Combining surface mapping and process data to assess, predict, and manage dust emissions from natural and disturbed land surfaces

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ABSTRACT

The impact of dust emission on air quality is a significant health and environmental concern. Accurately determining the source (natural versus anthropogenic) and load of dust is an important component of any mitigation effort. We develop an approach to assess dust emission potential based on study of Nellis Dunes Recreation Area, a popular off-road vehicle area close to Las Vegas, Nevada. A mapping approach to assess dust emission potential is presented, which may serve as a template to assess other areas for this hazard. A 1:10,000 map delineating units based upon surficial characteristics affecting dust emission (e.g., soil texture, rock cover, surface crusts, and vegetation) was created. Seventeen surface units are grouped into four major classes (sand, silt and clay, rock covered, and active drainages). A >500 km network of trackways was digitized into a geographic information system (GIS) to determine the distribution of tracks across surface types to assess the density of disturbance. Wind-erosion measurements and off-road experiments using different vehicles (four-wheeler, motorcycle, and dune buggy) were performed on the various surface types to assess the amount of dust generated. Dust emission risk maps for Nellis Dunes Recreation Area are presented for two types of processes: off-road vehicular (ORV) activity and wind erosion. Highest dust emissions for ORV activity occur on map units composed of silt and clay, and on desert pavements. These areas can also produce large amounts of dust through natural wind erosion when disturbed. In contrast, the sandy units produce high emissions through natural wind erosion, and therefore limiting ORV use in those areas provides no benefit to air quality.

INTRODUCTION

The impacts of dust emission, transport, and deposition on environmental quality are a major issue in many metropolitan areas. The health effects (Griffin et al., 2001; Jarup, 2003; Smith and Lee, 2003; Griffin et al., 2007; Meng and Lu, 2007) are a primary concern along with environmental pollution risks (Schulz, 1992; Wilkening et al., 2000; Pelig-Ba et al., 2001; Ozer et al., 2007). In addition, dust plays a significant role in soil genesis and fertility in arid and semiarid regions (e.g., Dan et al., 1969; Yaalon and Ganor, 1973; Dan and Yaalon, 1982; McFadden et al., 1987; Wells et al., 1995; McFadden et al., 1998; Algharaibeh, 2000; Agbenin, 2001; Hamelryck et al., 2002). The effect of dust on ecosystem function (McTainsh and Strong, 2007), on the continents (e.g., Sterk et al., 1996; Herut and Krom, 1996; Kennedy et al., 1998; Mikkelsen and Langrohr, 1998; Reynolds et al., 2001; Derry and Chadwick, 2007; Reynolds et al., 2006), and in the oceans (Duce and Tindale, 1991; Baker et al., 2003; Meskhidze et al., 2005; Chase et al., 2006; Cassar et al., 2007) and its influence on human activities, including economic, political, and societal issues cannot be underestimated (e.g., Riksen, 2004; Ai and Polenske, 2008; Bayer et al., 2009; Bollen et al., 2009).

Although there are multiple processes involved in producing and controlling dust emissions, these processes need to be considered at different scales. On local scales, factors that influence emissions are primarily wind erosion, agricultural practices, and human vehicular activity. Previous studies have examined the impacts of such vehicular activity on unpaved and paved roads (Pinnick et al., 1985; Gillies et al., 1999, 2005; Moosmüller et al., 1998; Venkatram, 2000; Venkatram et al., 1999; Kuhns et al., 2003; Etyemezian et al., 2003a, 2003b; Kuhns et al., 2003; Williams et al., 2008; Goossens and Buck, 2009a, 2009b). These studies are based upon physical considerations and experiments. However, for an adequate assessment of the effects off-road driving has on dust production, two types of data are required: process data (based on measurements of the emissions) and areal data (dust emission tied to specific surface areas or activities on those surfaces). The latter include information on the dust emission potential of the area under investigation (geology, soils, surface characteristics, meteorology, and climate) as well as data on the human activities themselves: use of the off-road trails, length and location of these trails, frequency of use of each trail, and total distance driven per year in each soil unit.

Nellis Dunes Recreation Area was studied because of its popularity for off-road vehicular activity and its proximity to an important metropolitan area, Las Vegas, Nevada, USA. The NDRA is administered by the Bureau of Land Management (BLM) and for the past 40 years this 36 km² area has provided the only publicly accessible area in southern Nevada for off-road driving with annual visitors estimated at over 500,000 (Goossens and Buck, 2009a). The limitless opportunities for vehicular recreation have resulted in over 530 km of trackways comprising 6% of the total surface area of the NDRA. In addition to the dust generated by vehicular traffic, the destruction of the natural surface crust exposes underlying sediment that provides an additional dust source, entrained during strong winds. This study was designed to provide a spatial data set to use in combination with process measurements (emissions data) to better understand the distribution and controls on dust emissions. A 1:10,000 map was produced in which units are based upon surficial characteristics that are known to affect dust emission (e.g., soil texture, rock cover, surface crusts, and vegetation). We then applied data from quantitative dust emission experiments to this map in order to provide a better understanding of the...
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areal distribution and controls on dust emission from NDRA. From this, a much more complete understanding of the response of specific map units to both anthropogenic disturbance (off-road vehicle driving or ORV) and natural wind erosion can be obtained. The results of this study are critically important for land management, in part because of the proximity of NDRA to a major metropolitan area (Las Vegas, Nevada, USA) (Fig. 1), but also because many of the surficial units in this study can be applied to other areas in the Mojave Desert, USA and other deserts worldwide. Although this study specifically addresses the dust emission aspect of ORV activity, it contributes to the larger body of research that is concerned with all environmental impacts of ORV use (Ouren et al., 2007).

GEOLOGIC AND CLIMATIC SETTING

The Nellis Dunes Recreation Area lies northeast of the City of Las Vegas in the northeastern portion of the Las Vegas Valley referred to as the Nellis Basin (Beard et al., 2007) (Fig. 1). It lies west of the Gale Hills at the southern end of the Dry Lake Range. The topography of the area slopes from a maximum of 850 m elevation in the northeast part of the NDRA to 650 m in the southwest. The NDRA is dissected by northeast-southwest-oriented drainages separated by a variety of higher (~0.5–30 m), inset and relict alluvial fan geomorphic surfaces (e.g., Peterson, 1981; Bull, 1991) that form linear plateaus frequently capped by poor- to well-developed desert pavements. The oldest rock units mapped in the northern part of the NDRA are faulted and folded Ordovician Pogonip Formation, Eureka Quartzite, and Ely Springs Dolomite (Beard et al., 2007). The largest block of exposed bedrock belongs to the Permian Bird Spring Formation and represents the highest elevations in the NDRA. Overlying the Paleozoic carbonates are Neogene units assigned to the Muddy Creek Formation (Beard et al., 2007). Much of the Muddy Creek Formation occurs as flat-lying to gently dipping limestone and marl. In the western areas, east of the I-15 interstate highway, Muddy Creek lithologies include conglomerate, sandstone, shale, and gypsum. The most prominent geomorphic feature in the study area is a northeast-southwest-oriented zone of sand dunes that separates the area into western and eastern zones. These sand dunes cover 9% of the NDRA.

