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Oceano Dunes: State of the Science

February 2023

Report prepared by the ***Scientific Advisory Group (SAG)***

Contributor notes: The contents of this report solely reflect the views of the SAG: Carla Scheidlinger, Mike Bush, John A. Gillies, William Nickling, Ian Walker, Earl Withycombe (retired October 2022), and Raleigh L. Martin (Chair). Carla Scheidlinger led the development of this report, and all other listed SAG members assisted with writing. Nitzan Swet and Zach Hilgendorf of the University of California, Santa Barbara (UCSB) contributed substantially to the topical chapter on "Geology and History of the Oceano Dunes." Leah Mathews and Bernard Bauer, who recently joined the SAG, provided useful comments on later stages of the report. Staff from the California Department of Parks and Recreation (CDPR) and the San Luis Obispo County Air Pollution Control District (SLOAPCD) provided helpful comments on draft versions of this report; however, the final contents do not reflect the views of these or any other governing authorities.

Suggested citation: Scientific Advisory Group, February 2023, Oceano Dunes: State of the Science

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I. EXECUTIVE SUMMARY

Purpose of this Document

The Scientific Advisory Group (SAG) independently prepared this "State of the Science" document to synthesize existing publicly available white papers, reports, studies, publications, and other materials relevant to understanding the dust problem at Oceano Dunes State Vehicular Recreation Area (ODSVRA) and related dust mitigation efforts. The purpose of this document is not to present new findings; rather, the goal is to succinctly describe what is already known on 7 key topics: (1) General Geology and History of the Dunes, (2) Dust Emissions, (3) Dust Controls, (4) Vegetation Restoration, (5) Restoration of Coastal Foredunes, (6) Modeling, and (7) Air Quality. In addition, this document calls attention to significant gaps in scientific understanding to be addressed through future studies. This Executive Summary provides a brief overview of the content of this report, including summaries of each of the 7 topical sections.

Overview

Monitoring, modeling, and knowledge of how dune surfaces emit dust have informed the work advised and conducted by the SAG regarding the ODSVRA. Dust control strategies on which the SAG consults include temporary measures as well as the long-lasting measures of vegetation restoration and foredune restoration. Knowledge of the dynamics of these control strategies and improvements in modeling approaches inform decisions regarding the most effective and economical deployment of dust control implementation.

Geology and History of the Oceano Dunes (Chapter II.1)

This chapter reviews the forces and materials that shape coastal sand dunes in Central California, in particular the Oceano Dunes. The Callender Dunes region represents the northern portion of the much larger Santa Maria Valley dune complex, which spans 29 km (18 miles) of coastline from Pismo Beach in the north to Point Sal in the south. The Callender Dunes are maintained by an estimated onshore supply of more than 60,000 cubic meters per year of sand deposited between Pismo Pier and Oso Flaco Creek. This material consists primarily of quartz and feldspar grains of sand sizes and finer that are derived from physical disintegration and chemical alteration of mostly sedimentary and some igneous rocks in the mountains and terraces along the margins of the Santa Maria basin. Dune systems and sand sheets are natural sources of mineral dust, and such dust can come from any of the five different dune forms that are present in the Oceano Dunes complex. Several decades of recreation activities in the dunes have impacted native vegetation cover and dune forms. Recent studies have shown that areas with the most intensive vehicle activity have seen significant declines in plant cover and related dune forms.

Foredunes, nebkha, incipient dunes, and their related plant communities have been particularly impacted and reduced in cover significantly.

Dust Emissions (Chapter II.2)

This chapter describes how the SAG has reached an understanding of both the natural and human-influenced mechanisms by which PM_{10} is emitted from the ODSVRA. Rates of dust emissions in relation to wind strength can be measured directly using the Portable In-Situ Wind Erosion Laboratory (PI-SWERL), and they can also be inferred by comparing concurrent measurements of wind strength and airborne PM_{10} dust concentrations. Differences in the measured rates of dust emissions (mg m^{-2} s^{-1}) between undisturbed and human-impacted locations at the ODSVRA inform understanding of the extent to which vehicle activity at the ODSVRA has led to an increase in airborne PM_{10} at and downwind of the ODSVRA. The physics of dust emissions is described, detailing the effects of saltation and the interaction between wind speed and dust emissions. The unique characteristics of sand dunes including particle size distribution and composition, soil moisture, and roughness and surface exposure are discussed. The impacts of vehicular operation on sand surfaces that affect emissivity have been quantified by: (1) direct measurement of the dune characteristics in both riding and non-riding areas using PI-SWERL; (2) evaluations of naturally produced dust emissions by evaluating emissions from the Oso Flaco region; and (3) studies of wind and emissions relationships using instrumented meteorological towers. The computed Wind Power Density (WPD, W m^{-2}) allows for direct comparison of emissions as affected by wind between years and in different locations.

Dust Controls (Chapter II.3)

A range of controls are used to reduce the amount of dust emitted from identified source areas. Dust control methods span a range of principles of operation including: (1) physical modification of the potentially emitting surface, (2) placement of physical elements onto or around the emitting surface to disrupt the emission process, and (3) covering the surface with a non-emissive and non-erodible layer. At the ODSVRA, implementation of the above dust control methods, respectively, (1) includes restricting vehicle activity, (2) involves straw bales, planting of vegetation, and sand fences, and (3) covers the sand with a layer of straw mulch. The methods of assessing and mathematically predicting effectiveness of each control measure type are discussed. Vegetation (including development of the vegetated foredune) is the only dust control method proposed for the ODSVRA that is considered to provide long-term dust mitigation benefits. Other implemented controls, including fencing, straw bales, straw blankets, and sand fences, are all converted to vegetation within 1-3 years. This phased implementation approach allows for the installation of vegetation at a rate that is attainable given factors of cost, labor, and plant availability, while still allowing for rapid reduction of emissions.

Vegetation Restoration (Chapter II.4)

The role of vegetation in the stabilization of sand dunes is discussed, as well as the natural processes that vegetate coastal sand dunes. The general principles of vegetation restoration including physical and chemical conditions, species composition, structural diversity, and potential threats are discussed as applicable to dunes along the California coast, and especially regarding the ODSVRA. Restoration methods for coastal dunes are also described, with details regarding surface and soil stabilization and preparation, fertilization, plant introduction, and irrigation. Specific actions undertaken at the ODSVRA are detailed along with a list of plant species used in both foredune and back dune areas. The placement and sizes of vegetation restoration projects within the ODSVRA are determined by modeling that utilizes dust monitoring data, meteorological data, and site configuration data such as location, size, orientation of existing dunes, and historical vegetation data.

Restoration of Coastal Foredunes (Chapter II.5)

The presence of a vegetated foredune system is predicted to provide an important level of dust control that has a greater impact than simply dust suppression within the actual foredune area. This is due to the aerodynamic changes that the foredune system imposes on the downwind area, as shown by the Computational Fluid Dynamics (CFD) model. At the ODSVRA, the foredunes that had previously been present in the area open to riding have been destroyed, presumably from the pressure of vehicle activity, including camping, that has increased over the years. Vegetation establishment in a foredune area is itself a dune-creation mechanism, as plant species that are adapted to the harsh conditions of the shoreline area trap moving sand and grow up through the forming dune to allow for even more trapping of sand, thus creating incipient foredunes and nebkha that evolve into a foredune system. A fenced site of approximately 48 acres located adjacent to and upslope of the high tide line was established in 2020, with 6 treatments implemented with combinations of straw, native plant seeds, sterile grass seeds, and installed container plants. Monitoring included evaluation of changes in surface topography and in plant species cover and diversity. Although some amount of nebkha formation was detected in all six of the treatments in 2022, the development of nebkha was most pronounced in the native seed and sterile grain plot.

Modeling of Particulate Matter Emission and Dispersion in the Atmosphere (Chapter II.6)

This chapter provides a concise overview of current understanding of the physics and modeling of mineral dust emission and dispersion in the atmosphere. Included as well is discussion of the models most appropriate for use in the design, placement, and evaluation of dust control measures at the ODSVRA. It discusses factors that affect how dust is lofted into the air by wind (entrainment) and how dust-sized particles originate in a sand environment. Four models that simulate the dispersion process of particles in the atmosphere - box model, Gaussian plume, Lagrangian particle dispersion, and computational fluid dynamics (CFD) – are discussed. A Lagrangian model has been selected for describing and predicting emissions in the ODSVRA. The Lagrangian model utilizes emissions, topographic, and meteorological data to evaluate the incremental change in total mass emissions (e.g., metric tons PM_{10} per day) and mass concentration (e.g., PM_{10} µg m^{-3}) that result from the actions taken to reduce dust emissions from the ODSVRA through the application of various control strategies.

Air Quality (Chapter II.7)

This chapter focuses on methods of qualifying, quantifying, and attributing PM_{10} emissions in a coastal dune environment that has been strongly impacted by the activity of off-highway vehicles (OHV). It summarizes research and monitoring conducted by the San Luis Obispo County Air Pollution Control District (SLOAPCD) and others dating back to 2007 that detail the quantity and distribution of PM_{10} emissions from the ODSVRA. Also reviewed are studies that seek to determine the composition of the PM_{10} that could attribute the provenance to various types of emissive surfaces. **Qualifying** the chemical nature of the PM_{10} should follow standards of analysis consistent with State and Federal regulatory guidance. **Quantifying** the amount of PM_{10} that is emitted should use collection strategies to describe the mass of dust emitted from an area that are well-understood and are, in some cases, specified by State and Federal regulations. **Attributability** is approached by studies comparing modeled emission rates from surfaces unaffected by heavy vehicle activity and the amount of vegetation present in the area prior to the initiation of heavy vehicle activity. This analysis relies on documentation of emissive differences between surfaces impacted by vehicles and surfaces un-impacted in this way.

Outstanding Questions (Section III)

Efforts to mitigate dust emissions at the ODSVRA are informed by decades of research on coastal dune processes and air quality impacts, along with years of intensive monitoring and modeling efforts specific to the ODSVRA. However, important knowledge gaps persist, including with regard to the specific effect of vehicles on PM_{10} air quality, the effectiveness of dust control measures, and the long-term evolution of the restored foredune. Continued monitoring and modeling is critical to inform long-term adaptive management for PM_{10} dust mitigation at the ODSVRA. Further scientific study at the ODSVRA could also improve generalized understanding of coastal dunes, their restoration, and associated air quality impacts. This section lays out both the “need to know " scientific questions of direct relevance to informing adaptive management at the ODSVRA, as well as the “want to know " scientific questions that would be worthy of investigation with the availability of additional resources.

Appendix I List of Acronyms

Acronym	*Description*
ARWP	Annual Report and Work Plan
BAM	Beta Attenuation Mass Monitor
BSNE	Big Springs Number Eight saltation trap
CALMET	CALifornia METeorological Model
CCC	California Coastal Commission
CDF	California Department of Forestry and Fire Protection Air Monitoring Site
C_d	Coefficient of Drag
CDPR	California Department of Parks and Recreation
CGS	California Geological Survey
CFD	Computational Fluid Dynamics
DCM	Dust Control Measure
DEM	Digital Elevation Model
DRI	Desert Research Institute
DRI-LPD	Desert Research Institute Lagrangian Particle Dispersion
E-BAM	Environmental Beta Attenuation Mass Monitor
LiDAR	Light Detection and Ranging
NSF	Normalized Sand Flux
NRCS	Natural Resources Conservation Service
ODSVRA	Oceano Dunes State Vehicular Recreation Area
PDF	Probability Density Function
PI-SWERL	Portable In-Situ Wind Erosion Laboratory
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter smaller than 2.5 microns
PM_{10}	Particulate Matter smaller than 10 microns
PMRP	Particulate Matter Reduction Plan
RPM	Revolutions Per Minute (or Rate of Rotation)
SAG	Scientific Advisory Group
SEM	Scanning Electron Microscope
SIO	Scripps Institution of Oceanography
SLOAPCD	San Luis Obispo County Air Pollution Control District
SOA	Stipulated Order of Abatement
TPM_{10}	Total PM_{10}
TWPD	Total Wind Power Density
UAS	Unmanned Aerial Systems
UCSB	University of California, Santa Barbara
USDA	United States Department of Agriculture
WPD	Wind Power Density
XRF	X-Ray Fluorescence
XRPD	X-Ray Powder Diffraction

II. TOPICAL CHAPTERS

II.1 Geology and History of the Oceano Dunes

II.1.1 Overview

The management of human activities and land use in dynamic landscapes requires understanding of fundamental geological and ecological processes that support various ecosystem services of interest. At the Oceano Dunes State Vehicular Recreation Area (ODSVRA), aeolian (windblown) processes have interacted with littoral (coastal) processes and plant communities to create a spectacular coastal dune system that operates on time scales that range from hours for individual wind events to millennia for longer-term dune evolution. As such, it is challenging to manage human activities in these types of environments when the intensity, duration, or frequency of use conflicts with natural processes required to maintain the landscape and the services it provides.

Coastal dunes are deposits of sand adjacent to a shoreline created by the action of wind. Wave and current processes in the nearshore provide sand to beaches, but they do not create coastal dunes. Instead, dunes are formed by transport of sand-sized particles to the upper beach and beyond by competent winds (typically >6 m s^{-1} or 13.4 mph). Littoral processes only control the availability of sediment for dune development by delivering or removing sand to/from the beach and by limiting the amount of dry sand available for aeolian transport through changes in beach width and moisture content with tides, storm surges, wave swash and runup, sea spray, etc. Typically, the largest coastal dunes develop in areas with broad surf zones, large tidal ranges, wide and flat beaches, strong and mostly onshore winds, and ample sand supply (Hesp and Walker, 2022).

The formation of coastal dunes is determined by essentially three factors: 1) sand supply and availability, 2) climate (including wind regime and precipitation), and 3) vegetation type and cover. The combination of these factors forms a variety of types of coastal dunes found on the central coast of California, including foredunes, nebkha, parabolic dunes, blowouts, transverse dunes, and transgressive dunes. An extensive review of coastal dune types is provided by Hesp and Walker (2022), and further details on the forms found within the ODSVRA are provided in Section II.1.4.

All sand surfaces subject to wind action have the tendency to emit some level of fine dust naturally as a result of the aeolian sediment transport process. Saltation is the primary mode of sand transport by wind, and it involves grains "jumping" across the sand surface in ballistic trajectories. Over time, these saltating grains impact and abrade small particles from one another, spall off clay coatings on their surfaces, and/or emit other fine particles within the sand surface. The fine particles are then lofted into the wind flow during saltation and can be transported great distances downwind. Under certain conditions, this can result in high levels of airborne particulate matter with ≤10 μm aerodynamic diameter, i.e., PM10, which can pose a public health risk.

Although dunes are composed of sand and finer particles and are formed by the saltation and deposition of sediment, they can also offer some benefits for reducing dust emissions. For instance, coastal dunes with vegetation (e.g., nebkha, foredunes) trap sand within plant cover and stabilize a portion of the sand surface. In addition, vegetation and dune topography can reduce shear stress, saltation, and dust emissions from the surface by extracting some of the wind energy directly and by creating zones of reduced wind speed in their wake. Many of the vegetated dunes within ODSVRA, however, have been destroyed or significantly reduced in plant cover, particularly in the vehicle riding areas, due to decades of recreational activity (Swet et al., 2022). In addition, it has been shown that dust-sized particles and dust emissions are more abundant in riding areas of ODSVRA compared to non-riding areas (see Chapter II.2), which provides compelling evidence that vehicle activity increases the amount of PM_{10} mineral dust emitted from the Oceano Dunes (Gillies et al., 2022).

In recognition of the dust emissions problem, the California Department of Parks and Recreation (CDPR) has been working closely with the SAG and SLOAPCD on a variety of mitigation measures to reduce emissivity of PM_{10} from ODSVRA, including sand fences, straw bales, surface stabilization with straw and native dune plants, and a recent foredune restoration project (Walker et al., 2022). This chapter will review the geology and geomorphology of dunes found within the Oceano Dunes region and discuss how scientific research and management efforts have been employed to help mitigate the dust emissions problem. Later chapters (i.e., II.3, II.4, and II.5) will detail relevant dust controls and dune restoration activities.

II.1.2 Geology of the Oceano Dunes

The ODSVRA exists within the Callender Dunes complex - an active transgressive coastal dune system (dunes formed by the downwind and/or alongshore movement of sand) that spans approximately 12 km (~7.5 miles) of coastline (Figure II.1.1A). Nearly a quarter of these dunes have been managed for vehicle recreation and camping in the ODSVRA since 1982, although unmanaged vehicle activity in the dunes predates establishment of the park by decades and ranges over a much larger area than the current ODSVRA boundaries. The Callender Dunes represent the northern portion of the much larger Santa Maria Valley dune complex, which spans 29 km (18 miles) of coastline from Pismo Beach in the north to Point Sal in the south and encompasses nearly 90 square kilometers (22,240 acres) of land. Three separate dune fields comprise the modern Santa Maria valley dunes complex (Cooper, 1967; Orme and Tchakerian, 1986; Orme, 1992) (Figure II.1.1B): (i) the Callender Dune sheet in the north, resting mainly on the Nipomo Mesa, north of Oso Flaco Lake; (ii) the Guadalupe Dunes sheet, located south of Oso Flaco Lake, which has transgressed the northern side of the Santa Maria River floodplain; and (iii) the Mussel Rock Dune Complex, also known as Lompoc Dune sheet, located south of the Santa Maria River, which has transgressed the southern side of the Santa Maria River floodplain and the Orcutt Mesa farther south. Also known as the Guadalupe-Nipomo Dunes complex, the Santa Maria Dune complex is the largest active transgressive coastal dune system in California (Orme, 1992).

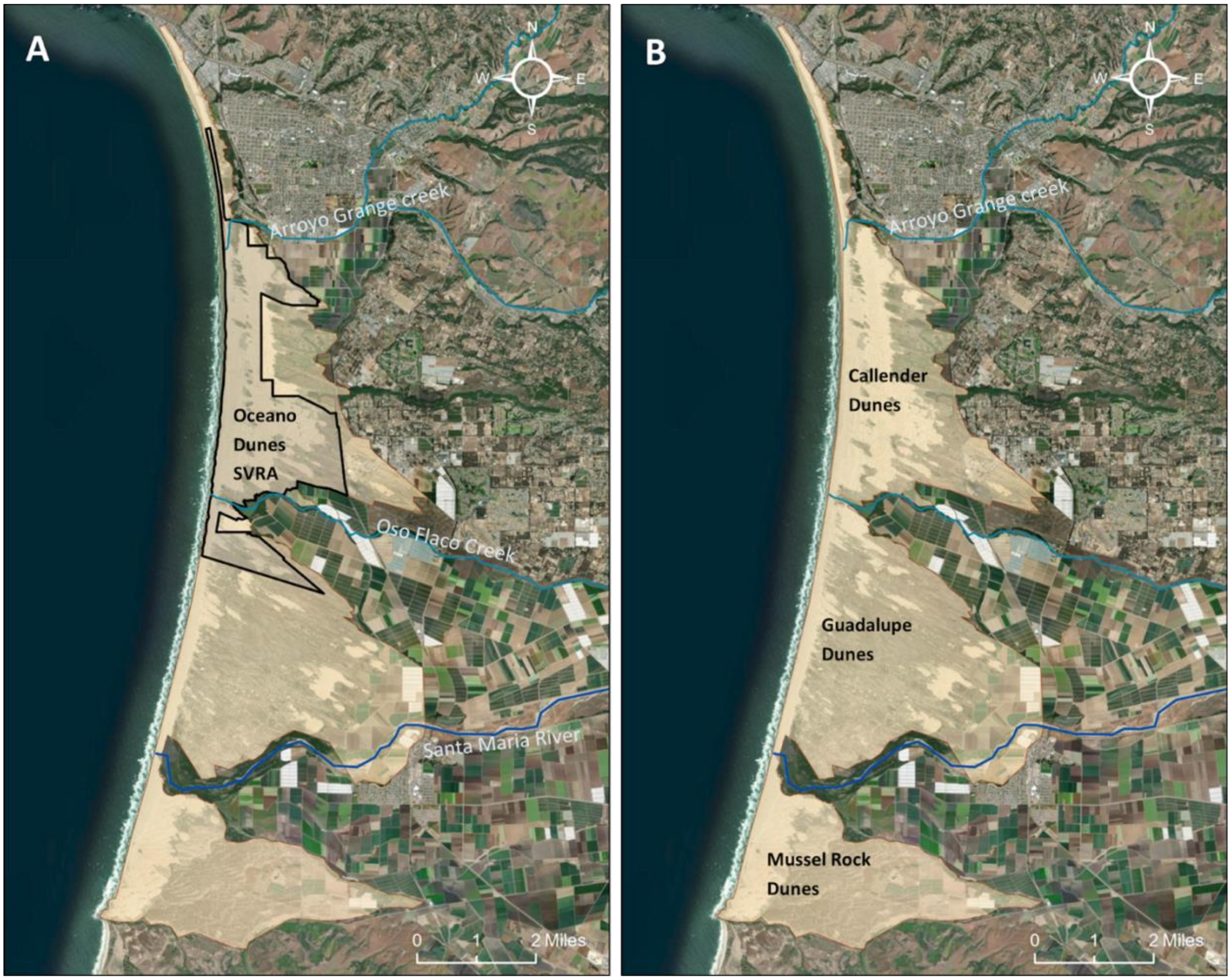

Figure II.1.1. *A) Location of Oceano Dunes State Vehicular Recreation Area (ODSVRA) (gray shading) within the modern Santa Maria Dunes complex (yellow shading). B) The ODSVRA resides within two separate dune sheets - the Callender Dunes north of Oso Flaco Lake and the Guadalupe Dunes between Oso Flaco Lake and the Santa Maria River. The third dune system of the Santa Maria complex is the Mussel Rock Dunes located south of the Santa Maria River. Base image from Earthstar Geographics, USGS, ESRI. Dune extents were digitized from the earliest historical imagery with full coverage from 1939.*

In terms of regional geology, the Santa Maria Dunes complex occupies the seaward portions of the Santa Maria Valley, which is part of the larger (5,000 square kilometers or 1.2 million acres) Santa Maria structural basin (Figure II.1.2). The Santa Maria basin extends between the Santa Ynez Mountains in the south and the San Rafael Mountains to the northeast and is part of a smaller tectonic microplate that is rotating between the North American and Pacific plates (Chen and Oertel, 1989). The basin is believed to have formed around 15 to 10 million years BP (before present) by plate extension (stretching) and resulting subsidence (sinking) and sedimentation within the basin (Shaw and Plesch, 2012, as cited in Barrineau and Tchakerian, 2021). From 10 to 5 million years BP the tectonic setting became transpressional (i.e., oblique plate boundary convergence) and created crustal folding, thrust belts, and related topographic lows. These low areas filled with marine and fluvial sediments through the Quaternary period (~2.6 million to present) (Chen and Oertel, 1989; Namson and Davis, 1990; Gutierrez-Alonso and Gross, 1997). During the Pleistocene epoch (~2.6 million to 11,700 years BP), sea level transgressed (rose) then regressed (fell) over the basin. Relict marine terraces and exposed Pleistocene aged dunes suggest that the shoreline within the Santa Maria Valley has mostly prograded seaward (westward) during much of the Quaternary due to significant sediment supply from the surrounding uplands (Masters, 2006; Sylvester and Darrow, 1979; Barrineau and Tchakerian, 2021). Offshore Quaternary aeolian and fluvial deposits below modern sea level indicate subsidence of the basin during this time (Chen and Oertel, 1989). This was followed by a rise in relative sea-level during the Holocene epoch (~11,700 years BP to present) with a still-stand in sea-level between 9,000- and 3,000-years BP at ~20-25 m below present levels, then a sea-level transgression to present time (Nardin et al. 1981; Barrineau and Tchakerian, 2021). As such, the landscapes within the Santa Maria basin have experienced significant sediment reworking and deposition over the Quaternary period by rivers, changes in relative sea level, and wind that have filled the valley with a mixture of fluvial, marine, and aeolian deposits (Chen and Oertel, 1989; Namson and Davis, 1990; Orme 1992; McCrory et al., 1995; Gutierrez-Alonso and Gross, 1997; Barrineau and Tchakerian, 2021).

