during the twentieth century. Like many other Native American communities, the Navajo people face economic disadvantage and, owing to livestock-management regulations and cultural ties, cannot readily relocate either their grazing lands or settlements [*Redsteer et al.*, 2010a].

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Among the environmental challenges faced by the Navajo Nation are shifting vegetation patterns, including the spread of invasive species, and aeolian sediment mobilization. Warming temperatures and recent drought have contributed to reduced streamflow and vegetation loss. These factors have increased aeolian sediment mobility such that regional dust storms are common and large, and migrating sand dunes affect grazing lands, housing, and transportation. Here we present recent sand transport and vegetation measurements to elucidate and quantify some of the factors affecting landscape stability in the Navajo Nation and discuss implications of aeolian sediment mobilization in this part of the Colorado Plateau for albedo on the Rocky Mountains snowpack.

With an area of 67,000 km^2 spanning parts of Arizona, New Mexico, and Utah (Figure 1), the Navajo reservation lands range in elevation from 1200 to 3000 m, with average annual rainfall varying regionally from 100 to 300 mm. This part of North America has a cultural history spanning thousands of years, but aridity and scarcity of arable and grazing land have challenged past and present civilizations there. Drought and depletion of natural resources are widely believed to have contributed to abandonment of large Ancestral Puebloan settlements in the twelfth and thirteenth centuries, in lands that overlap with the modern Navajo Nation; unfavorable hydrologic conditions also impacted the large Hohokam civilization of southern Arizona beginning in

