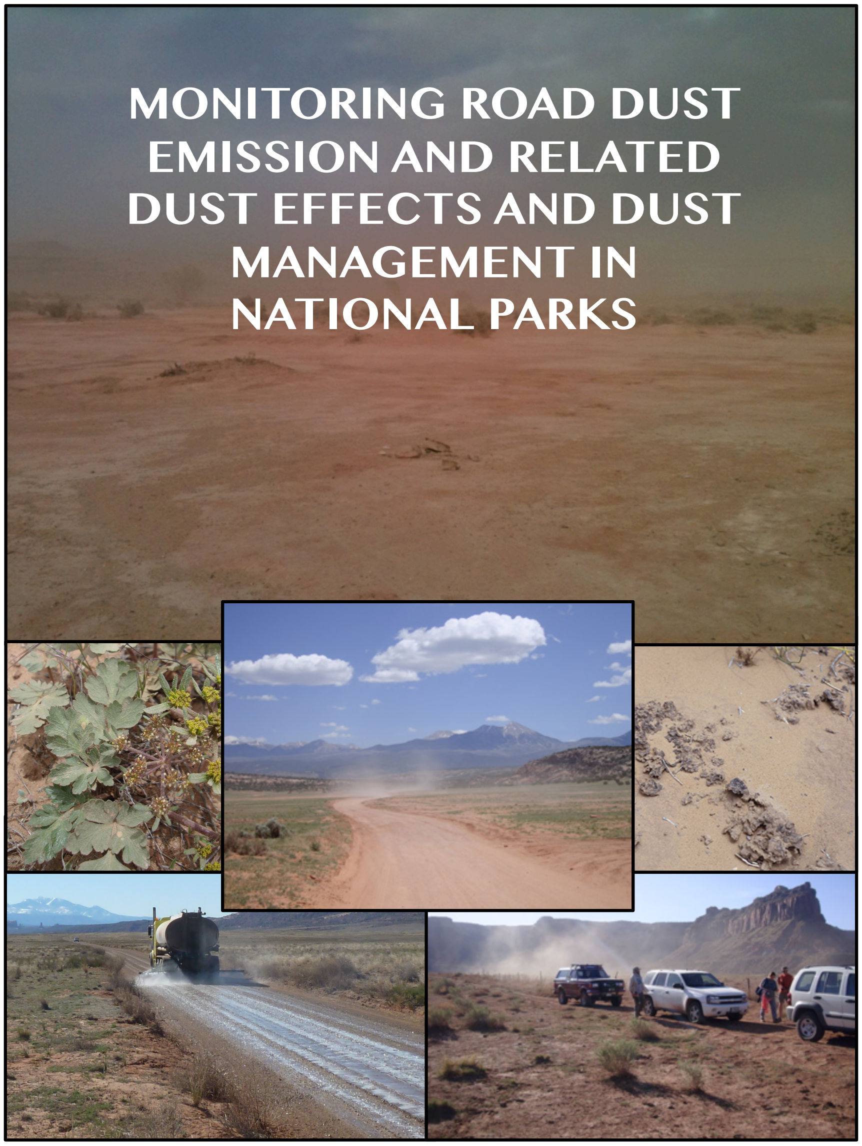

Project completion report to the National Park Service
Project #USU-CP-45

Submitted by Scott Hoffmann & Mark W. Brunson
Institute for Outdoor Recreation and Tourism
Dept. of Environment and Society
Utah State University

August 2012

ACKNOWLEDGEMENTS

This monitoring protocol was designed as part of a doctoral research study conducted at Utah State University. It was funded by the National Park Service, and was further supported by the Utah State University Agricultural Experiment Station and the Utah State University Ecology Center. Collaborators contributing to the research included scientists from Utah State University, the USDA National Park Service, the USDI Geological Survey, and the USDA Agricultural Research Service.

TABLE OF CONTENTS

INTRODUCTION

The high number of existing unpaved roads in the Colorado Plateau, and the ongoing expansion of this road system due to activities such as outdoor recreation, tourism, and energy development, raises critical questions about the emission of fugitive dust from roads as well as potential impacts on roadside vegetation. Dust emitted from roads in and near National Parks may influence local biotic and abiotic processes, and result in unexpected and largely unknown impacts to resource conditions. As these anthropogenic drivers of dust emission continue to intensify across the region, land managers are increasingly seeking ways to quantify and monitor road dust emission and transport, and evaluate ecological impacts caused by fugitive road dust as well as its contribution to overall dust emission at a landscape scale.

As dust impacts are monitored, land managers may be challenged with the question of whether and how to expend resources to mitigate dust emission. Chemical dust suppressants are currently in use in Arches National Park as part of an effort to reduce dust emission and stabilize road and trail surfaces within the park. The decision to pursue such mitigation efforts can be informed by data examining the degradation and ensuing migration of these dust suppressants away from roads and trails on which it is used, information that is useful to managers in other parks who may be contemplating the use of these chemicals.

This long-term monitoring protocol is intended to provide field technicians and land managers with a tool kit to measure the seasonal emission of dust from unpaved road surfaces, assess the potential impacts dust has on roadside vegetation in National Parks, and measure how far away from a road or trail a chemical dust suppressant may migrate. It is designed for use in the Colorado Plateau but is largely applicable to any semi-arid or arid landscape where road disturbance and dust emission occur.

CHAPTER 1
OVERVIEW OF THE COLORADO PLATEAU

TOPOGRAPHIC CHARACTERISTICS

The Colorado Plateau is a physiographic province that spans the states of Utah, Colorado, Arizona, and New Mexico. Sometimes referred to as the Colorado Plateaus, the province is actually composed of a collection of separate plateaus incised with deep canyons. The region covers approximately 340,000 km^2, and ranges from roughly 914 m to 3,879 m in elevation. Within the province exists 14 national parks and monuments, a testament to its natural beauty and the uniqueness of its landscape features. Broad valleys, mesa tops, plateaus, benches, fan terraces, and alluvial fans generally characterize the landscape. It is bounded by the Basin and Range physiographic province to the west and south, the Middle Rocky Mountain and Wyoming Basin provinces to the north, and the Southern Rocky Mountain province to the east.

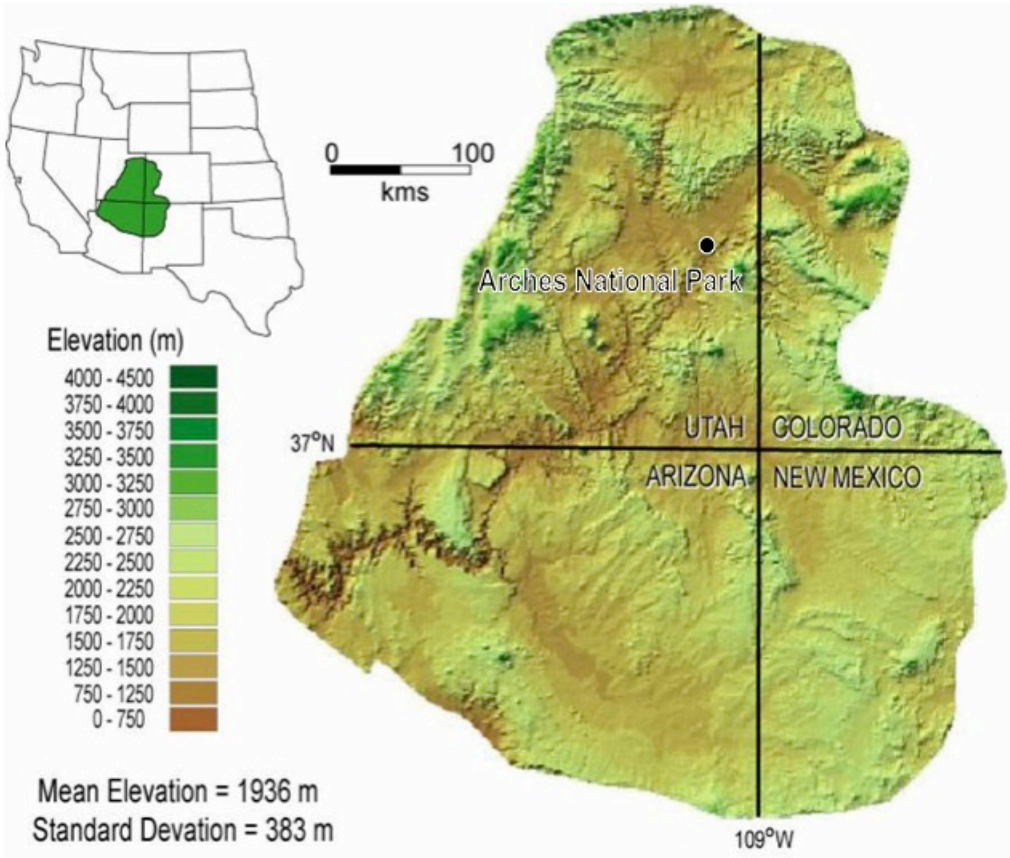

Figure 1. Location and elevational of the Colorado Plateau and Arches National Park.

CLIMATIC CHARACTERISTICS

Climate in the Colorado Plateau is driven by its location between two convergent moisture trajectories, one originating in the Gulf of Mexico that moves northwesterly and produces convective summer storms, the other originating in the Gulf of Alaska that produces southeasterly moving winter storm fronts (Schwinning et al. 2008). It has been suggested that fluctuations in climate resulting from these opposing trajectories over the past 10,000 years have influenced both the biotic communities and the human societies inhabiting the region (Schwinning et al. 2008).

Current climate patterns may vary dramatically with latitude and elevation, but in general the province has hot summers with frequent drought conditions, cold winters, and is classified as semi-arid.

Average annual precipitation is approximately 250 mm yr^{-1}, and annual precipitation near the study site, which lies just outside of Moab, UT, is approximately 229 mm yr^{-1} (Schwinning et al. 2008; Western Regional Climate Center 2010). Across the region, precipitation levels may range from 130 mm yr^{-1} to 670 mm yr^{-1}, depending on latitude and elevation (Schwinning et al. 2008). Precipitation may also be highly variable, which correlates with fluctuating El Niño and La Niña climate patterns (Cayan et al. 1999). Precipitation generally follows a bimodal pattern (Figure 3), with 35-50% of annual precipitation occurring in hot summer months (Comstock & Ehleringer 1992). Compared to surrounding regions, the Colorado Plateau receives more summer precipitation than the Great Basin, while receiving less and more variable summer precipitation than the Chihuahuan and Sonoran deserts (Schwinning et al. 2008). Winter precipitation that falls as snow in the higher elevation of the Colorado Plateau is believed to play a critical role in the soil moisture recharge that enables a consistent cool spring growing season for vegetation (Comstock & Ehleringer 1992).

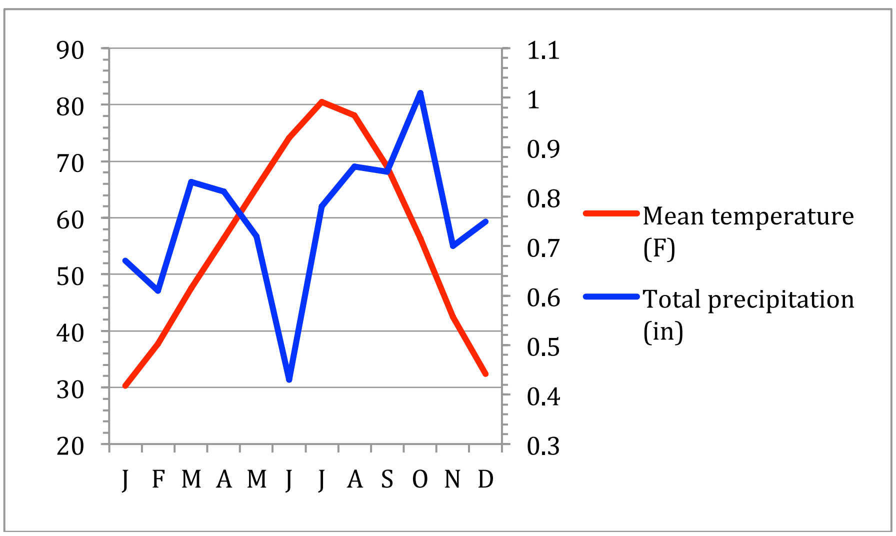

Figure 3. Annual temperature and precipitation patterns in the Colorado Plateau (Western Regional Climate Center 2010).

EDAPHIC CHARACTERISTICS

Soils in the Colorado Plateau include a range of types that vary with geologic origin. These may generally include soils high in clay content and sodium sulfate ($NaSO_4$) that have weathered from marine shales such as Chinle and Mancos formations, shallow rocky soils, immense sandstone outcrops, and well-drained sandy soils formed in deep aeolian deposits (Comstock & Ehleringer 1992). These soils may exhibit a wide range of nutrient availability due to aeolian transport and redistribution of sediment, spatial variability in bedrock geochemistry, nutrient loss following land-use change, and nutrient loss due to sediment deposition and erosion (Neff et al. 2006). A critical element to the formation, stability, and fertility of soils on the Colorado Plateau are the biological soil crusts that exist on the soil surface. These crusts play vital roles by trapping dust and associated nutrients, accelerating the weathering of bedrock, maintaining soil structure, stabilizing soil surfaces, altering hydrologic cycles, fixing carbon and nitrogen, and decreasing surface albedo (Belnap 2006; Belnap 2003; Belnap 2002; Belnap et al. 2001; Belnap & Gillette 1997).

VEGETATION CHARACTERISTICS

Cold winters and a semi-arid to arid precipitation regime are the primary drivers influencing plant communities in the Colorado Plateau (Comstock & Ehleringer 1992). Plants are typically most active in the spring when temperatures become warmer and water levels are highest as the snowpack melts and soil moisture recharge occurs. The region has generally low perennial plant cover in grasslands and shrublands (< 40%), and due to shifting climate conditions as well as soil surface disturbance and wind erosion it is expected that perennial cover will continue to decrease (Munson et al. 2011). A reference list of plant species found in southeast Utah National Parks can be found in Appendix A.

CHAPTER 2
OVERVIEW OF DUST, DUST EMISSION, AND DUST IMPACTS

AEOLIAN DUST PROCESSES

Dust is defined as terrestrially derived sediment with diameter less than 100µm that has been eroded, transported by wind, and deposited via aeolian processes over scales ranging from local to global (Okin et al. 2006; McTainsh & Strong 2007). Dust frequently occurs as a result of surface disturbance, after which soil particles become more susceptible to erosion processes such as wind and water. General dust entrainment involves the wind transport and deposition of dust particles via surface creep, saltation and suspension processes (Figure 4). Saltation involves the movement of larger sized particles in a bouncing manner over relatively shorter distances, which "sandblasts" the soil surface and frees up finer sized particles (Okin et al. 2006). These fine particles are then uplifted by airflow and transported via suspension. Finally, dust entrainment is also dependent on local climate conditions, perhaps the most important of which is wind velocity.