The NDRA is located in the Mojave Desert, where summer temperatures exceed 40 °C and the average annual temperature is 19.5 °C (Lazaro et al., 2004). Annual rainfall averages 105 mm with a range of 2 mm in June to 14 mm in February (Bureau of Land Management, 2004). Prevailing wind directions are from the northeast in the late autumn to early spring and from the south in the spring and summer (Goossens and Buck, 2009a). The average wind speed is 3.3 m/s (at a height of 10 m) with periods of higher winds in the spring that exceed 10 m/s (Goossens and Buck, 2010).

METHODS

Mapping of the NDRA began with the designation of 17 surface types based primarily on sediment size and degree of surface stabilization (surface crusts, rock fragments, and vegetation). Samples from each of the units were dried to determine grain-size characteristics. Mineralogical composition and distribution of the surface mineralogy was examined using the shortwave infrared (SWIR) and the thermal infrared (TIR) bands of the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument. This imagery was acquired on 6 July 2000 and obtained from Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/) supported by National Aeronautics and Space Administration and the U.S. Geological Survey. The SWIR component

Figure 1. Landsat band combination 7-4-1 showing the location of the study area relative to geographic features in the northeastern part of the Las Vegas Valley. The Nellis Dunes Recreation Area is outlined in red and occupies the Nellis Basin.
of ASTER has a 30-m spatial resolution that covers the spectral range of 1.6 to 2.4 μm over six bands. The TIR component covers the spectral range of 8.1 to 11.7 μm over five bands with a spatial resolution of 90 m. Analysis of the study area using the ASTER imagery focused on using the SWIR and TIR bands to isolate the occurrence of individual minerals and their relationship to mapped surface units. Calculation of a quartz (Rockwell and Hofstra, 2008) and carbonate index (Ninomiya et al., 2005) using bands 10–13 and bands 13–14, respectively, created images that defined the occurrences of these types of minerals. ASTER bands 8, 6, and 4 were combined to produce a SWIR image that was then further processed using a decorrelation stretch to enhance the differences between the individual bands (Mather, 2004).

The quartz and carbonate indices derived from the ASTER imagery are useful for characterization of surface mineralogy over large areas, but they do not provide the needed spatial detail for constructing a dust emission potential map at the scales involved. Thus, construction of the surface units map involved the use of high-resolution, Quickbird satellite imagery and field reconnaissance. The Quickbird imagery consists of two products. The first is a 0.6-m resolution panchromatic band and the second is a 2.4-m resolution multispectral product consisting of three visible bands and a near-infrared (0.45–0.90 μm) band. Field mapping, using the Quickbird imagery as a base, was accomplished through use of a ruggedized field computer with a global positioning system (GPS) attachment. This setup allowed field locations and unit contacts to be mapped with a high degree of accuracy. The contacts were then compiled using the Manifold GIS mapping package to produce the final surface units map. Developing the map in GIS allows creation of a georeferenced product that can be combined with other types of geographic information such as topography or aerial photography. Since the goal of the project involved, among other issues, addressing the impact of off-road vehicles on the various surface types, it was important to determine the location, width, and length of the unpaved tracks that exist throughout the NDRA. Trackway depth was not recorded because the extreme variability and density of the tracks made collecting those data impractical. Using the highest resolution Quickbird imagery (0.6 m), track centerlines were digitized and the widths measured. A structured query language (SQL) statement using a geospatial buffer extension was executed that converted the centerlines into polygons of the appropriate width. These polygons were then intersected with the surface units map to determine the area of surface units covered by ORV tracks. After the surface unit map was completed, it was combined with emission data collected in the NDRA to produce emission risk maps. Two types of emission were considered: ORV-produced emissions and wind-erosion–produced emissions. All emissions were determined by sampling airborne dust with Big Spring Number Eight (BSNE) dust collectors (Fryrear, 1986) at various altimetric levels between 25 and 100 cm. For ORV-produced emissions, the amount of dust transported in the emitted cloud was calculated by vertically integrating the dust profile over the entire height of the cloud (see Goossens and Buck, 2009a for more details). For wind-erosion–produced emissions, horizontal dust flux and dust concentration were calculated for all sample levels, and particle exchange theory was applied to calculate emission (Gillette, 1977; Goossens et al., 2001). In addition to these real emissions, we also measured potential emission, i.e., the emission under optimum meteorological conditions. These latter emissions were determined with a Portable In Situ Wind Erosion Laboratory (PI-SWERL; see Etyemezian et al., 2007 for a description of the instrument, and Goossens and Buck, 2009b for the procedure). All emission data (ORV, BSNE, and PI-SWERL) used in the present study were compiled by reexamining the original emission data sets collected by Goossens and Buck (2009a, 2009b), regrouping the data, and calculating the new combinations necessary for producing the risk maps.

**SURFACE UNITS**

Seventeen surface types, defined by characteristics that are known to control dust emissions (sediment grain size, surface crusts, rock cover, and vegetation), occur in the NDRA. Note that the order of organization of surface units and classes is arbitrary. These surface units can be grouped into four major classes:

1. Sands and sand-affected areas: active or stabilized sands, with or without rock fragments and/or vegetation.
2. Silt and clay areas: loose and slightly stabilized silt and clay deposits, with or without rock fragments.
3. Rock-covered areas: stabilized silty or sandy silt deposits with rock fragments on top, desert pavements over a silty sublayer (Av horizon), bedrock, and/or petrocalcic horizons.
4. Drainage areas: active drainages in sand and silt areas, and gravelly drainages.