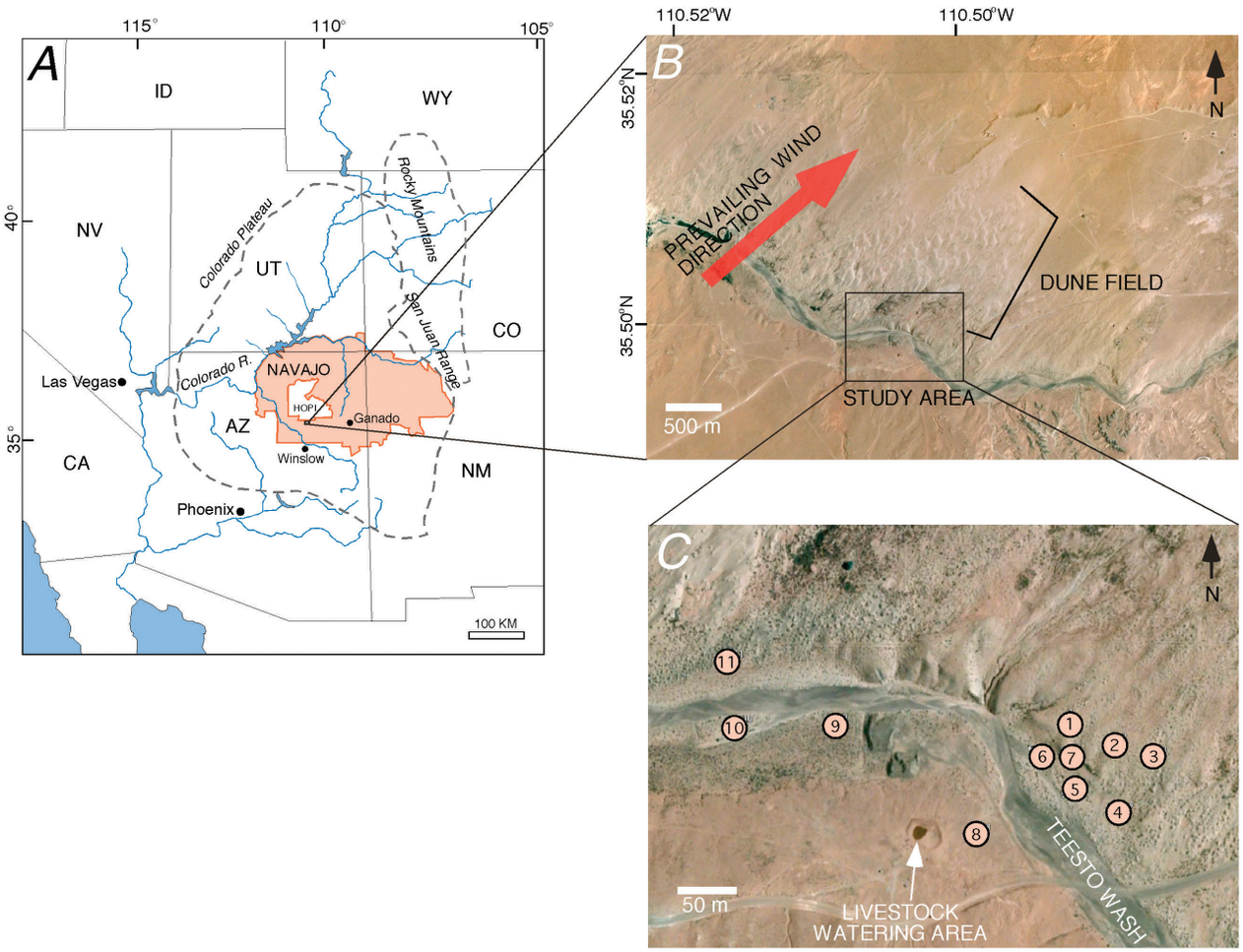


Figure 1. (a) Map of the southwestern United States, with shaded area indicating reservation boundaries of the Navajo Nation. The Hopi reservation is surrounded by Navajo lands. Regional wind direction over much of the Colorado Plateau is from southwest toward northeast. (b) Aerial photograph of the study area showing aeolian dune field downwind of ephemeral wash. (c) Sites where vegetation surveys were conducted. Sand transport, wind, and rainfall have been measured at site 7 since 2009. Images courtesy of Google Earth, © Google, Inc., 2007.

the twelfth century and led to their abandoning large settlements by the fourteenth century [e.g., *Euler et al.*, 1979; *Crown and Judge*, 1991; *Meko et al.*, 2007].

As of 2010, more than 169,000 of the 332,000 Navajo tribal members lived on the reservation [*Norris et al.*, 2010]. The population grew substantially in the late twentieth century; in 2000, the median age of the Navajo reservation population was 24 years, compared to 35.3 years for the general U.S. population. Forty-three percent of the Navajo population lived below the poverty line then, compared to 12% for the U.S. population as a whole [*U.S. Census Bureau*, 2000]. Historically, the Navajo subsistence resources and economy were tied closely to livestock. Political and economic forces encouraged the Navajo to expand sheep and goat herds in the mid-1800s, but by the 1880s, rangelands were being overgrazed to the point where native vegetation was diminishing [*Bailey and Bailey*, 1986]. Around 1900, regional vegetation communities also changed as the Eurasian annual plant Russian thistle (*Salsola* spp.) was introduced to the southwestern United States, where it spread quickly on loose, sandy soils. In its dry form known as tumbleweed, Russian thistle disperses great distances aided by wind and is one of the most widespread invasive plants in the Navajo lands today. Although cattle may eat its shoots when the plant is young and small, mature *Salsola* is thorny and unpalatable.

Precipitation occurs bimodally in this region, during winter storms (December–March) and the North American monsoon season (July–September), with 45% of annual precipitation falling during the summer monsoon [*Redsteer et al.*, 2010a]. These wetter seasons are separated by a dry, windy spring [e.g., *Draut and Rubin*, 2006; cf. *Jewell and Nicoll*, 2011; *Munson et al.*, 2011]. The past several decades have seen declining precipitation in the Navajo lands (Figure 2) and more rapid warming in the southwestern United States than elsewhere in North America, with associated ecological changes [*Westerling et al.*, 2006; *Seager*, 2007; *Weiss et al.*, 2009]. Declining precipitation, a shift from snowfall to rainfall, and increased potential evapotranspiration have contributed to reduced surface water in the Navajo lands; at least 30 streams and lakes that were perennial in the 1920s are now dry or ephemeral [*Redsteer et al.*, 2010a]. Climate models project increasingly drier and warmer conditions throughout the southwestern United States [*Seager et al.*, 2007; *Solomon et al.*, 2007; *Dominguez et al.*, 2010].

Sand dunes have formed and enlarged substantially in the Navajo lands since the mid-twentieth century. Nearly one third of the reservation area has loose, sandy soil that is easily entrained by wind and shaped into dunes [*Hack*, 1941; *Redsteer et al.*, 2010a]. Particularly after a 1950s drought, loss of perennial streamflow left riverbeds dry, providing a source from which the wind mobilizes sediment [*Redsteer et al.*, 2010b]. Aerial photographs show evidence for aeolian sand transport downwind of many streambeds in the Navajo Nation, commonly forming well-developed dune fields (Figure 1b), similar to source-bordering dunes found near other desert streambeds globally [*Bullard and McTainsh*, 2003]. Comparable sediment mobilization and dune activation has also occurred in other field settings in response to climatic change and fluvial sediment supply [*Muhs and Holliday*, 1995; *Lancaster*, 1997; *Clarke and Rendell*, 1998; *Cornelis*, 2006; *Draut*, 2012]. Aeolian sediment transport reduces air quality, causing health risks; sand dunes in the Navajo lands, migrating tens of meters per year, frequently impede road access and have destroyed houses (Figure 3) [*Redsteer et al.*, 2010a, 2010b].