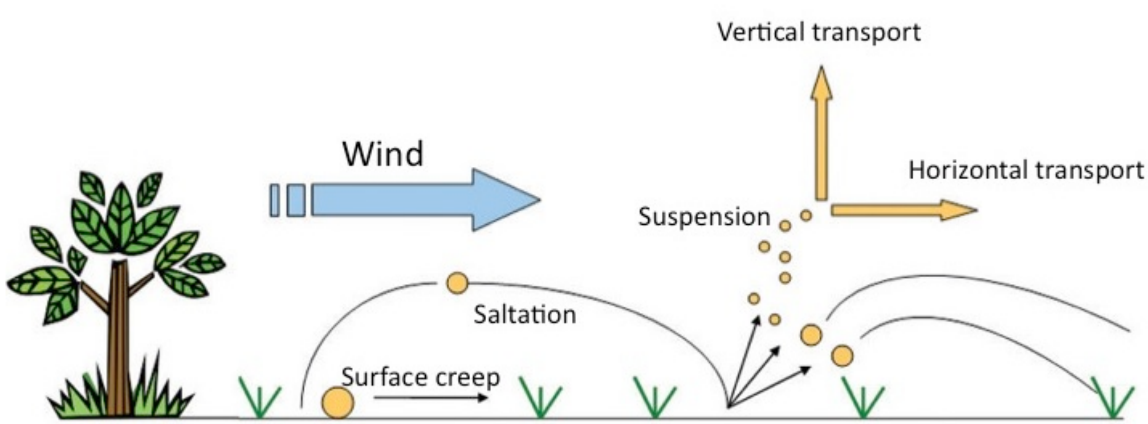

Figure 4. Mechanisms of wind-induced particle transport (from Field et al. 2010).

Neff et al. (2008) found that sediment cores from alpine lakes in the western United States showed a 500% increase in dust loads following the wave of western population migration in the nineteenth century. With this population growth came changes in land use including intensification of grazing, mining, and agricultural operations, which led to landscape disturbance such as vegetation loss, soil compaction, and decreased soil aggregate stability. These mechanisms lead to overall decreases in soil surface stability, making sediment erosion via wind and water more likely to occur. Thus, the way humans influence a landscape, which includes the above land uses as well as increased recreation, construction, alternative energy development, and other activities that lead to landscape surface disturbance, can and often does lead to increased amounts of aeolian dust emission.

These effects of land use are closely coupled with the influence of climate on dust fluxes, primarily in how precipitation and temperature affect soil moisture, soil type, wind patterns, surface hydrology, and plant cover. For example, under current climate change predictions for the southwestern United States, overall dust flux may be expected to increase with predicted increases in summer precipitation, but may vary locally depending on dust source type, land use, and vegetation cover (Reheis & Urban 2011). In general, effects of aeolian dust can include changes to climate due to radiative forcing in the atmosphere (Tegen et al. 1996), as well as detrimental effects to air quality and to human health (Mohamed & El Bassouni 2007; EPA 2011). Fertilization of oceans and other ecosystems (Kawahata et al. 2000), and alteration of cross-scale carbon and nutrient cycling may occur because soil nutrients are primarily attached to dust particles, and when aeolian dust transport occurs nutrients are lost from source areas and deposited in sink areas (Chadwick et al. 1999; Li et al. 2008; Okin et al. 2006; Okin et al. 2004). An increasingly recognized phenomenon in the western U.S. is the deposition of dust on snow pack in alpine systems, causing a shift in snow cover duration by 18 to 35 days due to decreased surface albedo and increased surface radiative forcing by the dust layer (Painter et al. 2007). This is likely to cause critical shifts in the timing and availability of snowpack runoff and seasonal water availability on a regional scale. Again, the coupling of increased dust emission due to anthropogenic and climatic factors, and the feedbacks that exist between them, are likely to exacerbate this trend.

EFFECTS OF DUST ON AIR QUALITY AND HUMAN HEALTH AND SAFETY

Continued inhalation of dust particles that fall within the size range of 2.5 μ (PM2.5) and 10.0 μ (PM10) can lead to respiratory and cardiac health problems in humans (EPA 2011). This may include irritated airways, difficulty breathing, asthma, chronic bronchitis, decreased lung function, irregular heartbeat, and premature death in persons with existing respiratory or cardiac disease. The EPA (2005) recognizes road dust as the primary source of both PM2.5 and PM10 across the United States, and has established air quality standards on acceptable levels. Dust emission may also result in hazy conditions and reduced visibility, which can result in diminished visitor experiences as well as safety issues for vehicular and pedestrian traffic. This is especially germane to the Colorado Plateau, a region internationally recognized for adventure recreation opportunities in striking, vast, and wide-open desert landscapes, wild and remote rivers, and deeply incised red rock canyons. With increasing visitation and a growing number of unpaved roads in the Colorado Plateau, the recognition and necessary management of fugitive dust as an ecological impact, a human health concern, and an air quality issue is likely to increase.

ECOPHYSIOLOGICAL EFFECTS OF DUST ON VEGETATION

Once entrained, dust emitted from road surfaces can be transported by wind and deposited at some distance away from the road. The range of dust deposition adjacent to and downwind from a road equates to the range of potential impacts to roadside and road proximate vegetation. Many of the documented effects of dust on plants relate primarily to plant ecophysiology, and each may be driven by multiple mechanisms. Inhibition of photosynthesis may occur and may be due to reduced chlorophyll content in leaves (van Heerden et al. 2007), higher leaf temperatures caused by increased absorption of infra-red radiation by leaves covered with dust (Sharifi et al. 1997; Hirano et al. 1995; Eller 1977), shading of leaves which can lead to increased reflectance of photosynthetically active radiation by leaves

(Grantz et al. 2003; Sharifi et al. 1997; Hirano et al. 1995), and decreased CO_2 assimilation due to clogging of stomata (van Heerden et al. 2007). Transpiration rate may be increased as a result of incomplete closure of stomata at night due to blockage by dust particles (Sharifi et al. 1997; Hirano et al. 1995), by water loss due to abrasion of the leaf surface (Eveling & Bataillé 1984), and by increase in leaf temperature caused by coating of leaves by dust (Hirano et al. 1995).

Figure 5. Dust cover on roadside plants in Arches National Park.

Recent research conducted in conjunction with an Arches study suggested that leaf conductance in four common roadside forb species found in Arches National Park was reduced over a six-week period in which the plants were experimentally treated with simulated road dust emission (Figure 6; Hoffmann, *unpublished data*). Again, it is hypothesized that dust impacts may lead to growth inhibition of certain plant species, and potential shifts in plant community composition along unpaved roads where dust emission occurs. Reduced conductance in native species could lead to competitive disadvantages with non-native species, with ensuing decreases in abundance, and this information would be critical to park managers tasked with preserving unimpaired conditions in national park. Assessing these types of changes is a principal objective of this monitoring program.

Helianthus annus (HEEA)

Oenothera pallida (OEPA)

Sphaeralcea grossulariifolia (SPGR)

Penstemon eatonii (PEEA)

Thus, dust can affect vegetation both directly (e.g. deposition on foliar surfaces) and indirectly (e.g. by altering the absorptance of incoming insolation and by influencing soil nutrient cycling; Grantz et al. 2003). Grantz et al. (2003) noted that some amount of dust emission and deposition is a natural part of semi-arid and arid systems, and that many desert plant species may be adapted to dust loading due to inherent semi-arid and arid climate conditions. As discussed earlier, however, Neff et al. (2008) have since shown that natural dust levels, at least in the southwestern U.S., might actually have been very low due to the stabilizing influence of biological soil crusts on undisturbed surfaces. Under either scenario the issue of road dust and related impacts is an increasingly important one to consider. This is especially true in the Colorado Plateau, where the continuing and rapid intensification of vehicular traffic on unpaved roads and trails may behave as a chronic stress to roadside soils vegetation and result in slower recovery after impact and in general degradation of an ecosystem over time (Grantz et al. 2003).

The impacts discussed have particular relevance to the Colorado Plateau because of its semi-arid climate. Relatively low precipitation levels may allow greater dust accumulation on leaf surfaces between precipitation events, as compared to wetter systems in which leaves are more regularly rinsed (van Heerden et al. 2007). A higher semi-arid temperature regime for the region, coupled with potential increasing leaf temperatures due to dust deposition, could hypothetically reduce productivity in certain species due to spring and summer temperature optimums for photosynthetic processes being exceeded (van Heerden et al. 2007; Sharifi et al. 1997). This coupling of temperature and productivity as it relates to dust deposition becomes more critical amid scenarios of global climate change, which generally predict the Colorado Plateau to experience a warmer future temperature regime. Increased aridity in the Plateau has been linked to reduced perennial vegetation cover (Munson et al. 2011; Figure 7), creating a potential feedback for increased wind erosion and dust emission as plant cover decreases and soil surfaces become more exposed.

Figure 7. Example of a degraded roadside grassland in Arches National Park.

THE IMPORTANCE OF BIOLOGICAL SOIL CRUST TO DESERT ECOSYSTEMS

Biological soil crust (BSC) is an important component of many semi-arid and arid ecosystems because the organisms that compose the crust provide soil surface stability (thus preventing erosion), decrease water infiltration rates (thus increasing plant water availability), and can be sources of organic carbon and nitrogen to soils (thus maintaining soil fertility). BSCs in the Colorado Plateau are composed of a symbiotic community of microorganisms, including cyanobacteria, mosses, and lichens, that exude organic materials that bind soil particles together to create a crust on the soil surface. This aggregation of soil particles provides stability and prevents the loss of soil particles via the erosive forces of water and wind. BSCs also provide texture to the soil surface, which slows water runoff and helps to increase infiltration, leading to longer periods of increased soil moisture following precipitation events, and thus increased water availability to plants where BSCs are present. Nutrient cycling in deserts can also be a limiting factor to plant productivity, and nitrogen deficits in particular are limiting in the Colorado Plateau. Lichens of the genera *Collema*, a common component of BSCs in the region, serve as primary atmospheric nitrogen fixers and contribute largely to the presence of organic nitrogen in soils. BSCs also contribute to the presence of organic carbon in soils, in the form of biomass and the organic materials exuded by crust organisms.

Figure 8. Pinnacled biological soil crust in Canyonlands National Park (courtesy NPS).

BSCs have evolved as robust organisms in the harsh desert landscapes they inhabit. They can withstand long periods of drought and dryness, as they only become metabolically active after wetting by even just a few millimeters of precipitation. Yet, in spite of their resilience to natural stressors, and their strong tension resistance (resistance to pulling forces), BSCs are extremely vulnerable to compressional disturbances such as grazing and trampling. Human disturbance in the Colorado Plateau is largely due to recreational activities such as hiking, mountain biking, and off-highway vehicle (OHV) driving, all activities that can dramatically impact BSCs. Once lost to disturbance, BSC can take anywhere from years to decades to regenerate, and with BSC loss comes the loss of the critical ecological functions they provide.

ROAD ECOLOGY AND DISTURBANCE

Roads have been demonstrated to have considerable impacts on the surrounding landscape, including changes to plant and animal populations (Angold 1997; Coffin 2007), altered roadside hydrology (Forman & Alexander 1998; Trombulak & Frissell 2000; Brooks & Lair 2009), reduction in roadside soil nutrient availability and other microbially derived nutrients such as N (Bolling & Walker 2000), and the introduction and spread of invasive species (Trombulak & Frissell 2000; Gelbard & Belnap 2003; Brooks & Lair 2009). Various types of road surfaces (i.e. paved, unpaved and improved, unpaved and unimproved, etc.) can result in different spatial relationships and disturbance patterns (Brooks & Lair 2009), and the specific properties related to these types should be taken into account when examining the impacts a road has on its adjacent soil and plant and animal communities. For example, roadside hydrology can be influenced by factors such as the height of berms and shoulders and road width, which will contrast on roads with different maintenance histories, such as graded unpaved roads versus non-graded unpaved roads. Other road characteristics such as topography and slope can influence water runoff and lead to differential erosion, water infiltration, and aquifer recharge patterns.

Wheeled vehicles on unpaved roads are particularly effective at producing fugitive dust (Goosens & Buck 2011; Kuhns et al. 2010), and unpaved roads in general are likely one of the most significant contributors to fugitive dust emissions in the United States (Watson et al. 2000). Dust flux from unpaved roads may be characterized both by the processes of saltation and suspension as larger particles are moved away from the road, as finer particles are suspended directly from the road surface, and as larger saltating particles impact roadside soils and suspend finer particles from the soil surface (refer to Figure 4). The horizontal distance a dust plume is transported is dependent on a variety of factors, and can be a result of vehicle dispersion parameters, as well as local road, soil, topography, and weather conditions for any given emission event. Vehicle characteristics that influence emission include contact of the tires, which create a shearing force that continuously breaks down particles and ejects them from the road surface, vehicle speed, turbulent air wakes created by vehicle movement, vehicle shape, vehicle weight, and number of tires (Watson et al. 2000). Gillies et al. (2005) found a linear relationship between vehicle speed and the amount of dust emitted from a road surface, as well as a roughly linear relationship between vehicle height and the turbulent wake size of a vehicle. Nicholson et al. (1989) found emission rate and particle size emitted to increase with the speed of a vehicle. Kuhns et al. (2010) demonstrated that tired vehicles can produce 2-4 times more fugitive dust than tracked vehicles, and that a vehicle's momentum (speed x mass) is strongly correlated to the amount of dust emitted from a road surface. They also found soil texture and the depth of the disturbed layer of road sediment to be strong indicators of emission.

Figure 9. Unpaved, graded road in Arches National Park.

Dust emission from unpaved roads can be inhibited when road sediment moisture is high, however vehicular movement also enhances moisture evaporation and the drying of sediment by increasing air movement between sediment particles and by exposing dry particles below the moist surface (Watson et al. 2000). The amount of sediment available for entrainment is dependent on the soil texture of the road substrate and on the depth of the disturbed surface layer (Kuhns et al. 2010). As illustrated in Figure 10, the fine sandy and sandy soils typical throughout much of the Colorado Plateau, and Arches in particular, have the higher emission rates than soils of smaller particle sizes.