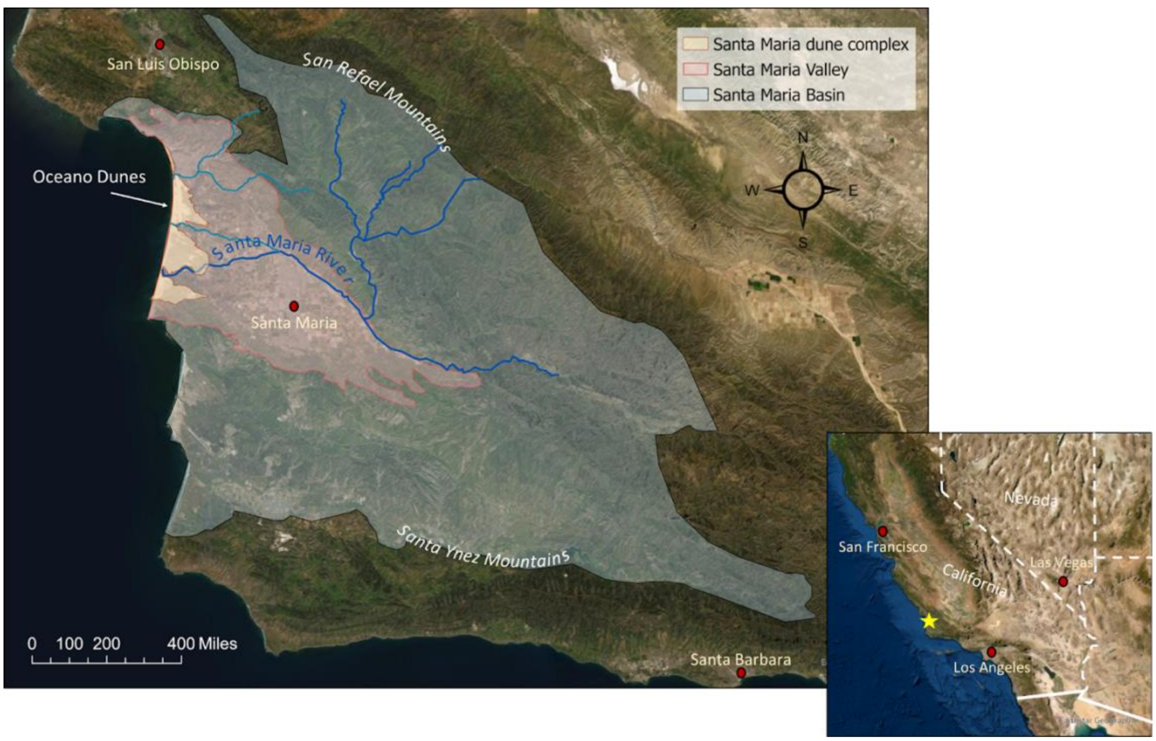

Figure II.1.2. *Map of the Santa Maria Basin (light gray), the Santa Maria Valley (pink), and the modern Santa Maria Dune complex (yellow). Base image from Earthstar Geographics, USGS, ESRI. Data obtained from USGS report (Sweetkind et al., 2010).*

The Callender Dune field, within which the ODSVRA resides, is a transgressive dune system that has been present and active in various developmental phases since at least the mid-late Holocene (Mulligan, 1985; Barrineau and Tchakerian, 2021). There is evidence, however, that the broader Santa Maria Valley dunes complex was active much earlier, since the late Pleistocene, and that the system has evolved through several phases over this time. The oldest phase (~25,000 to 80,000 years BP) is located inland on elevated terraces of the Nipomo Mesa. The youngest, most active phase of transgressive transverse dunes are located adjacent to the modern shoreline and developed during the late Holocene (~2,000 years BP to present) (Orme and Tchakerian, 1986; Bedrossian, 2011). These dunes likely transgressed over an earlier phase of parabolic dunes believed to have been formed during the marine transgressions of the early Holocene (Orme, 1992). Some of these relict parabolic dunes remain evident in the landscape today eastward of the Callender Dunes.

Today, the Callender Dunes are maintained by an estimated onshore sand supply of over 60,000 cubic meters of sand per year between Pismo Pier and Oso Flaco Creek (Bowen and Inman, 1966), which translates to about 5.1 cubic meters per meter of beach width per year (Walker et al., 2022). Alongshore sand supply is variable, however, both along the coast and through time. Further south in the Santa Maria Dune complex, field measurements by Mulligan (1985) provided an estimate of ~300,000 cubic meters of sand per year transported inland. Regardless of variations in the estimates, a significant amount of sand, on the order of 10^4 to 10^5 cubic meters per year, is delivered onshore by ocean currents, wave action, and wind to maintain the dunes at the ODSVRA today.

II.1.3 Sediments of the Oceano Dunes

Sediments in the Santa Maria Valley dunes complex consist largely of quartz and feldspar grains of sand and finer sizes (i.e., < 2 mm) that are derived from physical disintegration and chemical alteration of mostly sedimentary and some igneous rocks in the mountains and terraces along the margins of the Santa Maria basin. These finer sediments were transported toward the ocean by rivers and streams and occasionally stored and reworked on river floodplains and beaches along the way. The relatively steep topography, tectonically active terrain, and sparse vegetation cover of river basins in the region allow them to carry exceptionally high sediment loads to the ocean (Willis and Griggs, 2003). The Santa Maria River, and the smaller Arroyo Grande and Oso Flaco Creeks, deliver a variable flux of sediment to the coastal zone, where much of it is returned to the shoreline through nearshore currents and wave action (Orme, 1992; Orme and Tchakerian, 1986). Strong prevailing winds from the northwest then transport sand-sized (0.063-2 mm) particles from the beach into the dune complex via aeolian processes. Across the Callender Dunes over a distance of about 8 kilometers, average sediment size varies from approximately 0.2 mm in the north to 0.4 mm in the south, which is in the fine sand category (Bedrossian, 2011; Gillies et al., 2022).

Exchanges of sediment occur frequently between the surf zone, beach, and landward dunes in response to the suite of marine, atmospheric, and biogeomorphic processes at work on the coastal margin. The amount of sand supplied to a beach depends largely on littoral processes (tide levels, wave runup, storm surges, onshore or alongshore sand transport by waves and currents) that control both sediment delivery to the beach as well as beach width. Beach width is a critical factor in the formation of coastal dunes as it effectively controls the 'fetch' distance over which aeolian transport develops and, in turn, how much sand is delivered to landward dunes (Gillette et al., 1996; Bauer and Davidson-Arnott, 2003; Bauer et al., 2009; Houser, 2009; Delgado-Fernandez, 2010).

Aeolian sand transport over beaches and within dune systems is affected by a variety of factors including variable surface conditions (grain size and sorting, moisture content, natural binding agents, wrack), beach and dune topography (slope, roughness), vegetation (type and density), wind conditions (speed and direction), and time (Bauer et al., 2009; Eastwood et al., 2011; Hesp and Walker, 2022; Walker et al., 2022). Therefore, coastal dune form and function is intricately linked to, and controlled by, how sediment moves across the coastal margin in response to littoral processes, meteorological and climate conditions, and plant community dynamics (Walker et al., 2017; Davidson-Arnott and Bauer, 2021). In the ODSVRA, however, decades of recreational vehicles and camping activities, combined with invasive species in certain areas, have significantly altered the form and function of aeolian processes and coastal dune ecosystems. Indeed, many coastal dune systems in California have experienced anthropogenic pressures to varying degrees, yet few have seen the same intensity and duration of recreational use as the Oceano Dunes.

Dune systems and sand sheets are natural sources of mineral dust, although the volume of fine particles emitted depends on sediment characteristics (e.g., mineral composition, particle size distributions, relative age and source of sediments, etc.), regional climate, wind regime, soil moisture, and vegetation cover. Research on dust emissions indicates that finer particles are emitted during saltation of sand by three main mechanisms: i) abrasion from grain-to-grain impacts that generate dust-sized particles (e.g., Kuenen, 1960; Bristow and Moller, 2018; Swet et al., 2019), ii) grain collisions that remove clay coatings from particle surfaces (e.g., Bullard et al., 2004, 2007; Bullard and White, 2005; Swet et al., 2020), and iii) emission or re-emission of fine materials resident in the sand surface (Swet et al., 2019, 2020). At the Oceano Dunes, all of these mechanisms are observed to occur, though clay coating removal and re-emission appear to be the most common (Swet et al., 2019, 2020). Recent measurement of surface emissivity by the Desert Research Institute (DRI) using a portable PI-SWERL device (Etyemezian et al., 2007; Gillies, 2015) and modeling of dust emissions and dispersion at the Oceano Dunes (Mejia et al., 2019) have helped identify locations of high fugitive dust emissions that contribute to elevated PM_{10} levels at nearby monitoring stations. In turn, many of these locations have been targeted for mitigation of dust emissions using a variety of approaches including sand fences that limit saltation and trap sediment (Gillies et al., 2017), straw bales that impose roughness on wind flow to reduce shear stress and saltation development (Gillies and Lancaster, 2013; Gillies et al., 2018), and dune ecosystem restoration (Walker et al., 2022). More details on the dust emissions measurements, dust control measures, and modeling efforts at the ODSVRA are provided in Chapters II.2, II.3, and II.6, respectively.

II.1.4 Dune Types at the Oceano Dunes

The Callender Dunes system is a complex of several different dune types that have developed over recent geological time. These dune types include:

- **Foredunes**: shore-parallel dune ridges formed by aeolian sand deposition in vegetation or coastal wrack above the usual high-water elevation

- **Nebkha:** a dune mound or hummock that forms in discrete plants, or groups of plants, often with an elongate 'shadow dune' in the downwind direction
- **Parabolic dunes**: U- or V-shaped dunes characterized by short to elongate vegetated trailing ridges or 'arms' that terminate downwind in a depositional lobe or 'head' often with a steep slip face at the dune's landward extent
- **Blowouts**: a saucer-, cup-, bowl-, or trough-shaped depression or hollows formed by wind erosion on a pre-existing sand deposit, including larger dune forms
- **Transverse dunes**: linear to sinuous dune ridges formed roughly perpendicular to sand transporting winds which can migrate inland and often form with little to no vegetation
- **Transgressive dunes**: sand sheet and/or dune features formed by the downwind or alongshore movement (transgression) of sand over vegetated to semi-vegetated terrain

Figure II.1.3 shows an example of several coexisting dune forms in ODSVRA near Oso Flaco Lake. Backing the beach is a discontinuous, hummocky foredune complex with large nebkha with their shadow dunes and interspersed trough blowouts aligned generally with the dominant oblique onshore (NNW) wind direction. Parabolic dunes with vegetated arms, erosional deflation basins, and active depositional lobes lie inland and are fed by onshore sand supply through the foredune. In the distance, larger transgressive dunes of the Callender (left) and Guadalupe (right) Dunes can be seen migrating inland.

Dunes are also classified by their relative age, or time since development, into 'incipient' (new) forms that emerge first, 'established' (active) fully developed dunes that reflect contemporary aeolian processes, or 'stabilized' (relict) dunes that are no longer active and often host later stage successional plants or forests. For instance, along the eastern (inland) boundaries of the Oceano Dunes are relict parabolic dunes largely stabilized by vegetation. Some of these parabolic dunes have been modified or removed by human activities such as agriculture, infrastructure, or urban development. Small incipient dunes typically form in vegetation on the upper beach and can develop over a few weeks or months, but they can be ephemeral if eroded by high water events. Generally, dune development times vary, depending on dune size, vegetation cover and type, and variations in sand supply and climate conditions. For instance, larger established foredunes, parabolic dunes, and transverse dunes can take several decades to centuries to develop, while larger transgressive dune complexes can take centuries to millennia to evolve (e.g., Hesp, 2013; Houser et al., 2015; Hesp and Walker, 2022).

In riding areas of ODSVRA, vegetation cover and some dune forms have been heavily impacted or destroyed when compared to their historical extents (Swet et al., 2022). For example, incipient dunes, nebkha, and foredunes, and their related plant communities, have been reduced to historically low or negligible cover by decades of vehicle traffic and other recreational activities. Other active transverse dune ridges have been modified or stabilized by various methods, including revegetation efforts to restore former back-dune scrub forests and reduce dust emissions.

Figure II.1.3. *Active nebkha, blowout, and parabolic dunes that comprise the discontinuous foredune complex at North Oso Flaco Lake. Larger transgressive migrating dunes of the Callender (left) and Guadalupe (right) dunes can be seen in the distance.*

II.1.5 Land Use and Management History at the Oceano Dunes

Evidence of human presence around the Oceano Dunes exists into the early Holocene (as far as ~10,000 years BP) when the first indigenous people (Chumash Native Americans) settled in the area. It was not until the early 1900s, however, when more widespread activity in the dunes with horses and early vehicles became apparent. During the 1920s and ’30s, non-native plants like European beach grass (*Ammophila arenaria*), ice plant (*Carpobrotus edulis*), and South African veldt grass (*Ehrharta calycina*), were planted to stabilize sand and dunes around the former La Grande Beach Pavilion and near Oso Flaco Lake (Hammond, 1992). Currently, there are still large areas within the dunes that contain these species. The growth of invasive weeds over the years has resulted in increased plant cover and foredune stabilization in some areas of the Oceano Dunes (Bonk, 2010; Swet et al., 2022).

Several decades of recreational activities in the dunes have also impacted vegetation cover and dune form, particularly in the foredune zone backing the high-water mark (Swet et al., 2022). Since the 1950s, the Oceano Dunes have been a popular destination for recreational activities such as camping and vehicle riding. Prior to 1982, when the ODSVRA was established, these activities were unmanaged, and historically covered a much greater extent, until management of the portion of the area used by vehicles was taken over by CDPR. Since its establishment, recreation activities at the ODSVRA have been managed and only a portion of the dune area is open for camping and vehicle recreation activities. In total, CDPR manages ~17 square kilometers (4,215 acres) of the Oceano Dunes, which includes both open vehicle recreation areas and protected areas (Figure II.1.3). Over the years, CDPR has implemented several methods to protect sites of interest, including fencing areas for plant and animal protection, vegetation and dune restoration, invasive species removal, and protection of cultural sites.

Analysis of historic vegetation cover within the ODSVRA using aerial imagery from the 1930s to 2020 by Swet et al. (2022) shows that from 1939 to 1966 plant cover within the vehicle riding area was relatively stable at around 12%. As vehicle activities continued to increase between 1966 and 1985, plant cover declined significantly to 4%. Within the foredune zone (400 m inland from the high-water mark) vegetation cover declined from 5% in 1966 to less than 1% by 1985. This indicates that areas with the most intensive vehicle use have seen significant declines in plant cover and vegetated dune forms. Foredunes, nebkha, incipient dunes, and their related plant communities, have been especially heavily impacted and reduced in cover significantly. Since the establishment of the ODSVRA in the early 1980s, and particularly between 2005 and 2012, vegetation cover overall has increased with a net gain of 12% mainly around pre-existing vegetation ‘islands’ and at targeted restoration sites. In the open riding area, however, plant cover remained low compared to other areas, particularly in the foredune zone, which saw only a minor increase from 0.9% in 1985 to just over 2% in the 2010s (Swet et al., 2022). PI-SWERL testing by Desert Research Institute (DRI) indicated that the foredune zone in the riding area hosted some of the most emissive surfaces within ODSVRA. A 48-acre area was identified in 2019 by CDPR, in consultation with the SAG and SLOAPCD, for restoration of a foredune ecosystem at this location as a dust emissions mitigation measure, as discussed in more detail in Chapter II.5.

The subsequent chapters of this report will focus on the scientific efforts that have been important in understanding and controlling the emission of dust from this dune complex.

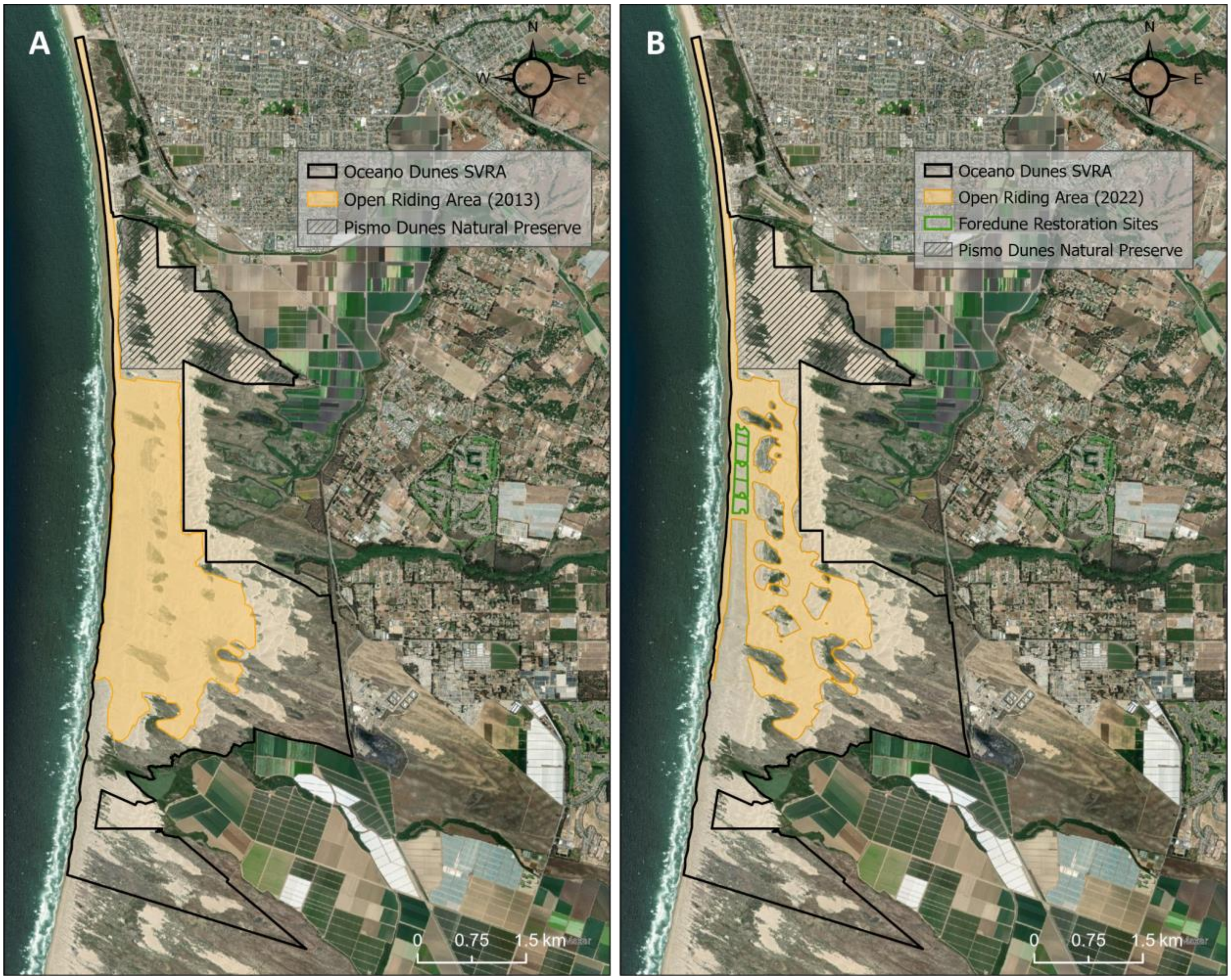

Figure II.1.4. *Open riding area (yellow shading) within the ODSVRA (Black) in A) 2013, and B) 2022. The ODSVRA border presented here includes the Pismo Dunes Natural Preserve that is technically not part of the ODSVRA but is a subunit of Pismo State Beach, which is administered by the Oceano Dunes District of CDPR. Agricultural fields that are part of the ODSVRA were removed from the present border.*

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II.2 Dust Emissions

II.2.1 General Statement

The Scientific Advisory Group (SAG) is interested in understanding both the natural and human-influenced mechanisms by which dust is emitted from the Oceano Dunes State Vehicular Recreation Area (ODSVRA). This interest is motivated by the need to understand the specific effect of vehicles and other human disturbance on enhancement of dust emissions relative to natural background levels. It is also motivated by the need to understand the effectiveness of dust mitigation treatments in reducing such dust emissions at the ODSVRA, as required by the Stipulated Order of Abatement (SOA) as amended (SLOAPCD Hearing Board, 2018, 2019, 2022). For the purposes of the SOA (see Section II.7.2.2), the SAG's focus has been on emissions of PM_{10} dust, i.e., particulate matter with an aerodynamic diameter of less than 10 microns. As will be described in the "Air Quality" chapter (Sec. II.7), PM_{10} air quality is a concern both for regulatory and health reasons. PM_{10} "air quality," which refers to the concentration of airborne PM_{10} dust as measured at specific monitoring sites, is closely related but distinct from PM_{10} "emissions," which refers to the rate at which PM_{10} dust is emitted from dune surfaces and other sources. Once PM_{10} is emitted, it is lofted into the air and carried downwind toward receptor sites. Because of the primarily onshore wind associated with PM_{10} dust emissions at the ODSVRA, such PM_{10} emissions are predominantly carried eastward into communities on the Nipomo Mesa and adjacent areas.

Whereas Chapter II.7 will focus on PM_{10} air quality, this chapter focuses on PM_{10} dust emissions. In addition to providing a brief primer on the general mechanisms of PM_{10} emissions from coastal dunes, this chapter also provides an overview of studies particular to PM_{10} dust emissions at the ODSVRA. It also describes how this understanding has informed major aspects of the PM_{10} dust mitigation process at the ODSVRA, including determinations of the role of vehicles (and other human disturbance) on elevating PM_{10} dust emissions, and the effectiveness of dust mitigation treatments on reducing PM_{10} emissions.

II.2.2 Background on the Relevant Science

The emission of mineral dust from sand dunes is a naturally occurring process, though human impacts can modify the rate and occurrence of such dust emissions. At the ODSVRA, there are examples of dust emissions occurring both at undisturbed sand dune locations and at sand dune locations that have been affected by human impacts. Rates of dust emissions in relation to wind strength can be measured directly using the Portable In-Situ Wind Erosion Laboratory (PI-SWERL), and they can also be inferred by comparing concurrent measurements of wind strength and airborne PM_{10} dust concentrations. Differences in the measured rates of dust emissions between undisturbed and human-impacted locations at the ODSVRA inform understanding of the extent to which vehicle activity at the ODSVRA has led to an increase in airborne PM_{10} at and downwind of the ODSVRA. Measurements of changes in dust emissions and airborne PM_{10} concentrations resulting from management actions at the ODSVRA inform understanding of how such actions affect progress toward air quality targets.

This chapter will evaluate studies that contribute to the understanding of PM_{10} emissions affecting air quality from coastal dunes. This chapter also provides context on how the science of PM_{10} emissions affects relevant dust control strategies. (Specific dust controls are described in further detail in Chapter II.3.)

II.2.2.1 Overview of Natural Dust Emissions Process at Coastal Dunes

Wind-driven emission of mineral dust from sand dunes is a naturally occurring process that is observed around the world at coastal and desert dune sites. This chapter focuses on coastal dunes, though many of the concepts described here are transferable to desert dune environments.

II.2.2.2 Definitions

In the context of dust emissions from sand dunes, "dust" typically refers to particles that are lightweight enough to remain airborne for extended periods of time. The term "mineral dust" is commonly used to refer to the subset of dust composed of earth minerals (e.g., quartz, feldspar) that are resident in the dune surface; however, caution should be exercised when interpreting references to "mineral dust," which may account only for specific elemental or mineralogical constituents and may underestimate all sources of fugitive dust arising from dune surfaces (Watson et al., 2012). In addition, "dust" is typically distinguished from "sand" by its size and therefore its ability to remain airborne: dust particles are smaller and lighter and thus able to remain airborne, whereas sand particles are larger and heavier and thus quickly settle back to the surface after being lifted by wind. The aerodynamic properties and health effects of wind-borne particles vary by particle size. Thus, the term "PM_{10} dust" is used to refer to those dust particles with diameters of less than 10 microns, which tend to remain airborne the longest and to have significant health impacts (CARB webpage, https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health). Note that PM_{10} refers to a broad class of "particulate matter," which includes not only mineral dust but also organic matter, sea salt aerosol, and other materials. The composition of PM_{10} is further described in the "Air Quality" chapter (Sec. II.7).