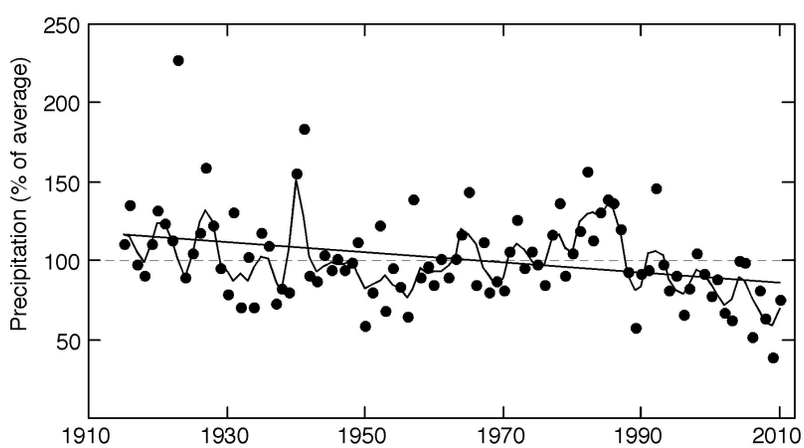


Figure 2. Rainfall on the southern Navajo reservation, as percentage of the 1915–2010 average. Plot shows combined data from Winslow and Ganado, the two stations nearest the study site with long-term records.

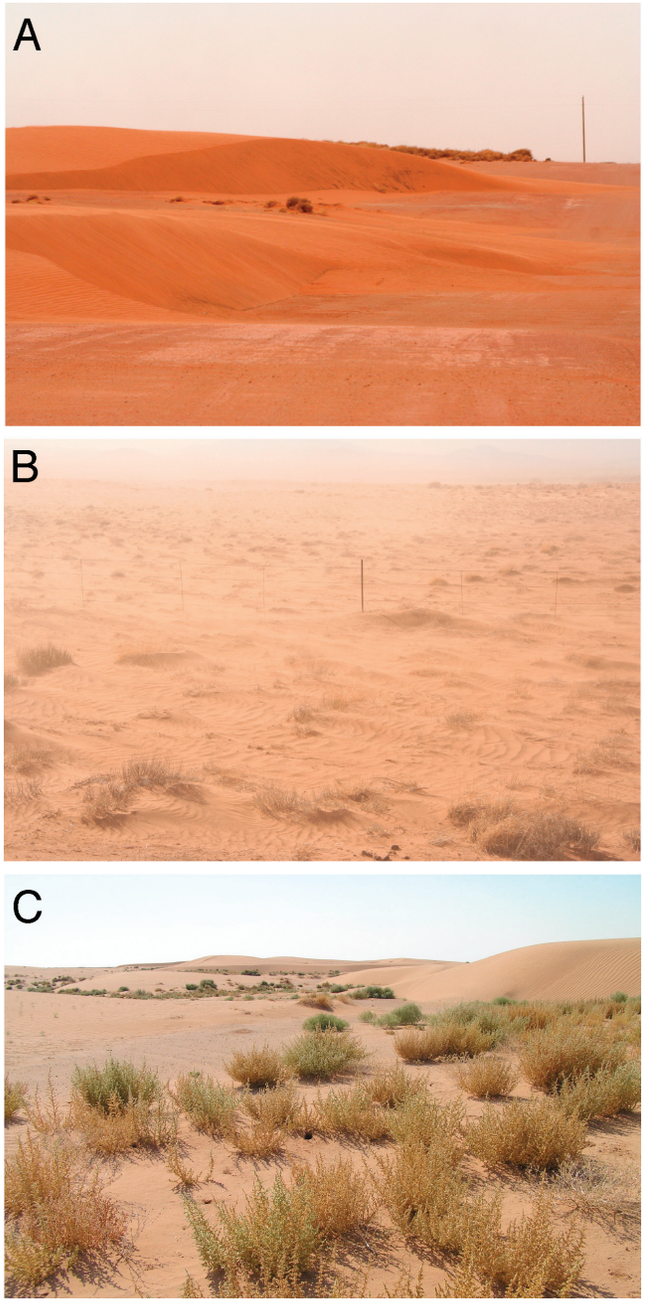


Figure 3. Photographs taken on the Navajo reservation in 2008. (a) Dunes migrating from left to right across a gravel road (road occupies foreground and is oriented toward and away from photographer). (b) Haze from airborne dust. Vertical fencepost in the center of the photograph is ~1 m tall. (c) Russian thistle dominates the vegetation in a dune field.