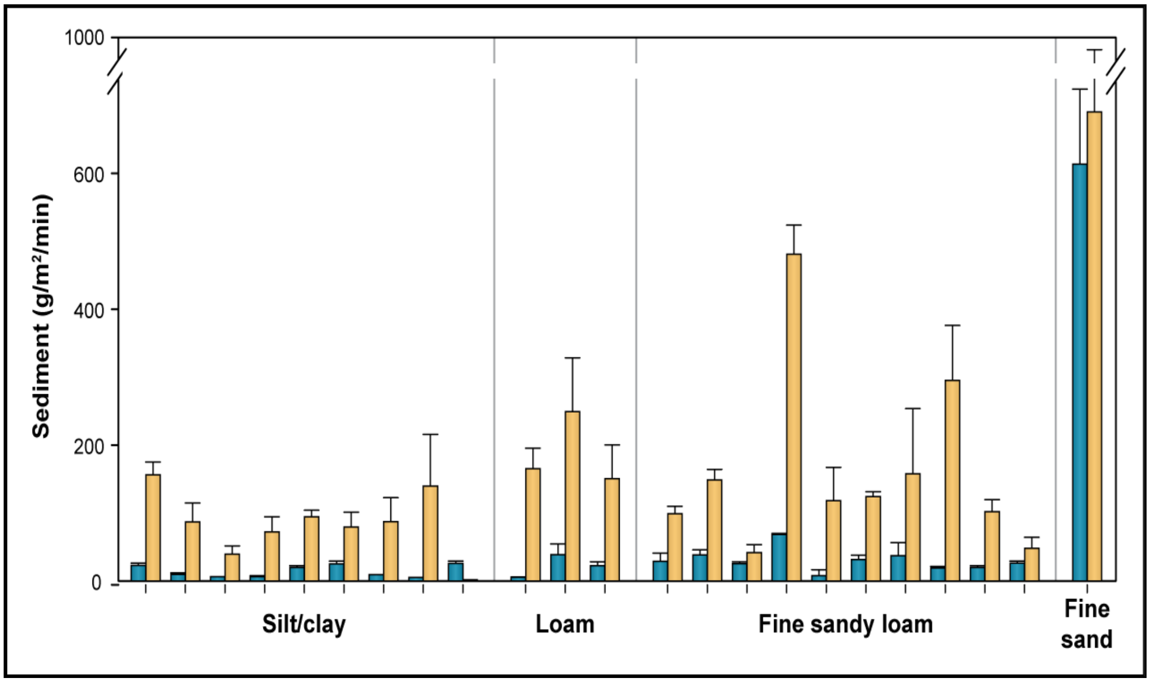

Figure 10. Horizontal aeolian dust flux for various soil types (Field et al. 2010); the substrate of an unpaved road surface will often represent the soil types adjacent to the road.

CHAPTER 3
OPTIONS FOR MANAGEMENT OF ROAD DUST

CHEMICAL DUST SUPPRESSION

In response to increased dust emission from vehicular disturbance, the use of chemical dust suppression products on unpaved road surfaces has increased considerably (Piechota et al. 2004). Of these treatments, magnesium chloride ($MgCl_2$)-based products are among the preferred management options for soil stabilization and for reducing the amount of airborne dust generated, due to ease of use, efficacy, and cost-effectiveness. As mentioned, $MgCl_2$ is currently in use in Arches National Park (Figure 11) and is likely to be considered as a dust mitigation method in other parks and public lands. Application of such products can result in a 42-61% reduction in total aggregate particulate loss from an unpaved road surface, and can reduce maintenance costs by 28-42% (Sanders et al. 1997).

Figure 11. Application of $MgCl_2$ to the Salt Valley Road in Arches National Park.

$MgCl_2$ is a hygroscopic compound, meaning it stabilizes the soil surface by absorbing moisture from the atmosphere and aggregating soil particles together (Figure 12). This may be supplemented by the manual addition of water. Use of these products substantially diminishes the amount of fugitive dust produced by road and trail traffic, and prevents soil erosion by creating a more stable road or trail surface.

Figure 12. Following treatment with $MgCl_2$ a road will maintain a moist appearance as the $MgCl_2$ compaction layer at the surface continues to absorb H_2O from the atmosphere, thus inhibiting dust emission.

In spite of the benefits of using $MgCl_2$ products for dust suppression, there may also be largely unexplored ecological impacts that are detrimental to ecosystem health (Goodrich et al. 2009, 2008; Piechota et al. 2004). These impacts may affect both soil structure and plant function and performance, and may be related to the presence of both the $MgCl_2$ compound as well as its dissociated components, the magnesium cation (Mg^{2+}) and the chloride anion (Cl^-). In addition to onsite (roadside) effects to the immediate road or trail surface, applied $MgCl_2$ products may degrade and be transported by water runoff or by wind as an aerosol, resulting in offsite effects as well. When compared to the amount of past research documenting the effects of other salts such as sodium chloride (NaCl) on soils and vegetation along roads and trails, considerably less is known about the ecological effects of $MgCl_2$-based dust suppressants (Goodrich et al. 2009, 2008). This information may be critical to public land managers working to develop regional and national protocols for dust suppression. It is particularly salient to land managers in the Colorado Plateau and other semi-arid and arid landscapes, where road treatments using $MgCl_2$ for dust suppression have been used throughout the past decade.

$MgCl_2$ EFFECTS IN SOIL

Potential effects of $MgCl_2$ in soil include alteration of water relationships, soil cation exchange, and soil nutrient availability. Use of $MgCl_2$ for road and trail stabilization aggregates soil particles, creating a hardpack surface that may reduce water permeability, increase surface runoff, and decrease overall soil moisture (Piechota et al. 2004). These altered runoff patterns may affect both onsite and offsite locations as the $MgCl_2$ compound is weathered and dissociates into its Mg^{2+} and Cl^- ionic constituents. Compared to sodium (Na^+), dissociated Mg^{2+} ions in soil are less toxic but more reactive, and may displace other positively charged metals and nutrients from negatively charged clay particles. In particular, Mg^{2+} may displace Ca^{2+} in soil due to its larger hydration radius and stronger binding force to soil particles (Kobayashi et al. 2005). Mg^{2+} retention by negatively charged soil particles is also stronger than for Na^+, which may lead to increased rates of Na^+ leaching from the soil. This may help to mitigate onsite soil Na^+ concentrations, but may also result in salinization of offsite areas as a result of Na^+ transport via water runoff (Cunningham et al. 2008).

In terms of soil concentration, it has been found that Mg^{2+} concentrations generally decrease with increasing distance from the point of $MgCl_2$ application. This effect of decreasing concentration with increasing distance is more dramatic than for Na^+ when present in the soil (Cunningham et al. 2008). In quantifying $MgCl_2$ transport, Goodrich et al. (2009) documented movement of $MgCl_2$ ions up to 6.1 m away from treated roads, and migration of ions throughout all soil horizons when applied at relatively high treatment concentrations.

$MgCl_2$ EFFECTS ON VEGETATION

The use of $MgCl_2$ as a dust suppressant on roads is expected to increase Mg^{2+} and Cl^- concentrations in roadside soils, and it has been generally demonstrated that Mg_2^+ toxicity may cause diminished photosynthetic performance and potential photooxidative damage in plants (Cakmak & Kirkby 2008). The Mg^{2+} ion is the central ion in the chlorophyll molecule, and plays a vital role in the functioning of numerous photosynthetic enzymes. This makes it an essential nutrient to the light and dark reactions of plant photosynthesis (Shabala & Hariadi 2005). Pezeshki (1988) found increases in overall ion content in leaf tissue, which includes Mg^{2+}, to be correlated with inhibited photosynthetic ability.

Mg^{2+} enrichment has been demonstrated to reduce growth in certain species, which may result from calcium (Ca^{2+}) imbalances caused by elevated levels of Mg^{2+} in the soil and plant (Kobayashi et al. 2005). Other potential effects of direct $MgCl_2$ exposure (during application) to vegetation include decreased growth rate, leaf burn, leaf drop, dieback, and plant mortality (Smith 1975; Goodrich et al. 2009).

Chloride was found to be more toxic overall than Na^+, although Cl^- is not as toxic as Na^+ at low exposure levels. Cl^- enrichment may reduce plant reproduction and vigor, effects that have been found to be greatest within a few meters of a treated road (Cunningham et al. 2008; Bryson & Barker 2002). These effects may be related to decreases in plant osmotic potential due to displacement of other ions by Cl^- (Bryson & Barker 2002). More recent research by Goodrich et al. (2008) found an increase in roadside vegetation damage with increasing rates of $MgCl_2$ application. They determined that while higher than normal foliar concentrations of either Mg^{2+} or Cl^- may be harmful to a plant, high concentrations of Cl^- were more strongly correlated with greater incidence of foliar damage.

The general lack of data on the use of $MgCl_2$ on unpaved roads leaves a great deal of uncertainty with regard to its potential ecological consequences. As noted by Kobayashi et al. (2005), potential effects could occur in soils already high in Mg^{2+} content via displacement of other necessary soil nutrients. Also, because $MgCl_2$ is a salt, it is unknown how plant species might differentially respond over time to soil salinization along roadsides following $MgCl_2$ treatment. Ultimately, the monitoring of $MgCl_2$ concentrations in soils alongside roads on which it has been applied will equip managers with baseline data useful to evaluate roadside ecological conditions as future research describing the effects of $MgCl_2$ on soils and vegetation is conducted.

CHAPTER 4
DUST IMPACTS, FOCAL ISSUES, AND DUST MONITORING OBJECTIVES

A CONCEPTUAL APPROACH TO CONDUCTING MONITORING RESEARCH IN SEMI-ARID AND ARID ECOSYSTEMS

Semi-arid and arid ecosystems are characterized by sparse vegetation and relatively low precipitation levels, factors that present unique challenges in terms of maintaining soil surface stability, plant water availability, and soil carbon and nitrogen. Figure 13 identifies specific factors hypothesized to be relevant to monitoring dust emission and dust impacts in semi-arid and arid ecosystems, and uses a stressor model to articulate relationships between disturbance, ecosystem stressors, principle ecosystem components (soil, vegetation, BSC), dust impacts, and potential indicators. Stressor models are particularly useful for describing the conceptual linkages between potential sources of stress in an ecosystem and the ecological response of the system components of interest. Figure 12 is meant to provide a useful conceptual foundation upon which to build a dust monitoring protocol for semi-arid and arid ecosystems.

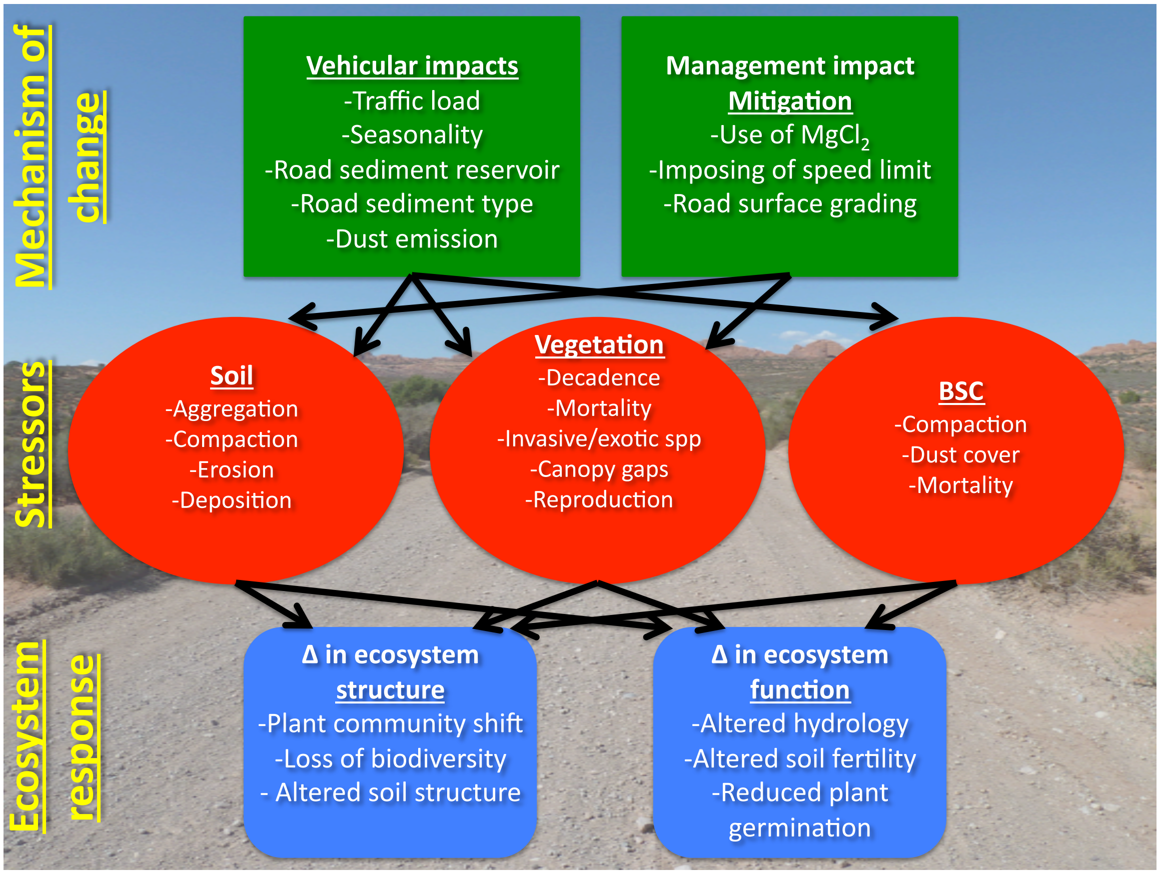

Figure 13. Stressor model illustrating conceptual linkages relevant to dust emission and monitoring.

Ecosystem structure and function in semi-arid and arid environments is dependent on the condition of soils, vegetation, and BSCs. Table 1 below identifies and discusses the indicators associated with each of these ecosystem components that relate to dust emission and dust impacts.

Ecosystem component	Associated indicators	Relevance to dust emission
Soil	Aggregation	Aggregated soil particles are more resistant to wind erosion
	Compaction	Compacted soils are indicative of disturbance, loss of stabilizing BSC cover, and increased erosivity of soils
	Erosion	Wind erosion of soil particles occurs on disturbed source areas
	Deposition	Eroded soils are transported by wind and deposited in sink areas
Vegetation	Decadence	Decline in plant performance (e.g photosynthetic yield, transpiration) due to dust impacts
	Mortality	Death of plant individuals due to dust impacts
	Community shift	Shifts in plant community composition as decadence and mortality may occur as new (more tolerant) species are introduced
	Invasive/exotic spp	Introduction of invasive/exotic spp as community shifts occur
	Canopy gaps	Loss of perennial grass cover and increase in shrub cover may lead to larger canopy gaps and higher erosion potential (although dependent on shrub species and spatial distribution)
	Reproduction	Dust deposition on reproductive organs may inhibit pollen availability or frequency in pollinator visits
Biological soil crust	Compaction	Indicative of disturbance, loss of stabilizing BSC cover, and increased erosivity of soils
	Dust cover	BSC decadence and mortality increases when covered by deposited dust in sink areas
	Mortality	Death of BSC organisms due to dust cover

Table 1. Associations between properties of ecosystem components in semi-arid and arid ecosystems and their relevance to dust emission and impacts.

POTENTIAL IMPACTS FROM DUST EMISSION IN ARCHES NATIONAL PARK

The potential impacts from dust emission most relevant to Arches National Park, as arguably the Colorado Plateau in general, are summarized in Table 2. These impacts include potential changes in the plant communities adjacent to unpaved roads due to dust emission, diminished visibility and air quality within the park, and also potential impacts that may arise if dust mitigation efforts using $MgCl_2$ were to continue within the park.

These particular impacts were selected for monitoring because they are generally indicative of overall system dust dynamics, are useful in predicting future changes that may occur in systems adjacent to unpaved roads, and are easily measured in the field to provide data that can be analyzed by park managers in a relatively straightforward and cost-effective manner. The data generated are meant to inform more refined research that managers may choose to conduct if measurable changes or trends are observed in the data generated by this protocol.