II.2.2.3 Physics of Dust Emissions from Sand Dunes

Dust emission from sand dunes typically occurs as a two-part process. First, wind of sufficient strength dislodges sand grains from the dune surface. These sand grains are typically too heavy to be launched high into the atmosphere; instead, they hop along close to the sand surface, dislodging other sand grains as they move. This process is known as "saltation." Second, as saltating sand grains repeatedly strike the ground, they dislodge smaller mineral dust particles, which are then lofted and become airborne. Because of the various forces that bind mineral dust to the dune surface and to other particles, the wind is of limited effectiveness in directly emitting dust from the surface. Instead, the impacts of wind-driven saltation are necessary to dislodge these dust particles from the ground. However, once dust particles are airborne, they are lightweight enough to remain suspended in the air column and to be transported extended distances downwind. Thus, understanding the process of saltation and how it emits dust is critical to understanding the emissivity of dust from dune systems (Kok et al., 2012).

II.2.2.4 The Origin of Dust from Sand Dunes

The underlying process of saltation-driven dust emissions is well established; however, the relative importance of different mechanisms by which sand dunes generate dust remain the subject of scientific debate. Three primary mechanisms are thought to predominate in the generation of dust from dunes (Swet et al., 2019, 2020):

1. **Emission of loose dust particles.** By this mechanism, loose dust particles in the surface, many of which previously settled out of the atmosphere, are emitted into the air column. This can include dust aggregate clusters that are broken up during saltation, with the fine particles entrained and removed, thereby leaving the coarse fraction behind as a lag deposit.
2. **Clay coating removal.** Through the gradual weathering of sand grains, coatings of clay form on the surfaces of sand grains. During saltation, these clay coatings are dislodged and form airborne dust.
3. **Abrasion of the sand grains.** The energy of saltation impacts breaks off small pieces of sand grains, which become airborne mineral dust.

All three of these mechanisms have been shown via laboratory and field studies to cause dust emissions, but their relative importance has been difficult to discern. Recent wind tunnel experiments (Swet et al., 2019, 2020) using natural sand from the Oso Flaco site at the ODSVRA indicate that emission of loose particles and clay coating removal are the most common sources of dust emissions for natural sand at the ODSVRA, whereas the contribution of abrasion is relatively minor.

II.2.2.5 Factors that Modulate Dust Emissions from Sand Dunes

Because the primary mechanisms for dust emissions from dunes are all driven by saltation, variations in the rate of saltation are an important determinant of the rate of dust emissions. Typically, there is a minimum wind speed below which saltation does not occur, and above which the rate of saltation increases with the wind speed. As the rate of saltation increases, so too does the rate of dust emissions. Emissivity describes the relation between wind speed and dust emissions – for a given wind speed it defines how much dust is emitted for a given surface.

Based on the physics of the dust emissions process, a variety of factors determine the emissivity. These factors can vary in space and time due to variations in underlying geological conditions and climatic patterns, short-term meteorological variation, and the naturally dynamic and evolving nature of sand dune evolution. Some key factors that affect saltation and resulting dust emissivity include the following:

1. **Particle size distribution and composition.** The surface composition of sand and gravel particles governs the minimum wind speed required for saltation and then the rate at which saltation occurs relative to wind speed above this threshold value. Surfaces covered with coarser particles tend to require higher wind speeds for saltation to occur. In addition, the composition of fine particles (either as loose dust or as clay coatings adhered to sand grains) will affect the rate of dust emission resulting from saltation. Mineral

hardness may also modulate dust emissivity when sand is composed of very soft minerals that are subject to abrasion (e.g., Jerolmack et al., 2011); however, as noted above, sand grain abrasion does not appear to contribute substantially to dust emissions at the ODSVRA, which is related to the predominance of hard minerals – quartz and feldspar – in the dunes at this location (Swet et al., 2019, 2020).

2. **Soil moisture.** Enhancement of soil moisture on the dune surface, resulting from rainfall, condensation, or groundwater and pore water fluxes to the surface, either as liquid or vapor, also strongly affects dune surface susceptibility to saltation and dust emission. There is typically a strong diurnal signal in surface moisture driven by solar heating during the day and longwave cooling at night which increases cohesion of particles on the dune surface and decreases their propensity for saltation and resulting dust emission (McKenna-Neuman, Nickling, 1989).
3. **Roughness and surface exposure.** On bare flat sand, the dune surface is directly exposed to the wind, such that wind of sufficient strength will initiate saltation and resulting dust emissions. Roughening of the dune surface alters the near-surface shear stress distribution and thus decreases the propensity for saltation and dust emission. The effect of roughness on reducing saltation and dust emissions tends to increase with the size and proximity of roughness elements, which affects the local surface exposure. Small elements like sand ripples will have a small and localized effect, whereas vegetation will tend to have a larger and longer-range effect. Efforts to install dust control treatments (fences, straw treatments, native vegetation) are based on these principles (e.g., Webb et al., 2014) (see Chapter II.3 for further discussion).

II.2.2.6 Human Impacts on Dust Emissions from Sand Dunes

Human impacts on dust emissions from sand dunes result primarily when human activities, including land-use changes and vehicular activity, cause changes to dunes that alter the factors described in the previous chapter as controlling dust emissivity. Such human impacts on dust emissivity may accumulate over time, and the resulting changes in emissivity may persist even after human impacts have ceased. Direct mechanical disturbance of the dune surface, such as from spinning vehicle tires, may also cause short-lived and localized dust emissions from sand dunes, though such short-term mechanical effects on emissivity appear to be small relative to the long-term effects of human impacts on altering dune surfaces. These various human impacts and their effects on dust emissivity are described here. Note that this chapter does not address the effects of dust mitigation techniques; these are treated separately in Chapter II.3 of this report, “Dust Controls.”

II.2.2.6.1 Global Human Impacts

Global climate and ecological change may modify the factors that underlie the overall configuration of coastal dune systems. These include ocean circulation and wave patterns that deposit or erode sand from the beach, changes in the hydro-climatic regime that affect soil moisture and plant survival, and long-term ecological changes that affect plant diversity. For example, studies have shown an overall increase in vegetative cover on coastal dunes in the past century (Jackson et al., 2019), and climate models predict a general increase in strong wind events in the coming decades (Sydeman et al., 2014). However, given the difficulty of assessing these global impacts in a local planning context, we do not consider them further in this report.

II.2.2.6.2 Human Impacts Through Local Coastal Management

Local coastal management decisions can affect all the factors that influence saltation and dust emissions from sand dunes. Direct land-use modifications such as wholesale removal of dunes for real estate development or purposeful introduction of invasive plant species to stabilize dunes may locally eliminate emissive dune surfaces and thus reduce dust emissions. (Of course, such extreme changes may also cause profound negative impacts on dune ecology and coastal resilience.) Other coastal management decisions can have indirect effects on the factors controlling emissivity. Changes in local water use patterns can affect hydrologic flows that influence soil moisture and dune plant survival. Construction of coastal structures (e.g., groynes, jetties) can influence sediment budgets that affect particle size and composition of dune surfaces. Introduction of non-native dune vegetation can modify dune ecology, with effects on roughness and exposure of dune surfaces. Changes to any of these factors (i.e., soil moisture, particle size and composition, plant cover and roughness) will affect dust emissivity as will be described in the Chapter II.3.

II.2.2.6.3 Human Impacts Through Vehicular Disturbance and Other Intensive Uses

In the absence of human disturbance, natural forces will shape coastal sand sheets into sand dunes exhibiting characteristic patterns of dune geomorphology, vegetation cover, and rippled sand surface with particle size distribution and composition patterns that reflect the local geological and meteorological conditions (see discussion of dune formation in Chapter II.5). Intensive human use of coastal dune areas, including vehicle activity and camping, may disrupt the naturally occurring features of coastal dunes. For example, the mechanical action of vehicle tires can turn over the surface layer of dunes, potentially increasing saltation and dust emissivity by bringing fine particles to the surface (i.e., changing particle size distribution) or breaking up the surfaces themselves. In addition, intensive use can inhibit the growth of new vegetation or even destroy existing vegetation. All these factors will lead to changes in the factors that govern dust emissivity from dunes. For example, a recent study at the Algodones Dunes in Southern California demonstrated a direct association between increasing vehicle activity and reduced vegetation cover and increased soil exposure (Cheung et al., 2021).

In addition to modifying the long-term emissivity of dune surfaces, the mechanical action of vehicle tires on the dune surface may also produce dust plumes. However, such vehicle-driven dust emissions are primarily associated with traffic on unpaved roads that are conducive to dust emission by direct mechanical action of vehicle tires (e.g., Gillies et al., 2005). In contrast, dust emissions from sand dunes are observed to occur regardless of whether active vehicular traffic is present, suggesting that the effect of vehicular activity is via long-term changes to the surface that influence dust emissivity.

II.2.2.7 Measuring Dust Emissions and Emissivity

Direct measurements of active dust emissions are extremely difficult because of the variable nature of such emissions over a wide area. Monitoring of airborne dust concentrations at downwind receptor sites is useful for relative comparisons through time, but monitoring results are less useful for discerning absolute rates of dust emissions from specific sources. This is because of the way in which dust is lofted and dispersed by turbulent winds after it is emitted from the ground surface.

Because of the limitations of direct measurements, dust emissions and emissivity are typically determined indirectly through a combination of measurements of surface properties and emissions-dispersion modeling. Here, some of the measurements that inform dust emissions modeling are described. These include measurement of surface properties that modulate emissions (i.e., the factors described in Sec. II.2.2.5 above), as well as experimental measurements of dust emissions under controlled conditions. Details on the modeling itself are presented in the “Modeling” chapter of this report (Sec. II.6).

II.2.2.7.1 Measurements of Surface Properties That Modulate Emissions

Chapter II.6 will describe several factors that modulate dust emissions. Here, examples of possible methods for determining these properties are briefly described.

II.2.2.7.1.1 Particle Size Distribution, Composition, and Moisture Content

Particle properties are typically determined by scooping samples from the top layer of the dune surface of interest and then performing laboratory analyses of collected particles for particle size distribution (PSD) and other properties (DRI, 2015, PSD Addendum). To determine moisture content, samples may be weighed, placed in an oven, and then weighed again. Then, the samples are sieved to determine gravel content (particles >2 mm). The remaining smaller particles may then be mixed with a dilute surfactant to break up aggregates, and then filtered through a sieve aided by the application of water (i.e., wet sieving) to separate sand (particles >63 µm diameter) and silt/dust (particles ≤63 µm diameter). The sand component is then dried again and sorted through a series of sieves to determine its size distribution. The silt/dust component is typically analyzed using a laser particle sizing instrument, such as the Malvern Mastersizer, which uses laser diffraction to determine the size distribution of these smaller particles. Additional analyses such as x-ray fluorescence (XRF), x-ray diffraction (XRD), and scanning electron microscopy can be used to determine the elemental composition and mineralogical components of constituent particles (e.g., Swet et al., 2019). Though such methods are useful for characterizing particle properties when deployed consistently, there are limitations to methods for collecting and analyzing dune sediments. These limitations include uncertainties associated with specific sampling procedures and alteration of particle properties when preparing samples for wet sieving. Such limitations should be considered when evaluating the results of particle size analyses.

Through collection and analysis of many surface samples across the dune surface of interest, these particle size and compositional analyses can be used to provide meaningful information about surface properties that control dust emissions, including median surface sand particle diameter (D_{50}) and percentage content of PM_{10} dust. D_{50} provides a key proxy for determining the relationship between wind speed and sand saltation, by setting the threshold (minimum) wind speed for saltation and then the relationship between the rate of saltation and wind speed above this threshold value (Kok et al., 2012). This threshold is modified by the moisture content of the sand and the percentage of gravel cover, both of which can inhibit saltation and dust emissions. Percentage content of PM_{10} dust provides a rough proxy for the rate at which dust will be emitted for a given rate of saltation (Swet et al., 2019). Thus, spatial variation in sand D_{50}, dust content, gravel cover, and soil moisture across the dune field could provide a general sense of the variability in the potential for dust emissions. It is important to note that the dune field is a dynamic environment; thus, any set of these particle measurements provides only one snapshot in time; surface soil moisture is subject to especially rapid variation within the span of a single day (Scheidt et al., 2010).

II.2.2.7.1.2 Roughness, Surface Exposure, and Sediment Movement

Roughness and surface exposure factors controlling dust emissions are typically determined through broader scale surveys of dune surfaces. One effective method to broadly map the high-resolution topography of dune surfaces, which has been used at the ODSVRA, is deployment of Unmanned Aerial Systems or UAS (UCSB and Arizona State University, 2021). While flying over the survey area of interest, the UAS captures a series of high-resolution digital aerial photographs, including multispectral imagery that can detect plant cover, which are referenced to ground control points. By stitching together and processing these UAS photos, it is possible to produce georeferenced high-resolution topographic maps of the dune surface, known as digital elevation models (DEMs). Such survey data have also been generated at the ODSVRA through the use of LiDAR (Light Detection and Ranging) collected via manned aerial flyovers, but collection of such data is significantly more expensive than use of UAS, and it is only cost-effective if the survey area is very large. Imagery collected via UAS can also be used to capture maps of vegetation cover and other features that limit surface exposure and associated dust emissions.

The effects of roughness and surface exposure are also manifest through variations in sand movement via saltation. These variations in sand movement can be determined by multiple methods. Movement of sand over short periods of time (seconds to days) can be determined through installation of traps or sensors near the ground surface. Traps such as BSNEs ("Big Spring Number Eight") (Fryrear, 1986) are deployed for a finite time interval, and then the sand accumulating in the trap is collected and weighed (e.g., Goossens and Offer, 2000). Such traps are a reliable but labor-intensive way to measure sand movement, and their use is well-established at the ODSVRA. A common use of the BSNEs is to measure spatial variations in sand movement across dust mitigation treatment areas, such as wind fences, straw bales, and revegetation. The "normalized sand flux" (NSF) is a measure of the reduction in sand flux within treatment areas compared to exposed dune surfaces, and it therefore provides an indication of how changes to the surface reduce sand movement and associated dust emissions. (Specific results of such NSF studies are explored in further detail in the chapter on "Dust Controls," Sec. II.3.) Short-term sand movement can also be detected by using automated detectors – commonly used sensors include the Sensit, Wenglor, and SANTRI. Though such detectors offer enhanced convenience, they may be less reliable and require calibration to relate the signal of saltation they acquire (e.g., particle counts) with saltation mass flux (kg m^{-1} s^{-1}) and are thus more complicated to interpret (Martin et al., 2019).

Long-term sediment movement can be determined through comparison of repeat UAS surveys. Differences between DEMs over time reflect areas of net erosion (loss of sand) or deposition (increase of sand). Spatial patterns of erosion and deposition reflect waves of sand moving through the system. Such long-term measures of sand movement can provide an indicator of dust emissions hot spots. As described in the chapter on Restoration of Coastal Foredunes (Chapter. II.5), these measures also provide an indicator of overall dune field evolution, including in response to specific management actions.

II.2.2.7.1.3 PI-SWERL

The Portable In-Situ Wind Erosion Laboratory (PI-SWERL®) is an instrument designed to directly measure emissivity of a surface susceptible to wind-driven dust emissions at various wind speeds (Etyemezian et al., 2007). Deployment of the PI-SWERL over a broad spatial grid can be used to generate a map of dust emissivity. Because of its portability and worldwide adoption as an instrument to measure emissivity, the PI-SWERL has been used extensively at the ODSVRA.

The PI-SWERL works by generating a range of wind speeds (or more precisely, wind shear stresses) within a confined chamber placed upon the dune surface. The PI-SWERL is placed on the ground, and a circular blade within the PI-SWERL (and above the ground surface) is rotated at a defined rate per minute (RPM). Sensors within the PI-SWERL detect both the rate of saltation and the concentration of PM_{10} dust. The blade speed is then increased in multiple steps, and the associated saltation flux and PM_{10} dust concentration are measured at each RPM. From these measurements, an equation is fitted to the data, which describes the relation between wind speed, sand flux, and PM_{10} emissions. The associated relation is described as the PM_{10} emissivity (mg m^{-2} s^{-1}). When such measurements are collected over a wide area, a spatial map of variation in PM_{10} emissivity may be generated. As described in Chapter II.6, "Modeling," such PM_{10} emissivity maps can be used to model dust emissions under various wind scenarios. Based on the dynamic nature of the dune system, which can cause significant variations in PM_{10} emissions through time, PI-SWERL surveys need to be repeated periodically.

One thing to note about the PI-SWERL is that it is only effective when used on relatively flat dune surfaces that lack vegetation or other significant roughness elements. Determinations of PM_{10} emissions within roughened areas need to be obtained through alternative methods, such as the measures of roughness, surface exposure, and sediment movement (described in Sec. II.2.2.7.1.2 above), and computational fluid dynamic (CFD) modeling (e.g., Furtak-Cole et al., 2022).

II.2.3 Description of the Problem at the ODSVRA

Discussion will be provided in the next sections relevant to scientific knowledge about the processes of sand saltation and PM_{10} emissions in general, as well as the most used tools to measure such processes. Here, we turn our attention to what such measurements have shown about dust emissions at the ODSVRA and how this informs our understanding of the associated PM_{10} emissions control program at this location.

II.2.3.1 Meteorological Setting at the ODSVRA

Long-term meteorological monitoring within the ODSVRA indicates that the wind climate is dominated by WNW prevailing onshore winds, with wind speeds tending to increase from north to south and from west to east (DRI, 2014, ODSVRA Wind and PM_{10}; see also Appendix II.2 of this chapter for further information on this DRI study). These winds are driven by the local sea breeze effect caused by the gradient between cold ocean waters and the warm land surface. Thus, the strongest winds typically occur during spring and early summer afternoons when the temperature gradient is largest. Occasional deviations from this common wind pattern may be caused by coastal storms or offshore wind events; however, neither of these circumstances should be associated with significant dust emissions events, either because the ground is too moist (in the case of coastal storms) or because the wind is blowing in the wrong direction (in the case of offshore wind events).

II.2.3.2 Saltation and Dust Emissions at the ODSVRA

II.2.3.2.1 Studies of Surface Properties and Vegetation Cover

As described in the preceding sections and in subsequent chapters (i.e., II.3 “Dust Controls" and II.4 “Vegetation Restoration”), variations in surface properties and vegetation cover are well known to determine the rates of sand movement and associated dust emissions. We present here some pertinent studies of surface properties and vegetation cover that have informed air quality analyses at the ODSVRA.

A comprehensive review of ODSVRA vegetation islands and their associated surface characteristics was prepared in 2007 by the California Geological Survey (CGS) (CGS, 2007), with the intent to inform continuing management of these areas. Appendix B of the CGS report describes analyses of sand samples collected within and near vegetation islands, showing that the vast majority of particles collected fall within the fine-sand size range (150 to 425 microns) with silt/clay fractions ranging up to 4.7%, with a mean of 0.7%, indicating the effectiveness of such islands for trapping fine particles. Appendix C of the CGS report describes the history of the ODSVRA and associated changes in vegetation cover through time as a result of management decisions. Appendix D of the CGS report provides detailed descriptions of individual vegetation islands, including historical change as inferred from historical aerial photos, current morphological characteristics, and the presence of native and non-native vegetation. Geologic and soil characteristics were also summarized in Chapter II.1 of this document.

A more recent study conducted by University of California, Santa Barbara (Swet et al., 2022) has analyzed vegetation cover in the ODSVRA using aerial photos dating back to 1939. This report concluded that between 1939 and 1985 there was a general decline in plant cover in the foredune and back dune zones of the vehicle riding area (from 11% to 4%) while vegetation in the broader ODSVRA increased from 1939-1966, then declined to 1985. In the riding area, overall change was identified as a 10% decrease in plant cover (mostly in areas closer to the beach) with only 2% positive gain (mostly in areas farther from the beach). After 1985, vegetation coverage increased in areas where targeted restoration was conducted. Based on their analyses, Swet et al. (2022) suggest specific actions to maintain vegetation cover, including opportunities to merge vegetation islands to increase their stability.

Over the years, other studies have been conducted to understand the surface characteristics of the Oceano Dunes that affect sand saltation and PM_{10} emissions at the ODSVRA. CGS led studies in which particles were sampled from dune surfaces and analyzed for particle size distribution (PSD) and mineralogical composition (CGS, 2011, PSD 1 and 2; CGS, 2015, PSD; CGS, 2016, PSD 1 and 2). The Desert Research Institute (DRI) also performed a comprehensive analysis of particle size characteristics across the ODSVRA (DRI, 2015, PSD Addendum). The key findings of these studies are that the majority of particles on dune surfaces are in the fine to medium sand range (diameter = 150-500 microns), with a small but significant fraction of surface particles composed of PM_{10} dust. Mineralogically, surface particles are dominated by quartz, plagioclase, and K-feldspar minerals. These analyses support the conclusion that the generally fine to medium grained sands would be available to be mobilized by wind, generating windborne dust from saltation that dislodges the fine dust particles found in the surface sediments. In addition, these studies have shown that grain size generally increases from north to south within the ODSVRA. Appendix II.2.B of this chapter provides more detailed summaries of some of the individual surface particle analysis reports referenced here.

Further description of potential vegetation restoration measures is provided in the chapter on “Vegetation Restoration” (Chapter II.4) and in “Coastal Foredune Restoration” (Chapter II.5).

II.2.3.2.2 PI-SWERL Studies

Multiple PI-SWERL campaigns have been conducted over the years to characterize the erodibility and emissivity of ODSVRA surfaces. In 2013, a comprehensive set of PI-SWERL measurements were obtained across the ODSVRA (DRI, 2015, ODSVRA Erodibility). This campaign showed significant variability in PM_{10} emissivity across the ODSVRA, with the highest emissivity generally corresponding to the areas with the most intensive vehicle usage. Another comprehensive PI-SWERL campaign was conducted in 2019 (See Sec. 2.3.4., CDPR, 2019, ARWP). As reported in Annual Report and Work Plans (ARWPs), localized PI-SWERL campaigns have also been conducted during intervening years. These PI-SWERL campaigns provide updated information about PM_{10} emissivity patterns across the ODSVRA, which may result both from natural evolution and from changes in vehicle usage patterns.

II.2.3.2.3 Studies of Saltation and Dust Emissions at the ODSVRA

DRI operated three instrumented towers along each of four transects oriented in the direction of the prevailing high winds, 292° (true North), in a monitoring campaign running from May through September 2013 (DRI, 2014, see also Appendix II.2.A below). Sand saltation was found to commence at a minimum hourly average wind speed of 3.6 m s^{-1} at 3 m above the ground surface and 3.8 m s^{-1} at 10 m above the ground surface. Mean hourly wind speeds at which saltation commenced rose slightly from north to south, due to the increase in sand particle size and surface roughness from north to south. Saltation mass flux was found to increase from west to east as a result of increased wind speed in this direction. This information contributes to understanding the differences seen in dust measurements taken at different points downwind of the ODSVRA.

Section II.2.2 above describes studies on the generalized processes of saltation and dust emissions. Several of these studies were conducted within the Oso Flaco section of the ODSVRA, so this site-specific context is also useful when considering natural dust emission processes at the ODSVRA within undisturbed parts of the park. (Studies examining the specific mechanisms of dust emissions within disturbed parts of the ODSVRA have not yet been conducted and are an important topic for future work in order to understand what emissions are attributable to vehicle activity as opposed to those from other sources.)

Two studies have looked specifically at saltation dynamics at Oso Flaco (Martin and Kok, 2017, 2019), a portion of the ODSVRA that has been undisturbed by vehicle activity since 1982. These studies confirm the prevailing understanding that saltation flux increases linearly with the shear stress (or as a square of the shear velocity) above a minimum “threshold” value for the onset of saltation. They also support the understanding that this threshold wind speed for saltation can be determined based on the overall characteristics of a given dune surface, such as the median particle diameter. These modulating characteristics are described in further detail in Sec. II.2.2.7.1.1 above.

Three studies have looked at mechanisms for PM_{10} emission at Oso Flaco. Huang et al. (2019) examined *in situ* dust emissions and demonstrated that vertical PM_{10} dust flux increases as a power function of wind shear velocity and in tandem with increasing saltation flux. However, in comparison to other dust emitting sites, the rate of dust emissions for this undisturbed section of the ODSVRA is small relative to other sandy sites that lack dune configurations. Furthermore, the sizes of emitted dust particles at ODSVRA are smaller than at other sites, with a median size (aerodynamic diameter) of about 0.3 microns. Swet et al. (2019, 2020) utilized sand from the Oso Flaco site in controlled wind tunnel experiments. In addition to finding that that loose particle emission and clay coating removal are the most common sources of dust emissions for natural sand at the ODSVRA (see Sec. II.2.2.4 above), they also performed x-ray powder diffraction (XRPD) and scanning electron microscope (SEM) measurements to look at the composition of sand grains and mineral coatings. XRPD analyses show that sand grains are about ½ quartz and ½ feldspar (with roughly equal proportions of K-feldspar and plagioclase feldspar). SEM images show that coatings contain a mixture of clays, feldspar, and quartz particles in comparable quantities.