Because the Navajo lands are fairly remote, quantitative measurements of environmental parameters are scarce. The U.S. Geological Survey began a pilot drought-monitoring program there in 2005 that deployed new weather stations and recently expanded to measure aeolian sand transport and vegetation. We present some initial results of that study, demonstrating the influence of seasonal weather patterns on sand mobility and vegetation. Aeolian sediment mobility is a useful indicator of dryland environmental conditions: the air quality and landscape stability issues it represents are vital to evaluating the habitability of the Navajo reservation and longevity of the Rocky Mountains snowpack as twenty-first century climate becomes warmer and drier.

2. DATA COLLECTION

Seasonal variations in aeolian sand transport and vegetation were measured in a study area that, although small compared with the vast size of the Navajo Nation, is representative of many settlements. Some 15,000–20,000 Navajo people reside in landscapes with similar ground cover to that of the 0.2 km^2 study area: sandy soils near a dune field and an ephemeral wash, in an area with livestock use and occasional off-road vehicle traffic (Figure 1).

Wind velocity, rainfall, and aeolian sand transport were measured beginning in March 2009 at the site marked "7" in Figure 1c [*Draut et al.*, 2012]. The weather station and sand traps were surrounded by fenced enclosures to prevent livestock damage, necessary considerations that precluded deploying a more extensive array of sand traps. Wind and rain data were recorded on a digital data logger using a 4 min sampling interval. An anemometer measured wind speed with a resolution of 0.2 m s^{-1}, at a height of 2 m. A tipping bucket gauge measured precipitation with a resolution of 0.2 mm. Windblown sand was collected in four passive sampling Big Springs Number Eight (BSNE) traps [*Fryrear*, 1986] mounted on a vertical pole 10 m upwind of the weather station, with sand trap orifices 0.1, 0.4, 0.7, and 1.0 m above the ground. Every 4 weeks, sand was emptied from the traps and weighed. Transport rates were calculated by dividing the total mass of sand in the traps by the number of days over which it accumulated. To avoid introducing uncertainty, measured sand fluxes were not extrapolated down to the bed; thus, although measurements do not account for the absolute total mass flux, trends in relative amounts of sand transport with time still are resolvable. Sand transport rates were normalized to show sand mobility without the effects of variable wind speed in different time intervals; each sand flux measurement was divided by the cumulative flux predicted for that interval by the *Dong et al.* [2003] transport equation. This formulation, a modification of that by *O'Brien and Rindlaub* [1936], was chosen because it treats wind strength as a function of velocity rather than shear velocity; to extrapolate shear velocity from having

measured wind speed at only one height would introduce unwanted uncertainty.

In 2010 and 2011, March and August vegetation cover was measured at 11 sites (Figure 1c). At each site, five 3 m radius circles were outlined, one at the junction of two orthogonal 20 m long transects and the other four at the transect ends [cf. *Draut and Gillette*, 2010]. Within each circle, the proportion of space occupied by vegetation was measured. Four substrate classes also were measured: sand, rock, biologic soil crust, and leaf litter. Along each transect, gap lengths were recorded where the measuring tape crossed bare sand without rocks, biologic soil crust, leaf litter, or overhanging plant canopy. This method was modified from the work of *Herrick et al.* [2005] to measure spacing and abundance of elements that affect aeolian sand mobility [*Buckley*, 1987; *Belnap and Lange*, 2003]. Gap lengths between plant bases also were measured [*Herrick et al.*, 2005].