Potential impacts	Description	Ecological and user attributes relevant to impact
DUST IMPACTS ON ROADSIDE VEGETATION AND BSCs	Ecophysiological impacts on local downwind plant species, including inhibited photosynthesis and stomatal conductance; shift in plant community composition from less dust tolerant species to more dust tolerant species; increase in invasive/exotic species more tolerant of disturbance; increase in bare ground due to loss of plants and BSCs, leading increase in erosion soil potential	Wind
		Precipitation
		Plant photosynthetic performance
		Plant transpiration
		Spp diversity/abundance
		Invasive/exotic spp presence/abundance
		Shifts in plant and BSC community composition
		Loss of plant/BSC cover; bare ground
		Seasonal dust emission
DUST IMPACTS ON AIR QUALITY & HUMAN HEALTH	Reduced visibility in dust corridors; increase in exposure to airborne particulate matter	Wind velocity
		Precipitation
		Road surface substrate
		Traffic load
		Human exposure to dust
		Seasonal dust emission
$MgCl_2$ IMPACTS ON ROADSIDE SOILS	Enrichment of roadside soils by Mg^{2+} and Cl^- ions as road treatment degrades and migrates with dust; compaction of soils along edge of road due to spray over of $MgCl_2$ during application	Migration of Mg^{2+} and Cl^- ions through roadside soil
		Rate of degradation of $MgCl_2$ road treatment
$MgCl_2$ IMPACTS ON ROADSIDE VEGETATION	Necrosis and/or damage to plant tissue due to direct contact with $MgCl_2$ during application; reduced seedling establishment; increase in invasive/exotic species following Mg^{2+} and Cl^- soil enrichment	Plant mortality and decadence
		Seedling emergence
		Invasive/exotic spp presence
		Shift in community composition
		Rate of degradation of $MgCl_2$ road treatment

Table 2. Potential impacts of dust emission and dust mitigation.

MANAGEMENT OBJECTIVES FOR MONITORING OF ROAD DUST IN ARCHES NATIONAL PARK

The objectives and methods used in this protocol have been designed to provide the National Park Service with the tools to implement long-term monitoring of dust emission and transport along unpaved roads, as well as potential impacts to roadside vegetation. While site specific to Arches National Park in design, the methods are meant to be broadly applicable to semi-arid and arid systems in general. The overarching goal of this monitoring protocol is to link anthropogenic disturbance, understanding of plant communities and BSCs at a site, identification of "at-risk" species, recognition of potential plant and BSC community transitions, and the management options and mitigation of dust emission and dust impacts.

The four impact classes identified in Table 2 highlight the key focal issues for land managers working to assess and mitigate dust emission and impacts. Individual monitoring objectives for this protocol include the collection of quantitative data to describe each of the ecological and user attributes that are most relevant to dust impacts (see Table 2). Table 3 uses these attribute objectives and identifies the specific parameters that can be monitored to characterize each.

Impact class	Indicator monitoring objectives	Relevant parameters
DUST IMPACTS ON ROADSIDE VEGETATION	Wind	*** Seasonal wind trends**
	Precipitation	*** Seasonal precipitation trends**
	Plant photosynthetic performance	*** Photosynthetic quantum yield & leaf temperature**
	Transpiration	*** Stomatal conductance**
	Spp diversity/abundance	**Plant community composition**
	Invasive/exotic species presence/abundance	**Plant community composition**
	Shifts in plant and BSC community composition	**Plant/BSC community composition**
	Loss of plant/BSC cover	**Plant canopy and BSC cover**
	Loss of plant/BSC cover	**Bare ground**
	Seasonal dust emission	**Dust emission from road**
DUST IMPACTS ON AIR QUALITY & HUMAN HEALTH	Wind velocity	*** Seasonal wind trends**
	Precipitation	*** Seasonal precipitation trends**
	Road surface substrate	**Soil type adjacent to road surface**
		*** Particle size distribution of road sediment**
		Size of road sediment reservoir
	Traffic load	**Daily/seasonal number of vehicular passes**
	Seasonal dust emission	**Dust emission from road**
$MgCl_2$ IMPACTS ON ROADSIDE SOILS	Migration of Mg^{2+} and Cl^- ions through roadside soil	*** Concentration of Mg^{2+} and Cl^- in roadside soil**
	Soil compaction resistance	
	Rate of degradation of $MgCl_2$ road treatment	**Size of road sediment reservoir**
$MgCl_2$ IMPACTS ON ROADSIDE VEGETATION	Plant mortality and decadence	**Plant community composition**
	Seedling emergence	**Plant community composition**
	Invasive/exotic spp presence/abundance	**Plant community composition**
	Shift in plant community composition	**Plant community composition**
	Rate of degradation of $MgCl_2$ road treatment	**Size of road sediment reservoir**

Table 3. Objectives and focal parameters for dust monitoring protocol.

As mentioned, a primary goal in this monitoring protocol was to use relatively straightforward and cost-effective methods to characterize dust emission and impacts in National Parks. Parameters labeled with an "*" in Table 3 are useful and relevant to a more comprehensive assessment of dust emission and dust impacts, but they will increase monitoring expenditures, time frames, and work load in terms of personnel and data management and analysis. They may also require instruments that not all park units may possess.

As many managers and parks will have only the need and/or resources for a more rapid assessment and analysis of fugitive dust emission from roads, the methods in this monitoring protocol have been developed with two options for data collection. Chapter 5 provides methods and general sampling design for *A Rapid Assessment Approach to Fugitive Road Dust Emission and Mitigation Monitoring*, and Chapter 6 provides supplemental methods and general sampling design for a more comprehensive (and expensive) approach to fugitive road dust monitoring. The methods in Chapter 5 are relatively straightforward for field technicians coming from a variety of backgrounds, and they are cost effective in terms of funding, time, equipment, and other resource constraints. Chapter 5 is meant to be a stand alone monitoring protocol that can be implemented in parks, but it has been developed in a way to enable managers the flexibility to select specific parameters and methods to address particular impact classes (e.g. only examine plant and/or BSC community composition transitions alongside unpaved roads as an indicator of dust impact on roadside vegetation). This should be based on their park's individual and site-specific data needs, as well as existing resource constraints in terms of sampling instrumentation, time frame, and field technician training.

It should also be noted that while all parameters will in some way influence fugitive dust emission from roads and the associated impacts that dust may have on park resources, some parameters can be designated "indicators of direct change," while others are more useful in interpreting the trends documented within these indicators of direct change in a specific park setting. For example, change in plant community composition and increased dust emission are indicators of direct changes to a park resource, while seasonal precipitation trends, for example a relatively wet spring versus a dry spring, may help interpret why certain plants are present or absent in a given season, or why dust emission rates may be higher or lower for that season. The rapid assessment approach in Chapter 5 uses only methods that characterize the indicators of direct change presented in Table 4. The supplemental methods in Chapter 6 include both indicators of direct change as well as interpretive indicators of dust dynamics. Managers seeking to implement a condensed dust monitoring program may focus entirely on specific indicators of direct change based on their park's site specific conditions and needs, or simply those indicators of direct change that are the simplest and most cost-effective to utilize to acquire some level of baseline data on dust dynamics within their park. Table 4 categorizes the relevant dust monitoring parameters for each impact class from Table 3 into indicators of direct change and also interpretive indicators of dust dynamics.

Impact class	Indicators of direct change	Interpretive indicators of dust dynamics
DUST IMPACTS ON ROADSIDE VEGETATION	**Photosynthetic quantum yield & leaf temperature**	**Seasonal wind trends**
	Stomatal conductance	
	Plant/BSC community composition	
	Plant canopy and BSC cover	**Seasonal precipitation trends**
	Bare ground	
	Dust emission from road	
DUST IMPACTS ON AIR QUALITY & HUMAN HEALTH	**Daily/seasonal number of vehicular passes**	**Seasonal wind trends** **Seasonal precipitation trends** **Soil type adjacent to road surface** **Particle size distribution of road sediment** **Size of road sediment reservoir**
	Dust emission from road	
$MgCl_2$ IMPACTS ON ROADSIDE SOILS	**Concentration of Mg^{2+} and Cl^- in roadside soil**	**Compressive soil strength**
	Size of road sediment reservoir	
$MgCl_2$ IMPACTS ON ROADSIDE VEGETATION	**Size of road sediment reservoir**	**NA**
	Plant community composition	

Table 4. Indicators of direct change in park resources and parameters influencing dust emission.

CHAPTER 5
A RAPID ASSESSMENT APPROACH TO FUGITIVE ROAD DUST EMISSION AND MITIGATION MONITORING

This protocol is intended to provide managers and field technicians with a rapid assessment tool kit to measure the seasonal emission of dust from unpaved road surfaces, and assess the potential impacts dust might have on roadside vegetation and BSC in National Parks. It is applicable to any semi-arid or arid landscape where road disturbance and dust emission occur. The methods included are recommended due to their ease of implementation and relative low cost. It is again stressed that these methods are only recommendations, and that specific indicators to be monitored will be selected by park managers based on their park's data requirements and needs, existing funding and instrumentation resources, time frame, and training capacity for field technicians. Thus, an even more condensed monitoring program can be initiated depending on an individual park's monitoring priorities by selecting only one or a few of the methods discussed. A typical monitoring season should begin roughly in late winter or early spring, depending both on local weather conditions leading into that season as well as the observed increase in park visitation, and will end roughly in late fall as park visitation tapers off or local weather deteriorates to winter conditions.

Table 5 summarizes the base indicators of direct change for each impact class that would fulfill a rapid assessment-monitoring program, and identifies the specific methods that are prescribed for each. A discussion of each method is provided below.

Impact class	Indicators of direct change	Method(s)
DUST IMPACTS ON ROADSIDE VEGETATION	**Plant/BSC community composition**	**Line-point intercept; photo frame**
	Plant canopy and BSC cover	**Line-point intercept, gap distance; photo frame**
	Bare ground	**Line-point intercept, gap distance; photo frame**
	Dust emission from road	**BSNE dust collectors**
DUST IMPACTS ON AIR QUALITY & HUMAN HEALTH	**Daily/seasonal number of vehicular passes**	**TrafX traffic counter**
	Dust emission from road	**BSNE dust collectors**
$MgCl_2$ IMPACTS ON ROADSIDE SOILS	**Size of road sediment reservoir**	**Road sediment mass**
$MgCl_2$ IMPACTS ON ROADSIDE VEGETATION	**Plant community composition**	**Line-point intercept; photo frame**
	Size of road sediment reservoir	**Road sediment mass**

Table 5. Indicators for a rapid assessment approach to fugitive road dust monitoring.

LINE-POINT INTERCEPT

The line-point intercept method can be used to assess changes in plant and BSC community composition, plant canopy cover, and bare ground along a transect within a study plot (Herrick et al. 2005). The study plot should be selected to be representative of the surrounding landscape as a whole, and will be located on both sides of an unpaved road. Transects of a determined length (e.g. 50 m) should be run either parallel to the road at multiple selected distances (e.g. 0.2 m, 0.5 m, 1.0 m, 2.0 m) away from the road edge, or perpendicularly to the road starting at the road edge. Transects should be permanently marked with rebar hammered in to the ground at each end, as well as with a high-precision GPS unit with sub-meter accuracy. If rebar is buried completely beneath the soil surface to minimize visual impact, a metal detector can be used to locate the transect for future sampling.

A measuring tape should be pulled taut and positioned as close to the ground as possible along the transect to be measured. Always walk along the same side of the transect within a plot. Beginning at distance "zero" on the transect, a surveyor's flag or other type of pin should be precisely dropped from a set height at selected point increments along each transect (e.g. every 0.25 m or 0.5 m), and the *top plant canopy* (identified either by genus and species or by functional group), *lower canopy layers*, and the *soil surface* cover at the point of contact recorded using the cover classes in Table 6. Closer sampling point increments will result in a more accurate representation of a transect, however should be determined at a site specific level based on time and funding constraints.

Plant canopy codes (if identified by functional group)		Soil surface codes	
AF	Annual forb	**R**	Rock fragment >5 mm in diameter
PF	Perennial forb	**BR**	Bedrock
AG	Annual graminoid	**L**	Litter[3]
PG	Perennial graminoid	**EL**	Embedded litter[1]
SH	Shrub	**D**	Duff[2]
TR	Tree	**M**	Moss
		LC	Lichen crust on soil (lichen on rock is recorded as "R"
		CYN	Dark cyanobacterial crust
		S	Bare soil, or soil unprotected by any of the above

Table 6. Cover classes for line-point intercept method.

[1] Embedded litter is identified as decaying organic material that would leave an indentation in the soil surface if removed

[2] Duff is identified as decaying organic material that has no clear boundary between litter and soil, and that would not be removed by wind or water forces

[3] Litter is defined as detached dead plant material in contact with the ground; herbaceous litter (dead material still attached the a plant) is recorded as "L"

If the pin at the point of sampling for either a top canopy or lower canopy layer touches no plant material, record "NONE" in the appropriate field on the data sheet. Continue to record plant canopy, lower canopy layer, and soil surface for each incremental sampling point along each transect. A data entry example is provided in Table 7 for the sample diagrams presented in Figure 14. The full data sheet for line-point intercept can be found in Appendix B.

Point	Top canopy	Lower canopy layers			Soil surface
		Code 1	Code 2	Code 3	
1	STCO (or PG)	L			R
2	STCO (or PG)	STCO (or PG)			S
3	NONE				EL
Etc.					

Table 7. Example data entry for line-point intercept.

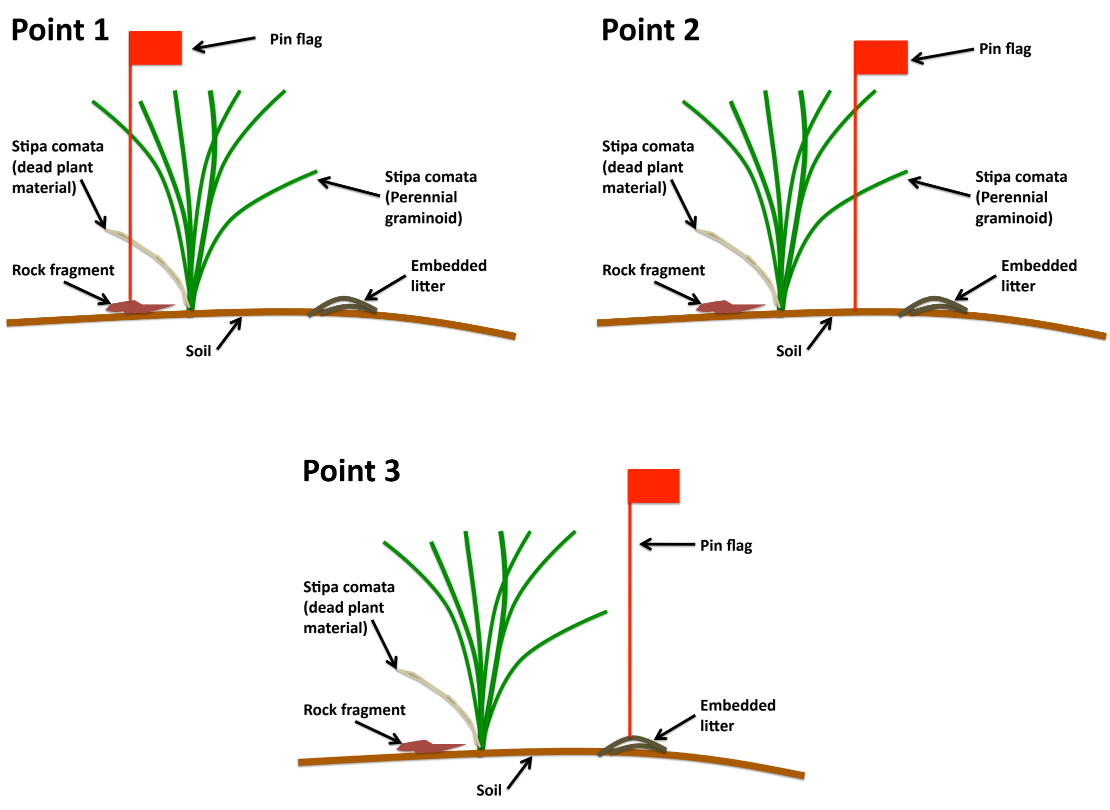

Figure 14. Sample pin placements for the 3 sampling scenarios in Table 7.