II.2.4 How the Science is Being Applied to the Problem

The above sections have described how saltation is a primary driver of airborne PM_{10} at the ODSVRA, and how PM_{10} emissivity, i.e., the relation between wind and PM_{10} emissions, is governed by various measurable characteristics of dune surfaces. Here, we describe some specific studies examining how intensive vehicle activity and other human disturbances at the ODSVRA have enhanced PM_{10} emissivity and thus worsened PM_{10} air quality at the ODSVRA, and, conversely, how management actions to mitigate dust emissions have reduced PM_{10} emissions and improved air quality. Later chapters of this report will provide more specific descriptions of these dust control measures (Chapter II.3) and their resulting effects on PM_{10} air quality (Chapter. II.7).

There are two types of measurements that have shown how human disturbance (i.e., by vehicles) modifies PM_{10} emissions at the ODSVRA. In the first type, long-term changes in the PM_{10} emissivity of dune surfaces, as measured by the PI-SWERL, are compared to changes in human impacts over time. In the second type, changes in PM_{10} concentrations at downwind receptor sites are compared to management changes.

The temporary closure of the ODSVRA to vehicle activity because of COVID-19 during the summer of 2020 afforded an opportunity to look at temporary changes in both PM_{10} emissivity and concentrations, thus providing two independent lines of evidence to examine the effects of vehicles on emissivity (Gillies et al., 2022). The first line of evidence (PM_{10} emissivity) used PI-SWERL analyses conducted several months after the closure that showed a noticeable reduction in PM_{10} emissivity relative to before the closure. The second line of evidence (PM_{10} concentration) used analyses that compared total PM_{10} to total "wind power density (WPD, W m^{-2})" using a ratio or normalized quantity (TPM_{10}:TWPD) as a proxy for PM_{10} emissions that accounts for variations in wind speed. These data showed a distinctive reduction in the TPM_{10}:TWPD ratio through the summer of 2020, indicating that the removal of vehicles led to a substantial decline in airborne PM_{10} for the same WPD conditions. These findings contrasted with the SAG's original expectation that observable reductions in PM_{10} emissivity may take several years to materialize (SAG, 2020, ODSVRA Closure), indicating that dune surfaces experience much more dynamic change than previously anticipated. CGS also prepared a study of the effect of the 2020 closure, arguing that despite slower-than-usual winds and the absence of vehicle activity, downwind PM_{10} concentrations were greater than usual (CGS, 2020, Wind and PM Exceedances; see also Appendix II.2.A below). However, the SAG disputed the findings of this CGS study, noting that the way in which this study defined wind events was highly unusual (SAG, 2020, CGS Response).

Examination of long-term changes in the TPM_{10}:TWPD ratio over time also provides an indicator of the effectiveness of dust mitigation treatments toward reducing airborne PM_{10}, providing further indirect evidence for the role of vehicles and the effectiveness of dust mitigation treatments to counteract their effects. An analysis published by DRI (DRI, 2021, Increments of Progress) showed that there has been a reduction in the TPM_{10}:TWPD ratio over time as an increasing number of dust mitigation treatments have been installed, suggesting an overall reduction in PM_{10} emissions. This study complements related modeling and air quality indicators published in SOA-required Annual Reports and Work Plans (ARWPs) and SLOAPCD reports. For example, SLOAPCD Annual Air Quality Reports since 2017 have reported "difference-in-differences" analyses comparing the ratio of PM_{10} concentrations at the CDF monitoring site (subject to vehicular impacts) to PM_{10} concentrations at the Oso Flaco site (undisturbed). Similar to the TPM_{10}:TWPD analyses, SLOAPCD difference-in-differences analyses provide further evidence for air quality improvements resulting from dust mitigation efforts (SLOAPCD, 2022).

Despite this strong evidence for the role of vehicles in enhancing PM_{10} emissions and concentrations at the ODSVRA, and the effects of dust mitigation treatments toward reducing such emissions, the specific mechanisms by which vehicle activity causes such an enhancement in PM_{10} emissions remain poorly understood and should be the subject of future study in order to understand what emissions are attributable to vehicle activity as opposed to those from other sources.

II.2.5 Summation

This chapter has provided a summary of what we know in general about the emissions of PM_{10} from sand dunes and what we know in particular about the factors governing PM_{10} emissions at the ODSVRA. PM_{10} emissions are caused by wind-driven saltation, the impacts of which emit dust particles from the dune surface and release clay coatings from sand grains. Increasing wind speed is associated with increasing PM_{10} emissions, and such emissions are enhanced by the action of vehicles on the dunes. However, the specific mechanisms producing the vehicle-driven enhancement in PM_{10} emissions remain poorly understood and should be the subject of future study to inform determinations of how much of the measured emissions are attributable to vehicular activity.

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Appendix II.2.A Reports on ODSVRA Wind Climate and Dust Characteristics

Summaries are provided in the order in which they are first cited within Chapter II.2 above. The citation format is provided in parentheses in the header for each summary below.

Wind and PM_{10} Characteristics at the ODSVRA from the 2013 Assessment Monitoring Network, Prepared for the California State Park by the Desert Research Institute, 2014 *(DRI, 2014)*

In this study, the Desert Research Institute (DRI) operated three instrumented towers along each of four transects oriented in the direction of the prevailing high winds, 292° (true north). Each tower was outfitted with anemometers to measure wind speed and direction, Sensit piezoelectric sensors to measure saltation activity, and MetOne Aerosol Particle Profilers to measure particle number concentrations. On one or two positions on each transect, Environmental Beta Attenuation Monitors (E-BAMs) were operated to measure PM_{10} concentrations. This monitoring campaign ran from May through September 2013, but only data collected between May and July by the anemometers and Sensits are included in this report. The northernmost transect was located in the dune preserve area, the two middle transects were located within the riding area at the ODSVRA, and the southernmost transect was located south of Oso Flaco Lake. Each tower hosted an anemometer at a height of 3 meters, and an additional anemometer at a height of 10 m was included on the third tower in the three northern transects and the second tower in the southernmost transect viewed from west to east.

Wind speeds were found to increase from north to south and from west to east. Wind roses from each of the four transects were found to be very similar with respect to prevailing wind direction and frequency of directional bins. Sand saltation was found to commence at a minimum hourly average wind speed of 3.6 m s^{-1} at 3 m above the ground surface and 3.8 m s^{-1} at 10 m above the ground surface. Mean hourly wind speeds at which saltation commenced rose slightly from north to south, due to the increase in sand particle size and surface roughness from north to south. Saltation mass flux was found to increase from west to east as a result of increased wind speeds over the same area. When data were filtered to include only hours in which E-BAMs measured PM_{10} concentrations greater than 50 µg m^{-3} and when saltation was active, the resulting wind roses were reduced to only winds from the 22.5° arc centered on 292°. A comparison of saltation flux to wind speed indicated a power relationship with an intercept at the threshold wind speed.

An Analysis: May and June Wind Strength Year to Year and State PM_{10} Exceedances With and Without OHV Recreation, Oceano Dunes SVRA, 2020 *(CGS, 2020, Wind PM Exceedances)*

This analysis compared average wind speeds recorded at the CFD monitoring station in May and June of each year from 2013 through 2020 with the numbers of exceedances of the State PM_{10} ambient air quality standard also recorded at the CDF monitoring station. Hourly wind speeds in this analysis were filtered for those above 8.05 kilometers per hour (5 miles per hour), coming from the northwest quadrant, and recorded between 11:00 am and 7:00 pm in the months of May and June. The conclusions of this analysis were that average wind speeds in May 2020 were the third lowest of the years evaluated while the numbers of exceedances of the State standard were the third highest. Because the ODSVRA was closed to vehicle activity in May and June 2020, these conclusions questioned the relationship between vehicle activity and PM_{10} air quality at the CDF monitoring station.

The SAG disputed the findings of this CGS study, noting that the way in which this study defined wind events was highly unusual, leading to potentially erroneous conclusions (SAG, 2020, CGS Response). Specifically, the approach to wind speed averaging fails to account for the nonlinear growth in dust emissions with wind speed. DRI analyses using the more standard metric of "wind power density (WPD)," which account for the nonlinear relationship between dust emissions and wind speed, show in fact that 2020 had a greater potential for high PM10 concentrations than suggested by the CGS study (DRI, 2021, Increments of Progress).

Appendix II.2.B Reports on ODSVRA Surface Particle Analyses

Summaries are provided in the order in which they are first cited within Chapter II.2 above. The citation format is provided in parentheses in the header for each summary below.

Part 1, Comparison of Sieved Sand Samples with NRCS Soils Data, California Geological Survey, 2011 *(CGS, 2011, PSD 1)*

In an effort to better understand the size distribution and variability of ODSVRA sand particles, sixty sand samples from within the ODSVRA and other lands managed by the California Department of Parks and Recreation (CDPR) were analyzed. Sand within the ODSVRA was found to be composed almost exclusively of fine (150 – 425 microns, as defined in the paper) and medium (425 – 2,000 microns) grain diameter, with fine sand comprising 70% or more by mass in 48 of the samples. Silt and clay fractions in these samples were typically less than 1%. One deviation from this latter finding was that the silt/clay component was higher (0.0 to 4.7%) on the northern and eastern sides of vegetation islands than on the western sides (0.0 to 1.0%). The sand, silt, and clay values within the ODSVRA corresponded well with the Natural Resources Conservation Service (NRCS) ranges for Beaches and Dune Land soil classes.

Oceano Dunes SVRA – Sand Grain Size Analyses, Part 2, Microprobe Analyses of Grain Size and Mineral Composition, California Geological Survey, 2011 *(CGS, 2011, PSD 2)*

This study expanded upon the Part 1 research by sieve sizing and microscopic examination of the fractions of sand samples smaller than 45-micron diameter that were collected in a transect across the seasonal western Snowy Plover exclosure area. Of nine samples collected in a downwind transect, two were from the beach area to the west, three were from within the exclosure area, and four were from a riding area to the east of the exclosure area. Two samples of very fine material collected on the western and eastern fences of the exclosure area were also sized and examined. Two additional sand samples were collected from Pismo Beach and from the Dune Preserve. Less than 0.1% of particles found in sand samples were less than 45 microns in diameter. In contrast, >96% of the particle mass in the fence samples were smaller than 10 microns. Samples from within the exclosure area contained greater fractions of PM_{10} and $PM_{2.5}$ within the 45-micron sieve samples, with beach samples exhibiting greater fractions than samples collected from the riding area. The eastern fence sample contained greater fractions of PM_{10} and $PM_{2.5}$ (67% and 66% by mass) than the western fence sample (53% and 51%). Of significance, the western fence sample contained a high fraction of ultrafine (<1 micron) particles that were absent in the eastern fence sample.

All unsieved samples consisted of 75% to 87% quartz and feldspar with feldspar slightly predominant. Within the <10-micron portion of the <45-micron fraction clay particles constituted 3%. The clay fractions were higher in the beach samples than in the exclosure and riding area samples. Quartz and feldspar constituted 69% to 71% of the fence samples, and the clay fraction was 2%.

Results of Sieve Analysis of Dune Sand Collected at Oceano Dunes SVRA and Vicinity, California Geological Survey, 2015 *(CGS, 2015)*

The purpose of this study was to determine if there were seasonal and locational variations in sand grain sizes at the ODSVRA. Sand samples were collected twice at 32 locations within the ODSVRA riding and Dune Preserve areas, once on January 23, 2014, and again on June 18, 2014. All samples were collected on the windward side of sand dunes to maintain geomorphic consistency. (However, collecting samples only on one side of the dune rather than along a transect may introduce a systematic bias, which should be considered when interpreting these results.) Each sample was dry sieved down to a 200 mesh (75 micron) screen. The sieve data showed very little seasonal variation for most of the collection sites. A definite trend in increasing grain size, however, was seen from north to south that appeared to correspond with increasing wind speeds from north to south as reported by the Desert Research Institute (DRI). The standard deviation of grain size was also found to increase from north to south. No differences in particle curvature – an indication of abrasion – were found across the collection sites. None of the sand samples contained clay plus silt contents greater than one percent.

II.3 Dust Controls

II.3.1 Generalized Understanding of Dust Controls

Dust controls are used to reduce the amount of particulate matter (PM) emitted from identified source areas. These areas may emit dust due to wind erosion processes or due to activities (mechanically induced) that loft the PM into the air where it can be transported by wind. Dust controls are required when it can be demonstrated that the contributions of PM from localized sources create conditions identified as being a nuisance or as contributing to a degradation of air quality that results in the exceedance of Federal or State standards. The Federal standard for a 24-hour mean concentration of PM_{10} is 150 µg m^{-3}; the State of California 24-hour mean concentration standard is 50 µg m^{-3} (CARB website https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health).

Dust suppression requires that the surface emitting PM be modified in some manner to lower the amount of PM emitted during the dust-creating process. At the Oceano Dunes State Vehicular Recreation Area (ODSVRA), the predominant dust creating process is the saltation of the sand by wind that releases dust-sized particles (refer to Chapter II.2), and it has been established that vehicle activity augments dust emission during saltation (Gillies et al., 2022). Such enhancement does not require vehicle activity to be active at the specific time saltation occurs, because the processes related to the continual activity of vehicles enhance the underlying long-term emissivity of the dune sand.

Dust control methods span a range of principles of operation including:

1. physical modification of the potentially emitting surface,
2. placement of physical elements onto or around the emitting surface to disrupt the emission process,
3. covering the surface with a non-emissive and non-erodible layer,
4. binding the surface sediments with a topical application or adding an amendment to the sediment that enhances particle cohesion.

Of these types of dust controls, the ODSVRA currently uses methods 1, 2, and 3 most frequently.

II.3.2 Background on the Relevant Science

At the ODSVRA, Method 1 includes restricting vehicle activity and Method 2 involves straw bales, planting of vegetation, and sand fences. Method 3 covers the sand with a layer of straw mulch. Method 4 has been tried only on a small scale.

II.3.2.1 Method 1: Physical Modification of the Potentially Emitting Surface

By restricting vehicle activity, the surface of the dunes is allowed to return to its pre-disturbance state. Vehicle activity enhances emissivity as demonstrated by multiple studies (e.g., Wilshire and Nakata, 1976; Goossens and Buck, 2009a, 2009b, 2011; Gillies et al., 2022, Marston 2020), but the causal mechanisms remain unresolved. It has been hypothesized that, without the physical disruption of the surface by vehicle activity, small particles will be emitted from the surface during wind driven saltation, and the reservoir of erodible particles will be diminished via a winnowing process, leaving the coarse particles behind as a lag deposit. As a result of this process, saltation decreases, thus reducing the emissivity. Such a physical modification would allow the larger sand particles to remain, which are less readily moved by wind events (see Chapter II.2).

This strategy of restricting vehicle activity is used in a very limited fashion at the ODSVRA, and it is employed mostly to protect vegetation projects or existing vegetation islands. It has been proposed that fencing alone could be a low-cost dust control measure (SAG, 2022), but it would remove large areas from vehicle access that would otherwise be available to recreational vehicle users. The recent semi-permanent exclosure of plover nesting areas within the ODSVRA offers the opportunity to better understand the effectiveness of this approach in the future (CDPR, 2022, ARWP).

II.3.2.2 Method 2: Physical Elements or Surface Modifications Placed or Implemented to Disrupt the Emission Process

Roughening of a surface as a means to protect it from wind erosion has been an accepted practice for decades (Chepil, 1944), and this aligns with understanding of the factors that control dust emissions (see Chapter II.2, Dust Controls). The scientific underpinnings to explain how it works can be traced to the foundational research of Chepil (1945, 1950) based on his scientific studies to aid in reversing the Dust Bowl years in North America (Chepil, 1957). This early research was designed to understand and aid in the development of surface roughening using tillage implements to mitigate wind erosion and soil losses on agricultural land in the Great Plains of the U.S. The use of roughness to modulate wind erosion is based on a roughened surface having the enhanced ability, compared to a smooth surface, to absorb momentum from the wind and provide zones of shelter.

II.3.2.2.1 Non-erodible Roughness Elements

Non-erodible roughness elements, whether by virtue of their size (e.g., cobbles, bales of straw) or by virtue of their being anchored in the soil (e.g., vegetation), reduce sediment loss by wind in four ways:

1. Roughness elements shelter the surface by covering a portion of it.
2. The presence of a sufficient number of them will reduce the shear stress in the intervening area by extracting momentum from the wind at a height above the surface.
3. They provide, in the case of solid and porous elements, a zone of reduced shear stress in their lee; and in addition, porous elements such as vegetation can trap particles within their structure.
4. The presence of non-erodible elements can affect the number and efficiency of grain/bed collisions by saltating particles.

Field and wind tunnel measurements of sand transport through roughness that is on the order of a few centimeters (Al-Awadhi and Willetts, 1999) to tens of centimeters in height (e.g., Lancaster and Baas, 1998; Gillies et al., 2006) have revealed that the reduction in sand transport scales as a power function of the roughness density, which in turn is defined by a number of elements that protrude from the surface into the air (roughness elements), the width and height of those elements, and the area of the surface that contains all the elements. The equation for roughness density (Equation (1)) is in Appendix II.3.A. According to Yang, Shao (2005), roughness begins to suppress sand transport when roughness density $\lambda = 0.012$.

Gillies and Lancaster (2013) observed that sand flux across the transition from a smooth surface into a surface roughened by large, superposed roughness elements (straw bales), decreased rapidly (i.e., exponentially) with increasing distance into the roughness and the rate of change scales with λ (Gillies et al., 2006; NAS, 2020). Past the zone of rapid sand flux decrease, sand flux reaches a stable value that also scales as a function of λ (Gillies et al., 2015). Gillies, Lancaster (2013) and Gillies et al. (2015 and 2018) also observed that the height of the roughness element influences the effectiveness of the roughness element array to control sand transport. A general equation (Equation 2 in Appendix II.3.A), based on empirical studies, relates sand flux reduction in the interior of an array of roughness, as expressed by Normalized Sand Flux (NSF); it has been found to be applicable for roughness that has a height of approximately 0.30 m. Although the distribution pattern of the roughness can greatly affect the effectiveness of the roughness to control wind shear reduction on the intervening surface (Webb et al., 2014), Gillies et al. (2015) observed that as long as the distribution was relatively dispersed (i.e., by limiting the amount of close groupings), the difference in effectiveness of a well-ordered array of roughness compared with a distribution that mimicked the distribution of vegetation, in their case for vegetation at the Keeler Dunes, Keeler, CA, was not discernable.

This strategy of straw bales has been used in the ODSVRA, and it has been found to be successful. Straw bales are not considered a permanent dust control measure, and they are usually replaced after several years with vegetation.

II.3.2.2.2 Vegetative Controls

Vegetation on the surface, whether natural or planted, is a form of superposed roughness and operates physically in the same fashion as solid element roughness to modulate the wind and sediment transport. Vegetation differs from solid element roughness due to its porosity/permeability, which due to its higher coefficient of drag (C_D) (Gillies et al., 2000, 2002), enhances its ability to absorb momentum. Understanding or quantifying the effectiveness of vegetation is complicated by the range of plant morphologies, flexibilities, porosities, and the distributions across the landscape they develop in response to the environmental constraints on their growth. Finding a metric that relates plant characteristics and their distribution across space to their cumulative effect on sand transport by wind has been a rich area of research. Mayaud and Webb (2017) note that an explicit link remains to be made between the impact of vegetation on wind flow and the subsequent impact on sediment transport processes.

Early studies sought to relate vegetation effects on sand transport as a function of percent cover of the surface that was occupied by plants (looking from above). A theoretical study by Musick and Gillette (1990) suggests 16% cover should suppress wind erosion (i.e., sand transport and dust emissions). Although Wasson and Nanninga (1986) report sand transport on surfaces with percent cover as high as 45%, it is likely that this is due to a distribution of vegetation effect, as Gillette and Pitchford (2004) noted some areas with relatively high percent cover of vegetation can have, due to their distribution (street-like open corridors aligned in the prevailing wind direction), high sand transport rates.

Lancaster and Baas (1998) examined how salt grass on portions of Owens Lake, CA, affected sand transport using % cover as their metric to characterize the vegetation. They developed an empirical relationship between % cover and sand flux (Equation 3 in Appendix II.3.A). According to this empirical relation, a reduction of sand flux of 90% should be achieved by a salt grass percent cover of 12%. It must be noted, however, that the morphology of salt grass is very different from shrub-like vegetation, and this relation cannot be used for other plant types with confidence.

The percent cover metric fails to adequately account for the aerodynamic properties of plants and the effects of those properties on momentum absorption and sand movement, making it not generally applicable. Researchers have sought other means to more effectively measure the properties of plants and their distribution that relate to their effect on sand transport. To better understand how plant characteristics and their distribution affect sand transport by wind, researchers examined how well λ worked as a predictor of sand flux reduction for plants (e.g., Walter et al. 2012a, 2012b). The use of λ as a roughness descriptor links it to the theory of shear stress partitioning (Raupach 1992; Raupach et al., 1993). To fully apply the Raupach et al. (1993) shear stress partitioning model requires knowledge of the drag coefficients (C_D) of the plants in the distribution, which is usually not readily available.

Gillies et al. (2000, 2002) measured drag coefficients of several plants and noted that they generally do not have stable values (i.e., they change with wind speed as they become more aerodynamic), but when they reach a relatively stable value at high wind speed, they have stable drag coefficients higher than solid elements of similar form (i.e., size and shape), which makes them more effective in absorbing momentum. Walter et al. (2012a, 2012b) and Kang et al. (2018), observed in wind tunnel testing using live and artificial plants, respectively, that the Raupach et al. (1993) model could explain the shear stress partitioning relation for plants, but note that characteristics such as porosity and flexibility, and shape/size of vegetative roughness elements influences the stress partition and its dependency on λ.

Okin (2008) presents an alternative model to that of Raupach et al. (1993) for determining the effect of vegetation on sand transport and dust emissions. The Okin (2008) model assumes the sheltering effect of a plant interacting with the wind is determined as a function of distance from the vegetation (x) normalized by the vegetation height (h) and expressed as the scaled gap size (x/h). The gap, x, is the distance between roughness elements with respect to the direction the wind is passing over the roughness. In this framing, the protective effect of vegetation increases with increasing vegetation height and decreasing gap size. As in the shear stress partitioning approach, plant shape, porosity, and flexibility influence the protective effects of vegetation, but vegetation height and canopy gap size are the most important controls on the level of protection afforded by the plants.

Because of the important role of vegetation in dust mitigation, further information on the science of vegetation restoration is provided in Chapter II.4 of this report.

II.3.2.2.3 Sand Fences

Another wind erosion control method that is a form of roughness is fencing. Fencing is essentially a two-dimensional form of roughness that is deployed as a linear feature perpendicular to the wind direction that has the highest probability of causing erosion due to its magnitude and frequency of occurrence. Fencing material used for wind erosion control is always porous/permeable.

The effectiveness of a fence to reduce wind speed on the downwind side depends on the geometry of the fence design, with the elements of height, length, width, porosity, opening size/distribution/geometry, and orientation relative to the wind being most important (Li, Sherman, 2015). Fence porosity (e), the ratio of a fence's open area to its total area, is considered the most important single parameter controlling its performance and coefficient of drag (Ranga Raju et al., 1988) and is usually reported as a percentage of open area (Bean et al., 1975).

Sand fences are deployed to reduce wind speed over erodible surfaces, which should lower the probability of entrainment and reduce transport rates of sand in their lee. The degree of wind speed reduction in the stream-wise direction defines the shelter distance (d), which can be referenced to the distance downwind to reach a specified proportion of the undisturbed wind speed (e.g., 50% or 100% of the wind speed or shear stress required to achieve the threshold for transport). For fences that have holes to create porosity (as opposed to vertical slats) shelter distance is maximized for fence porosities, e, between e = 0.30-0.40 (Cornelis and Gabriels, 2005; Dong et al., 2006; Jensen, 1954; Bofah and Al-Hinai, 1986). Bitog et al. (2009) report from wind tunnel testing that e = 0.2 created the greatest decrease in wind speed from the surface to the height of the fence. For slat-type fences, Dong et al. (2011) found the maximum wind speed reduction occurred at e = 0.1.