In this study, sand is defined as the fraction 63–2000 μm, silt as the fraction 2–63 μm, and clay as the fraction <2 μm. The distribution of the surface units as a proportion of the total area of the NDRA is illustrated in Figure 2. More detailed descriptions of the surface units are given below, and a summary, for quick reference purposes, is provided in Table 1. Quantitative information for each unit is shown in Table 2. Photographs of each surface type, grouped by class are shown in Figures 3–6.
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### TABLE 1. GENERALIZED SURFACE UNIT DESCRIPTIONS

<table>
<thead>
<tr>
<th>Surface unit</th>
<th>Description</th>
<th>Rock fragments</th>
<th>Surface crust</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Active dunes without vegetation. Decimeter to several meters thick.</td>
<td>Sparse: may have exposed petrocalcic horizons</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>1.2</td>
<td>Active dunes with vegetation. Coppice dunes &lt;50 cm high may be present.</td>
<td>Sparse: &lt;5% rock cover</td>
<td>Absent</td>
<td>Isolated shrubs</td>
</tr>
<tr>
<td>1.3</td>
<td>Anthropogenic disturbed sand surfaces. Typically &lt;2- to 3-cm-thick loose sands overlying petrocalcic horizons or bedrock.</td>
<td>Common: mixed with 2–3 cm thick loose sand overlying bedrock</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>1.4</td>
<td>Patchy, shallow (1- to 3-cm-thick), loose sand overlying silty or rocky subsoil.</td>
<td>Common: not interlocking, rocks in subsoil are exposed at surface.</td>
<td>Absent</td>
<td>Isolated shrubs</td>
</tr>
<tr>
<td>1.5</td>
<td>Very fine sand and coarse silt outcrops. Commonly badlands.</td>
<td></td>
<td>Absent</td>
<td>Mostly absent</td>
</tr>
</tbody>
</table>

### Silt and clay areas

<table>
<thead>
<tr>
<th>Surface unit</th>
<th>Description</th>
<th>Rock fragments</th>
<th>Surface crust</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Silt and clay outcrops with biological crust.</td>
<td>Sparse: &lt;3%–4% rock cover</td>
<td>Biologic</td>
<td>Isolated shrubs</td>
</tr>
<tr>
<td>2.2</td>
<td>Silt and clay outcrops with gravel.</td>
<td>Common: &lt;15%, not interlocking</td>
<td>Physical, patchy distribution</td>
<td>Usually absent</td>
</tr>
<tr>
<td>2.3</td>
<td>Aggregated silt deposits. Commonly badlands, aggregates &lt;5 mm diameter.</td>
<td>Common: mixed with silt overlying bedrock</td>
<td>Physical</td>
<td>Absent</td>
</tr>
</tbody>
</table>

### Rock-covered areas

<table>
<thead>
<tr>
<th>Surface unit</th>
<th>Description</th>
<th>Rock fragments</th>
<th>Surface crust</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Well-developed desert pavements with underlying silty Av horizon.</td>
<td>Abundant: tightly interlocking rock fragments nearly 100% surface cover</td>
<td>Many: 60%–80%, poorly interlocking</td>
<td>Rare, isolated shrubs</td>
</tr>
<tr>
<td>3.2</td>
<td>Rock-covered surface with silt and clay.</td>
<td>Abundant: tightly interlocking rock fragments nearly 100% surface cover</td>
<td>Many: 60%–80%, poorly interlocking</td>
<td>Common shrubs (10%–15%)</td>
</tr>
<tr>
<td>3.3</td>
<td>Rock-covered surface with sandy loam.</td>
<td>Abundant: tightly interlocking rock fragments nearly 100% surface cover</td>
<td>Many: 60%–80%, poorly interlocking</td>
<td>Common shrubs (10%–15%)</td>
</tr>
<tr>
<td>3.4</td>
<td>Rock-covered with encrusted sand and biological crusts.</td>
<td>Common: 20%–30%, poorly interlocking</td>
<td>Physical, biological, continuous</td>
<td>Common shrubs (10%)</td>
</tr>
<tr>
<td>3.5</td>
<td>Bedrock and/or exposed petrocalcic horizons.</td>
<td>Continuous rock outcrop</td>
<td></td>
<td>Absent</td>
</tr>
</tbody>
</table>

### Active drainages

<table>
<thead>
<tr>
<th>Surface unit</th>
<th>Description</th>
<th>Rock fragments</th>
<th>Surface crust</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Gravelly drainages, without fine sediment.</td>
<td>Abundant: 90%–100%, noninterlocking gravel clasts</td>
<td></td>
<td>Absent</td>
</tr>
<tr>
<td>4.2</td>
<td>Gravel and sand drainages.</td>
<td>Abundant: 70%–80% with sand mixture</td>
<td></td>
<td>Absent</td>
</tr>
<tr>
<td>4.3</td>
<td>Gravel and silt and clay drainages.</td>
<td>Abundant: 70%–80% with sand mixture</td>
<td></td>
<td>Absent</td>
</tr>
</tbody>
</table>

### TABLE 2. SOIL TEXTURE, ROCK, AND VEGETATIVE COVER

<table>
<thead>
<tr>
<th>Surface unit</th>
<th>Gravel (&lt;2000 µm) (wt%)</th>
<th>Sand (2000–63 µm) (wt%)</th>
<th>Silt and clay (&lt;63 µm) (wt%)</th>
<th>Median grain diameter (fraction &lt;500 µm) (µm)</th>
<th>Total area (%)</th>
<th>Nonvegetated areas (%)</th>
<th>Vegetation cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand and sand-affected areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>0.0</td>
<td>99.9</td>
<td>0.1</td>
<td>210</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>1.2</td>
<td>13.9</td>
<td>85.0</td>
<td>0.9</td>
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<td>4.3</td>
<td>4.6</td>
<td>8.7</td>
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<td>49.7</td>
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<td>1.4</td>
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<td>1.5</td>
<td>10.8</td>
<td>85.6</td>
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<td>152</td>
<td>4.3</td>
<td>4.3</td>
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<td>Silt and clay areas</td>
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<td>10.1</td>
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<td>85</td>
<td>94.3</td>
<td>98.5</td>
<td>4.4</td>
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<td>Active drainages</td>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>94.8</td>
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<td>97.9</td>
<td>97.9</td>
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<td>63.9</td>
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<td>4.3</td>
<td>60.5</td>
<td>38.5</td>
<td>0.6</td>
<td>202</td>
<td>35.8</td>
<td>47.0</td>
<td>21.4</td>
</tr>
</tbody>
</table>
Sand and Sand-Affected Areas

**Surface Unit 1.1: Dunes with No Vegetation**
Active sand dunes and sand sheets with no vegetation that occur mostly, though not exclusively, as prominent ridges. The depth of the active sand layer varies from a few decimeters to several meters. Sparse rock fragments and underlying petrocalcic horizons may locally outcrop where the sand layer is thin. Surface crusts are absent.

**Surface Unit 1.2: Dunes with Vegetation**
Dune sands with sparse shrubs. The sand is active and there is no surface crust. Small coppice dunes may be present. Rock fragments may occur on the surface, but rock cover is low (<5%) and does not affect the deflation.

**Surface Unit 1.3: Disturbed Sand Surfaces**
Mixture of loose and active sand, rock fragments, and underlying bedrock. This unit typically occurs in areas where shallow (<2–3 cm) sands cover a substratum of petrocalcic horizons and/or bedrock and disturbance by human activity is high.