Figure 15. Field technician conducting a line-point intercept in lower Indian Creek, UT.

PHOTO FRAME

The photo frame method can be used to assess changes in plant and BSC community composition, plant canopy and BSC cover, and bare ground within a study plot. The method may be more time consuming in terms of implementation and data analysis, but the images produced render a far more precise method for evaluating the indicators listed. A primary benefit of the photo frame method is that images can be archived for future reference, minimizing the sampling error involved with field interpretation of indicators present as well as the need to use different field technicians over multiple sampling periods.

The photo frame can be fabricated from modular aluminum tubing or PVC tubing, and consists of a boom arm with camera attachment fixed vertically to a 1 m^2 quadrat frame base. A high-resolution digital camera is attached to the boom arm of the photo frame and centered over the 1 m^2 quadrat at a height comfortable for the field technician to operate the shutter of the camera (Figure 16). It is critical that the height of the camera remain consistent throughout a monitoring program so images are replicated through time. Remote control shutters are useful if multiple field technicians are used. A sunshade may also be effective on sunny days to prevent shadows from obscuring the images.

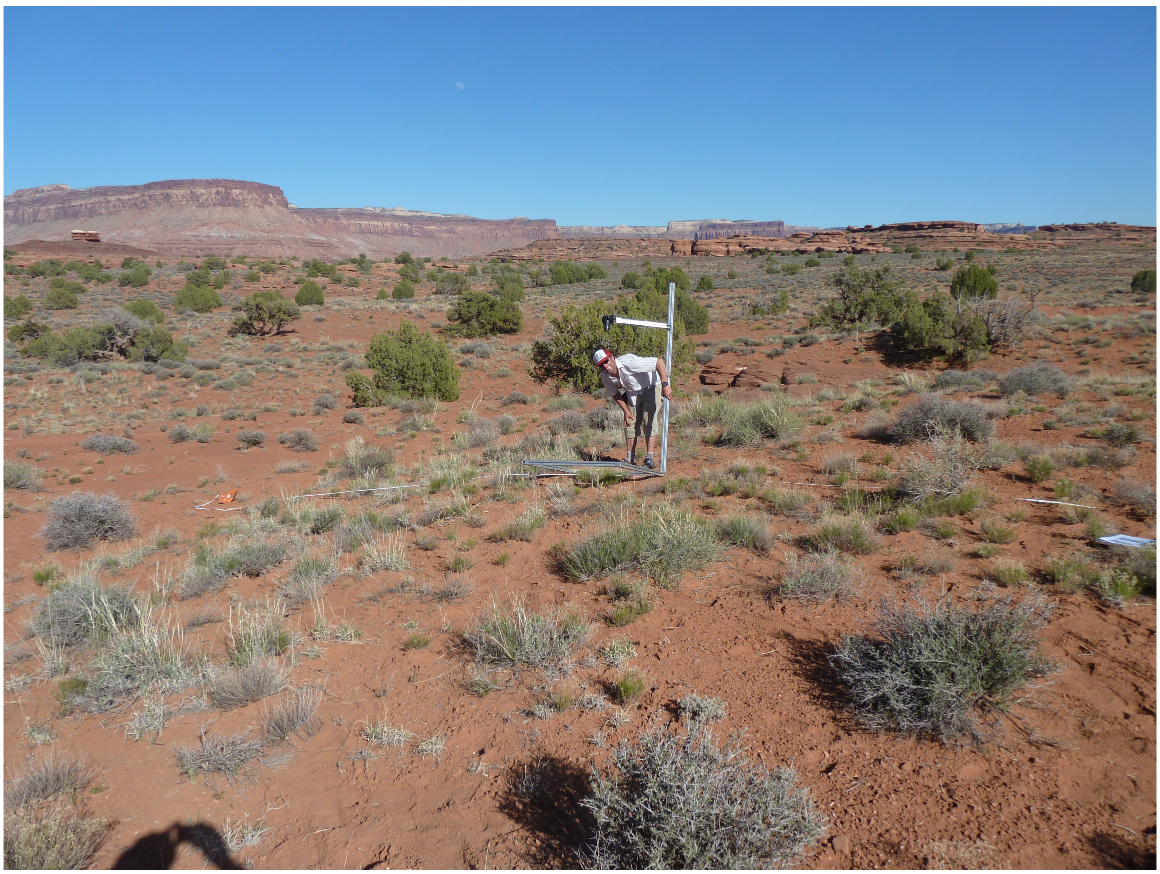

Figure 16. Field technician placing photo frame along transect in lower Indian Creek, UT.

The study plot should be selected to be representative of the surrounding landscape as a whole, and will be located on both sides of an unpaved road. Transects of a determined length (e.g. 50 m) should be run either parallel to the road at multiple selected distances (e.g. 0.2 m, 0.5 m, 1.0 m, 2.0 m) away from the road edge, or perpendicularly to the road starting at the road edge. Transects should be permanently marked with rebar hammered in to the ground at each end, as well as with a high-precision GPS unit with sub-meter accuracy. If rebar is buried completely beneath the soil surface to minimize visual impact, a metal detector can be used to locate the transect for future sampling.

A measuring tape should be pulled taut and positioned as close to the ground as possible along the transect to be measured. Always walk along the same side of the transect within a plot. Beginning at distance "zero" on the transect, move the photo frame along the transect and collect images of 1 m^2 sampling quadrats at designated increments along the transect (e.g. 0-1 m, 4-5 m, 9-10 m). A sample image is provided in Figure 17. Once images are generated, numerous photo-editing software packages exist (some at no cost) that are capable of overlaying a grid of varying mesh sizes over an image to enable identification of the specified indicators at each grid crosshair. This aspect of the image analysis is dependent on the precision required by a park's monitoring plan, as well as the time frame involved with analysis of data. The proportion of an indicator's presence within a 1 m^2 quadrat can also be estimated using the images. As with the line-point intercept method, closer sampling frame increments will result in a more accurate representation of a transect, however should be determined at a site specific level based on time and funding constraints.

Figure 17. Sample image of 1 m^2 quadrat along a transect

GAP DISTANCE

The gap distance method can be used to assess changes in the proportion of plant canopy and BSC cover, and changes in the proportion of bare ground along a transect within a study plot (Herrick et al. 2005). The study plot should be selected to be representative of the surrounding landscape as a whole, and will be located on both sides of an unpaved road. Transects of a determined length (e.g. 50 m) should be run either parallel to the road at multiple selected distances (e.g. 0.2 m, 0.5 m, 1.0 m, 2.0 m) away from the road edge, or perpendicularly to the road starting at the road edge. Transects should be permanently marked with rebar hammered into the ground at each end, as well as with a high-precision GPS unit with sub-meter accuracy. If rebar is buried completely beneath the soil surface to minimize visual impact, a metal detector can be used to locate the transect for future sampling.

A measuring tape should be pulled taut and positioned as close to the ground as possible along the transect to be measured. Always walk along the same side of the transect within a plot. Beginning at distance "zero" on the transect, document where gaps between vegetation (bare ground) exist by recording the position along the tape where plant canopies start and end. When recording this, the field technician should be looking straight down at the tape, with a line of sight perpendicular to the ground. Typically, annual grasses are included in this measurement, but annual forbs are not due to their ephemeral nature. Canopy gaps and/or basal gaps may be recorded, and the minimum gap size recorded may be selected as appropriate for the study plot (20 cm is a standard minimum gap size, however smaller or larger minimums may be used depending on site characteristics and monitoring design goals). A data entry example is provided in Table 8 for the sample transect provided in Figure 18. The full data sheet for gap distance can be found in Appendix B.

Canopy gaps: Minimum size = *20* cm						
Starts	**Ends**	**Gap size**	**25-50**	**51-100**	**101-200**	**>200**
32	56	24	-	-	-	-
69	90	21	-	-	-	-

Basal gaps: Minimum size = *20* cm						
Starts	**Ends**	**Gap size**	**25-50**	**51-100**	**101-200**	**>200**
29	60	31	31	-	-	-

Table 8. Example data entry for canopy and basal gap distance.

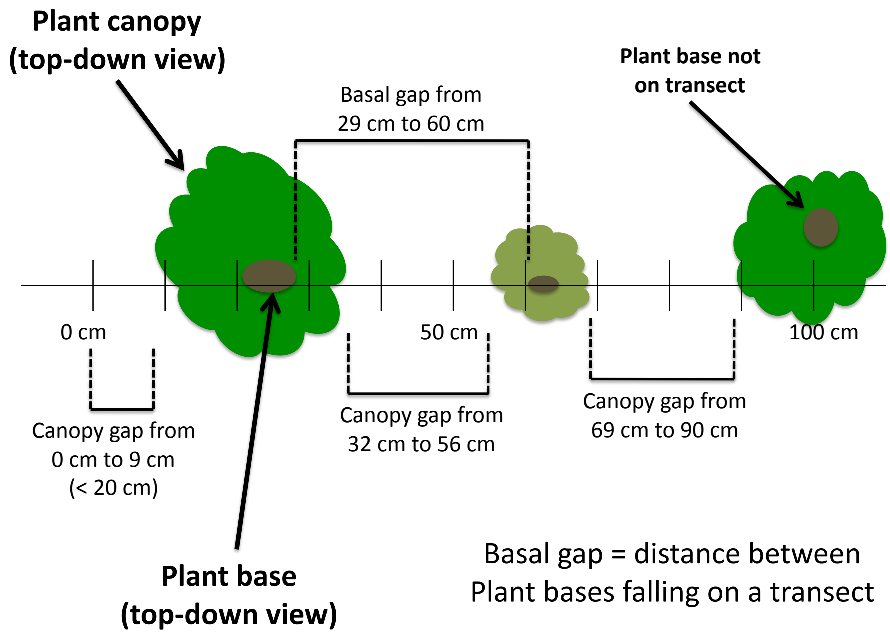

Figure 18. Sample transect for canopy and basal gap distance measurement in Table 8.

Figure 19. Transect in place for gap distance measurement.

Figure 20. Field technician conducting gap distance measurements in lower Indian Creek, UT; a photo frame can be seen in the background.

BSNE DUST COLLECTORS

Big Spring Number Eight™ (BSNE) dust collectors can be used to assess daily and seasonal dust emission from unpaved roads. The US Geological Survey's Canyonlands Field Station in Moab, UT has established guidelines for the use of BSNEs, and this protocol will be followed for their inclusion in this monitoring program. Individual BSNE units can be assembled either in the field or prior to placement in the field. Three BSNE wind vane assemblies should be slid onto each supplied conduit and fastened in place using the provided washers and couplings. The conduits can then be hammered into the soil at study plots in an array selected based on monitoring goals. A typical array consists of individual BSNE units laterally spaced 2 m apart and positioned at various distances from the road (e.g. 1.0 m, 3.0 m, 8.0 m, and 16.0 m). BSNE units should be placed on both sides of the road, with buckets facing the dominant seasonal wind direction for the study plot (Figure 21). The precise location of each BSNE unit should be recorded using a high-precision GPS unit with sub-meter accuracy. Appropriate distance from the road may be determined by physical and topological features distinct to a particular study site, for example the slope of the roadside landscape, landforms near the roadside, drainages present, etc., however a study site with minimal potential interference from such features will generate more reliable and more accurate estimations of dust emission. The ideal site consists of zero slope where wind patterns are unobstructed by physical land features.

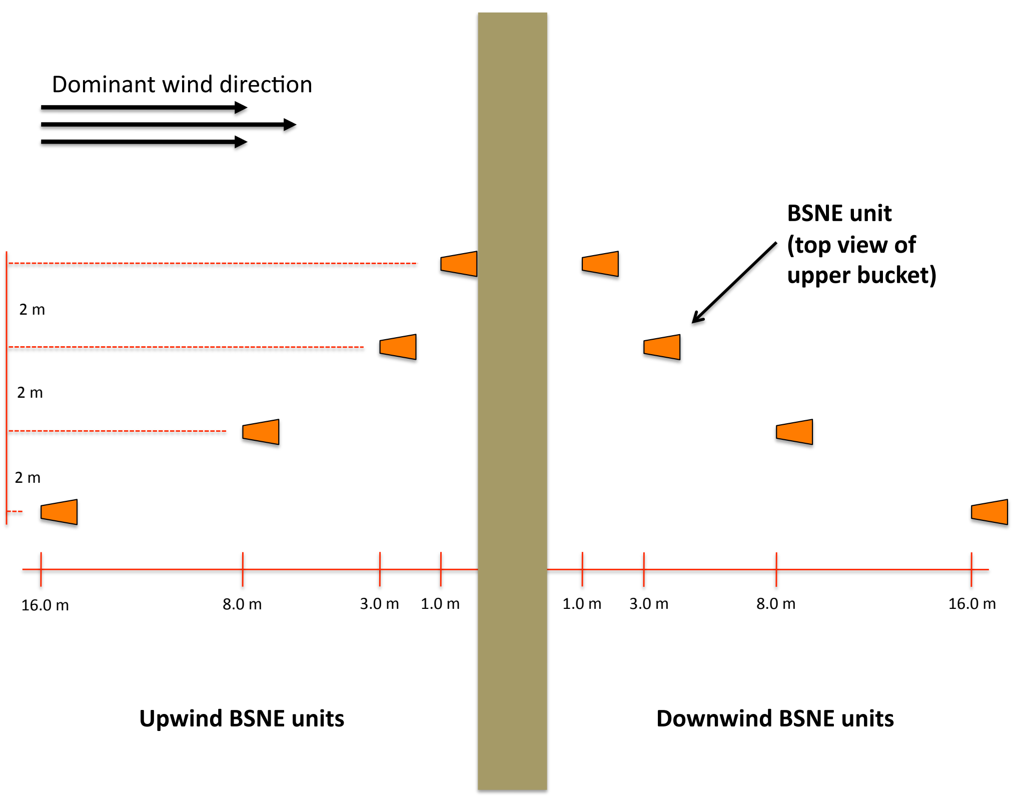

Figure 21. Example of BSNE array relative to road edge.