A single row of fencing provides a very limited amount of protection from erosion on the downwind side. The length of the zone of shelter in the lee of a single fence was described by Bradley and Mulhearn (1983) in equation (4) in Appendix II.3.A. Using generalized wind and sand characteristics, for a 1.22 m (4 feet) high (h) sand fence the distance downwind of the fence where sand motion begins again will be at >15h (i.e., >18.3 m, >60 feet). This distance decreases as shear velocity increases. At the higher regional values of shear velocity, sand motion would begin at >1.7h (i.e., >1.42 m, >4.7 feet) past the fence.

Gillies et al. (2017) evaluated the effectiveness of porous plastic mesh sand fences to reduce sand transport at the ODSVRA for two spacings (10h and 7h, where h = fence height) and reported that sand flux through the arrays diminished exponentially with increasing parallel rows of fencing.

Sand fences can be designed to control wind erosion and dust emissions when placed directly on the surface that needs control and can also be used to protect stockpiles of wind erodible material. Wind fencing is not an effective means to remove PM_{10} or smaller particles that are already suspended in the air that encounter a single fence or an array of fences as the wind transports particles. The efficiency to remove particles is low and the height over which the particles interact with the fence is likely only a small fraction of the height above the surface that contains the particles. An array of fences will be more effective than a single line at reducing PM_{10} in suspension as the slowing of the wind will enhance particle deposition as the wind travels over the array, but this will be a small fraction of the total burden of PM_{10} in the air flow. The inefficiency to remove PM_{10} by a single line of fencing is the main reason that the WeatherSolve fence cannot, as proposed (WeatherSolve Structures, 2019), provide an effective means to reduce PM_{10} that originates in the ODSVRA and would encounter this fence on the eastern boundary of the ODSVRA. A more detailed assessment of the WeatherSolve fence's failure to work as suggested in the company's proposal is provided by the SAG (2020). Fences downwind of windblown dust sources do not reduce or catch emissions; this is another reason that the WeatherSolve proposal would be ineffective.

II.3.2.3 Method 3: Covering the Surface with a Non-emissive and Non-erodible Layer

Straw blankets are created by breaking apart straw bales that have been delivered to the site and distributing it over the surface that is to be controlled. The layer of straw "blankets" the surface, and prevents movement of the sand particles, thereby preventing dust emission. Since the straw blanket breaks down over time, it is considered to be a temporary measure that precedes the installation of plant material through the straw blanket, as described above in Section II.3.2.2.2.

II.3.2.4 Method 4: Binding the Surface Sediments with a Topical Application, Creating Dust Suppression

Wind erosion and dust emissions from a source area can also be controlled by methods that increase inter-particle bonding. The more strongly bonded the particles are to each other, the greater the shearing stress in the wind will be required to overcome the bond strength. This increases the threshold wind shear stress required to entrain the particles (Nickling and Eccelstone, 1981), and also the horizontal flux of particles in saltation.

Water is likely the most commonly used topical application to control dust emissions. It is typically applied on roads or susceptible surfaces using a water truck with a spray bar or spray nozzle. For dust control at Owens Lake, CA, for some applications water is sprayed on dust emitting surfaces via a network of sprinkler heads that are activated if high winds are forecast. When applying water as a dust control, the soil moisture content needs to exceed 6% to provide sufficient particle binding to be resistant to most high wind events (Nickling and McKenna-Neuman, 2009).

Chemicals added to water to enhance their ability to bind particles together create a category of dust treatment called surfactants. These products can be used effectively for large-scale projects that require PM_{10} control, but following application, disturbance of the treated surface would likely degrade the effectiveness rapidly. The greater the disturbance, the more rapid the loss of effectiveness. Typical application uses water with one or a combination of surfactant materials (e.g., organic, mineral, or engineered polymers). They control dust by keeping the soil/aggregate surfaces wet, or wet longer than otherwise expected, drawing moisture from the air, encapsulating dirt particles, and/or binding dust particles together or to larger particles. Depending on the type of surfactant used, balancing potential environmental concerns with the longevity of a particular application might be necessary. Because most surfactants are water-soluble, rainwater can dissolve them, and they could potentially contribute to water quality concerns as run-off enters nearby water bodies, streams, and rivers.

II.3.3 Description of the Problem at the ODSVRA

Any dust control measure used at the ODSVRA will involve removing some amount of area from the total area available for vehicle activity. The impact on implementation of dust controls, then, is inherently at odds with the desires of the vehicle community to maximize riding area.

The overall approach advised by the Scientific Advisory Group (SAG) has been to implement the most effective methods of dust control in the areas where modeling shows that they will have the greatest effect on reducing PM_{10} emissions (see Chapter II.6, Modeling). In addition, the approach has also worked to implement dust controls that will have immediate effect on reducing PM_{10}, even if they cannot be considered to be permanent. For that reason, a combined approach to dust control implementation has been adopted.

The only dust control method proposed for the ODSVRA that is considered to be long-lasting is vegetation. Other implemented controls, including fencing, straw bales, straw blankets, and sand fences, are all converted to vegetation within 1-3 years. This phased implementation approach allows for the planting of vegetation at a rate that is attainable given factors of cost, labor, and plant availability, while still allowing for rapid reduction of emissions. Further information on dust control strategies is provided in the Particular Matter Reduction Plan (CDPR, 2019, PMRP) and in Annual Reports and Work Plans prepared by the California Department of Parks and Recreation (CDPR).

II.3.4 How the Science is Being Applied to the Problem

Selection of type and location of dust control implementation is guided by the science of how the dust control method selected is expected to work, and how permanent and applicable to the site the dust control strategy is. CDPR must also consider logistical factors, including impacts on public safety operations, when identifying dust control locations.

For fencing, areas are selected that can be protected from vehicle activity without creating new areas of restriction. That is, areas that are already excluded from riding, such as vegetation islands, past vegetation dust control areas, and sand fences, can be extended by exclusion fencing without introducing new noncontiguous areas that would exclude vehicle activity.

For the placement of surface roughness elements, either straw bales, sand fences, or vegetation, similar placement strategies are used, although the results of modeling as described in Chapter II.6 provide information that allows for such dust controls to be positioned where they will have the greatest effect in reducing PM_{10} emissions. Justifications for the type of dust control method, its extent, and its placement, are always guided by the science of how, and how well, each control strategy works, and where it can be placed to be most effective.

Covering the surface with a non-emissive and non-erodible layer is a strategy that has been implemented as a precursor to the establishment of vegetation. Straw bales are broken into a straw mat layer that is non-emissive, and it serves as a matrix into which plants and seeds can be introduced to provide a permanent dust control strategy.

As for the use of particle binding agents or surfactants to reduce dust, the sand dunes of the ODSVRA represent a challenging environment for using such materials to immobilize large areas of sand under dynamic conditions. These challenges include the inundation of an area by mobile sand under high wind speeds, the efficacy of binding essentially pure sand (particle binding benefits from greater amounts of silt/clay), the topography of the dunes, and the stability of the slopes (treated layer may slough off at steeper angles).

As the most established long-term method for dust control, vegetation restoration has received considerable scientific attention. Therefore, this report provides further scientific background on vegetation restoration in Chapter II.4 of this report, and more general context on dune restoration (including foredunes) in Chapter II.5 of this report. Chapter II.6 then provides a description of methods for modeling the effectiveness of these various dust control methods.

II.3.5 Summation

As of the time of publication of this report, the dust control strategies implemented at the ODSVRA are those with effectiveness that are well-enough understood to be strategically implemented at this site. They are controls that have been studied sufficiently in other similar settings that allow for their implementation with confidence at the ODSVRA.

The first-line strategies for immediate realization of dust control have been sand fences, straw blankets, straw bales, and exclusion fencing. The strategies by which each method is implemented are based on the science described here for each method, allowing for confidence of predicting how much dust control can be realized from each method based on how they are implemented. Height and element density guide the installation of roughness elements, including straw bales, vegetation, and sand fences. Surface erodibility can be controlled almost completely, if temporarily, by straw blankets. Vegetation installed into straw blankets is a strategy that has been used extensively by CDPR and its effectiveness has been confirmed by modeling and monitoring (see Chapter II.6).

There have been small-scale tests of surfactants and particle binding agents conducted at the ODSVRA in 2015-2016, but the California Coastal Commission has specifically prohibited these treatments at ODSVRA in recent permitting actions.

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Appendix II.3.A Chapter Equations

The following equations are referenced within the text of Chapter II.3, Dust Control.

(1) Roughness Density:

Roughness density is referred to as λ, which is defined as:

$$\lambda = (n\ b\ h)\ /\ S$$

where *n* is the number of elements, *b* the element breadth, *h* the element height, and *S* the area of the surface that contains all the elements.

(2) Normalized Sand Flux (NSF)

NSF is the relationship between flux inside the roughness area to flux outside the roughness area as it relates to λ. From Gillies et al. (2015):

$$\mathrm{NSF} = 0.0003\ \lambda^{-1.894}$$

(3) Relationship Between % Cover of Vegetation and Sand Flux:

$$Q_n = 0.95\ \exp(-0.20\ C)$$

where Q_n is saltation flux within the vegetation divided by saltation flux without vegetation present (same as normalized sand flux, NSF above), and *C* is % cover.

(4) Effect of Sand Fences

$$u_{*lee}\ /\ u_* = 0.201\ \ln(\mathrm{ND}) + 0.429$$

where $u_{*\mathrm{lee}}$ is the shear velocity at positions downwind of the fence, u_* is the shear velocity without the fence present, and ND is normalized distance (distance downwind of fence divided by fence height).

Assuming a typical threshold u_* value for fine sand of 0.3 m s^{-1} ($u_{10\mathrm{m}}$ >8 m s^{-1}), for a 1.22 m (4 feet) high (*h*) sand fence when u_*=0.3 m s^{-1}, the distance downwind of the fence where significant sand motion begins again will be at >15*h* (i.e., >18.3 m, >60 feet). This distance decreases as regional u_* increases. At regional u_*=0.6 m s^{-1}, sand motion would begin at >1.7*h* (i.e., >1.42 m, >4.7 feet) past the fence.

II.4 Vegetation Restoration

II.4.1 General Statement

II.4.1.1 Dunes and their Dynamics

Dunes are reservoirs of sand formed by wind from wave-delivered sand along the coast. One of their beneficial functions is to help keep a seashore intact. They provide a flexible barrier to the movement of high tides and waves into low-lying areas behind a beach, reducing erosion. When they give way to storm winds and water, these shifting mounds of sand will soon reappear. The changes brought about by the decades of vehicle activity at the Oceano Dunes State Vehicular Recreation Area (ODSVRA) have caused such a permanent change, and many foredune areas have become unstable, smaller, or have disappeared altogether. Modeling related to dust emissions at the ODSVRA has shown that dune formations and the vegetation associated with them are also important in controlling the emission of dust. This chapter on Vegetation Restoration describes the science associated with dune vegetation dynamics and restoration as it applies to the development of vegetation Dust Control Measures (DCMs) at the ODSVRA.

II.4.2 Background

II.4.2.1 Role of Vegetation in Dune Stabilization

Unvegetated dunes are extremely vulnerable to the forces of wind and water, and they require stabilization if they are to function as protective structures along the coastline. They can be stabilized with structural measures such as sand fences, or with vegetative measures, including a variety of plants adapted to a coastal environment (NRCS, 1992). In many cases, vegetation is the least expensive, most durable, most aesthetically pleasing, and only self-repairing technique available (Woodhouse, 1978). Dune plants are especially effective at stopping and holding wind-borne sand. Their growth produces surface roughness that decreases the wind velocity near the ground, reducing wind erosion of the sand surface. Also, the plant stems and leaves above the sand surface greatly interfere with sand movement by saltation and surface creep (Woodhouse, 1978; Gillies et al., 2015; Walker et al., 2022). As the vegetation clump fills and becomes buried, sand spills farther and farther into the interior of the stand of the vegetated area. A cover of dune plants tends to regenerate trapping capacity by growth even as it fills because the plants are stimulated to grow by the deposition of sand around them.

II.4.2.2 Natural Processes That Vegetate Dunes

The vegetation of coastal dunes usually becomes established when seeds or plants are trapped along shorelines during very high tides or by surface roughness that traps seeds as they are blown by the wind (Olafson, 1997; Hesp and Walker, 2022). Trapping of seeds or the installation of plants is the first step necessary for the development of coastal dune vegetation. It is also crucial that the seeds or plants are suitable for establishment in the area. The initial establishment of suitable seeds or plants must then be followed by one or two years of favorable growing conditions, including adequate seasonal precipitation, moderate temperatures, and lack of physical disturbances other than those naturally associated with the coastal environment.

II.4.2.3 General Principles of Vegetation Restoration

In order for vegetation to be restored to natural conditions, the physical, chemical, and biologic conditions of the original vegetation should be well understood. The goal of any vegetation restoration effort is to optimize an increasing potential for native species and communities to recover and continue to reassemble, adapt, and evolve. When there are nearby locations that support native vegetation of the type needed for the restoration site, such a location can serve as a reference site, allowing comparison to be made between the condition of a restoration site and a natural community of plants. Such sites are very important in guiding the activities of a restoration project (Gann et al., 2019).

Figure II.4.1 (Gann et al., 2019) shows a generalized model of the conditions of a site that should be evaluated when implementing a vegetation restoration effort. *Physical conditions* to be evaluated include the physical and chemical qualities of the substrate and the interaction of water with the physical and chemical characteristics. *Species compositio*n, including desirable plants, animals, and undesirable species, should be assessed. The *structural diversity* of the vegetated site includes characteristics of the vegetation strata, the trophic levels present, and the spatial mosaic of the site. When vegetation alone is being considered, the ecosystem functions and external exchanges are less important to planning, but the evaluation of *potential threats* to the vegetation is very important.

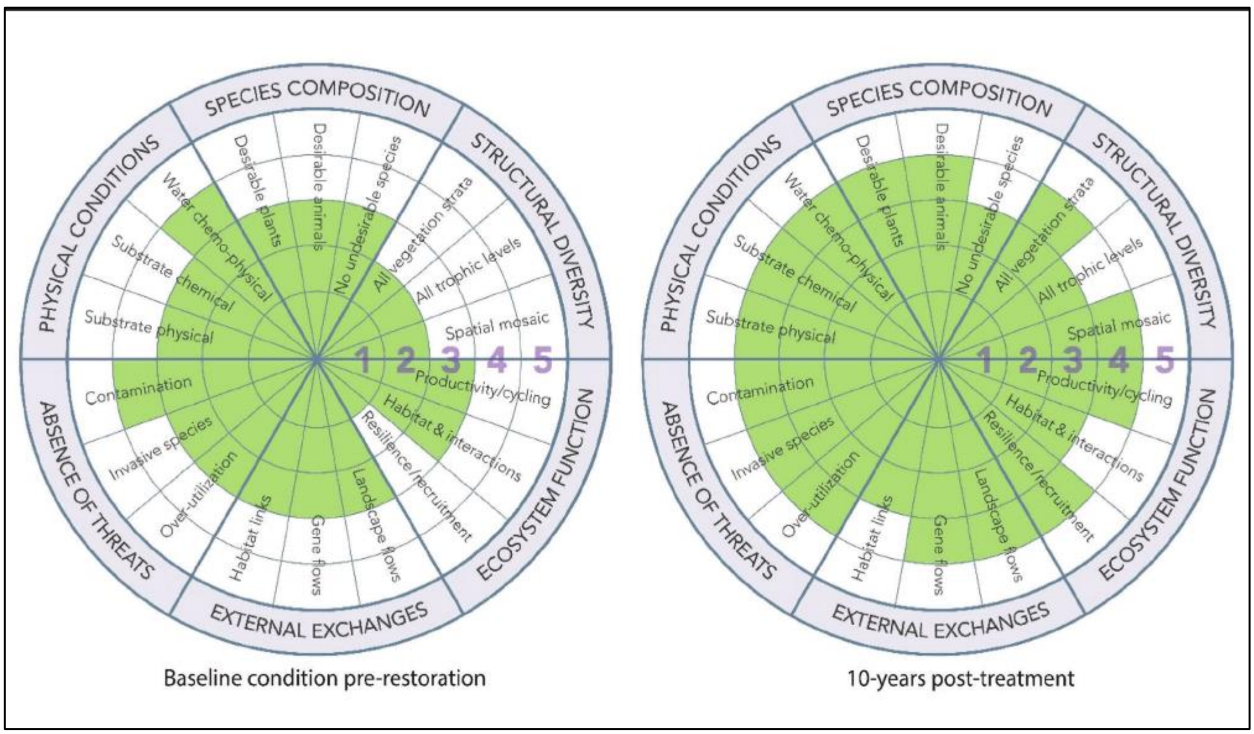

Figure II.4.1. *Generalized model of site condition for vegetation restoration (Gann et al., 2019)*

II.4.2.3.1 Physical and Chemical Conditions

Physical conditions include soils, landforms, precipitation, and other climatic variables. When restoration of vegetation is contemplated in the same location where it was present prior to disturbance, the soils can be assumed to be similar in physical and chemical properties unless chemical contamination, such as oil spills or pipeline leakages, has occurred. Landforms may need to be restored or re-created to support the vegetation desired. The amount of precipitation that occurs in the area, and its seasonality, will be a factor in determining appropriate revegetation strategies, as will climatic variables such as patterns of maximum and minimum temperature over the course of a year.

II.4.2.3.2 Species Composition

The vegetation species present at a reference site, and selected for introduction to a restoration site, may depend on the variability of the restoration site as regards landforms, soils and physical factors. In general, however, restoration plantings should try to mirror native species diversity found in adjacent natural reference areas to assure that the species are adapted to the site, and to provide food and shelter for wildlife in addition to site restoration and stabilization (Williams, 2007). Attention should be paid to species that occupy different physical settings on the site, recognizing that different species may be adapted to specific physical landforms or microsites defined by physical or chemical soil differences.

II.4.2.3.3 Structural Diversity

Structural diversity refers to the forms of plants in any vegetation community. Strata may be identified as low (grasses and forbs), low canopy (perennial herbs and low shrubs) and upper canopy (large shrubs and trees). In a plant community, structural diversity is likely to be related to the diversity of functional traits (traits that influence or define specific processes within that plant community) such as the ability to limit light penetration through the leaf canopy and may thus contribute to resistance to invasion by nonnative species by preventing germination (LaRue et al., 2019). Some sites, however, may naturally contain less structural diversity than others, due to frequency of physical disturbance such as wind and associated soil movement, and limiting factors such as nutrient or chemical composition content of the soil.

II.4.2.3.4 Potential Threats

Protecting vegetation restoration sites from potential threats is an important consideration in habitat restoration projects. Threats could include physical disturbance including overutilization of a site, invasive species, and chemical contamination (Gann et al., 2021). The ability to protect newly installed vegetation from overutilization and contamination may be simply a matter of restricted access. Protection from invasive species can be accomplished through planting strategies and by including a high diversity of both species and structure (LaRue et al., 2019).

II.4.3 Vegetation Restoration for Coastal Dunes: The Situation at the ODSVRA

This section discusses vegetation restoration actions that are specific to coastal dunes and to the dune complexes at the ODSVRA. It describes how the principles of vegetation restoration are specifically implemented for the restoration of these coastal dunes. Vegetation restoration in the dunes of the ODSVRA is an important DCM, and it is the only one of the various DCMs that is considered to be long-lasting, as long as human-caused disturbances are sufficiently reduced or eliminated. Restoration of vegetation, therefore, is critical in the control of dust emissions and in the reduction of PM_{10}.

The United States Department of Agriculture (USDA) Soil Conservation Service (now known as the Natural Resources Conservation Service, or NRCS) has provided a succinct description of the ways in which unstable dunes on marine coastlines can be restored:

> Dunes stabilized with [vegetation] provide an interesting natural barrier, reducing the velocity of waves [and wind] and absorbing their energy. These stabilizing plants are tolerant of salt, intense heat, soils lacking humus, and a limited water supply. As sand piles up around plants, new roots develop on the buried stems and new shoots emerge from the sand's surface. The result is a dense mat of vegetation which anchors the dune below its surface and traps more windblown sand (USDA, 1992, page 3).

Although dunes can be stabilized with non-biological methods such as sand fences or other barriers, the most effective and sustainable solution is vegetation, as described above. This method involves the use of specially adapted plants able to tolerate conditions in a dune environment. When they thrive, they produce sufficient vegetation to anchor the dune, trap windblown sand, and reduce the movement of additional sand from the vegetated area, thus suppressing dust generation.

The principles of vegetation restoration can be applied to dunes along the California coast in general, and at the ODSVRA in particular. Here, we address the restoration principles outlined above and how they relate to restoration actions in coastal dunes.

Coastal dunes in Central and Northern California occur in scattered locations from Point Conception, California, north to Coos Bay, Oregon. Dunes within the ODSVRA lie in the general northwest-southeast direction of the underlying geologic structure and prevailing winds of the area (see Chapter II.1). The mosaic of sparse to dense vegetation in dune systems is driven by sand deposition, erosion, and lateral movement. Coastal dunes often front portions of inlets and tidal marshes. They may also occur as extensive dune fields dominating large coastal bays. Dune vegetation typically includes herbaceous, succulent, and low-shrub species with varying degrees of tolerance for salt spray, wind and sand abrasion, and substrate stability (Maun, 2009). Dune succession is highly variable, with species composition often changing over time as the plants modify the environment and promote growth of different species that enter the site after the initial establishment of vegetation, as originally suggested by Cowles (1899). Species composition, then, can vary significantly in both space and time, between locations in a dune field and between the disturbance occurrences that drive or disrupt successional processes (Explorer Nature Serve, accessed March 23, 2022).

II.4.3.1 Physical Conditions

Rainfall in the Central Coast is highly seasonal, with most precipitation occurring in the winter months and continuously dry summers. The typically mild winter temperatures permit plants to grow throughout most of the year. Dune sands are very poor soils, with no organic matter accumulation (Wiedemann, 1984), a neutral pH, limited nutrients, and poor moisture-holding capacity. Due to their proximity to the ocean, a salinity gradient establishes in a dune complex, and this appears to be important, as germination or emergence stages are more vulnerable than are established plants to soil salinity or wash over of saltwater such as may occur during storms or high tides (Pickart, Barbour, 2007).

Finally, farther inland from the interdunes are back dunes, which can consist of a variety of dune forms (e.g., transverse dunes, barchanoid ridges, parabolic dunes, etc.) separated by troughs. These dunes can be partially or fully stabilized by backdune specific plants and later successional woody dune scrub species.

Coastal dune fields may be roughly divided into areas of foredunes, interdunes, and back dunes (Miller, 2015). These areas are topographically distinct landforms (see Section II.1.4), and they require different strategies for restoration as they experience different physical environments, and thus, ecological conditions. Nearest to the ocean, foredunes are created and maintained by the sand blown from the beach deposited in vegetation. They can reach appreciable heights (2–15 or more m) and are frequently quite dry (Miller et al., 2010). Behind the foredunes are often interdune corridors, which are low, and relatively flat and homogeneous in elevation. The sand in the interdune typically contains more organic material, can have a higher moisture content than other dune areas, and can occasionally flood. Water from the ocean can inundate interdunes with major storms, brackish lagoons, freshwater ponds, rivers, or groundwater emergence can inundate interdunes during major storms. Heavy rainfall events can also flood interdune areas. These sources of moisture, and related adhesive and capillary forces within the sand matrix, create freshwater or brackish lenses within coastal dunes that can provide significant stores of interstitial water available to plants. Finally, farther inland from the interdunes are back dunes, which can consist of a variety of dune forms (e.g., transverse dunes, barchanoid ridges, parabolic dunes, etc.) separated by troughs. These dunes can be partially or fully stabilized by backdune specific plants and later successional woody dune scrub species (Miller et al., 2010).

Wind is a major disturbance process in coastal dunes and is part of the physical environment. It drives seasonal movement of dunes, in turn causing burial of upland vegetation or developed areas along the eastern edge of the dune sheet. Wind-driven sand and salt stunt and abrade plants, including those in stabilized dune areas, and can kill both buds and leaves of shrubs or trees. Severe winds may also bury or remove vegetation from the seaward edges of the dunes, although pioneering dune species are very salt tolerant and are adapted to survive strong winds. Removal of vegetation exposes the sand to wind erosion, leading to the formation of blowouts or the complete destruction of stabilized dunes.

Chemical contamination in the ODSVRA has not been documented, and is unlikely except for in small, isolated areas where the fueling or maintenance of vehicles has occurred with inadequate protection for spillages.