**Surface Unit 1.4: Patchy Layers of Sand over Silty or Rocky Subsoil**
These surfaces constitute a thin layer of loose sand (1–3 cm) covering the subsoil. Many underlying clasts are exposed at the surface. There is no surface crust; the sand is active, and small dunes may locally occur.

**Surface Unit 1.5: Outcrops of a Mixture of Very Fine Sand and Coarse Silt**
These outcrops may occur in badlands and on steep slopes, but also on plateaus. In NDRA, they typically have a yellow color. These surfaces are almost free of vegetation and are usually stabilized by a silty sandy crust.

Silt and Clay Areas

**Surface Unit 2.1: Silt and Clay with Crust**
These surfaces usually occur near drainage channels in silt areas. The sediment is predominantly composed of silt and commonly shows a continuous cyanobacterial crust. Some vegetation (isolated shrubs) is typical. A few scattered rock fragments (<3%–4%) may occur, based on sediment texture analyses.

**Surface Unit 2.2: Silt and Clay with Gravel**
Mixture of silt and gravel, but with considerably more (>85% in weight) silt than gravel on the surface. A surface crust may be present, although many areas are not encrusted. These surfaces do not occur in drainage areas but are derived from Muddy Creek Formation sediments, which are typically located on hill slopes and plateau escarpments.

**Surface Unit 2.3: Aggregated Silt Deposits**
Silt and clay surfaces where the particles are bound in aggregates up to 5 mm in diameter. The percentage of free particles is low. A surface crust is common, but the crust may be disturbed or even absent. These surfaces are entirely devoid of vegetation, and their erosion produces badlands-style topography.

**Surface Unit 2.4: Disturbed Silt Surfaces**
Mixture of noncrusted silt and rock fragments overlying bedrock. They occur in areas where the surface has been disturbed by human activity and are the silt equivalent of surface unit 1.3.

Figure 3. Photograph of sand and sand-affected area surface units: 1.1—Dunes with no vegetation; 1.2—Dunes with vegetation; 1.3—Disturbed sand surfaces; 1.4—Patchy layers of sand over silty or rocky subsoil; and 1.5—Very fine sand and coarse silt.

Rock-Covered Areas

**Surface Unit 3.1: Desert Pavements**
Well-developed and mature desert pavements over a (usually silty) subsoil (Av horizon). The rock fragments are partially embedded in the silt, and rock cover density is close to 100%. Vegetation (shrubs) may locally occur, but most desert pavements are devoid of any vegetation.

**Surface Unit 3.2: Rock-Covered Surfaces with Silt and Clay Zones**
The top layer is composed of silt with some very fine sand and contains many rock fragments (cover percentage: 60%–80%). Pavements are less well developed as compared to unit 3.1. The areas in between the rock fragments show a continuous and permanent surface crust. Vegetation...
(shrubs) typically covers 10%–15% of the surface. These surfaces occur anywhere in the landscape and are the dominant surface unit in the Nellis Dunes Recreation Area.

**Surface Unit 3.3: Rock-Covered Surfaces with Sandy Loam**

These surfaces resemble surface unit 3.2, but the top layer contains small amounts of sand. The sand has been blown in from nearby sand areas. In the Nellis Dunes field, they typically occur in silt areas located close to the sand dunes. Vegetation (shrubs) typically covers 10%–15% of the surface.

**Surface Unit 3.4: Rock-Covered Surfaces with Encrusted Sand**

This type of surface is similar to the 3.2 and 3.3 surfaces but is largely composed of sand, with small amounts of silt. It is covered by a continuous cyanobacterial crust. This crust is much weaker than the silt crusts of surface units 3.2 and 3.3. Vegetation (shrubs) is common and covers ~10% of the surface.

**Surface Unit 3.5: Bedrock and/or Petrocalcic Horizons**

Outcrops of bedrock and exposed petrocalcic horizons. The percentage of rock cover is close to 100%. Silt may have accumulated only near a few sparse shrubs and in deep cracks. Outcropping bedrock is commonly Paleozoic and Neogene carbonates.

**Active Drainages**

**Surface Unit 4.1: Gravelly Drainages**

Active drainages with almost pure gravel. In the Nellis Dunes Recreation Area, these surfaces typically occur in the channels of the major drainages. The gravel is almost free of sand, silt, and clay, and its cover percentage is close to 100%.

**Surface Unit 4.2: Gravel and Sand Drainages**

Active drainages with a mixture of gravel and sand. They occur in sand areas, in particular within the smaller sized valleys, and also in the upstream zone of the larger drainages where there is insufficient water to wash the sand. Vegetation is usually absent.

**Surface Unit 4.3: Gravel and Silt and Clay Drainages**

Active drainages with a mixture of silt and gravel. They are the silt equivalent of surface unit 4.2 except that many of them have considerable vegetation (usually shrubs). Silt and gravel drainages without vegetation also occur, especially in first-order channels in badlands.

**Surface Unit 4.5: Encrusted Sand**

These areas are covered by a dense cyanobacterial crust. This crust is most evident in those areas where there is significant sand present. The central part of the sand dune area is characterized by slightly meandering, NW-SE–oriented ridges of reversing dunes indicating that sand transport alternates from two opposing directions (NE and SW). Smaller, more amorphous sand accumulations occur in the areas in between the reversing dunes. Their morphology changes through time reflecting the most recent direction of sand transport. The abrupt

**Remote Sensing**

ASTER multispectral satellite imagery using band combinations 8-6-4 from the SWIR and the quartz and carbonate indices from the TIR bands were examined for the study area. The quartz index indicates quartz sand in the central and western parts of the study area (bright areas in Fig. 7A). The carbonate index (bright areas in Fig. 7B) shows that the concentration of carbonates is confined to the eastern parts of the study area. The ASTER band combination that provides the best surface unit determination is the 8-6-4 SWIR combination (Fig. 8). Here, the sandy areas underlain by units 1.1, 1.2, and 1.4 are shown in yellow (Fig. 8; area A), denoting the quartz composition of the sands. The main belt of dune sands is well defined, stretching from the southwest into the central portion of the map areas. Sandy areas also lie to the west (Fig. 8; area B), where they are separated from the main belt by a deeply incised wash (Fig. 8; area C). The sandy zones are more sparse and isolated in area B compared to those in area A. Silty units, such as 2.3, are the light purple areas (Fig. 8; area D) that occur primarily in the northwest. These units are capped by thin gypsum layers that are shown in darker purple (Fig. 8; area E). Paleozoic carbonates of the Bird Spring Formation occur in the northern part of the NDRA (Fig. 8; area F), whereas the better expressed carbonate signature derived from limestone clasts of the Muddy Creek Formation (Beard et al., 2007) occur in the south and eastern part of the NDRA (Fig. 8; area G).