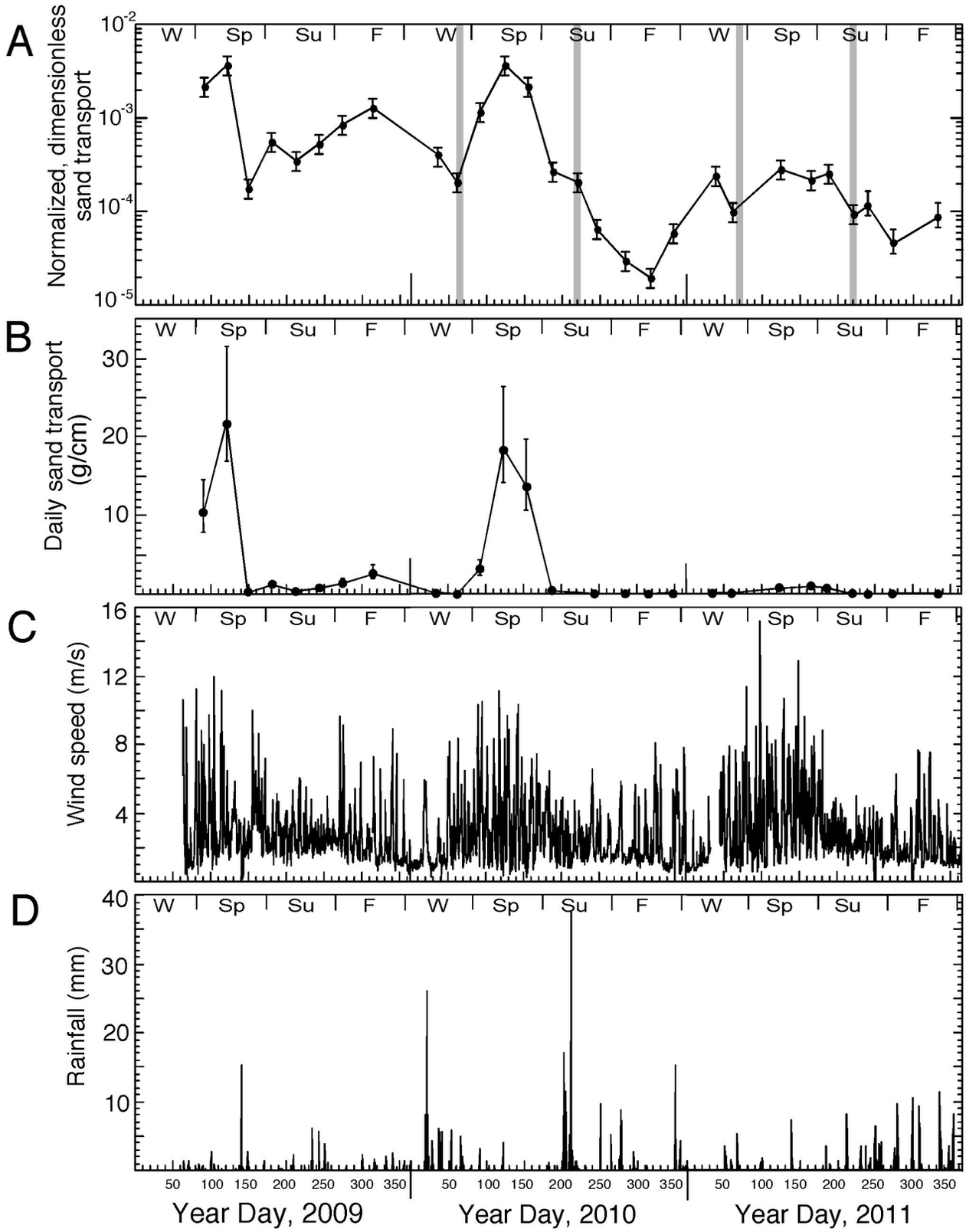
3. RESULTS

The greatest aeolian sand transport in the study area occurred from springtime winds, with spring sand transport in 2009 and 2010 ten times greater than in other seasons (Figure 4). As important factors in aeolian activity, seasonal trends in vegetation cover (Figure 5) are related to precipitation (Figure 4d). The study interval spanned a range of rainfall conditions. During 2009 and 2011, the El Niño–Southern Oscillation (ENSO) cycle was in a La Niña phase; 2010 was a weak El Niño year. In 2009, Arizona experienced its fourth driest year in 117 years on record, and the preceding 3 years also had been abnormally dry [*National Climatic Data Center*, 2011]. Wetter conditions returned in 2010, which was Arizona's 85th driest year on record with above-normal rainfall statewide, although northeastern Arizona received below-average rainfall (Figure 2). Dry conditions prevailed in 2011, the 23rd driest on record in Arizona, with the annual rainfall total in mid-August 2011 (the time of the fourth vegetation survey) being only 20% of the 2010 rainfall for the same time period and the summer monsoon having brought only 14% of the rain as had fallen by mid-August in 2010.