II.4.3.2 Species Composition

It is the strategy of many current dune stabilization efforts to utilize only native species for revegetation, and to utilize principles of restoration rather than of revegetation to accomplish long-term goals of stabilization. Revegetation, strictly speaking, involves the introduction of vegetation to an area that once was vegetated, but does not imply that native species would be the exclusive vegetation components to be introduced. Restoration, in contrast, aims to restore the site to its natural vegetated condition. The activities described in this document focus on restoration of vegetation.

Foredunes are lower in overall plant diversity than interdunes or back dunes. The species that dominate this portion of the dune areas are ones that are the most salt tolerant and that best survive in the shifting foredune environment. As documented in the coastal dunes of San Luis Obispo County (MBNEP, 2020), the most common foredune species are sand verbena (*Abronia maritima*) and beach burr (*Ambrosia chammisonis*) (Pickart and Barbour, 2007). The interdunes slightly farther back support species slightly less tolerant of salt and sand inundation, such as beach evening primrose *(Camissoniopsis cheiranthifolia cheiranthifolia)*, croton (*Croton californica*), and dunedelion (*Malacothrix incana*). Back dune areas typically have the highest plant diversity (Miller et al., 2010) and contain some woody species, as well as species also common to both interdunes and foredunes. This is at least, in part, because there is a greater amount of fertile soil and water, and a much lower salt content. Common species here include silver dune lupine (*Lupinus chammissonis*), senecio (*Senicio blochmaniae*), and coastal buckwheat (*Eriogonum parvifolium*), which are perennial herbs or shrubs. These species are the ones that are recommended for restoration in the non-foredune coastal dunes in this region. In addition, other species that are found on a designated reference site may be used as well.

It is standard policy to use plant propagation materials such as seeds, rhizomes, cuttings, or other material that may propagate a plant species that are collected from areas local to the restoration site, and to use only native species (Johnson et al., 2010). Where non-native species have been used for restoration of dune habitats, displacement of native herbaceous and even shrub species may occur by direct overgrowth or indirectly through competition for resources. The impacts include changes to soil pH, buildup of organic matter, and restriction of sand movement. These factors can inhibit the long-term recovery of native dune vegetation and impair the outlook for stabilizing the dunes (Explorer Nature Reserve, accessed March 23, 2022).

There may be, however, other species that should be considered that are not necessarily local to the environment or which have been introduced from elsewhere and have become naturalized. This could include species native to other nearby sites but not found in the specific location where restoration is occurring. They could also include species native to elsewhere in the world, but which have become so prevalent at the restoration area as to approach being considered native. To evaluate such species, guiding criteria should be that ecologically appropriate plant materials are those that exhibit ecological fitness for their intended site, display compatibility with other members of the plant community, and demonstrate no invasive tendencies (Jones, 2013). Sea rocket (*Cakile maritima)*, for example, is a foredune species native to Europe, North Africa and western Asia, but which has become common in foredunes of the central California coast and does not displace or outcompete native species.

II.4.3.3 Structural Diversity

Along the coast-to-inland gradient, as along other geographic of climatological gradients, the vegetation structure changes both in space and time, due to the process known as succession, by which the landscape and structure of a biological community evolves through time (Cowles, 1899; Maun, 2009). Initial successional stages that characterize foredunes are often homogenous with generally uniform, if harsh, environmental conditions (Morrison and Yarranton, 1974). Only a few highly specialized pioneer species that tolerate sand burial can colonize and stabilize these highly mobile sediments. Further successional stages of back dune areas are characterized by initial dune stabilizers that occur next to burial-intolerant species that may include perennial dicots as well as sedges and grasses. Older stabilized dunes have a greater total cover, and woody shrubs and even trees may be more abundant (Peyrat and Fichtner, 2011). This pattern indicates that structural diversity in the foredune and interdune areas is low, as plants are continually being covered by moving sand, and re-emerging. In the interdune and back dune areas, with more stable and more fertile soil conditions, however, conditions allow for the development of a low to mid canopy layer of perennial herbs or woody plants. Such species should be included in the mix of vegetation components for restoration of these dune areas.

II.4.3.4 Potential Threats

Although inherently adapted to natural disturbances, dune systems have undergone, and continue to undergo, rapid and significant human-induced change and degradation. Recreation, including pick-up trucks, off-highway vehicles, camping, horseback riding, and hiking, compact or displace sand, introduce weed seeds and fungal spores, or damage native plants. Intensive activity by recreational vehicles and camping has completely destroyed vegetation in some areas (Christy et al., 1998; Pickart and Barbour, 2007), and has caused severe erosion and disruption of dune processes. This disturbance factor is present at the ODSVRA (Swet et al., 2022).

To counter and reverse such damage, restored dune areas must be protected so that vegetation can develop in a natural way without anthropogenic disturbance. Fencing is the most reliable way of excluding vehicles and human traffic, although flagging, signage, and public education may be important as well.

Protection of the developing vegetation from invasive non-native plant species has already been mentioned. Weed seeds may be brought in by vehicles on tires, by people on shoes, and by horses on hoofs and in feces. These are additional reasons that such traffic should be prevented in restoration areas of the dunes.

II.4.3.5 Restoration Methods for Coastal Dunes

There are three main actions required for dune restoration. First, the surface must be stabilized and/or physically contoured. Because of the inherently mobile nature of dune soils, which are predominantly sands, some amount of soil stabilization and possibly physical contouring may be necessary to introduce plants successfully, although the foredune restoration project described in Chapter II.5 required only imprinting using a sheepsfoot. This step may entail grading the site to conform it to the landscape, and/or using sand-trapping fences (NRCS, 1992). Dune construction may in some locations involve the placement of sediment from dredged sources on the beach, followed by reshaping of these deposits into dunes using bulldozers or other means (Linham and Nicholls, 2010). As existing sand resources should not be used to construct dunes, and because of the enormous volume of sand that naturally washes into the ODSVRA, this kind of mechanical construction is neither possible nor desirable for Oceano Dunes, and it is unnecessary due to the effectiveness of wind action in the formation of dunes. Another method is to build fences on the seaward side of an existing dune or sand sheet to trap sand and help stabilize any bare sand surfaces (USACE, 2003). Although sand fencing can help to trap sand and stabilize dunes, it should only be used in conjunction with the establishment of native vegetation (NRCS, 2011). Sand fencing can also create dune structures by trapping blowing sand, thereby creating structures that may be helpful for restoration of dune vegetation. The use of sand fences, as described here, may not be appropriate for certain dune restoration projects, as other methods may be better suited for the specific locale.

Second, the surface and soils require preparation. Further stabilization of the new or restored dune may be required prior to planting. For this process, the use of temporary mulches or blankets such as straw can be used to minimize the effects of wind on the proposed plantings (NRCS, 1992). Straw bales and/or blankets can themselves stabilize surfaces in advance of any vegetative cover that may be introduced (Zhang et al., 2016; Gillies et al., 2015). In addition, observed changes in soil particle size and soil water content indicate that the overall physical properties of the soils can be significantly improved after straw placements are implemented, providing a good environment for vegetation community construction and ecological restoration (Zhang et al., 2018). Such applications can be converted to vegetation at a later date.

Fertilization is not recommended for foredune development since native foredune soils have very low nutrient levels, and nutrient addition may favor the colonization by weedy or nonnative species. In back dune environments, where soils commonly have more organic material and nutrients, fertilizer may be helpful in encouraging rapid growth of seeds and transplants (Martinez et al., 2021).

Finally, plants must be introduced. Seed introduction is by far the least expensive manner of introducing vegetation to a dune restoration site (Palmerlee, 2010). Seeding, however, depends on the availability of a sufficient quantity of native seeds of the required species. Seed availability can be constrained by suitable collection sites that are not protected by any land tenure, by how much seed may be produced by a species, and by labor availability to collect and process the seed. Seeding is usually done by broadcasting, either by hand, using a seed spreading device, or by a mechanical seeder pulled by a tractor. Hand broadcasting or spreading may be more appropriate methods for the coastal dune fields, where terrain can be steep or unstable for heavy equipment.

Planting can also be achieved by transplanting vegetative units from nursery stocks or nearby intact dunes (USACE, 2003). Properly prepared and installed transplants have a higher survivorship than do plants germinating in the field from seed (Godefroid et al., 2011). Transplants can be generated in a greenhouse setting and then introduced by hand into a site that has been stabilized by application of a straw blanket or mulch. Fewer seeds are required for the production of transplants than for seed broadcasting, although transplants are more expensive to develop and to introduce into the field, being quite labor intensive. Transplants are typically started from seed broadcast into greenhouse flats, and they are transferred as seedlings into containers of suitable size for introduction into the field. These plants are grown in a greenhouse or other protected setting until their roots are sufficiently developed as to hold together in a bundle when removed from the container. The plant is put into a hole in the ground that has been excavated to depth and width that allows for the entire plant to be inserted intact, and to be backfilled with the excavated soil or sand, tamping to assure good root-soil contact (NRCS, 2011). Fertilizer may be used during planting, often in the form of a slow-release pellet that will benefit only the installed plant rather than weeds that may establish around the transplant. Planting is done only in the winter to spring months, so that the transplants can take advantage of precipitation. Supplementary watering is not recommended.

II.4.4 Application of the Science to Vegetation Restoration at the ODSVRA

These principles of vegetation restoration have been applied at the ODSVRA in a program implemented by CDPR since 2007, and they continue to the present day. Sites in the interdune and back dune areas have been the focus of restoration until 2019, when a foredune establishment program was initiated where historical records indicate a foredune complex existed prior to the use of the land as an official vehicle recreation area. Since the implementation of a Stipulated Order of Abatement (SOA) in 2018 (and amended in 2019 and 2022) ordered by the Hearing Board of the San Luis Obispo County Air Pollution Control District (SLOAPCD) to reduce the amount of dust emitted from the ODSVRA, evaluation of appropriate DCMs has been conducted by a Scientific Advisory Group (SAG). An Annual Report and Work Plan (AWRP) has been prepared by CDPR, in consultation with the SAG, annually since 2018; each ARWP is informed by data collected from dust monitors, modeling approaches to determine where and what type of DCMs should be implemented, and feasibility analysis based on funding and logistical capabilities. Vegetation restoration is considered the only long-lasting DCM available for this area, and new acres of restored vegetation are installed each year in accordance with the ARWP.

The location and areal extent of the vegetation restoration efforts have also been informed by an historical vegetation study (Swet et al., 2022) conducted using georeferenced aerial photos dating back to 1939. These photos indicate where vegetation had existed historically and allow for a reasonably accurate assessment of where vegetation restoration might best be implemented. Specifically, the previous existence of a foredune system within the riding area was documented, and its extent and location informed the project described below and in Chapter II.5.

II.4.4.1 Interdune and Back Dune Projects

CDPR has planned and implemented its vegetation restoration program in accordance with vegetation restoration practices as described above. Relating to physical and chemical conditions, restoration is performed in areas that had supported dune vegetation in the past, and which had not been contaminated in any way by chemicals or other forms of contamination. Sites targeted for revegetation are initially stabilized with a blanket of straw that is either blown on mechanically or distributed by hand from straw bales delivered to the site. The straw blankets may also be seeded with sterile hybrid grass seeds to provide additional stabilization. The sterility of the grass plants assures that they will not become a permanent member of the evolving plant community. The treated area is fenced to prevent impacts from vehicle or foot traffic, which reduces the principal potential threat to the evolving restored vegetation.

Careful attention has been paid to species composition and structural diversity. The planting palette that is used consists of species that are all native to the local dune area, and seeds are collected from mature vegetation on site or in closely adjacent dune areas such as Oso Flaco immediately to the south. The suite of species is therefore not only appropriate to the sites, but it is also locally adapted to environmental conditions. The selected species are perennials and include low-growing species that expand using underground stems such as *Abronia maritima* (sand verbena), larger-statured plants such as *Senecio blochmaniae* (dune ragwort) and dunedelion (*Malacothrix incana*), and woody shrubs such as *Lupinus chamissonis* (dune bush lupine). These species are introduced as either container transplants or as seeds, using the methods described above. A complete list of species used for these restoration efforts is in Tables II.4.1 (interdune and back dune areas) and II.4.2 (foredune area). Note that some species appear in both lists, as they are transitional between foredune and interdune areas.

Table II.4.1. *Species planted in interdune and back dune areas at the ODSVRA*

Species	**Common Name**
Acmispon glaber	Deerweed
Achillea millefolium	Yarrow
Astragalus nuttallii	Nuttall’s milkvetch
Camissoniopsis cheiranthifolia	Beach suncups
Carex praegracilis	California field sedge
Corethrogyne filaginifolia	California sandaster
Dudleya lanceolata	Lanceleaf live-forever
Eriastrum densifolium	Giant woollystar
Erigeron blochmaniae	Bloc’man's leafy daisy
Ericameria ericoides	California goldenbush
Erysimum suffrutescens (insulare)	Island wallflower
Eriogonum parvifolium	Seacliff buckwheat
Eriophyllum staechadifolium	Seaside woolly sunflower
Horkelia cuneata	Wedgeleaf horkelia
Juncus lescurii	San Francisco rush
Lupinus chamissonis	Dune bush lupine
Monardella undulata ssp. crispa	Crisp monardella
Myrica californica	Pacific wax myrtle
Phacelia ramosissima	Branching phacelia
Salix lasiolepis	Arroyo willow
Senecio blochmaniae	Dune ragwort

Table II.4.2*. Species planted in foredune areas at the ODSVRA*

Species Name	Common Name
Abronia latifolia	Coastal sand verbena
Abronia maritima	Red sand verbena
Achillea millefolium	Yarrow
Ambrosia chamissonis	Silver burr ragweed
Atriplex leucophylla	Beach saltbush
Camissoniopsis cheiranthifolia	Beach evening primrose
Eriogonum parvifolium	Seacliff buckwheat
Eriophyllum staechadifolium	Seaside woolly sunflower
Fragaria chiloensis	Beach strawberry
Malacothrix incana	Dunedelion

The locations chosen for restoration are being informed by on-site data collected by CDPR and their contractors (e.g., DRI and UCSB). Data collected regarding wind speed and direction, along with emission and concentration of blowing dust, inform models that allow for prediction of locations for vegetation restoration that would provide the best benefits for dust control and air quality. Other considerations such as planting logistics, vehicle riding habits, transportation and safety corridors, and the ability to provide pre-stabilization of a proposed planting site using sand fences are also considered in selecting planting sites.

II.4.4.2 Foredune Restoration

A 48-acre site in an area that had supported foredunes in historic times (Swet et al., 2022) was fenced off and a foredune restoration project was initiated in 2020. This project is described more fully in the next chapter. It was planned and conceived with attention to the principles of restoration in general, and with specific understanding of the morphodynamics, species composition, and plant community succession typical of foredunes in the Central Coast of California. The species list used in the foredunes is in Table II.4.2.

II.4.5 Summation

Dune restoration is the only one of the DCMs used in the ODSVRA that is considered to be long-lasting and nature-based. Therefore, its utilization must be sited and implemented correctly. The placement and sizes of restoration projects within the ODSVRA are determined by modeling (Mejia et al., 2019) that utilizes dust monitoring data, meteorological data, and site configuration data such as location, size, orientation of existing dunes, and historical vegetation data. Foredune restoration activities are described in Chapter II.5, modeling approaches are described in Chapter II.6, and general and specific approaches to dune vegetation restoration have been considered in this chapter.

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II.5 Restoration of Coastal Foredunes

II.5.1 General Statement

Globally, coastal dune restoration has a long and storied history dating back centuries to places where the goal was typically to control wind erosion, sand drift, dune migration, and the seeming unruliness of natural dune landscapes. Today, dunes on many developed coastlines are experiencing continued anthropogenic pressures and various forms of engineering or restoration (see extensive reviews in Jackson and Nordstrom, 2011; Martinez et al., 2013a; Elko et al., 2016; Nordstrom and Jackson, 2021). The objective of many early restoration approaches was to stabilize coastal dunes and halt their natural dynamics, often by planting forests, later successional species, or invasive species. As a result, many artificially stabilized dunes have dysfunctional ecological regimes that lack certain needed geomorphic processes, such as aeolian sand transport, erosion, and burial, that provided needed disturbances required to maintain dune ecosystem structure and function.

In recent decades, more ‘dynamic’ approaches to dune restoration have emerged that aim to re-establish natural biogeomorphic disturbances, including aeolian processes, and re-introduce native floral and faunal communities as a means to restore lost ecosystem form and function (e.g., Van der Meulen et al., 1989; Houston 1991, 1997; Martinez and Psuty, 2004; Nordstrom, 2008; Arens et al., 2013a, b; Hesp and Hilton, 2013; Lithgow et al., 2013; Walker et al., 2013; De Jong et al., 2014; Konlechner et al., 2015; Darke et al., 2016; Ruessink et al., 2018; Bird et al., 2020; Hilgendorf et al., 2022). Substantial research suggests that a more dynamic dune landscape, wherein natural geomorphic and biotic processes are stimulated and restored, creates an ecosystem more resilient to environmental and climatic change impacts.

In this chapter, we introduce and discuss restoration of coastal dunes, with particular focus on foredunes.

II.5.2 Background on the Relevant Science

Dynamic dune restoration focuses on either removing vegetation or (re)introducing plant cover, with various combinations of approaches in between. De-vegetation approaches typically aim to reactivate formerly stabilized dunes by removing plant cover, often invasive and/or later successional woody species. Various methods are used, including fire, mowing, grazing, herbicides, mechanical or manual pulling, or soil tillage to enhance aeolian processes and promote more dynamic ecosystem form and function. This is often accompanied by replanting of native dune species (e.g., van Boxel et al., 1997; Nordstrom et al., 2002; Arens et al., 2004; Rozé and Lemauviel, 2004; Van Der Meulen et al., 2004; Arens and Geelen, 2006; Nordstrom, 2008; Hilton et al., 2009; Kollmann et al., 2011; Pickart, 2013; Hesp and Hilton, 2013; Walker et al., 2013; Darke et al., 2016; Conery et al., 2019; Pickart, 2021; Pickart et al., 2021; Hilgendorf et al., 2022). The second approach involves revegetation to re-establish dunes that depend on plant cover to promote aeolian deposition and dune development in areas where they have been removed or destroyed, intentionally or unintentionally. A restoration and dune rebuilding approach has been taken for the Oceano Dunes State Vehicular Recreation Area (ODSVRA) foredune restoration site (see Walker et al., 2022). Revegetation in coastal dunes was discussed in Chapter II.4.

Spanning these two end members of dynamic dune restoration are a variety of approaches that combine methods of dune building and/or vegetation management with other nature-based or engineering solutions (e.g., sand fencing, sand mounding, geotextiles, etc.) (see Nordstrom, 2008, Martinez et al., 2013, and Nordstrom and Jackson, 2021, for recent reviews). The role of vegetation in the spectrum of approaches ranges from acting as the primary agent of dune building under unimpeded aeolian processes to functioning as a stabilizing agent for restored dunes with limited aeolian activity. The objectives of dynamic dune restoration projects are wide ranging, but ultimately the aim of most is to effectively re-establish and/or enhance aeolian processes and dune morphodynamics for improved function and resiliency.

There have been numerous case studies on coastal dune restoration in recent years, especially on foredunes (e.g., Lithgow et al., 2013, Martinez et al., 2013b, Sigren et al., 2014; Darke et al., 2016; Hilton et al., 2013; Eamer et al., 2013; Walker et al., 2013; Nordstrom, 2008; Nordstrom and Jackson, 2021; Hilgendorf et al., 2021, 2022). These studies suggest methods for implementing dune restoration, monitoring system responses, and assessing the effectiveness of various approaches, some of which have been described in Chapter II.4. Of particular importance is the understanding that vegetation establishment in a foredune area is required for dune formation and maintenance. Most psammophilous (sand-loving) species that live on the coastal margin are adapted to, and require, the seemingly harsh conditions of sand abrasion, burial, erosion, salt spray, etc., as important ecological processes for their establishment and growth. In return, these species trap appreciable amounts of windblown sand as they grow and develop dunes that may eventually evolve from relatively isolated nebkha into an established foredune system.

Furthermore, the literature includes common methods used to detect, quantify, and assess foredune restoration efforts, including the use of high-resolution surveying and remote sensing coupled with spatial statistics (e.g., Eamer et al., 2013; Walker et al., 2013, Hilgendorf et al., 2021; Walker et al., 2022). Such methods allow for high accuracy monitoring and examination of geomorphic responses, sediment budget changes, and evolution of vegetation cover that are required to promote and maintain dune formation.

II.5.3 Description of the Problem at the ODSVRA

Vegetated foredunes and back dune scrub ecosystems that were historically present in the ODSVRA area have been impacted significantly by decades of intensive vehicle activity that has increased in recent decades. Analysis of historic vegetation cover within the ODSVRA using aerial imagery from the 1930s to 2020 by Swet et al. (2022) shows that from 1939 to 1966 plant cover within the vehicle riding area was relatively stable at around 12%. As vehicle activities increased between 1966 and 1985, plant cover declined significantly to 4%. Within the foredune zone (400 m inland from the high-water mark) vegetation cover declined from 5% in 1966 to less than 1% by 1985. These results indicate that areas with the most intensive vehicle use have seen significant declines in plant cover and related dune forms. In particular, foredunes, nebkha, and incipient dunes, and their related plant communities, have been heavily impacted and reduced in cover significantly.

Following the establishment of the ODSVRA in the early 1980s, and particularly between 2005 and 2012, vegetation cover has increased in the park with a net gain of 12%, mainly around pre-existing and protected vegetation "islands" and targeted restoration sites. In the open riding area, however, plant cover and dune system coverage remained low compared to other areas, particularly in the foredune zone, which saw only a minor increase from 0.9% in 1985 to just over 2% in the 2010s (Swet et al., 2022). PI-SWERL testing by the Desert Research Institute (DRI) indicated that the foredune zone in the riding area was among the most emissive surfaces within the ODSVRA. A 48-acre area was identified in 2019 by the California Department of Parks and Recreation (CDPR), in consultation with the Scientific Advisory Group (SAG) and San Luis Obispo County Air Pollution Control District (SLOAPCD), for restoration of a foredune ecosystem as a dust emissions mitigation measure, discussed in more detail in the following chapter.

Recent computational fluid dynamics (CFD) modeling of wind flow over established foredunes near Oso Flaco Lake (Furtak-Cole et al., 2022) indicated that the roughness and sheltering effects offered by established foredunes and nebkha contribute to reduced surface shear stress and dust emissions potential that extends for some distance downwind of the foredune itself. Thus, due to the lack of a foredune system, combined with intensive recreational activity and high surface emissivity, dust emissions attribution modeling in the ODSVRA by DRI (Mejia et al., 2019) indicated that restoration of a foredune within the riding area was an important mitigation strategy for controlling dust at the ODSVRA, in accordance with the requirements of the Stipulated Order of Abatement (SOA).

II.5.4 How the Science is Being Applied to the Problem

The Oceano Dunes foredune restoration project was designed to re-establish a dune ecosystem in a highly emissive area that once hosted a foredune and related plant communities. Detailed analysis of historical aerial photography of the area by the University of California Santa Barbara (UCSB) (Swet et al., 2022) showed that the foredune complex consisted of a suite of different dune forms, similar to that shown in Figure II.1.3, that extended inland for hundreds of meters from the high-water mark. Given the climate, wind regime, plant ecology, and sand supply of the region, a discontinuous nebkha foredune with interspersed trough blowouts backed by parabolic dunes is consistent with observations elsewhere globally (Hesp et al., 2021a, 2021b), as evidenced further south of the ODSVRA in the Santa Maria Dunes complex. Invasive species introduced to the region decades ago, however, combined with other human activities (agriculture, urban development, oil and gas exploration/extraction) have modified the landscape markedly since the air photo record began in the 1930s. Indeed, it is difficult to find any coastal dune systems in California that have not been modified in some way. This is important as most restoration efforts seek local 'reference sites' for targeting and designing ecosystem states and, so, it can be difficult to find suitable local sites for reference. At the ODSVRA, the SAG, in consultation with CDPR and SLOAPCD, identified the foredunes at north Oso Flaco as a suitable reference site for designing the foredune restoration project (Walker et al., 2020; Swet et al.,

2022) (Figure II.5.1A). In addition, observations that small nebkha have established without active restoration efforts within the seasonal exclosure for nesting Western Snowy Plovers (Figure II.5.1B), which was closed to vehicle riding for seven months each year, indicated that re-establishment of foredunes would be feasible if the restoration area were protected from vehicle traffic. In addition to providing dust emission mitigation, re-establishment of the foredunes can be expected to restore habitat for many plant and animal species, and to improve other ecosystem services that an expanded dune area could provide (see Chapter II.4). A more highly vegetated area is not, however, desirable habitat for nesting for Western Snowy Plover or California Least Tern.