**Field Mapping**

Detailed mapping of surface units using a Quickbird imagery base indicates that the overall distribution of surficial units in the NDRA follows a northeast-southwest trend (Plate 1). This orientation is particularly evident in the western part of the study area, where a rough zonation of rock-covered surfaces (3.x units) progresses from silty clay zones (3.2) to sand-encrusted areas (3.4). The sandy dune areas (1.1 and 1.2) are often rimmed by a thin layer of patchy sand (1.4). This type of zonation is most evident in those areas where there is significant sand present.

The central part of the sand dune area is characterized by slightly meandering, NW-SE–oriented ridges of reversing dunes indicating that sand transport alternates from two opposing directions (NE and SW). Smaller, more amorphous sand accumulations occur in the areas in between the reversing dunes. Their morphology changes through time reflecting the most recent direction of sand transport. The abrupt
changes from sand-dominated units to rock-covered surfaces with silt and clay zones (3.2) are often partitioned by deeply incised drainages such as those that mark the eastern edge of the dune field in the south-central portion of the study area. Sand that is transported from the west becomes trapped within the drainages, which prevent much of the sand from entering the areas to the east.

The surficial units in the northwestern part of the NDRA are primarily controlled by the lithologies of the underlying Muddy Creek Formation. Although some sand is present (3.3 and 1.5), the most significant unit is the aggregated silt deposit (2.3). This unit contains no vegetation and is characterized by badland-style topography. These areas contain some of the highest density of vehicular trackways. The northeast-southwest orientation of this unit follows underlying mudstone of the Muddy Creek Formation from which this surface unit is derived. West and east of the main belt of unit 2.3, yellow sand units (1.5) occur stratigraphically above the 2.3 units. These are, in turn, overlain by more resistant stratigraphic units of Muddy Creek limestone and gypsum that are preserved as topographic highs.

East of these areas where there are significant sand and silt units, the landscape is dominated by relict and inset alluvial fan geomorphic surfaces (e.g., Peterson, 1981; Bull, 1991), especially common are the rock-covered surfaces with silt and clay (3.2). These large expanses are occasionally interrupted by finer grained silt units (2.2 and 2.3) and well-developed desert pavements (3.1) along the flanks of drainages. The desert pavements are easily identifiable from the Quickbird imagery and appear as elongated areas that are darker in color and have a smoother surface texture with little vegetation. The desert pavement surfaces occur in areas east of the main silt occurrences.

Bedrock and/or petrocalcic units (3.5) occur as three outcropping types. They are (1) petrocalcic horizons, (2) Paleozoic limestone, and (3) Neogene limestone of the Muddy Creek Formation. Petrocalcic horizons exposed at the surface are often of limited lateral extent and represent areas of soil erosion. These occur along the tops and sides of all of the highest, and oldest, geomorphic surfaces. Many of these zones occur in the western part of the study area, but most of them are below the resolution of mapping. Paleozoic limestone of the Permian Bird Spring Formation forms hills in the northern part of the NDRA. South of this area isolated outcrops occur where the surficial material is thin. Limestone layers in the south-central and southeastern parts of the NDRA are different from the gray-black limestone, characteristic of the Paleozoic strata in the north. These units are relatively flat-lying and consist of white to grayish, laminated limestone and are part of the Muddy Creek Formation. The outcrop occurs as thin ledges that are separated by zones of map unit 3.2 (rock-covered surfaces with silt and clay crust).

Some of the map units correspond well with specific geomorphic surfaces or to bedrock formations, while others do not. Units that correspond to exposed bedrock are 1.5, 2.2, 2.3, and 3.5. The active drainages (4.1, 4.2, and 4.3), correspond to Q4 surfaces of Bull (1991). In most Quaternary maps, only unit 1.1 would be defined as an active, eolian geomorphic surface (e.g., Qe of House et al., 2010) because of the dune forms and thickness of the eolian sand. The other units in this study with active but thin, eolian sands (1.2, 1.4, and 3.4) overlie a wide variety of outcrop or relict alluvial fan surfaces that correspond to Q1–Q3 of Bull (1991) or Qea of House et al. (2010). Unit 3.1 is defined by well-developed desert pavements and is found on early Holocene–latest Pleistocene inset fans, corresponding to Q3 surfaces of Bull (1991) and Qay1 of House et al. (2010). The remaining units cross a broad spectrum of geomorphic surfaces. The most extensive unit, 3.2, is found on a wide variety of geomorphic landforms that have poorly developed desert pavements, reflecting a combination of processes including young surfaces where desert pavements have not fully developed, to very old surfaces where they have degraded (House et al., 2010). These

Figure 5. Photograph of rock-covered area surface types: 3.1—Desert pavements; 3.2—Rock-covered surfaces with silt and clay zones; 3.3—Rock-covered surfaces with sandy loam; 3.4—Rock-covered surfaces with encrusted sand; and 3.5—Bedrock and/or petrocalcic horizons.
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include Pliocene ballenas with exposed and fragmented stage 6 petrocalcic horizons (Gile et al., 1966; Peterson, 1981; House et al., 2010), middle-early Pleistocene fan remnants, early Holocene–latest Pleistocene and late-middle Holocene inset fans, and colluvial slopes of bedrock outcrops (Peterson, 1981; House et al. 2010). Although unit 3.3 is mostly present on middle to early Pleistocene fan remnants, its distribution is primarily controlled by proximity to local sand sources and not geomorphic position. Unit 2.1 occurs on latest and middle Holocene inset fans and inside active drainages along bars, where biological soil crust formation is favored (Williams et al., 2010). Disturbed surfaces (1.3 and 2.4) can occur on any geomorphic surface.

DISCUSSION

Dust Emission Potential of the Nellis Dunes Recreation Area

Studies have shown that soils with a high content of fine particles produce the most dust during human activities such as vehicular traffic (Cowherd et al., 1990; MRI, 2001) or agricultural tillage (Soret and Mutters, 1998). Based on the mapping in the Nellis Dunes Recreation Area, one might therefore assume that the units containing higher concentrations of finer grained silt and clay (2.x units) would have the highest potential for dust emission when entrained due to off-road vehicular activity. Goossens and Buck (2009a) examined the dust emission potential for vehicular driving on each of the surface types described and mapped in this study. Their experiments evaluated dust emission in terms of the type of vehicle (four-wheeler, dune buggy, and dirt bike) and the speed at which that vehicle moves over the surface. The total suspendable particle emission was higher for silty surfaces compared to sandy surfaces. For the current study, we consulted their original database, regrouped the data, and calculated the emissions (in g per driven km) at a driving speed of 40 km h⁻¹ for an average vehicle, defined here as the average result of the four-wheeler, the dune buggy, and the dirt bike (Fig. 9A). For values of driving speed up to 50 km h⁻¹, the results were similar. Specifically, the units that showed the highest dust emission (>2000 g km⁻¹) are 2.2 (silt and clay with gravel) and 3.1 (desert pavement with underlying silty A horizon). Units that show little to no dust emission (<10 g km⁻¹) are 1.1 (dunes

Figure 6. Photograph of active drainage areas: 4.1—Gravelly drainages; 4.2—Gravel and sand drainages; and 4.3—Gravel and silt and clay drainages.