The lips of each BSNE bucket opening should be set at precise heights off the ground: 15 cm, 47.5 cm, and 97.5 cm (Figure 22). This positioning is used to ensure repeatability of height of the lower box, and achieves target heights of 50 cm and 100 cm from the ground for the center of the upper two buckets, respectively. Bailing wire can be used to secure the buckets to the wind vane assembly.

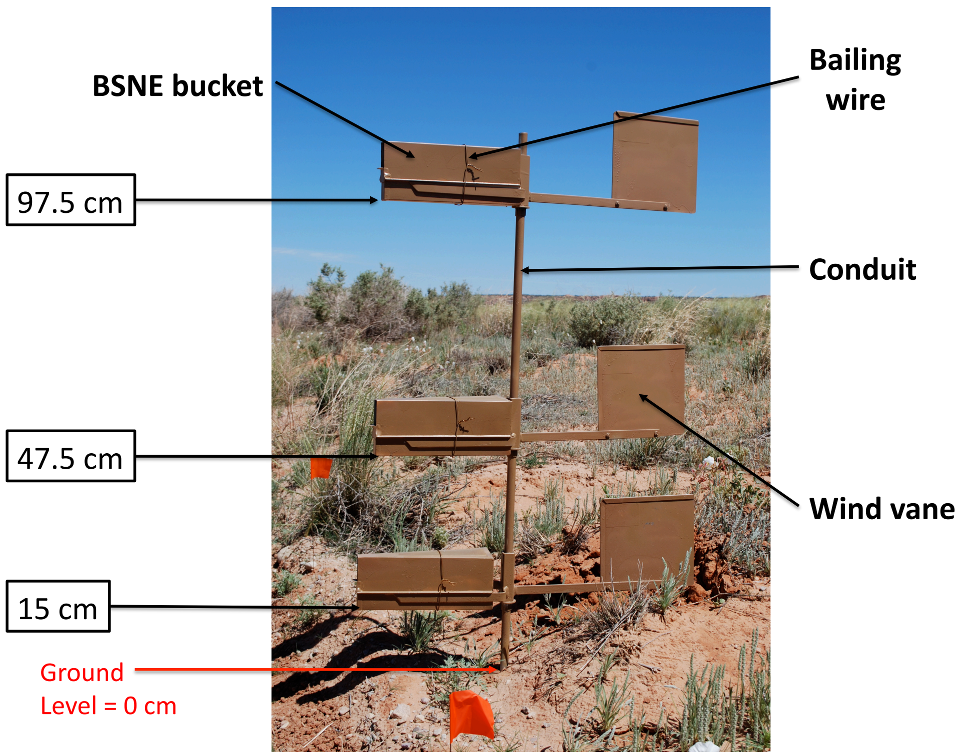

Figure 22. BSNE assembly and height placement; the BSNE units used in this Arches study were painted brown to match the surrounding landscape and minimize visual impact.

Once the BSNE units are installed they can be spray painted to match the immediate soil and plant environment to comply with NPS standards of minimizing visual impacts to the surrounding landscape (see Figure 21). Additionally, because variable wind directions will occur seasonally during the time periods associated with a long-term monitoring program, and to ensure accuracy in knowing the dust collected by the BSNE units came from the adjacent road surface and not the surrounding landscape, BSNE units on both sides of the road should be fixed in place. This can be accomplished using an additional shaft of rebar hammered into the soil beside each BSNE unit and secured to the unit with bailing wire (Figure 23). The wind vane part of the assembly may or may not be removed by cutting depending on intended future use of the BSNE units. Each BSNE unit should be labeled with a Site/Plot ID Number, and each bucket should be labeled by height (either “low, middle, high,” or “15 cm, 50 cm, 100 cm”).

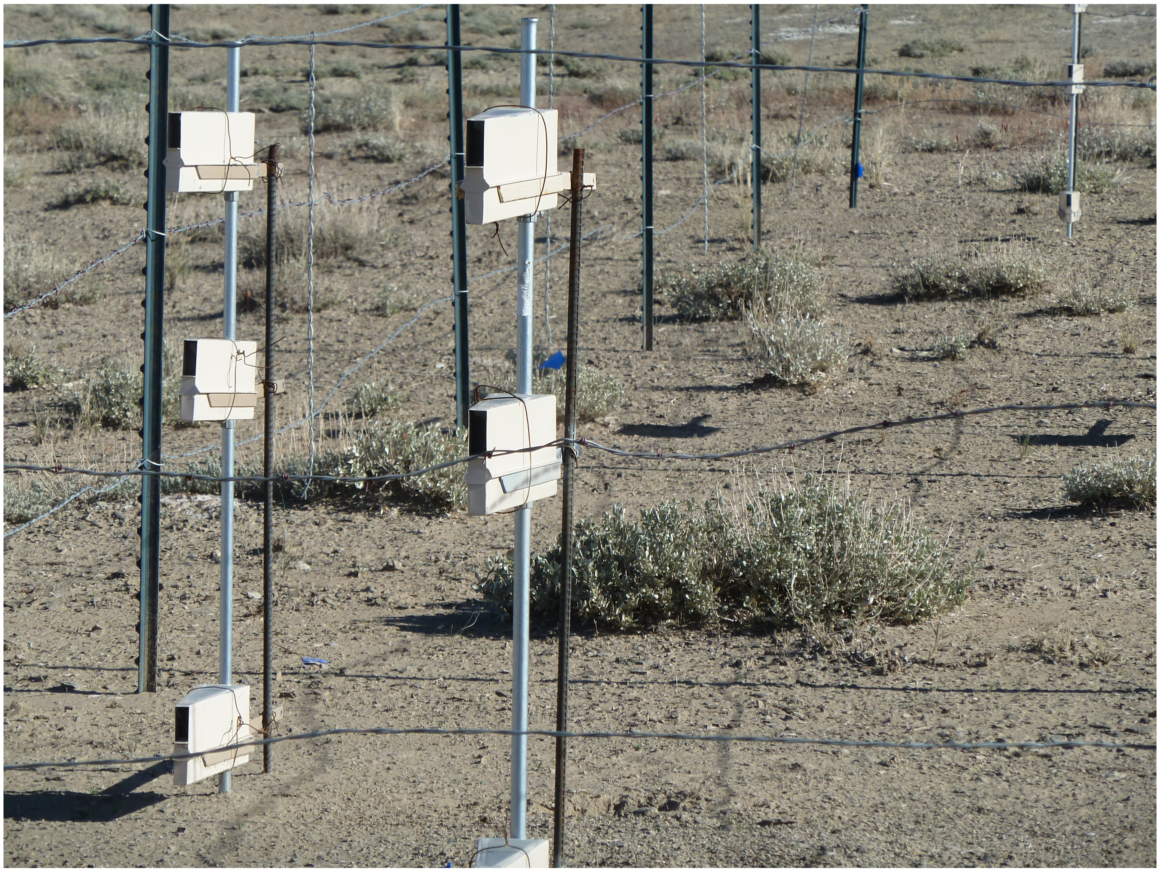

Figure 23. BSNE units fixed in place using rebar and bailing wire to prevent rotation in shifting winds.

BSNE units should be thoroughly cleaned using deionized water at the start of each monitoring season (typically early spring). During the monitoring season, BSNE buckets can be sampled at regular intervals to be chosen based on access and field technician availability. Each sampling should consist of the following:

1. **Using a fine-bristled brush ~0.5-1.0” in width, brush off any sediment stuck to the outside of the bucket.**
2. **Carefully open each bucket, shielding from the wind if necessary to prevent any loss of sediment, and brush sediment into sealable hard plastic Ziploc containers (a hard plastic container will simplify removing contents for weighing once samples are back in the lab).**

3. **Do not use metal objects to dislodge material from buckets.**
4. **Label each container with: Date, Site/Plot Number, Bucket ID, Bucket Height (top, middle, bottom" or "15 cm, 50 cm, 100 cm").**
5. **If buckets contain water from recent rainfall, or moist sediment, use a spray bottle with deionized water to remove the sediment and dry thoroughly in the lab for later weighing.**
6. **Replace each bucket into its appropriate wind vane assembly, making sure the ID and height labels are correct for each. If the bucket feels loose in the vane, squeeze the arms of the vane together for a tighter fit. Replace the bailing wire around each bucket to secure into place.**
7. **Finally, check the height of each bucket on each BSNE unit to confirm the heights are correct**

Dust samples should be returned to the lab or some other facility where they will be dried and sample mass determined. After weighing each sample, the mass of sediment collected in each of the downwind buckets should be subtracted from the mass of sediment in the corresponding upwind buckets to account for this dynamic. Corresponding upwind buckets are those buckets that are at the same distance from road and height as downwind buckets (i.e. there will be two buckets per study plot that have the same distance from road and height, one downwind and one upwind). Data should be recorded on the data sheet found in Appendix B.

ROAD SEDIMENT MASS

The mass of road sediment per surface area of road can be measured to estimate the total size of the road sediment reservoir available for emission. While included as an interpretive indicator of measuring total dust emission from a road and the associated impacts to air quality and human health, it can also be used as an indicator of direct change when monitoring for impacts caused by the use of the chemical dust suppressant $MgCl_2$. Once $MgCl_2$ is applied and the compaction layer is allowed to establish itself at the road surface, there should be minimal to no dust emission from the road surface. As this layer degrades due to weathering and the mechanical pulverization of vehicles using the road, increasingly more sediment will become destabilized and available for emission via vehicular traffic. Measuring the mass of road sediment available in this reservoir serves as an indicator of the lifespan of an $MgCl_2$ application, and can inform the timeframe associated with subsequent applications to maintain stable road surface conditions and continued inhibited dust emission.

To determine road sediment mass, a road segment should be selected and marked as a study plot, with GPS data collected to demarcate the boundaries. Rebar may be used as a permanent marker if approved in the research permit. Road width and road segment (plot) length should be recorded. A sample (minimum N=5) of random 1 m^2 quadrats should be marked within the plot using a 1 m^2 PVC frame. All sediment within each frame should be swept into a sealable container or bucket, labeled with Date, Plot Number, and Sample ID, and transported to a lab or other facility for determination of mass (Figure 24).

Figure 24. 1m^2 quad that has been sampled for road sediment

Samples may be passed through a 2000 μ (2 mm) mesh sieve either in the lab or in the field to lessen the weight of samples having to be transported back to the lab. If the purpose of the monitoring program is for dust emission, these particle sizes (< 2μ) represent those most likely to be moved via vehicular traffic and blown by wind from the road surface. If the purpose of the monitoring program is to evaluate the degradation of $MgCl_2$ application, managers may choose to leave all particle sizes and rock fragments in the sample, as the breakdown of larger aggregates consisting of these materials is indicative of degradation. Finally, average road sediment mass per road segment should be calculated and data recorded on the data sheet found in Appendix B.

TRAFX TRAFFIC COUNTER

Vehicular traffic on unpaved roads in National Parks can be easily monitored using a TrafX™ brand vehicle counter (Figure 25). Passing vehicles disrupt the electromagnetic field surrounding the vehicle counter, and the counter records a pass for each disruption. The TrafX counter can be paired to a data dock in the field for rapid downloading of traffic data at the study site.

Figure 25. TrafX vehicle counter manufacturer information

Manufacturer instructions should be followed for traffic counter installation. Attention should be paid to the width of the road where the TrafX counter is placed, as the electromagnetic field emitted by the counter can be adjusted to cover various distances. One counter will have the capacity to cover traffic approaching from two directions if calibrated correctly. Another important counter setting to consider is the timing of a single recorded pass. The vehicle counter can be calibrated to reset itself after a certain length of time during an electromagnetic disruption, and if it resets too quickly a single slow moving vehicle may be recorded as multiple passes. Posted speed limits and observed driving patterns on a road can inform how this setting is used, but typically a reset time of 2 seconds will be appropriate.

The TrafX vehicle counter itself should be placed in its provided weatherproof casing for field placement. For added security, the casing containing the counter can be placed in a heavy-duty Ziploc™ bag or hard-shelled container. Be sure there are no metal objects or materials positioned near the TrafX vehicle counter, as these can disrupt the electromagnetic field emitted by the counter and result in unreliable data. Once the location for the TrafX vehicle counter is selected for the study site, it should be buried roughly 4-6” beneath the soil surface and covertly marked using natural features so as make it retrievable by field technicians without attracting attention from passing vehicles (Figure 26). GPS coordinates for the TrafX location should be recorded. Data from the TrafX vehicle counter can be downloaded at the study site and returned to an office or lab for transfer to permanent computer storage and analysis. The data dock is capable of holding multiple months worth of data, however the TrafX counter itself should be checked regularly to prevent batteries from expiring in the field. Timing of battery checks and data retrieval can be made on a site-specific basis.

Figure 26. Marked TrafX burial location along the Salt Valley Road in Arches National Park.

CHAPTER 6
SUPPLEMENTAL METHODS TO FUGITIVE ROAD DUST EMISSION AND MITIGATION MONITORING

Chapter 6 identifies methods that can be implemented for a more thorough examination of the indicators of direct change influencing ecosystem function, for example plant physiological response to dust and measures of soil fertility. They also include the collection of interpretive indicators of dust emission, again those parameters that influence the patterns of emission and associated impacts. These methods are more expensive, require additional hours spent at study sites by field technicians, and may involve the export of samples to outside agencies or laboratories for analysis. They will, however, provide a comprehensive data set that managers can rely on to make more informed decisions about dust management and mitigation in their parks.

SEASONAL PRECIPITATION AND WIND TRENDS

A combination of a rain gauge and data logger can be used for long-term monitoring of precipitation trends at a study plot. An example unit is the HOBO® RG3-M Data Logging Rain Gauge (Figure 27a). Seasonal precipitation data will enable a better assessment of the temporal aspects of fugitive road dust emission, and can serve as an indicator of how much dust emission is likely to occur in a season. When soil moisture rates are high, dust emission in general will be reduced. Many parks have such gauges already in place for long-term vegetation monitoring studies, and often a gauge at an existing nearby study site can provide this data. Similarly, an anemometer and data logger can provide data on wind direction and wind speed trends at a study site (Figure 27b). Fugitive road dust due to vehicular traffic is dependent on wind for both transport distance and direction away from the point of emission. Seasonal fluctuations in wind speed are important indicators of when fugitive road dust emission, as well as dust emission in general, is most likely to occur.