Sand mobility (normalized sand transport) (Figure 4a) varied over more than two orders of magnitude during the study interval and was greatest in winter and spring 2009 and 2010 when windy weather followed abnormally dry conditions. Sand mobility decreased to its lowest measured values in fall 2010, coincident with vegetation having increased over that summer (Figure 5). The 2010 monsoon season included a rain event on July 31 (year day 212) (Figure 4d) that produced the only known recent discharge in the study area wash: 38 mm of rain (29 mm within 20 min) caused an estimated 10 m^3 s^{-1} flow in the wash, and storm runoff incised >1 m into nearby gravel roads.

Vegetation cover in 2010 increased substantially between surveys in late winter (March) and those during the summer monsoon season (August) (Figure 5a). No similar increase occurred from winter to summer during the much drier year of 2011; both annual and perennial plant cover decreased between March and August 2011, even though warm temperatures and longer daylight hours typically favor plant growth then (Figure 5a). Changes in cumulative canopy gap length (Figure 5b) reflect the increase and subsequent decrease in vegetation abundance during 2010–2011, as substrate measurements indicated no substantial change in biologic crust, rock, or accumulated leaf litter that factor into the cumulative gap-length calculation; most study sites consistently had >95% sand substrate.

Vegetation growth during the 2010 summer monsoon was accompanied by disproportionately greater increase in annual plants relative to perennials (Figure 5a). Such growth also was reflected in the decreasing basal gap length between winter and summer 2010 (Figure 5c): transects intersect more plant bases after new annual plants have germinated. Basal gap length decreased in 2011 relative to 2010 as annual plants died and did not increase during 2011 because annuals did not germinate extensively during the very dry summer of 2011. Invasive Russian thistle is by far the most abundant annual plant in the study area; in the four successive surveys, it composed 100%, 70%, 96%, and 93% of the annual plant cover. After the 2010 monsoon rains, total vegetation cover increased by a factor of 2.3, whereas Russian thistle increased by a factor of nearly 15. The abundance and rapid increase of Russian thistle during 2010 likely interfered with the capacity of the BSNE traps to collect aeolian sediment. By winter 2011, Russian thistle had died and produced abundant wind-mobile tumbleweed that accumulated in thick piles at the upwind side of the fence enclosing the sand traps, apparently inhibiting sand movement locally until the tumbleweed was removed during our monthly maintenance visits. These conditions likely affected the relation between measurements of vegetation cover and sand mobility. Canopy gap length, at first, corresponded well with measured sand mobility as plant cover grew between March and August 2010 and as several dry years transitioned into the wetter year of 2010 (Figures 4 and 5). Even though plant cover in summer 2011 was only half of that in summer 2010, measured sand transport did not increase correspondingly. This was likely an artifact of antecedent Russian thistle abundance, such that tumbleweed that grew during the 2010 monsoon rains interfered with sand collection in 2011.


A
Normalized, dimensionless sand transport
B
Daily sand transport (g/cm)
C
Wind speed (m/s)
D
Rainfall (mm)
W Sp Su F
Year Day, 2009
Year Day, 2010
Year Day, 2011