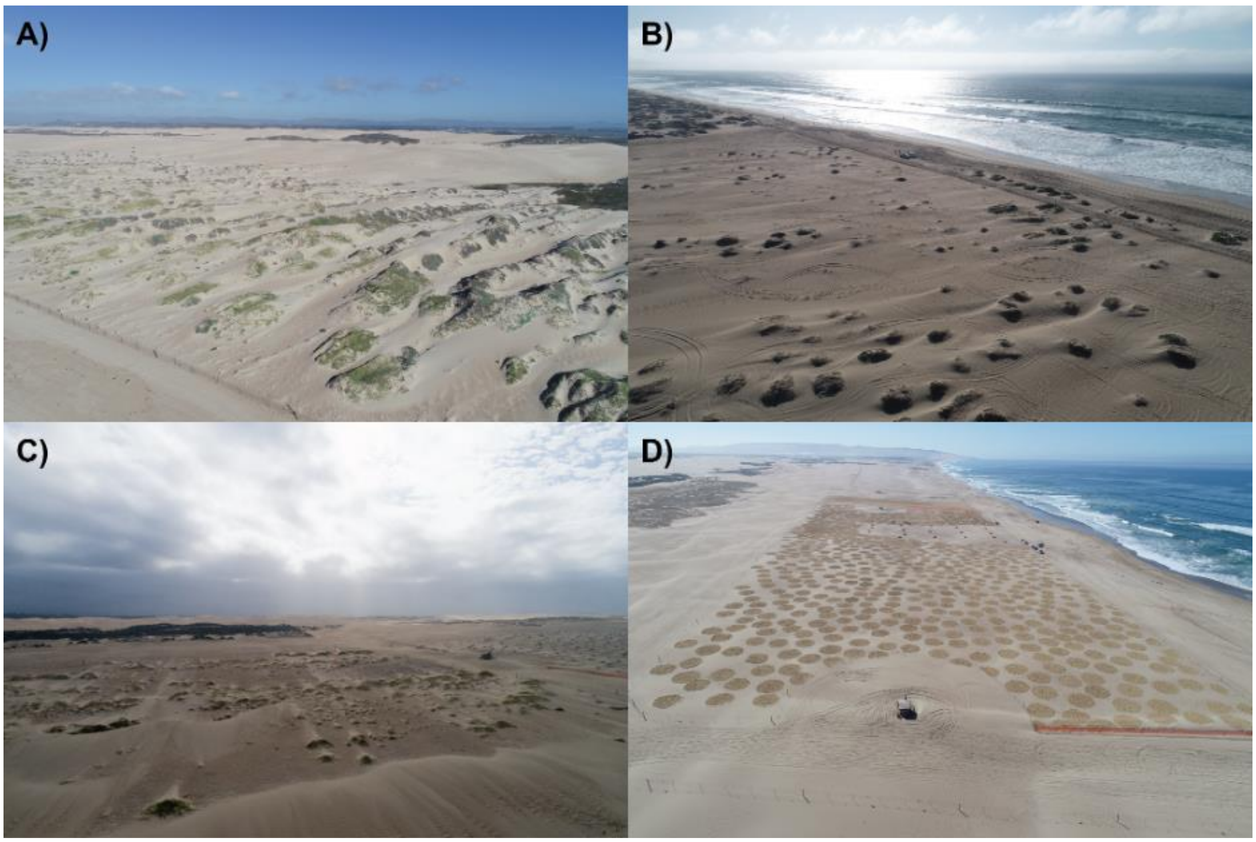

Figure II.5.1. *A) View of established discontinuous foredunes at a reference site south of the restoration site near Oso Flaco Lake, looking northeast. B) Nebkha development at a location between the reference site and the restoration site that is closed seasonally (March - Oct.) to vehicle traffic for nesting birds, looking southwest. C) Transverse dunes and nebkha development in the T3 plot in Oct 2021, after two growing seasons, looking east. D) Treatment plots 4, 5 and 6 (low- and high-density planting nodes, broadcast straw) during installation in Feb. 2020, looking south*

The Oceano Dunes foredune restoration project is a 'nature-based' dynamic revegetation approach designed to re-establish a foredune by introducing or seeding vegetation, then relying on natural interactions between native plants and aeolian processes to rebuild the ecosystem. The footprint for the site was identified initially by the PM_{10} emissivity map produced by DRI, then refined to a 48-acre site consisting of three separate areas defined by logistical considerations, namely seasonal exclosures for endangered nesting birds and necessary transportation corridors for restroom access and public safety, in collaboration with CDPR staff and input from SLOAPCD. Five treatment types and a control site with minimal intervention were developed by the SAG and CDPR field staff, based on collective expertise and extensive experience at the site and on dune restoration projects elsewhere (Figure II.5.2). The area was fenced, and the following treatments were implemented in February 2020:

1. **Control site.** No vegetation treatments (plants or seeds) were introduced, but the sand surface was textured with a lugged (sheepsfoot) roller to indent the surface and encourage moisture capture and the potential for germination of native seeds, if present.
2. **Native seeds.** Sheepsfoot-rolled surface with broadcast native plant seeds and broadcast fertilizer.
3. **Native seeds and sterile rye grass.** Sheepsfoot-rolled surface with broadcast native plant and annual sterile ryegrass seeds and fertilizer.
4. **Low density planting nodes.** Randomly spaced planting nodes with 7.3 m diameter straw circles covering the sand surface by roughly 10-12 cm to protect a cluster of 9 native plant seedlings and seeds within 1 m of the node center. Fertilizer was applied only near the plant clusters.
5. **High density planting nodes**. Randomly spaced straw planting nodes with the same planting method, seed species, and fertilizer application as in treatment 4, but with a closer spacing.
6. **Broadcast straw with native seeds and seedlings.** 100% straw cover at 10-12 cm depth with scattered native seeds, sterile grass seeds, and roughly evenly spaced distribution of native plant seedlings.

Prior to implementation of the treatment plots, the site was surveyed using an uncrewed aerial system (UAS or drone) in October 2019 to capture baseline aerial imagery, map vegetation cover, and produce a high-resolution topographic map, or digital elevation model (DEM), of the sites. From this, detailed changes in treatment responses have been detected and quantified. Since 2019, six mapping campaigns have been conducted in late February and September of each year (October 2019 to February 2022). Recent reports (Hilgendorf et al., 2022) and a recently published study by UCSB (Walker et al., 2022) describe the methods and rationale for the project and its treatment types, along with performance results for these first two years of the project.

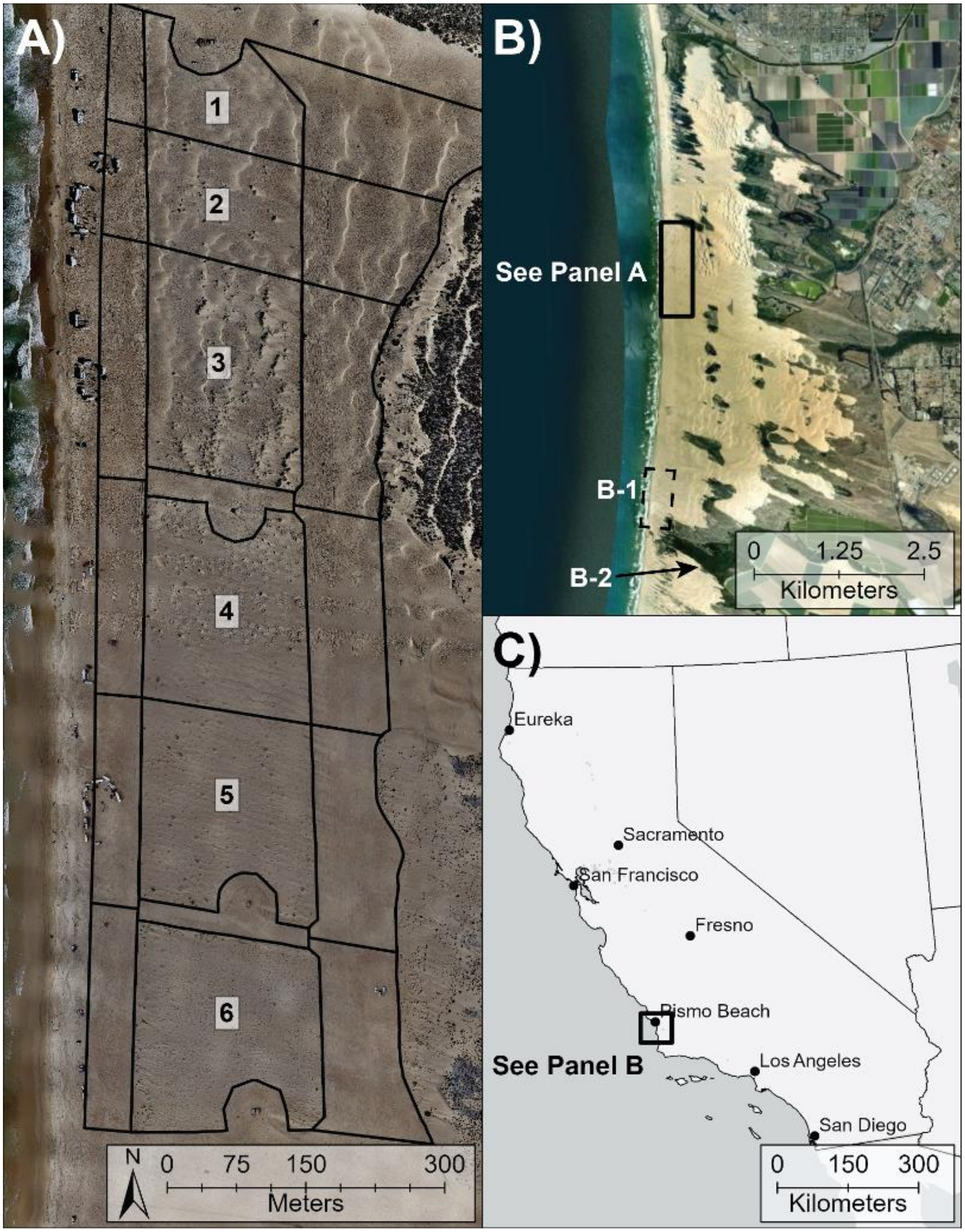

***Figure II.5.2**. A) UAS orthomosaic of the foredune restoration treatment plots (T1-6) from Oct. 2021, prior to treatment actions. B) Study site location in the Callender Dunes within the ODSVRA (National Agricultural Imagery Project photo from 2020). B-1 (dashed box) shows the location of the reference site north of Oso Flaco Lake (B-2). C) Location of the study area near Pismo Beach, CA, USA.*

The hypothesis guiding the restoration project is that the treatments will differ in their ability to promote deposition and dune development and that more intensive planting-based treatments would outperform simpler (i.e., seed-only) treatments. The UAS surveys and related DEMs were used to quantify sediment budgets and exchanges between beach, foredune, and back dune components of the landscape, as well as changes in plant cover and dune development over a two-year period (October 2019 to 2021) (Walker et al., 2022). This information is then used to interpret how each of the treatments is responding to aeolian processes and stimulating foredune development. The development, success, and performance of restoration projects requires careful monitoring and evaluation against measurable criteria (e.g., Martinez and Psuty, 2004; Lithgow et al., 2013; 2015; Walker et al., 2013; 2023; Nordstrom and Jackson, 2021). Based on this study, and with reference to other dune restoration projects, a suite of criteria was developed to assess the performance of the ODSVRA dynamic dune restoration project, including:

1. **Establish and maintain a positive sediment budget.** To build a new foredune system, continued gains of sand volume over time are required, particularly through the early stages of incipient dune development and plant community re-establishment. Eventually, as nebkha grow and coalesce into a larger foredune and alter onshore wind and sand transport, volumetric gains may slow or plateau as the system reaches its fully developed state.
2. **Maintain aeolian activity, open sand surfaces, and landward sand transport.** Saltation of sand, along with related erosion and deposition patterns, are critical processes for dune development, maintenance, and ecological function. The amount and extent of aeolian activity depends on regional plant ecology, climate, and sand supply. In this area of California, fully developed natural foredunes consist of open sand transport corridors and blowout dunes that allow for landward sand transport and dune development, not continuously vegetated ridges with high plant cover, as are found farther north in California and Oregon.
3. **Increase foredune plant cover, survivorship, and species richness.** Where a new foredune ecosystem is being developed, it is imperative that plants establish and survive to initiate sand accumulation and incipient dune growth. Care must be used to not overplant at densities that inhibit aeolian processes, which often requires onsite trials and reference sites to assess. Eventually, plant cover density might plateau in balance with dune form/position, aeolian activity, soil nutrients, and regional climate. Most established foredunes also typically host multiple species, with some endemic or endangered, so maintaining or improving species richness is important. As possible, initial planting palettes should reflect the range of early-stage successional species common to natural foredunes in the region. As foredune ecosystems evolve, longer-term plant community succession and the occurrence of continued disturbance processes (e.g., coastal or wind erosion, sand transport) should be considered. The planting of later succession stage species early on in the restoration process should be avoided, as this can prematurely stabilize the system and halt important developmental processes.
4. **Enhanced dune development.** The establishment and growth of foredunes and related dune forms (e.g., nebkha, blowouts, parabolic dunes, etc.) with their associated processes of sediment erosion and/or deposition is a key sign of improved performance. Important feedback mechanisms exist between wind flow, sand transport, vegetation cover, and

dune form that are required to build and maintain natural foredunes (see reviews by Hesp and Walker, 2022; Walker and Hesp, 2022). As the system evolves, the configuration and variety of dune forms will change and continue to reorganize into a morphology that reflects plant cover, aeolian activity, sand supply, and regional climate.

5. **Relative cost of implementation.** The costs of developing and implementing a dune restoration project at large (landscape) scales with any intervention treatment(s) are not trivial. As actual costs are site specific and vary over time and by region, it is more useful from a cumulative assessment approach to rank treatments based on relative cost. At the ODSVRA, rankings of relative cost to implement each of the treatments were based on relative effort and anecdotal accounts from CDPR staff.
6. **Dust control potential.** The ODSVRA dune restoration project was designed to reduce dust emissions from an area identified as highly emissive. The new terrain and vegetation roughness disrupts wind flow in the lower atmosphere that initiates saltation and lofts dust. Over time, as more sand is deposited and the dunes grow, there are additional downwind wake effects of reduced shear stress and dust emissions. To date, no monitoring of dust emissivity or downwind emissions reductions have been conducted at the restoration site. Instead, at this early stage of development, the effectiveness of dust control is estimated as a function of the combined effects of increasing vegetation cover (aerodynamic roughness), initial straw cover (temporary surface stabilization), and dune development (form roughness and sand accumulation).

After two full seasons of plant growth and aeolian activity, results show that all treatments are accumulating sand (a positive sediment budget per criterion 1) and maintaining aeolian activity (per criterion 2), most are developing sizable nebkha (an important stage in foredune development per criterion 4), and some are increasing plant cover and species richness (per criterion 3). Relative costs were lowest with the seed-only treatments (T2, T3) and markedly higher for the treatments requiring straw dispersal and planting of seedlings (T4-T6). There is no clear winner, yet two of the treatments - T3 with native plant and sterile grass seeds, and the T5 high-density straw planting node treatment - are performing well toward developing an incipient foredune. A full interpretation of these initial results and performance assessment is available in Walker et al. (2022). SAG encourages continued monitoring of the restoration treatments and dune development for at least 5 years following implementation, which will inform potential adaptive management decisions on how the treatments might be maintained or modified to ensure foredune evolution toward a more 'established' stage as part of the adaptive management process.

II.5.5 Summation

Shifting sands, dynamic dunes, and dust emissions are all natural processes that have been ongoing at the Oceano Dunes for thousands of years. Geologically, human activities are relatively recent in this landscape and have increased significantly in the past century. The dunes and related plant cover within the ODSVRA have been impacted heavily, particularly since the rise in vehicle activity in the 1960s. Prior to the establishment of the ODSVRA in 1982, recreational activities and vehicle traffic in the dunes was unmanaged and land use impacts were largely unmanaged. By 1985, most of the vegetated foredunes, nebkha, and incipient dune systems had been reduced to negligible cover (less than 1%).

In 2019, a 48-acre area within the foredune zone at the ODSVRA, which had been shown to have a highly emissive surface in 2013, was identified by CDPR, in consultation with the SAG and SLOAPCD, for restoration of a foredune ecosystem as a dust emissions mitigation measure. A restoration plan was developed using several planting, seeding, and straw cover treatments to stimulate foredune development. After two years of development, all treatments are performing positively on most performance metrics and appreciable incipient dune development is underway in most treatments. Observation and evaluation of the restoration site responses will continue through at least 2025.

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II.6 Modeling of Particulate Matter Emission and Dispersion in the Atmosphere

II.6.1 General Statement

The objective of this chapter is to provide a concise overview of current understanding of the physics and modeling of particulate matter dust emission and dispersion in the atmosphere. Included as well is discussion of the models most appropriate for use in the design, placement, and evaluation of dust control measures. This chapter builds on previous chapters of the report, including those describing the underlying science of dust emissions (Sec. II.2) and dust controls (Sec. II.3).

II.6.2 Background on the Science: Modeling Dust Emissions

Particulate matter dust in Earth's atmosphere is a dominant aerosol, and on a local to regional scale, emission of dust can degrade air quality below accepted regulatory health-based standards. Understanding the process of dust emission from sediments (e.g., dune sands), as well as the environmental controls on that process, remains a scientific challenge. This section reviews the critical elements of the dust production system, focusing on the process components at the interface between the atmosphere and the surface. It will review and discuss our current understanding of the threshold of dust entrainment, the vertical flux of dust from susceptible surfaces, and the different ways the surface itself affects the entrainment process and particle flux. The discussion will focus on sand-dominated systems as opposed to dust emitting areas typical of inland desert environments (e.g., playas, topographic depressions) that are rich in clay and organics and have various amounts of sand-sized particles, except for providing a comparison of the range of emission rates associated with desert source areas versus emission rates from dune systems.

Models of dust emission will be presented within the context of topical sub-sections.

II.6.2.1 Entrainment and Saltation

II.6.2.1.1 Thresholds of Entrainment for Sand and Dust

Winds capable of entraining particles from a surface are invariably turbulent. This turbulent air flow creates a shearing stress (N m^{-2}) across the surface. If this shearing stress reaches sufficient strength, it can cause the freely available particles to move, i.e., to be entrained into the flow. The entrainment occurs when the shearing stress exceeds the resistive forces acting to keep particles in place. For sand-sized particles (63 µm to 2 mm diameter) in a dry state, the main resistive forces are created by gravity, the magnitude of which will be a function of the particle volume and its density, and whether the particle is sheltered from the flow by its surroundings. As particle size decreases (<63 µm diameter) an additional set of forces begin to add resistance against entrainment by the shearing stress. The forces resisting motion of small particles are cohesive in nature (e.g., electromagnetic attraction, van der Waals force).

The presence and amount of liquid water in the form of films or bridges between particles is a critically important control on particle entrainment as the binding energy created by moisture resists the shearing stress of the flow to entrain the particle. Entrainment is seldom attained if the percent of liquid water content reaches 4%, as determined gravimetrically from the difference between the mass of sand plus water versus the mass of just the sand, but it has been observed even under conditions of high moisture levels (Namikas and Sherman, 1995). This issue is further discussed in Chapter II.3, Dust Controls.

II.6.2.1.2 Dust Emissions by Saltation

Research on the emission of dust-sized particles from surface sediments and the critical link to the saltation (surface movement of particles) process began in the 1970s with the pioneering work of Gillette and colleagues (e.g., Gillette et al., 1972; Gillette and Goodwin, 1974; Gillette, 1977). From dimensional analyses it can be shown that the kinetic energy flux of saltating particles, which is derived from the shearing stress driving the particles, is the major pathway bringing energy to the soil surface. Shao et al. (1993) used this framework to develop a dust emission model that links the emission of dust-sized particles from the surface with the kinetic energy of the saltating particles, which is modulated by the resistive or bond strength of the sediments being impacted by the saltating particles.

The flux of dust-sized particles, expressed as a function of particle diameter is, according to Shao (2004), a function of the fraction of dust freely available (not bonded in the sediment), the dust particles aggregated together (bonded together or to larger particles), the bulk density of the sediment, and the sediment (or soil) plastic pressure (a measure of how strong the soil particles are bound together by the moisture present), with the driving force being the horizontal saltation flux, which is a function of the shearing stress of the wind.

Experiments using portable wind tunnels (e.g., Nickling and Gillies, 1989; Houser and Nickling 2001a, b) and newer dust emission measurement instruments (e.g., PI-SWERL, Etyemezian et al., 2007; Sweeney et al., 2008) on real world surfaces have shown that the flux of dust (F) is proportional to the shearing stress (u_*) expressed as a power function, i.e., with F increasing as u_* to the power of n varying between 2 and 5, but all field data show considerable scatter. Simply put, emission of dust from a given surface strongly depends on wind speed over that surface, along with other factors that modulate the susceptibility of dust particles to emission by this wind.

II.6.2.1.3 Origin of Dust-Sized Particles in Sand-Dominated Environments

Dune systems have been identified as sources of dust, and mechanisms of dust production involve the creation of fine dust particles emitted during active saltation of dune sand because of: (1) abrasion by particle-to-particle impacts that split or splinter (spall) to form dust-sized particles (Kuenen, 1960; Bristow and Moller, 2018; Swet et al., 2020); (2) particle-to-particle collisions that remove clay coatings (Bullard et al., 2004, 2007; Bullard and White, 2005); and (3) entrainment and resuspension of loose dust particles from the sand surface (Swet et al., 2019). At the Oceano Dunes, Huang et al. (2019) suggested that abrasion of feldspar grains and removal of clay coatings on quartz sand grains are the dominant mechanisms for dust emission.

Laboratory experiments by Swet et al. (2019, 2020), however, indicated that removal of clay coatings and loose dust resuspension are the primary mechanisms for dust emissions within undisturbed surfaces at the Oceano Dunes, whereas the contribution of abrasion (even from feldspar grains, which are less hard than quartz grains) is negligible.

II.6.2.2 Dispersion Modeling

In developing a model for dust emissions and transport from the Oceano Dunes State Vehicular Recreation Area (ODSVRA), it is necessary to have data that characterize all aspects of the dust emission process. Dispersion modeling is needed to aid in understanding how the emissions released during the saltation process contribute to air quality degradation at monitoring sites, as well as to provide a way to identify the source areas for the particles and the relative contribution of the source areas to the measured airborne PM_{10}. Other chapters (i.e., II.2 Dust Emissions and II.7 Air Quality) describe these relevant data sources, which include wind speed patterns, surface characteristics, and landforms and their distribution in the landscape. Models that are developed to integrate these data sources can predict the concentration and mass of dust emitted from complex surface areas within a geographical setting such as the ODSVRA. This section will describe the models used, and the methods used to acquire the data to run those models.

Dispersion modeling uses mathematical formulations to characterize the atmospheric processes that disperse particles emitted by a source. Based on emissions and meteorological inputs (e.g., https://www.epa.gov/scram/air-modeling-observational-meteorological-data), a dispersion model can be used to predict concentrations of particles at selected downwind receptor locations. It also uses equations that describe the atmosphere, and chemical and physical processes within the plume of particles being transported by the wind. The mathematical treatments of dispersion in models are in all cases a simplification of the actual physical process involved, not least because the process is inextricably linked to turbulent processes that must be simplified to make the calculations manageable. Four physical frameworks have been developed to simulate the dispersion process of particles in the atmosphere: box model, Gaussian plume, Lagrangian particle dispersion, and Computational Fluid Dynamics (CFD). These four model types will be described, and their strengths and weaknesses noted. Because emitted dust particles associated with earth minerals are chemically inert, the focus of modeling is on the dispersion of such inert particles rather than the negligible chemical transformations that they may experience while airborne.