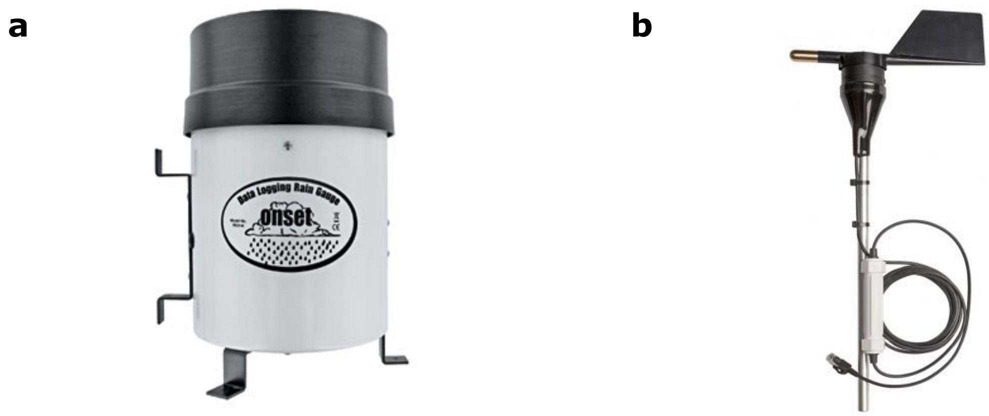

Figure 27. Onset HOBO® Rain Gauge (a) and Onset Wind Speed and Wind Direction Sensor (b).

PHOTOSYNTHETIC QUANTUM YIELD & LEAF TEMPERATURE

Dust cover on leaf surfaces can affect leaf temperature, which can further influence photosynthetic rates and overall photosynthetic performance. A Walz™ Mini-PAM Photosynthesis Yield Analyzer (Figure 28) can be used to quickly and easily measure photosynthetic quantum yield and leaf temperature of the leaves of roadside plants. Sample plants can be selected from individuals occurring on the study transects established for line-point intercept and gap distance measurements. Leaves to be sampled should be dark-adapted prior to measurement by placing a garbage bag or box over the individual sample plant for 15 minutes immediately before collecting the measurement. Three randomly picked leaves per plant should be sampled and mean values determined per plant. Managers may choose to sample plants of all species present along study transects, or may choose to focus only on species of interest or species believed to be most at risk to dust impacts.

Figure 28. Walz™ Mini-PAM Photosynthesis Yield Analyzer.

STOMATAL CONDUCTANCE

Dust particles trapped on a leaf surface can potentially clog stomata and affect leaf transpiration, which is the exchange of H_2O vapor and CO_2 between the interior of the leaf and the atmosphere. Windblown dust may also abrade leaves as particles "sandblast" their surface, which may lead to increased H_2O vapor loss in affected plants. A Decagon™ model SC-1 Steady State Diffusion Porometer, or similar instrument, can be used to quickly measure stomatal conductance of sample leaves (Figure 29). The porometer should be calibrated to field conditions (relative humidity and temperature) before daily sampling begins, as well as every 2-3 hours if relative humidity and temperature conditions are variable throughout the sampling period.

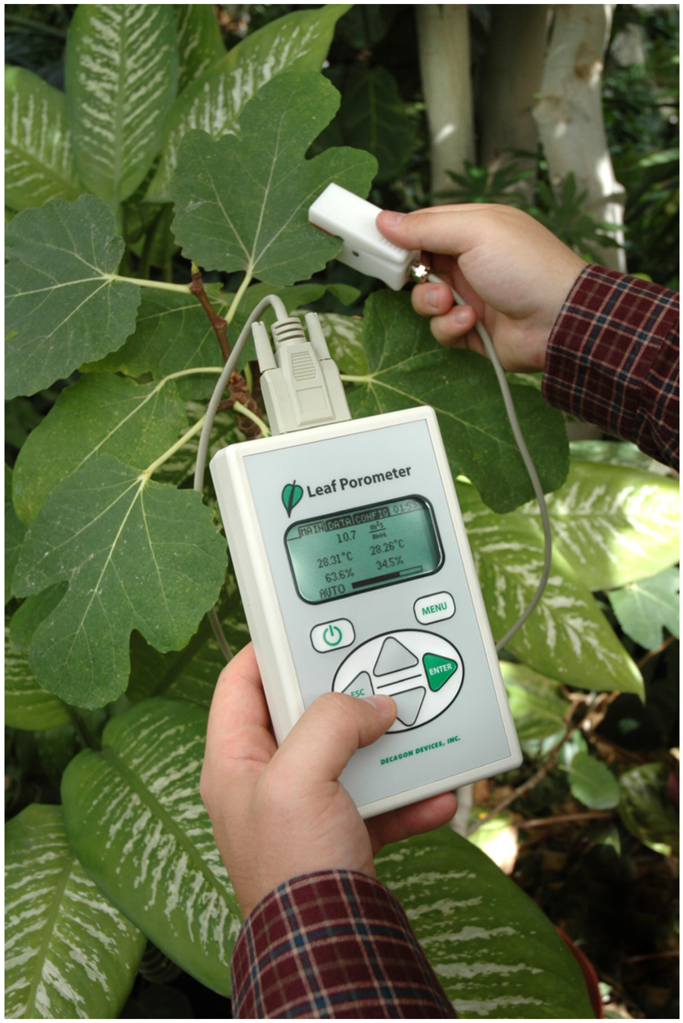

Figure 29. Decagon™ SC-1 Steady State Diffusion Porometer.

PARTICLE SIZE DISTRIBUTION OF ROAD SEDIMENT

Sediment samples collected from BSNE units can be sent to the U.S. Geological Survey in Denver, Colorado for a laser fractionation analysis to determine the particle size distribution for each distance increment away from road and for each bucket height. This data will characterize the particle sizes being transported away from the road, and provides information on what particle sizes are present throughout the potential zone of impact adjacent to a road. Particles of different sizes may have different effects on adjacent soil structure and roadside vegetation. Samples should be sent to:

Harland Goldstein
U.S. Geological Survey
Denver Federal Center
MS-980
Denver, CO 80225
Phone: 303.236.5506

CONCENTRATION OF Mg^{2+} AND Cl^- IN ROADSIDE SOIL

A systematic soil sampling design can be used to gather 30 baseline samples and 60 post-treatment samples to examine the extent to which $MgCl_2$ and its ionic constituents, Mg^{2+} and Cl^-, are transported away from an unpaved road through the roadside soil profile. An example of one possible sampling scheme is given here.

In a 100 m study plot on a road that has undergone $MgCl_2$ application, (Figure 30) sampling intervals can be designated at 0 m, 25 m, 50 m, 75 m, and 100 m. Baseline samples can be taken at 25 m, 50 m, and 75 m to characterize soil variability within the site. Samples should be collected on both sides of the road at the following distances from the road edge: 0.2 m, 2.0 m, 8.0 m, 16.0 m, and 35.0 m. The road edge will be designated as the point at which any road berm intersects with the graded road surface. Samples can be collected at the following depths for each distance increment: 0-1 cm, 1-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm.

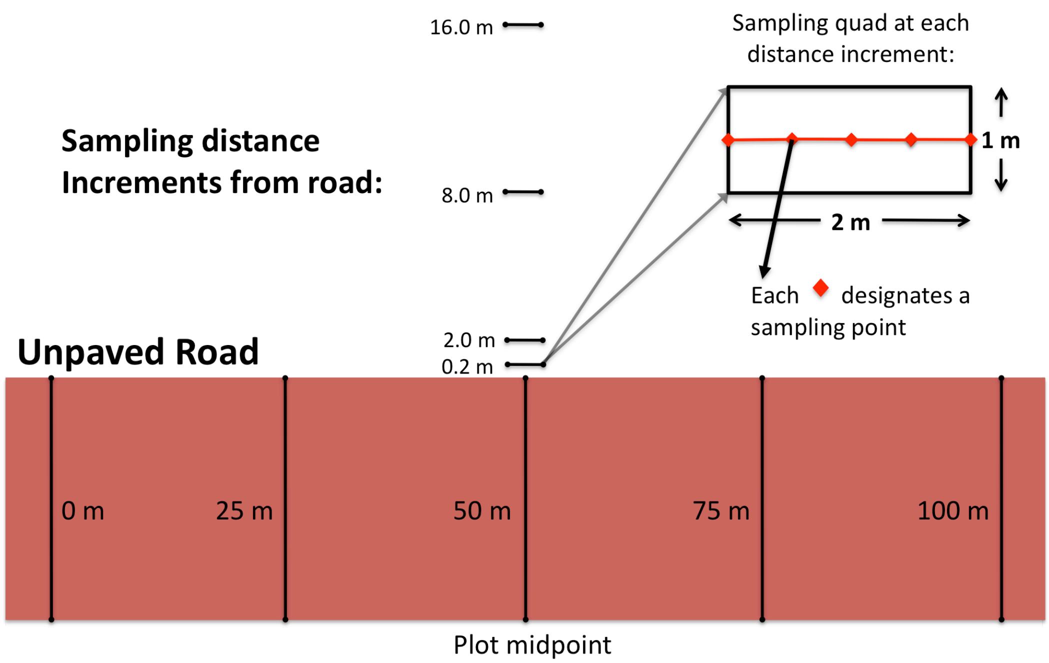

Figure 30. Soil sampling scheme for ionic analysis of $MgCl_2$-treated unpaved roads.

Due to the coarse nature of the sandy soils found in much of the Colorado Plateau, typical sampling using soil auger or slide hammers may not provide adequate precision for the preferred depth intervals. If this is the case, samples can be collected by first digging a pit roughly 50 cm in depth using a sharp shooter shovel, then a measuring tape and hand spade can be used to gather an appropriate amount of soil at each of the determined depths (Figure 31). If the soil being sampled is more toward the loam or clay end of the texture spectrum a standard soil auger may be adequate.

Figure 31. Soil pit being measured for sampling.

Post-treatment samples can be collected at the following distances from the road: 0.2 m, 2.0 m, 8.0 m, and 16.0 m. As the migration of Mg^{2+} and Cl^{-} ions from the road edge is expected to be slow, only the distances of 0.2 m, 2.0 m, and 8.0 m may initially be analyzed. If analysis indicates ion migration up to the 8.0m distance for any one sampling event, the maximum distance for the following sampling can be extended to 16.0 m. Samples should be collected at the 50 m plot midpoint at the following depths for each distance increment: 0-1 cm, 1-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm. The post-treatment samples should collected from within 1x2 m quads positioned around the point of the initial baseline sample (Figure 30).

The goal of this sampling scheme is to minimize potential soil variability among the samples, and to achieve some level of replication among the samples. Samples should be collected immediately following treatment of the road, and every two-four months thereafter for the duration of the monitoring program, depending on specific park data requirements.

Soil samples should be prepared into 1:1 soil:H_2O suspensions, vacuum filtered through a 45-μm filter, and electrical conductivity (EC), pH, Cl^- content, and NO_3^- content measured. The samples can then be submitted to the Utah State University Analytical Laboratory (USUAL) for elemental analysis via inductively coupled plasma (ICP) spectrometry at a cost of approximately $15 per sample. Samples may also be sent in an unprepared form, and USUAL will mix, extract, and conduct ICP analysis for a cost of approximately $25 per sample. Samples should be sent to:

USUAL
9400 Old Main Hill
Logan UT 84322
Phone: 435.797.2217

CHAPTER 7
GLOSSARY OF TERMS RELEVANT TO DUST MONITORING AND MITIGATION

Aeolian dust	Particulate matter that is eroded, transported, and deposited by wind
Aeolian processes	Natural processes driven by wind, or the ability of wind to erode, transport, and deposit materials in a way that influences the structure of the Earth's surface
Air quality	A measure of the quality of the air or atmosphere based on the necessary conditions or standards required by humans and other life forms
Anion	A negatively-charged ion
Anthropogenic	Caused by human activity or use
Arid climate	A climate region where the ratio of average annual precipitation to potential evapotranspiration falls within the range 0.05-0.2
Bare ground	Unprotected ground cover, or absence of stabilizing ground cover, making a soil surface vulnerable to surface erosion by wind and water; stabilizing ground cover could include plants, BSCs, rocks, and litter
Biological soil crust	Highly specialized communities of cyanobacterial, lichens, and/or mosses that form a living crust on the soil surface that is composed of soil particles bound together by organic materials

Cation	A positively-charged ion
Cation exchange	The exchange of positively-charged soil nutrient ions between soil particles and the soil solution; determines soil fertility
Chemical dust suppression	Chemical products (e.g. water, salts, emulsions, oils, polymers, and lignins) that change the physical properties of the soil surface to inhibit dust emission; typically used on construction sites, in mining applications, and on unpaved roads
Chlorophyll	Green pigment in leaves used in light capture as the first step in photosynthesis
Conductance	The measure of the rate of passage of CO_2 or H_2O vapor through the stomata of a leaf
Decadence	The deterioration of plant physiological structure or function, indicative of an overall decline in health or performance
Defoliation	The loss of leaves from a plant
Dust emission	The erosion of soil particles from a land surface or road via wind
Dust entrainment	The transport of eroded dust via wind
Dust flux	The overall quantity of soil particles that are moved during dust emission, dust entrainment, and dust deposition
Ecophysiology	A science that seeks to describe the physiological mechanisms underlying ecological observations
Feedbacks	A process in which past or present ecological phenomena influence future events
Fertilization	The deposition of nutrients via dust particles on a landscape or ocean, resulting in a

	change in nutrient availability in that system
Foliar	Relating to a leaf or leaves
Fugitive dust	Soil particles that are emitted as a result of some type of land disturbance
Grassland	Plant community dominated by grasses
Hydration radius	The effective size of an ion or molecule plus its associated water molecules in solution; influences cation exchange and binding of cations to soil particles
Hydrology	The occurrence, distribution, movement, and properties of water within a landscape
Ion	An atom or molecule with an unequal number of electrons, resulting in a net positive or negative charge
Leaf burn	The browning of plant tissue that may eventually lead to wilting
Leaf drop	A premature falling of leaves on a plant
Litter	Dead plant material sufficiently intact to be recognizable
Magnesium chloride ($MgCl_2$)	($MgCl_2$) A chemical dust suppressant commonly used on unpaved roads and trails
Monitoring	Data collected to characterize a current state and/or trends in the condition of a natural resource
Morphology	The physical and structural characteristics of organisms
Necrosis	The premature death of cells in living plant tissue
Nutrient cycling	The exchange of organic and inorganic material back into the production of living

matter

Osmotic potential	Component of water potential dependent on solute concentration (i.e. of a leaf)
Perennial	Species whose individuals typically live more than two years
Photosynthesis	A process by which light energy is used to reduce carbon dioxide (CO_2) to organic compounds, providing food for plants to maintain metabolic processes
Photosynthetically active radiation (PAR)	Solar radiation (light) in the wavelength range 400-700 nm that plants and other photosynthetic organisms use in the process of photosynthesis
Photosynthetic quantum yield	A measure of photosynthetic efficiency expressed in moles of photons absorbed per mole of CO_2 fixed or O_2 evolved, or the number of photons required to reduce 1 mole of CO_2 with respect to photorespiration
Plant community composition	The number and relative abundance of individual species present in a plant community
Plant cover	The relative area covered by plant species in a location; may be measured as plant basal cover or plant canopy cover
Plant mortality	The premature death of an individual plant
Plant productivity	The rate at which biomass is produced per unit area by plants, as a result of photosynthesis
Photooxidation	Damage to a plant due to excess absorption of light energy, most likely to occur when the plant is experiencing some other form of stress
PM2.5	Particulate matter of size 2.5 microns and

smaller

PM10 Particulate matter of size 10 microns and smaller

Radiative forcing A measure of the influence that a climate forcing factor (e.g. snowpack albedo, dust particles coating a leaf) has in altering the balance of incoming and outgoing energy in the Earth's atmosphere