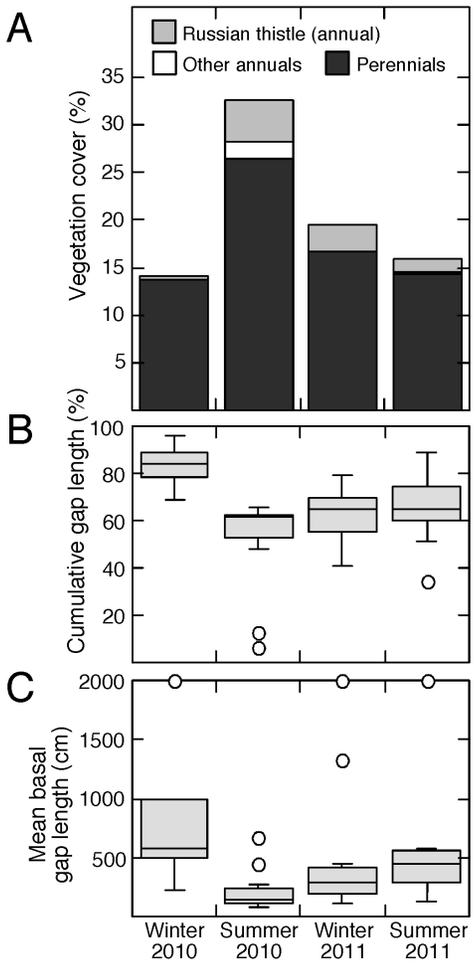


Figure 5. Vegetation measurements, winter and summer 2010 and 2011. (a) Area covered by vegetation (measurements from circular plots at all 11 sites combined). (b) Cumulative gap length where bare, open sand was present on linear transects (percent of total transect length). Boxes span the interquartile range of data collected at the 11 study sites; horizontal line through each box is the median value. Circles show outlier points with values more than 1.5 times the interquartile range, and whiskers show highest and lowest non-outlier points. (c) Mean basal gap length (distance between plant bases) on linear transects.

4. DISCUSSION

The data presented here reflect conditions at the upwind edge of a dune field. In other nearby areas with rapidly migrating sand dunes almost or entirely devoid of vegetation, sand mobility and transport likely are much greater than in our study area. We have not included such terrain in the study because rapid dune migration (e.g., 30 m during spring 2011) makes it impossible to deploy equipment in the field or to reoccupy the same location for vegetation measurements. Instead, we focus on conditions within a landscape where dunes are presently stable enough for people to still live, work, and raise livestock. Relationships discussed here among vegetation cover and aeolian sediment erodibility on this Navajo Nation landscape are highly relevant also to other areas of the world with similar environmental problems [e.g., *Kurosaki et al.*, 2011; *Okin et al.*, 2011].

Relative abundance of annual and perennial plants exerts an important control on aeolian sand mobility and thus on landscape stability [*Urban et al.*, 2009; *Munson et al.*, 2011]. Annual plants can germinate, mature, and disperse seeds with only one season of good rainfall, but to maintain and increase perennial plant cover in the long term would require sufficient moisture in multiple consecutive seasons, not only during the summer monsoon. Perennial plants tend to have stiffer, more durable stems and roots and to accumulate more leaf litter around their bases, protecting the land surface from wind erosion more efficiently than do annual plants [*Belnap et al.*, 2009; *Okin et al.*, 2011]. Therefore, although a year with good monsoon rains and abnormally dry conditions in other seasons would cause short-term plant growth, it would not reduce aeolian sediment movement in the long term. The disproportionate increase of annuals such as Russian thistle from a good summer monsoon is unlikely to increase landscape stability. Because the windy season occurs in early spring before most annual growth, and because invasive exotic plants crowd out slower-growing native plants and use water that otherwise could be available to perennials, the proliferation of Russian thistle may actually decrease landscape stability. Although both annual and perennial plants increased during the wetter

Figure 4. (opposite) Sand transport, wind speed, and rainfall at the study site, 2009–2011. (a) Aeolian sand mobility, represented as dimensionless values obtained by normalizing the sand transport measurements of Figure 4b against cumulative sand flux predicted for each time interval, as a function of wind speed, by the *Dong et al.* [2003] transport equation. Gray vertical bars indicate times of vegetation surveys. Beginning in winter 2011, sand transport measurements probably were artificially low owing to tumbleweed accumulating at the upwind side of the sand trap enclosure. (b) Direct measurements of aeolian sand transport, in grams per cm width, obtained using sand mass collected in BSNE traps divided by the number of days over which it accumulated. Error bars factor in a 70%–130% efficiency range for BSNE traps [*Goossens et al.*, 2000]. (c) Wind speed, expressed as daytime (06:00–18:00) and nighttime (18:00–06:00) averages of 4 min data. (d) Daily rainfall totals summed from 4 min measurements.

summer of 2010, decreasing sand mobility then, the subsequent loss of even perennial plant cover in a dry year such as 2011 (Figure 5a) poses a substantial risk to landscape stability in a setting prone to wind erosion.