Figure 7. Results of band mathematics calculations and ratios using Advanced Spaceborne Thermal Emission Reflection Radiometer thermal infrared bands. (A) Quartz index with brighter areas showing the occurrence of quartz. The bright areas in the center of the image denote the location of the main dune field. (B) Carbonate index with brighter areas indicating the occurrence of carbonates. The carbonate signature in the southeast portion of the study area reflects outcropping of limestone units within the Muddy Creek Formation.
with no vegetation) and 3.5 (bedrock and/or petrocalcic horizons). The remaining surface units showed intermediate dust emissions (usually between 200 and 1000 g km\(^{-1}\)) during off-road experiments.

The next logical step to determine both the direct emissions caused by ORV and natural emissions generated from ORV-disturbed surfaces is to examine the distribution of the surface units in terms of the density of trackways. The density of tracks can be expressed either as the total length of tracks within each mapping unit or by using a metric that calculates the length of trackway (km) within a particular surface unit to the total surface area of that unit (km\(^2\)). This metric is a derivation of the road density, as described by Forman (2002), which is frequently used as a method to assess the impact of roads on environments. The definition of road density is the length of road (km) divided by the total area (km\(^2\)) and is expressed as km/km\(^2\). However, for this study, we are concerned with the trackway density within each surface unit. Thus, we utilize the length of track within each surface unit and divide it by the surface area of each surface unit to calculate the trackway density (km/km\(^2\)). The locations of the various tracks in the Nellis Dunes Recreation Area are shown in Figure 10. It should be noted that track locations are particularly variable in those areas underlain by the sandy units 1.1 and 1.2 due to their temporary nature. Windblown sand in these active dune areas often covers tracks; hence many trackways appear to abruptly terminate within these sandy zones. In Figure 10, these areas are delineated by brown shading. If the track density is higher (more km) within a unit that has a higher dust emission potential (more g/km), then more dust should be produced than with a similar track density in a lower dust emission potential unit. The trackway density in all 17 units is shown in Figure 11. The units with the lowest trackway density are 1.1 (2.2 km/km\(^2\)) and 3.5 (2.3 km/km\(^2\)). The sand dunes of unit 1.1, as stated previously, do not preserve trackways very well due to being quickly covered by windblown sand. Thus, the actual trackway density and utilization of this unit for ORV activity is probably higher. Bedrock and outcropping petrocalcic horizons (unit 3.5) have low values for track density, since it is difficult for ORV activity to leave trackways in this type of material. However, tracks can occasionally be traced across these areas where a thin layer of sediment covers the rock surface. The highest trackway density units are 1.3 (40.2 km/km\(^2\)) and 2.4 (36.9 km/km\(^2\)), which is expected because surface disturbance is part of their definition (see section Surface Units). The units with the next highest density of trackways are 2.3 (33.1 km/km\(^2\)) and 1.4 (29.4 km/km\(^2\)). The 2.3 unit is silty and devoid of any vegetation and rocks and thus very easy to drive; hence it is used by all drivers (including the less experienced ones), which explains the high density of trackways. The 1.4 unit is sandier and often borders areas adjacent to the sand dune units of 1.1 and 1.2. The high trackway density of 28.1 km/km\(^2\) for unit 4.2 (gravely and sandy drainages) reflects the popularity of these washes as trackways, particularly in those areas close to the main dune field.

Although the surface types 2.2 and 3.1 generate the highest dust emissions during off-road driving (Fig. 9A), only 4.9% of the tracks pass through these surfaces (Table 3). The unit that contains the highest proportion of tracks (38.5%) is 3.2. This unit has a fairly significant dust emission potential, especially when compared with sandy surface units (1167 g km\(^{-1}\), i.e., the fourth highest value of all units; see Fig. 9A). Therefore, it is important to consider not only the emissivity of a unit but also the amount of potential ORV use when deciding upon management plans. Total dust emission at NDRA is significantly more complicated than just measuring ORV emissions on map units and quantifying the distribution of trackways in those units. Variables that affect ORV dust emissions include the amount of traffic, the variations in vehicle speed, the distances driven, and the number of units driven across. In addition, besides dust production by off-road driving activities, NDRA is also prone to severe wind erosion, especially in the western areas. Because the traffic characteristics other than trackways could not be measured without significant resources in this open-access off-road area, a previous study with a Portable In Situ Wind Erosion Laboratory (PI-SWERL) focused on quantifying potential dust emission on all 17 map units for areas in and outside of trackways (Goossens and Buck, 2009b). This study showed that, during episodes of wind erosion, most dust in NDRA is expected to be emitted from the sandy areas (units 1.1, 1.2, 1.3, 1.4, 3.3, and 3.4). This is illustrated in Figure 9B, which shows the potential emission flux (in μg m\(^{-2}\) s\(^{-1}\)) at a friction velocity of 0.55 m s\(^{-1}\). The silty areas emit less dust, and the drainage areas (except the sandy drainages) only emit very small amounts of dust. The data in the figure were extracted from the original PI-SWERL database and regrouped to show separate emissions for undisturbed terrain and the trackways, respectively. In the trackways the results are somewhat different (Fig. 9C): the silt units produce the most dust, followed by the sand units and the drainages. However, the tracks represent only 6% of the total area in NDRA. Therefore, the emission potential of the surface units with respect to dust production is different for the two types of dust-producing mechanisms in NDRA (off-road driving and wind erosion).