Rhizosphere The narrow zone of soil that surrounds and is influenced by the roots of plants

Road sediment reservoir The total amount of material or sediment on a road surface that is available to erosion by vehicular traffic and wind; can include larger particles such as gravel, rock fragments, and bedrock that may over time be mechanically pulverized to smaller erodible sizes

Salinization The increased concentration of salt in soils

Saltation The intermittent bouncing motion over short distances of larger-size sand particles due to wind

Semi-arid climate A climate region where the ratio of average annual precipitation to potential evapotranspiration falls within the range 0.2-0.5

Shrubland Plant community dominated by shrubs

Sink area Area in which eroded, windblown dust is deposited

Soil aggregate Groups of soil particles bound to each other more strongly than to adjacent particles; pores exist between soil aggregates

Soil aggregate stability The ability of soil aggregates to resist disruption when outside forces, such as those associated with water or disturbance, are applied

Soil compaction	Mechanical compression of a soil surface, leading to the displacement of air from pores within the soil; leads to increased runoff and erosion, as the soil is less able to absorb water, as well as constricted root growth; may also be chemical in nature, e.g. following the use of $MgCl_2$, which forms a compaction layer at the soil surface to prevent the erosion of soil particles via wind
Soil moisture	The quantity of water contained in a soil body or sample
Soil moisture recharge	The replenishment of soil moisture by precipitation or snowmelt following a dry season
Soil structure	The manner in which soil particles bind, or aggregate, and the arrangement of soil pores between aggregates; influences the movement of water and air through soil, as well as biological activity, seedling emergence, and patterns of root growth
Soil surface disturbance	Impacts to an area or landscape due to recreation, grazing, mining, oil and gas development, etc., that change the structure and functioning of the soil surface
Soil texture	The relative proportion of sand (0.05-2.0 mm diameter), silt (0.002-0.05 mm diameter), and clay (<0.002 mm) particles in a soil body or sample
Soil type	The complex classification of soils based on their physical, chemical, and mineral properties; many soil classification systems exist throughout the world
Source area	Area from which dust is emitted and transported away from

Species diversity	The number of different species represented in a sample of individuals
Stomata	(plural form of *Stoma*) Pores in a plant leaf surface, surrounded and regulated to open and close by a pair of guard cells, that serve as the site for exchange of CO_2 and H_2O gases
Surface albedo	The amount of solar radiation that is reflected by a surface (e.g. a snowpack); the reflectivity of the Earth's surface
Surface creep	The movement (rolling or sliding) of larger particle-size sand grains along the ground surface due to impact from saltating soil particles
Surface hydrology	The spatial and temporal relationships between precipitation and the ensuing runoff of water on a landscape
Suspension	The holding of very small particles (typically <100 μm) in the atmosphere during aeolian transport
Transpiration	The exchange of CO_2 gas and H_2O vapor between the interior of a leaf and the Earth's atmosphere (when stomata are opened to diffuse CO_2 in to the leaf, H_2O vapor is lost to the atmosphere)
Visitor experience	The perception, feelings, and reactions a person has when visiting a recreation area
Water use potential	In plants, the potential or tendency of water to move between a plant and the soil
Wind erosion	The physical weathering of and removal of soil particles from the Earth's surface by wind
Wind velocity	A vector value consisting of wind speed and wind direction

CHAPTER 8
REFERENCES

Angold, P.G. 1997. The impact of a road along adjacent heathland vegetation: Effects on plant species composition. *Journal of Applied Ecology*, 34:409-417.

Belnap, J. 2006. The potential roles of biological soil crusts in dryland hydrologic cycles. *Hydrological Processes*, 20:3159-3178.

Belnap, J. 2003. The world at your feet: Desert biological soil crusts. *Frontiers in Ecology*, 1(4):181-189.

Belnap, J. 2002. Nitrogen fixation in biological soil crusts from southeast Utah, USA. *Biology and Fertility of Soils*, 35:128-135.

Belnap, J., R. Rosentretter, S. Leonard, J. Hilty Kaltenecker, J. Williams, and D. Eldridge. 2001. Biological soil crusts: Ecology and management. United States Department of the Interior, Bureau of Land Management, Technical Reference 1730-2.

Belnap, J. and D.A. Gillette. 1997. Disturbance of biological soil crusts: Impacts on potential wind erodibility of sandy desert soils in southeastern Utah. *Land Degradation and Development*, 8:355-362.

Bolling, J.D. and L.R. Walker. 2000. Plant and soil recovery along a series of abandoned desert roads. *Journal of Arid Environments*, 46:1-24.

Brooks, M.L. and B. Lair. 2005. Ecological effects of vehicular routes in a desert ecosystem. In "The Mojave Desert: Ecosystem Processes and Sustainability," eds. R.H. Webb et al. The University of Nevada Press, Reno, NV. pp. 168-195.

Bryson, G.M. and A.V. Barker. 2002. Sodium accumulation in soils and plants along Massachusetts roadsides. *Communications in Soil Science and plant Analysis*, 33(1-2):67-78.

Cakmak, I. and E.A. Kirkby. 2008. Role of magnesium in carbon partitioning and alleviating photooxidative damage. *Physiologia Plantarum*, 133:692-704.

Cayan, D.R., K.T. Redmond, and L.G. Riddle. 1999. ENSO and hydrologic extremes in the western United States. *Journal of Climate*, 12:2881-2893.

Chadwick, O.A., L.A. Derry, P.M. Vitousek, B.J. Huebert, and L.O. Hedin. 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature*, 397:491-497.

Coffin, A.W. 2007. From roadkill to road ecology: A review of the ecological effects of roads. *Journal of Transport Geography*, 15:396-406.

Comstock, J.P. and J.R. Ehleringer. 1992. Plant adaptation in the Great Basin and Colorado Plateau. *The Great Basin Naturalist*, 52(3):195-215.

Cunningham, M.A., E. Snyder, D. Yonkin, M. Ross, and T. Elsen. 2008. Accumulation of deicing salts in soils in an urban environment. *Urban Ecosystems*, 11:17-31.

Eller, B.M. 1977. Road dust induced increase of leaf temperature. *Environmental Pollution*, 13:99-107.

EPA. 2011. Particulate Matter: Health and Pollution. [URL] http://www.epa.gov/pm/health.html.

EPA. 2005. National Summary of Particulate Matter Emissions. [URL] http://www.epa.gov/air/emissions/pm.htm.

Eveling, D.W. and A. Bataille. 1984. The effects of deposits of small particles on the resistance of leaves and petals to water loss. *Environmental Pollution*, 36:229-238.

Field, J.P., J. Belnap, D.D. Breshears, J.C. Neff, G.S. Okin, J.J. Whicker, T.H. Painter, S. Ravi, M.C. Reheis, and R.L. Reynolds. 2010. The ecology of dust. *Frontiers in Ecology and the Environment 2009*, doi:10.1890/090050.

Forman, R.T.T. and L.E. Alexander. 1998. Roads and their major ecological effects. *Annual Review of Ecological Systematics*, 29:207-231.

Gelbard, J.L. and J. Belnap. 2003. Roads as conduits for exotic plant invasions in a semi-arid landscape. *Conservation Biology*, 17(2):420-432.

Gillies, J.A., V. Etyemezian, H. Kuhns, D. Nikolic, and D.A. Gillette. 2005. Effect of vehicle characteristics on unpaved road dust emissions. *Atmospheric Environment*, 39:2341-2347.

Goodrich, B.A., R.D. Koski, and W.R. Jacobi. 2009. Condition of soils and vegetation along roads treated with magnesium chloride for dust suppression. *Water Air and Soil Pollution*, 198:165-188.

Goodrich, B.A., R.D. Koski, and W.R. Jacobi. 2008. Roadside vegetation health condition and magnesium chloride ($MgCl_2$) dust suppressant use in two Colorado, U.S. counties. *Arboriculture & Urban Forestry*, 34(4):252-259.

Goosens, D. and B.J. Buck. 2011. Assessment of dust emissions, chemistry, and mineralogy for management of natural and disturbed surfaces at Nellis Dune Recreation Area, Nevada. USDI Bureau of Land Management, Final Report for Task Agreement Number FAA010017. 297 pp.

Grantz, D.A., J.H.B. Gamer, and D.W. Johnson. 2003. Ecological effects of particulate matter. *Environmental International*, 29:213-239.

Herrick, J.E., J.W. Van Zee, K.M. Havstad, L.M. Burkett, and W.G. Whitford. 2005. Monitoring manual for grassland, shrubland, and savanna ecosystems: Volume 1 Quick Start. The University of Arizona Press, Tucson, AZ. 42 pp.

Hirano, T., M. Kiyota, and I Aiga. 1995. Physical effects of dust on leaf physiology of cucumber and kidney bean plants. *Environmental Pollution*, 89(3):255-261.

Kawahata, H., T. Okamoto, E. Matsumoto, and H. Ujiie. 2000. Fluctuations of eolian flux and ocean productivity in the mid-latitude North Pacific during the last 200kyr. *Quaternary Science Reviews*, 19:1279-1291.

Kobayashi, H., Y. Masaoka, and S. Sato. 2005. Effects of excess magnesium on the growth and mineral content of rice and

Echinochloa. *Plant Production Science*, 8:38-43.

Marion, J.L. and C. Carr. 2007. An assessment of recreation impacts to cliff and rock outcrop environments in Shenandoah National Park. USDI U.S. Geological Survey, Final Research Report. Virginia Tech Field Station, Blacksburg. VA. 86 pp.

Kuhns, H. J. Gillies, V. Etyemezian, G. Nikolich, J. King, D. Zhu, S. Uppapalli, J. Engelbrecht, and St. Kohl. 2010. Effect of soil type and momentum on unpaved road particulate matter emissions from wheeled and tracked vehicles. *Aerosol Science and Technology*, 44:187-196.

Li, J., G.S. Okin, L. Alvarez, and H. Epstein. 2008. Effects of wind erosion on the spatial heterogeneity of soil nutrients in two desert grassland communities. *Biogeochemistry*, 88(1):73-88.

McTainsh, G. and C. Strong. 2007. The role of aeolian dust in ecosystems. *Geomorphology*, 89:39-54.

Mohamed, A.M.O. and K.M. El Bassouni. 2007. Externalities of fugitive dust. *Environmental Monitoring and Assessment*, 130:83-98.

Munson, S.M., J. Belnap, and G.S. Okin. 2011. Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. *Proceedings of the National Academy of Sciences*, 108(10):3854-3859.

Neff, J.C., A.P. Ballantyne, G.L. Farmer, N.M. Mahowald, J.L. Conroy, C.C. Landry, J.T. Overpeck, T.H. Painter, C.R. Lawrence, and R.L. Reynbolds. 2008. Increasing eolian dust deposition in the western United States linked to human activity. *Nature Geoscience*, 1:189-195.

Neff, J.C., R. Reynolds, R.L. Sanford Jr., D. Fernandez, and P. Lamothe. 2006. Controls of bedrock geochemistry on soil and plant nutrients in southeastern Utah. *Ecosystems*, 9:879-893.

Nicholson, K.W., J.R. Branson, P. Giess, and R.J. Cannell. 1989. The effects of vehicle activity on particle resuspension. *Journal of Aerosol Science*, 20:1425-1428.

Okin, G.S., D.A. Gillette, and J.E. Herrick. 2006. Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. *Journal of Arid Environments*, 65:253-275.

Okin, G.S., N. Mahowald, O.A. Chadwick, and P. Artaxo. 2004. Impact of desert dust on the biogeochemistry of phosphorous in terrestrial ecosystems. *Global Biogeochemical Cycles*, 18(GB2005):1-9.

Painter, T.H., A.P. Barrett, C.C. Landry, J.C. Neff, M.P. Cassidy, C.R Lawrence, K.E. McBride, and G.L. Farmer. 2007. Impact of disturbed desert soils on duration of mountain snow cover. *Geophysical Research Letters*, 34.

Pezeshki, S.R., R.D. DeLaune, and W.H. Patrick, Jr. Effect of salinity on leaf ionic content and photosynthesis of *Taxodium distichum L*. *American Midland Naturalist*, 119(1):185-192.

Piechota, T., J. van Ee, J. Batista, K. Stave, and D. James. 2004. Potential Environmental Impacts of Dust Suppressants: "Avoiding Another Times Beach." U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-04/031.

Reheis, M.C. and F.E. Urban. 2011. Regional and climatic controls on seasonal dust deposition in the southwestern U.S. *Aeolian Research*, 3:3-21.

Sanders, T.G., J.Q. Addo, A. Ariniello, and W.F. Heiden. 1997. Relative effectiveness of road dust suppressants. *Journal of transportation Engineering*, 123(5):393-397.

Schwinning, S., J. Belnap, D.R. Bowling, and J.R. Ehleringer. 2008. Sensitivity of the Colorado Plateau to change: Climate, ecosystems, and society. *Ecology &* Society, 13(2):28. [online] URL: http://www.ecologyandsociety.org/vol13/ iss2/art28/.

Shabala, S. and Y. Hariadi. 2005. Effects of magnesium availability on the activity of plasma membrane ion transporters and light-induced responses from broad bean leaf mesophyll. *Planta*, 221:56-65.

Sharifi, M. Rasoul, A.C. Gibson, and P.W. Rundel. Surface dust impacts on gas exchange in Mojave Desert. *Journal of Applied Ecology*, 34:837-846.

Smith, E.M. 1975. Tree stress from salts and herbicides. *Journal of Arboriculture*, 1(11): 201-205.

Tegen, I., A.A. Lacis, and I. Fung. 1996. The influence of climate forcing of mineral aerosols from disturbed soils. *Nature*, 380:419-422.

Trombulak, S.C. and C.A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology*, 14(1):18-30.

Van Heerden, P.D.R., G.H.J. Kruger, and M. Kilbourn Louw. 2007. Dynamic responses of photosystem II in the Namib Desert shrub, *Zygophyllum prismatocarpum*, during and after foliar deposition of limestone dust. *Environmental Pollution*, 146:34-45.

Watson, J.G., J.C. Chow, and T.G. Pace. 2000. Fugitive dust emissions. In Wayne (Ed.) *Air Pollution Engineering Manual, 2nd Ed.* John Wiley & Sons, Inc., New York: pp 117-135.

Western Regional Climate Center, 2010. [online] URL: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?utmoab.

CHAPTER 9
APPENDIX A: PLANT SPECIS LIST FOR ARCHES NATIONAL PARK

Plant spp list for ARCH

CHAPTER 13
APPENDIX B: DATA SHEETS FOR LINE-POINT INTERCEPT AND GAP DISTANCE

Data sheets for line-point, gap distance, BSNE