Climate projections indicate that the southwestern United States will become increasingly warm and dry during the twenty-first century [e.g., *Seager et al.*, 2007]. Models also suggest that intense storms and associated flooding may increase [*Trenberth*, 1998]. In such a scenario, perennial streamflow would continue to decline in the Navajo lands [*Redsteer et al.*, 2010a], whereas stronger, more frequent episodic floods are possible. Because dry stream beds are sources of aeolian sediment, flash floods during storms could supply additional material that would be entrained by wind the following spring [cf. *Muhs and Holliday*, 1995; *Lancaster*, 1997; *Han et al.*, 2007]. Such altered patterns of rainfall and streamflow could further increase sediment supply into the aeolian dunes downwind of dry streambeds that have become common in the Navajo Nation since the 1950s [*Redsteer et al.*, 2010b]. Increased aeolian sand transport in springtime also could destabilize vegetation that initially thrived under the previous fall monsoon rain because wind-blown sand damages plants by abrasion and burial [*Okin et al.*, 2006]. We propose that a negative feedback cycle could develop whereby the summer-fall monsoon rain that promotes plant growth also supplies ephemeral washes with new sand that damages those plants once it is mobilized by wind.

Increased aeolian sand transport and dune activity in such a future climate regime would further compromise living conditions for the Navajo and other cultures in the southwestern United States. Because many Navajo residents not only have strong traditional ties to these lands but also do not have the economic means to relocate elsewhere, a future combination of climate change, greater sediment mobility, and growth of invasive plants that neither stabilize dunes nor serve a purpose for people or livestock would negatively impact residents over the long term.

Aeolian sediment mobility in northeastern Arizona has consequences not only for human health and infrastructure but also for the snowpack in the Rocky Mountains of Colorado, which supplies water to millions of people. Satellite imagery has shown aeolian dust plumes originating repeatedly from the Navajo lands in and near the study area during the time interval covered by this study [*U.S. Geological Survey*, 2012]. Wind-borne dust from the southwestern Colorado Plateau settles on the snow in the southern Rockies, reducing its albedo and leading to earlier spring melting [*Painter et al.*, 2007, 2010; *Center for Snow and Avalanche Studies*, 2011; *Phillips and Doesken*, 2011]. Accelerated snowmelt poses a concern for resource managers who anticipate that demand for water will increase as warmer, drier conditions prompt a shift from snowfall toward rainfall and also increase aeolian sediment transport from the Colorado Plateau. This is a particular concern during the La Niña phases of the ENSO cycle, when northeastern Arizona tends to have higher wind velocities and less rainfall than during the El Niño phases [*Enloe et al.*, 2004; *Phillips and Doesken*, 2011].

Previous studies indicate a link between strong winds in northeastern Arizona and dust events in the southern Rockies, with a daily average wind velocity above 6.7 m s^{-1} having been proposed as a threshold value for dust events [*Phillips and Doesken*, 2011]. High springtime sand transport measured at our study site in 2009 and 2010 is broadly consistent with dust-on-snow monitored in the San Juan range of the southern Rocky Mountains; the dust-on-snow mass there was greater in spring 2009 than in any of the previous 7 years [*Skiles et al.*, 2011]. Making more specific connections between trends in aeolian sand mobility in our study area and dust deposition in the southern Rocky Mountains is challenging because, over the 350 km between the study area and the nearest snowpack downwind where dust events are recorded, the source area is so large that even with a substantial reduction in sediment mobility, as apparently occurred in late 2010, the wind still supplies ample material to the San Juan range. A longer record from the study area and other locations may clarify connections between source-area aeolian events and dust deposition on mountain snowpack downwind.

5. CONCLUSIONS

Problems faced by populations living in marginal landscapes against a backdrop of climate change are not restricted to developing countries or to prehistoric cultures in the desert southwest of North America; they also occur today in this same region among marginalized societies with limited economic means. In the Navajo Nation, decreasing perennial streamflow and warming, drying trends lead to aeolian sediment mobilization that affects air quality, housing, and transportation and potentially reduces albedo of the Rocky Mountains snowpack. Initial results of an intended long-term monitoring program in a 0.2 km^2 site show that sand mobility decreased substantially as 1 year with near-normal monsoon rainfall (2010) somewhat abated a decade-long drought, temporarily doubling vegetation cover. Vegetation that grew during 2010, with adequate rain, died off rapidly during subsequent dry conditions in 2011. Short-term increases in rainfall that promote annual but not long-term perennial plant growth will not improve landscape stability because annual plants are less efficient than perennials at stabilizing sand against wind erosion. Climate projections

suggest that warmer, drier conditions and potentially enhanced sediment supply from flash floods in ephemeral washes will combine to increase sediment transport and dune activity, worsening the present challenges to people living in this region.

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L. Amoroso and M. Hiza Redsteer, U.S. Geological Survey, 2255 North Gemini Drive, Flagstaff, AZ 86001, USA.

A. E. Draut, U.S. Geological Survey, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA. (adraut@usgs.gov)