**Use of Surface Unit Maps for Assessing Dust Emissions**

Surface unit maps such as the one developed for NDRA provide a basic tool for quantifying dust emission in a given area. They are applicable to a variety of processes causing dust emission, such as wind erosion, off-road driving, and agricultural tillage activity. To be significant,
 quantitative data should be available for all map units regarding dust production, and for each type of process considered. The identification of the units is primarily based on their potential to emit dust. Therefore, dust emission units do not necessarily need to correspond with geologic, geomorphic, or pedologic units, although direct or indirect relationships with these units usually exist. The type of surface, combined with the composition of the subsoil, usually determines the vulnerability of a unit to emit dust. The criteria for selecting emission units for mapping are thus mainly based on visual perception: presence and amount of rock fragments, presence and amount of crusts, presence and amount of vegetation, textural composition of the top layer (sand, silt, and clay), and sometimes, though not always, topographic position and
Figure 9. Dust emission potential of the 17 surface units. (A) Emission caused by off-road driving (average emission for a four-wheeler, a dune buggy, and a dirt bike, at a speed of 40 km h⁻¹). Data calculated from an unpublished data set, portions of which are used in Goossens and Buck (2009a). (B) Potential dust emission outside off-road vehicle tracks as measured with the Portable In Situ Wind Erosion Laboratory (PI-SWERL) at a friction velocity of 0.55 m s⁻¹. (C) Potential dust emission in ORV tracks as measured with the PI-SWERL at a friction velocity of 0.55 m s⁻¹. Data shown in the (B) and (C) figures were calculated from an unpublished data set portions of which are used in Goossens and Buck (2009b).

geomorphic setting. Although these characteristics are relatively stable over time, more variable factors such as rainfall and, at the local scale, disturbance caused by animal activity also affect the emission of dust. Assessing the dust emission potential of an area is thus a complex task, involving the integration of various data sets.

Surface unit maps are indispensable when emissions should be calculated for nonlinear emission sources. This is true for different levels of scale: local (example: individual agricultural fields), regional (example: Nellis Dunes Recreation Area), or even much more extended areas (example: deserts). Surface unit maps are also critical tools when constructing risk maps. Such risk maps are very important instruments in management because they display the vulnerability of an area to natural processes or anthropogenic disturbances. Two examples of risk maps were created in this study (shown below), but many more are possible.

Example 1: Risk Map for Dust Emission Caused by Off-Road Vehicular Activity

A risk map for off-road vehicular activity in NDRA can be derived from the data in Figure 9A, which depicts the absolute as well as relative capacity of the units to produce dust. The units that form distinct emission classes are grouped and then displayed as “risk units” (Fig. 12). The detail shown by such maps depends on the number of classes defined and is thus subject to “good practice” by the cartographer, which is dependent on balancing the map objectives with graphical or perceptual limitations (MacEachren, 1994). In many cases, a compromise between the number of classes and the structure of the field area itself (occurrence of the surface units) will be necessary to produce an optimum risk map. This also means that the threshold values in such maps may slightly vary from one study area to another, and also depend on the scale of the mapping. The more surface units that are defined and the more detail in the mapping, the more the thresholds will be of regional instead of just local significance.

For ORV-created emissions in NDRA, the following classification provided the most detail: highly erosive units: >3000 g km⁻¹; very erosive units: 1500–3000 g km⁻¹; erosive units: 600–1500 g km⁻¹; moderately erosive units: 100–600 g km⁻¹; and slightly erosive units: <100 g km⁻¹. Note the nonlinearity in the threshold values, which was necessary to retain enough detail over the study area. The risk map for ORV activity is shown in Figure 12. Note that it shows emission of PM10 (the fraction <10 μm, i.e., not total dust) because the data in Figure 9A refer to this fraction only. Similar maps could be constructed for other dust fractions provided the appropriate emission data are available.

In the Nellis Dunes Recreation Area, the units showing the highest emission risk for ORV driving cover only a small portion of the land and mainly occur in the north and east. They correspond to silt and clay surfaces with gravel (2.2), desert pavements (3.1), and silty drainages (4.3). The least risky units are the sand areas (1.1, 1.2, 1.3, 1.4, 1.5, and 3.4), the nonsilty drainages (4.1 and 4.2), and the bedrock areas (3.5). ORV activity in the sand dunes of units 1.1 (dark-green area in the center left) and 1.2 (most of the light-green area on the map) is easy and comfortable to drivers yet produces some of the least dust emissions from those activities. ORV activity in the nonsilty drainages (4.1 and 4.2) also produces little PM10 emission. ORV activity on bedrock (dark-green areas in the upper right corner of Fig. 12) is uncommon and difficult because of the pronounced topography and highly irregular terrain. Therefore, an appropriate management plan for NDRA that addresses direct emission generated during ORV activity would need to encourage drivers to stay within the areas covered by sand and avoid the silt and clay areas with gravel, desert pavements, and silty drainages (i.e., units 2.2, 3.1, and 4.3, respectively).
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Example 2: Risk Map for Dust Emission Caused by Wind Erosion

Risk maps for dust emission caused by wind erosion can be based on potential emission or real emission. Although the latter option is more logical, it has the disadvantage that the data collection is more problematic and also more time consuming and expensive. Wind erosion is highly variable over time and strongly affected by rainfall, which in arid regions is usually characterized by local variations in both occurrence and intensity. As a result, long-term dust emission data are required to produce reliable emission maps. A minimum duration including both the seasonal and annual variability is three years, according to the rule of “good practice” in meteorology (Zangvil et al., 1991). However, in the southwestern USA, the longer El Niño–Southern Oscillation (ENSO) cycle strongly governs seasonal and annual variability of natural dust emissions (Okin and Reheis, 2002; Reheis, 2006). Measurements of potential emission (i.e., emission under optimum meteorological conditions) usually correlate well with true emissions (Fig. 13) and can be obtained more rapidly using field wind tunnels or the PI-SWERL instrument. In the current paper, we provide a risk map based on potential emission derived from PI-SWERL measurements. The classes are based on the information shown in Figure 9B, and the thresholds are shown in the legend of Figure 14. As with the map in Figure 12, Figure 14 only refers to the PM10 fraction (not total dust). The pattern in Figure 14 differs significantly from that in Figure 12. Apart from the bedrock areas (3.5), which show very low risk in both maps, the ranking in the two maps is opposite: the highest risk for dust emission due to wind erosion now occurs in the sand areas (units 1.1–1.5, and especially 1.2), whereas silt and clay areas with gravel, desert pavements, and silty drainages produce little dust, but only if they are undisturbed by human activity.

Management Implications

The total risk for emission in NDRA depends on both wind erosion and ORV activity and their proportions of the total emission. Our results show that the map units with the highest dust emission for ORV activity are 2.2 (silt and clay with gravel) and 3.1 (desert pavement); and that these areas can also produce large amounts of dust through natural wind erosion once disturbed. Therefore, based on these data, we suggest limiting ORV use and/or new disturbances within these areas. Unit 3.2 contains the highest surface area of tracks in NDRA. Although limiting ORV use in this unit may be unpopular, land managers may want to significantly limit both ORV use and especially the creation of new tracks because it also has a fairly significant dust emission potential. In contrast, limiting ORV use in the sandy units (1.x) hardly provides a benefit to air quality because these units emit only very small amounts of dust during ORV activity. Relocating ORV driving from the silt to the sand units therefore is the most recommended action to be taken in the NDRA to reduce the emissions.

Our approach in this study combines surface unit mapping and emission data to provide an overall assessment of emission risk within a spatial framework. Such an approach provides a template for land-use management in assessing whether access should be controlled in those areas where emission potential is highest. The use of high-resolution mapping allows agencies to focus such access controls to specific areas of risk rather than limiting access to broad swaths of land, balancing the interests of public access with the goal of improving air quality.
CONCLUSIONS

Quantifying the amount and spatial distribution of dust emissions at NDRA is vitally important for land management decisions in southern Nevada. Over 300,000 visitors annually use this area for ORV recreation (Goossens and Buck, 2009a) and are thus directly exposed to the emissions. Moreover, geomorphic evidence (type and orientation of the dunes in NDRA) and meteorological data show that dust emissions from NDRA are frequently blown into the Las Vegas metropolitan area, potentially affecting more than 2 million people.

Assessment of the dust emission potential of an area is a complex task, involving the integration of various data sets. One of the most important data sets necessary for understanding emissions and determining management techniques is a detailed map delineating units based upon the surficial characteristics that control dust emissions. In this study, we produced a surface unit map for the NDRA in which we delineated 17 surface units based upon surficial characteristics that can be readily distinguished in the field and that are known to affect dust emissions. These characteristics included soil texture, vegetation, the amount and density of surface clasts, presence or absence and type of surface crusts, and geomorphic landforms (i.e., active drainages and active sand dunes). Multispectral and high-resolution satellite imagery was used to aid in classifying and determining the distribution of surficial units. The results of this mapping revealed distinct differences in surficial characteristics that follow a northeast-southwest trend, with quartz-rich sands in the central and western parts of the study area, and carbonate-dominated units in the north and eastern areas. Although many of the surficial units are strongly controlled by the underlying geology, for example, silt units correspond to underlying mudrock of the Muddy Creek Formation; the importance of geomorphic processes in controlling surficial characteristics and therefore dust emissions is enormous. Many of the mapping units in this study correspond to specific geomorphic surfaces (active drainages, sand dunes, and well-developed desert pavements with Ah horizons), or to erosional or depositional processes (i.e., exhumed soils or thin sand sheets). In NDRA, dune type and orientation suggest two predominant (but opposing) directions of sediment transport during episodes of dust emission: from southwest to northeast and from northeast to southwest. Meteorological data alone are inadequate to provide this information because wind erosion, and thus the emission of dust, does not only depend on wind speed but also on the characteristics and the specific conditions of the soil

![Emission due to off-road driving](https://www.geoscienceworld.org/gsa/geosphere/article-pdf/7/1/260/3340974/260.pdf)

Figure 12. Risk map for dust emission (only PM10) caused by off-road vehicular activity in the Nellis Dunes Recreation Area.
Figure 13. Comparison of Portable In Situ Wind Erosion Laboratory (PI-SWERL)–measured potential emissions and actual emissions caused by wind erosion. Paired measurements were done for all 17 surface units in Nellis Dunes Recreation Area; each dot in the figure represents one surface unit. Actual and potential emissions were measured during the same time period (2–16 May 2008). Since the soils stayed completely dry over the entire period, surface conditions were identical during all measurements. Actual emission flux (y-axis) is the average for the period 2–16 May 2008; potential emission flux (x-axis) is the flux for a 3000 rpm rotational speed of the PI-SWERL blade, corresponding to an aerodynamic friction velocity of 0.55 m s⁻¹. All data are for the particle fraction <10 μm (or PM10) because the PI-SWERL measures only that fraction.

Figure 14. Risk map for potential dust emission (only PM10) caused by wind erosion in the Nellis Dunes Recreation Area.
surface, and the temporal changes of the latter do not necessarily evolve parallel with changes in the wind speed. Together with process-based information, field observation and mapping are necessary components in the assessment of the dust emission potential in any natural area.

The surface unit map is an essential component in determining dust emissions for vehicular activity as well as for natural wind erosion. To explore the former, a map of anthropogenic trails was created using high-resolution satellite imagery. The concentration of tracks was calculated both as the total length of tracks within each mapping unit and by calculating the trackway density (km²/m²), which is the length of trackway within a particular surface unit divided by the total area of that surface unit. When combining the results of this study with those of Goossens and Buck (2009a), who measured dust emissions with three different four-wheelers, we find that the surface types that generate the highest dust emissions during off-road driving (2.2 and 3.1) contain only a small proportion of tracks. However, the unit with the highest proportion of tracks (3.2) was found to have a fairly significant dust emission potential (Goossens and Buck, 2009a). Therefore, future management plans should consider both the emissivity of a surface as well as the density of trackways occurring upon it.

Combining the surficial map with the potential emissions measured by the PI-SWERL (reported in Goossens and Buck, 2009b), which simulate wind erosion, we find that during episodes of wind erosion most dust in NDRA will be emitted from the sandy areas (units 1.1, 1.2, 1.3, 1.4, 3.3, and 3.4). The silty areas (2.x) will emit less dust, and the drainage areas (4.x) (except the sandy drainages) will emit very little dust. Therefore, the order of the surface units with respect to dust production is different for the two types of dust-producing mechanisms in NDRA (off-road driving and wind erosion).

Risk maps for dust emission (only PM10) were constructed for off-road vehicular driving and wind erosion. These maps showed that areas with a high emission risk for ORV driving usually provide low emission risk for natural wind erosion. However, many areas that have a low emission risk for natural wind erosion change dramatically if the area is disturbed. Therefore ORV use of such areas can drastically increase emission risks. The total risk depends on the relative contribution of each type of process. In terms of management, ORV driving in NDRA needs to be discouraged in silt and clay areas with gravel, on desert pavements, and in silty drainages. Driving on sandy surfaces (especially dust surfaces) can be encouraged because ORV driving does not greatly increase dust emissions in these areas, which by themselves are already naturally emissive. On active sand dunes, the tracks created by ORVs will also quickly disappear, leaving little to no visual disturbance behind.

ACKNOWLEDGMENTS

The U.S. Bureau of Land Management (BLM) funded this project through a Southern Nevada Public Land Management Act (SNPLMA) Conservation Initiative, and granted permission for mapping in the Nellis Dunes Recreation Area. Lisa Christianson (BLM) provided administrative assistance throughout the project. The Quickbird imagery used in this study was provided through the SNPLMA Round 5 Conservation Boundary, Final Environmental Impact Statement: Science, v. 317, p. 1067–1070, doi: 10.1126/science.1144402.


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