II.6.2.2.1 Box Models

Box models are based on the conservation of mass. The area to be modeled is treated as a box that allows inputs and outputs into a control volume but not complex processes (e.g., chemical transformations) that may occur within that volume. This approach requires the input of simple meteorology and emissions data and the movement of particles in and out of the box is allowed. The inside of the box is not defined, and the air mass (volume) is treated as if it were well mixed and pollutant concentrations uniform throughout. Such box models are unsuitable for modeling particle concentrations within a local environment, where concentrations and thus particle dynamics are highly influenced by local changes to the wind field and emissions. This type of model, therefore, has limited utility at the ODSVRA, due to the influence of local topography, vehicle activity, and vegetation islands.

II.6.2.2.2 Gaussian Plume Models

Gaussian models are based on a Gaussian distribution of the plume in the vertical and horizontal directions under steady state conditions. The Gaussian distribution is a continuous function that approximates the binomial distribution of events. The Gaussian distribution is commonly referred to as the "normal distribution" and described as a "bell-shaped curve".

Mixing height is the maximum height that rapid vertical mixing takes place in the atmosphere. The width of the plume is determined by the standard deviation of the lateral concentration distribution (σ_y) and the standard deviation of the vertical concentration distribution (σ_z), which are defined either by atmospheric stability classes (Pasquill, 1961; Gifford Jr., 1976) or travel time from the source. Larger values of σ_y and σ_z (usually at greater distances from the source) represent a plume with a widespread and low peak (height); smaller values represent a plume that is narrower with a higher peak.

Gaussian models, while the most commonly used, are not without limitations. This type of model assumes that wind speed and direction are constant, emission rates are constant, the terrain is flat, particle deposition is negligible, and the shape of the plume is conical. Regardless, Gaussian models have proven to be accurate within 20% for predicting particle concentrations at ground level at distances less than 1 km, and accurate within 40% for elevated emissions when tested under conditions close to ideal (Reed, 2005). This type of model also has limited utility at the ODSVRA due to the variable conditions described above.

II.6.2.2.3 Lagrangian Particle Models

Lagrangian models define a region of air as a volume containing an initial concentration of particles. A Lagrangian model then follows the trajectory of this volume as it moves downwind. The concentration of particles as the volume moves is the product of the source term, i.e., the emission rate of particles from a particular source, and a probability density function (PDF) that defines the change between positions. The PDF is used to specify the probability of the random variable (e.g., dust concentration, wind speed, turbulence intensity) falling within a particular range of values, as opposed to taking on any one value. In the context of atmospheric diffusion, the PDF is designed to incorporate changes in concentration due to the mean fluid velocity, the turbulence of the wind, and molecular diffusion. A Lagrangian model uses meteorological data to calculate the variance of the wind velocity fluctuations and Lagrangian autocorrelation function. This function is the correlation in time that successive velocities along the path and throughout the duration of particle travel are related. This function may therefore be interpreted as the extent to which a particle “remembers” its velocity between time zero and time *t* (Daoud et al., 2003). The farther apart in space that particle velocity is compared between reference points, the greater the difference between them will be. As Lagrangian particle models calculate the diffusion characteristics using semi-random numbers, they are not confined by stability classes as are Gaussian dispersion models. The Lagrangian modelling approach is preferred for the ODSVRA.

II.6.2.2.4 Computational Fluid Dynamics Models

Computational fluid dynamic (CFD) models provide complex analysis of fluid flow based on conservation of mass and momentum by resolving the Navier-Stokes equations using finite difference and finite volume methods in three dimensions. The Navier-Stokes equations describe the motion of viscous fluids and arise from Newton's second law (i.e., the acceleration of an object depends directly upon the net force acting upon the object, and inversely upon the mass of the object). The Navier–Stokes equations are used to describe the physics of many phenomena of scientific and engineering interest including the flow of wind over surfaces. These models have the potential for great utility at the ODSVRA, especially in the evaluation of the design and projected effectiveness of foredune projects (Chapter II.5). While CFD models are typically considered to provide the most accurate descriptions of fluid and particle flow, especially across complex topography, they are computationally very expensive to execute. Therefore, they are typically only used for modeling relatively small areas (e.g., a specific section of foredunes).

II.6.3 Description of the Problem at the ODSVRA

The Stipulated Order of Abatement (SOA) requires a substantial reduction in emissions from the ODSVRA. In order to attain that goal, implementation of dust controls is required. (Chapter II.3 describes dust control strategies appropriate for use at the ODSVRA.) Of critical importance is the determination of optimal locations for such controls, and predictions of how much control can be realized from the various strategies available. Knowledge of how location, size, and type of dust control measures affect actual air quality, expressed as PM_{10} emissions, can allow for the most efficient implementation of dust control measures that will use the most appropriate strategies and locations to realize progress towards the SOA goal. Modeling has been used to address these two issues.

Collection of air quality data relevant to the ODSVRA has been done by the SLOAPCD, using two monitoring stations known as Mesa2 and CDF. These two stations are located generally downwind (inland) from the ODSVRA. Data from the stations show air quality expressed as the mass concentration of PM_{10} at these locations. The models used thus far to predict emissions from the various dust control strategies have been verified by data collected from these stations. Such models establish confidence in the prediction of how various dust control measures implemented at various locations can be expected to reduce PM_{10} emitted from the dune area.

Of importance, then, is the development and implementation of models that are relevant to the topography and wind conditions of the ODSVRA. Such a model has been developed, and is described in the following section, along with the strategy for collection of the data to inform the model.

II.6.4 How the Science is Being Applied to the Problem: The DRI-LPD Model

This section will describe the Desert Research Institute (DRI) Lagrangian Particle Dispersion (DRI-LPD) model that is used to provide estimates of mass emissions from the ODSVRA as well as predictions of PM_{10} concentrations at downwind receptor sites such as CDF and Mesa2, which are PM_{10} monitoring stations operated by the SLOAPCD. The quantification of mass emissions (metric tons PM_{10} per day) and concentration (μg m^{-3}) of PM_{10} using the DRI-LPD model is an accepted method for such purposes as stated in the SOA. DRI's rationale for this modeling approach will be presented.

II.6.4.1 Description of the Model

In developing a model for dust emissions and transport from the ODSVRA, the local landscape over a range of length scales (i.e., ~10 m – 10 km) needs to be considered due to the complexity of the dune topography and changes in surface characteristics over relatively short distances. Within a distance of less than 10 km there are changes from ocean to beach, to bare dunes with vegetation islands, to vegetated dunes, to relatively flat surfaces being farmed, and finally to the topographic rise of the Nipomo Mesa with its patchwork mixture of vegetation and urban developments. To successfully apply an emission and dispersion model in this setting requires information on the fine scale of the emissions, winds, surface characteristics, and dispersion processes.

Recognizing the need to adequately simulate emission and transport of particulate matter from the ODSVRA to areas downwind at this range of scales, Mejia et al. (2019) developed a very-high resolution measurement-based model for predicting concentrations of PM_{10}. The Mejia et al. (2019) model uses the CALifornia METeorological model, CALMET (Scire et al., 2000), using a grid size of 20 m × 20 m to help resolve the detailed flow over and around the dune field, together with the larger scale kinematical and channeling effects of the terrain and slope flows. CALMET estimates the shearing stress generated by the wind on each grid cell in the modeling domain, which is used to drive the emission relationship in each grid cell. The wind field data are coupled with a Lagrangian Stochastic Particle Dispersion Model (LSPDM). The LSPDM simulates the dispersion of particles based on Bellasio et al. (2017) but modified by Mejia et al. (2019) to optimize its performance in the physical setting of the particular coastal dune environment at the ODSVRA. This is achieved, in part, by using a modeling approach that accounts for the stochastic nature of the turbulence via a probability density function (i.e., the PDF for turbulence).

II.6.4.2 Data Collection for the Model

The underlying emission grid in the Mejia et al. (2019) model is based on measurements of emissivity of the sand dune surfaces using the PI-SWERL instrument (Etyemezian et al., 2007, 2014) (Fig. II.6.1).

Figure II.6.1. *The PI-SWERL at a test location in the riding area of the ODSVRA.*

Emissivity measurements have been made following a standardized set of protocols that have been maintained from 2013 through to 2020 and will be continued into the future. For the testing carried out at the ODSVRA, the PI-SWERL was operated with a set sequence of target revolutions per minute (RPM) values (2000, 3000, and 3500, named the "Hybrid 3500" test). Dust emissions at each of the three steps where RPM is held constant are calculated by averaging the 1 second dust concentrations over the duration of the step. The pertinent equation is provided in Appendix II.6.A, at the end of this chapter.

The measurement of emissivity of the sand surfaces of the ODSVRA from 2013 through to 2019 has included all or a portion of the measurement grid with the measurements typically completed in five days, weather permitting. Each PI-SWERL Hybrid 3500 test results in three paired values of E (emissions) not all of which may pass a quality control screening. The resulting grid of emissions across space forms the basis of the emission grid used in the dispersion modeling.

The PI-SWERL emissivity measurements are point measurements across a very large spatial domain. To fill in measurements where they are lacking, an interpolation scheme was developed to create an emission relationship for each of the 20 m by 20 m grid cells that are modeled using the DRI-LPD model.

In addition to PI-SWERL emissivity data, meteorological measurements are also incorporated into the model. These include surface meteorological data collected at instrumented towers within the ODSVRA and at an offshore buoy site. They also include upper air meteorological data obtained from the North American Regional Reanalysis Model and the nearby Vandenberg National Weather Service sounding site (CPDR, 2019, PMRP). Data collected via SODAR (sonic detection and ranging) at a location near the ODSVRA are also used to constrain model meteorology for years after 2019.

II.6.4.3 How the Model is Used

Mejia et al. (2019) report good agreement between the model-derived values of PM_{10} and measured values at selected receptor sites (i.e., CDF and Mesa2), but model estimates tend to show a slight bias for days with high measured PM_{10}. The model of Mejia et al. (2019) for the ODSVRA dust emission and transport system provides a useful and efficient tool to study the impact of dust reduction strategies on downstream dust dispersion. It is used by the California Department of Parks and Recreation (CDPR) to evaluate the incremental changes in total mass emissions (e.g., metric tons PM_{10}/day) and mass concentration (e.g., PM_{10} µg m^{-3}) that result from the actions taken to reduce dust emissions from the ODSVRA through the application of various control strategies. Accuracy of the Mejia et al. (2019) model for determining PM_{10} emissions and concentrations at the ODSVRA has been verified through comparison to observed concentrations at receptor sites (CDPR, 2020, ARWP).

II.6.5 Summation

Modeling is a critical tool in the ability of the CDPR to implement dust control strategies in such a way as to optimize air quality benefits to the areas downwind of the ODSVRA. Models that address the particular conditions of the ODSVRA site, including topography, emissivity, existing vegetation, and the impacts of vehicle activity, are the most useful in allowing for the efficient and effective placement of dust control measures that can be consistent with the mission of the ODSVRA as well as progressing towards attainment of the SOA goals.

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Appendix II.6.A PM_{10} Dust Emissions from PI-SWERL

The following equation is used to calculate PM_{10} dust emissions from PI-SWERL surface measurements:

$$E_i = (C_{DT,i} \times (F_i / (60\times1000)) / A_{eff}$$

where E_i is the emission of PM_{10} in units of mg m^{-2} s^{-1} at each RPM step $C_{DT,I}$ is the average PM_{10} concentration in mg m^{-3} (during the times that the RPM is held constant), F_i is the clean air flow rate (m^3 s^{-1}) in (and out of) the PI-SWERL chamber, and A_{eff} is the effective area of the PI-SWERL annular blade (0.035 m^2 as recommended by Etyemezian et al., 2014). The emissivity relation for a test location is defined by the three set point RPM values that are converted to shear velocity (u_*, m s^{-1}) by the relationship provided by Etyemezian et al. (2014):

$$u_{*,eff} = C_1 \times \alpha^4 \times RPM^{C2/\alpha}$$

where C_1 is a constant equal to 0.000683 and C_2 is a constant equal to 0.832, α is dependent upon the surface roughness and its value is assigned based on the information provided in Table 2 of Etyemezian et al. (2014). For sandy surfaces tested with PI-SWERL at the ODSVRA, a value of 0.98 is used. The emissivity relation is derived for a test by using non-linear least squares regression to produce the best fit equation $F=au_*^b$ where the a and b values are the coefficients from the regression.

II.7. Air Quality

II.7.1 General Statement

The Scientific Advisory Group (SAG), for the implementation of the Stipulated Order of Abatement (SOA) at the Oceano Dunes State Vehicular Recreation Area (ODSVRA), is charged with advising the California Department of Parks and Recreation (CDPR) on the best ways of attaining control of dust emissions from the Riding Area of the ODSVRA. Dust, for the purpose of the SOA, is defined as PM_{10}, or particulate matter less than 10 microns in aerodynamic diameter. Therefore, this chapter on Air Quality only considers PM_{10}, rather than any other components of airborne material that may affect air quality. Furthermore, it limits discussion to methods of controlling PM_{10} emissions in a coastal dune environment that has been impacted by vehicle activity at the ODSVRA rather than of any other location or type of impact.

This chapter will evaluate studies that contribute to the understanding of PM_{10} air quality associated with dust emissions from coastal dunes. This chapter also provides context on how the science of PM_{10} air quality affects relevant dust control strategies. (Specific dust controls are described in further detail in Chapter II.3.)

II.7.2 Background on the Relevant Science

II.7.2.1 Early and Ongoing Ambient PM_{10} Studies at the ODSVRA

The generally dusty nature of the sand dunes found in the ODSVRA has been studied for over a decade, beginning with work conducted on the Nipomo Mesa by the San Luis Obispo County Air Pollution Control District (SLOAPCD) in 2007 (SLOAPCD, 2007). This study documented that PM_{10} concentrations in the area around the ODSVRA were higher than in any other area of the County, and that concentrations declined with distance downwind of the ODSVRA. Peak PM_{10} concentrations occurred on high wind days when winds blew from the ODSVRA to study site monitors. Mass and ion analysis of PM_{10} filters indicated that mineral material produced the largest contribution to ambient PM_{10} on these days.

SLOAPCD continued its work on monitoring dust emissions in this area in 2008–2010 (SLOAPCD, 2010). This study, which involved three independent research groups, found that (1) ambient PM_{10} downwind of the ODSVRA did not originate from an offshore source, (2) neither the ConocoPhillips facility nor agricultural fields were significant sources of ambient PM_{10}, (3) ambient PM_{10} impacting the Nipomo Mesa on high episode days consisted of fine particle size geological material transported from upwind areas, (4) the primary source of high PM_{10} concentrations on the Nipomo Mesa was open sand sheets in the dune areas of the coast, (5) open sand sheets exposed to vehicle activity emitted significantly greater amounts of PM_{10} than undisturbed sand sheets, and (6) vegetated dune areas emit few windblown particles. Areas of disagreement were discussed in critiques of the studies and included discussions of how wind speed was measured (CGS, 2010), how roughness was determined (Illingworth and Rodkin, Inc., 2010), and how data analyses were conducted (TRA Environmental Sciences, Inc., 2010). These critiques are ongoing, and the Scientific Advisory Group (SAG) has taken issue with the methods used in several of these critiques, which appear to have been skewed in favor of minimizing the perceived impact of off highway vehicles on the emission of PM_{10} (see Sec. II.7.2.3 below).

An additional study in 2012 after adoption of Rule 1001 (see Section II.7.2.2 below), also carried out by the SLOAPCD, was conducted with the goal of mapping the spatial extent and concentration gradient of the ODSVRA dust plume to better understand its impacts on the Nipomo Mesa and Oceano neighborhoods (SLOAPCD, 2013). Continuous PM_{10} monitors and wind sensors were deployed on the Nipomo Mesa and near the boundaries of the ODSVRA from March through May 2012. This study found that wind directions during high wind hours were uniformly from within a narrow arc between 289 and 295 degrees (i.e., WNW). These winds turn slightly northerly as flows move across the Nipomo Mesa. PM_{10} concentrations were found to diminish quickly with distance downwind of the ODSVRA. In the Oceano neighborhood, the PM_{10} concentration gradient was highest adjacent to the ODSVRA boundary and to Pier Avenue, due to track-out sand being resuspended by traffic, and it declined to background levels within 0.4 miles downwind of these facility boundaries.

Summaries of several of the studies described above are included in Appendix II.7.A of this chapter. Additional studies providing comprehensive overviews of past studies are included in the reference list (i.e., SLOAPCD, 2016, PM Overview; MIG, 2017, Dune Geology; CDPR, 2022, SOA History).

II.7.2.2 San Luis Obispo County Air Pollution Control District Rules and Orders

Evidence of higher levels of PM_{10} in the Nipomo Mesa than elsewhere in the SLOAPCD region, as described above, led to a focused effort on determining the source of that PM_{10}. Data from air quality monitors in the SLOAPCD area dating from 1995 show a consistently high level of PM_{10} associated with the CDF and Mesa2 monitoring stations. An initial evaluation of data from 2004-2005, as part of the Nipomo Mesa Phase 1 Particulate Matter Study, indicated the primary cause of those levels were northwesterly wind events carrying particulate matter from the Oceano Dunes State Vehicular Recreation Area (ODSVRA) (SLOAPCD, 2007). Based on this Phase 1 Study, the SCOAPCD Board in 2007 ordered additional studies to determine the reason for these high levels of dust, and to assess the impacts of vehicle activity on the emission of dust. The South County Phase 2 Particulate Study, which included 3 independent investigations to measure differences between riding and non-riding areas, showed that PM levels downwind of the ODSVRA were higher than from a control area. These conclusions led to the development of the Rule 1001 Coastal Dune Dust Control Requirements in 2011 (SLOAPCD, 2011, Regulation X). Rule 1001 requires implementation of dust control measures and air monitoring for coastal dunes where vehicle activity occurs. CDPR articulated its plans and timeline for emissions reductions projects, through publication of a Rule 1001 Particulate Matter Reduction Plan (PMRP) (CDPR, 2013, PMRP).

The continued acquisition of air quality data in the region led to disputes regarding the effective implementation of Rule 1001. In April 2018, CDPR entered into a legally binding Stipulated Order of Abatement (SOA) with SLOAPCD to outline specific steps to be taken to reduce PM_{10} emissions from the ODSVRA. A new SOA PMRP was also developed in 2019 to describe methods of implementing dust control (CDPR, 2019, PMRP). Air quality objectives were specified in the SOA, including requirements to meet federal ambient PM_{10} air quality standards of 150 µg/m^3; to meet State ambient standard of 50 µg/m^3; and to reduce baseline mass emissions by 50% as an initial target. The SOA also established a Scientific Advisory Group (SAG) to evaluate, assess, and provide recommendations on the mitigation of windblown dust from the ODSVRA.

Following its initial adoption in 2018, the SOA has been amended twice: first in 2019 to strengthen oversight over implementation of the SOA PMRP, and again in 2022 to extend the duration of the SOA PMRP (from 4 years to 6 years) and to clarify that the goal of dust mitigation measures is to "eliminate emissions in excess of naturally occurring emissions from the ODSVRA that contribute to downwind violations of the state and federal PM_{10} air quality standards" (SLOAPCD Hearing Board, 2018, 2019, 2022).

Effort was made to assure that scientific concerns regarding these and other various SLOAPCD rules and orders have been adequately addressed. A 2012 memo (CGS, 2012) critiques the SLOAPCD *South County Phase 2 Particulate Study* upon which Rule 1001 is based. The memo calls out deficiencies in how the relationship between wind speed and sand movement was calculated, challenges assumptions about the amount of vegetation present in the years prior to vehicle activity, and it raises certain other data analysis issues. A related CGS critique of the SOA and SOA PMRP was published in 2019 (CGS, 2019, PMRP Review). This critique called into question assumptions regarding the baseline data on which provisions of the SOA are based.

Summaries of several of the studies described above are included in Appendix II.7.A of this chapter.

II.7.2.3 $PM_{2.5}$ and PM_{10} Speciation Analyses

Because efforts to control emissions of PM_{10} from the ODSVRA have direct consequences for vehicle use in the dunes, it is not surprising that the determination of what is emitted from that area, and how much of it, is controversial. Though research in sandy environments strongly suggests that undisturbed and/or vegetated surfaces are substantially less emissive than surfaces subjected to the physical impact of vehicle activity (see references in Chapters II.2 and II.3), some members of the rider community have pushed for a series of studies seeking to demonstrate that vehicle activity has only a small (or negligible) impact on particulate matter dust emissions from the ODSVRA. We summarize the most influential of such studies here, along with the responses of the SAG and SLOAPCD to assertions of minimal vehicular effect.

In 2017-2018, two studies were conducted that sought to characterize the crystalline silica content of PM samples collected from the ODSVRA and from monitors operated by SLOAPCD (Forensic Analytical Lab, 2017, 2018). These studies concluded that the total quantity of the collected dust that was composed of crystalline silica (particles containing quartz, which is usually of sand derivation) was minimal. Crystalline silica is important in that such particles can become trapped in lung tissue, causing serious health problems. It also is most likely sourced from sand, although it may originate from stone, concrete, or mortar. These findings regarding the absence of crystalline silica were confirmed in a 2018 report from SLOAPCD (SLOAPCD, 2018, Crystalline Silica). Further silica sampling by SLOPACD in 2019 confirmed that ambient crystalline silica levels are below regulatory thresholds, though silica is detectable in almost all samples (SLOAPCD, 2019, Crystalline Silica).

A separate series of studies by atmospheric scientists at Scripps Institution of Oceanography (SIO) were commissioned to examine the composition of particulate matter downwind of the ODSVRA, with the specific goal of looking for sources of airborne PM_{10} dust originating outside of the ODSVRA, such as from marine sources or other terrestrial sources. The first of these studies (SIO, 2018) examined the composition of dust collected in Environmental Beta Attenuation Mass Monitor (E-BAM) samplers and concluded that DNA from marine microbes in seawater samples was found in onshore samples collected from wind fence accumulations and E-BAM filter strips. No difference in DNA sequences was found in riding area sand versus non-riding area sand. In the second study (SIO, 2020, Year 1 Report), a comparison was done of elemental mass contribution totals to SLOAPCD $PM_{2.5}$ Beta Attenuation Mass Monitor (BAM) measurements at CDF. The study reported that 43-62% of CDF BAM $PM_{2.5}$ could not be ascribed to specific elemental constituents. Elemental analysis also showed that $PM_{2.5}$ filter mass contained 4% to 7% sea salt, 26% to 46% mineral dust, and less than 6% organic matter. These results were used to support the argument that the BAM monitors severely overestimate elemental mass, and that mineral dust accounts for less than half of the emitted $PM_{2.5}$ from the area. In a follow-on study (SIO, 2020, Year 1 Supplemental Report), SIO reported that during 10 days on which 24-hour PM_{10} BAM measurements exceeded 140 µg/m^3, $PM_{2.5}$ filters averaged 38% less mass than $PM_{2.5}$ BAM measurements. X-ray Fluorescence (XRF) analysis of all $PM_{2.5}$ filters reported that mineral dust contributed 17% of mass and salt contributed 11%. On high PM_{10} days, mineral dust contributed 33% to gravimetric mass and salt contributed 7%.

At issue here is the comparability of E-BAM, BAM, and filter-based collection methods, as well as how PM was quantified, and what air quality standard should be used. The SAG commented on the SIO Year 1 report and supplement, and the SLOAPCD commented on the supplement, critiquing both the assumptions and methodology of these reports (SAG, 2020, SIO Review and SIO Supplement Review; SLOAPCD, 2020, SIO Review). Controversy remains, but of importance is the use of the $PM_{2.5}$ standard by SIO instead of the PM_{10} standard specified in the SOA, as well as the methodology used to determine particle composition.

SIO collected additional $PM_{2.5}$ and PM_{10} samples in spring 2021, and they reported on the analyses of these samples in a Year 3 interim report (SIO, 2021). In a review (SAG, 2021, Response to SIO), the SAG disputed three major aspects of this report: (1) its treatment of health and legal imperatives, (2) its assessment of the effects of vehicles on PM emissions, and (3) the inadequate justification provided for key analyses and interpretations. A review by SLOAPCD also noted significant issues with PM_{10} sampling methods (SLOAPCD, 2021, SIO Review). The SAG also expressed concern that the determination of mineral dust contribution rests on a series of untested assumptions regarding the interpretation of XRF analytical results. A recent Desert Research Institute (DRI) report, "Examining Dust Emissions and OHV Activity at the ODSVRA" (Gillies et al., 2022), presents strong evidence, based on years of data collection, supporting the current understanding of the effect of vehicles.

A summary of SIO speciation analyses was recently published as a new peer-reviewed article (Lewis et al., 2023). As with the previous SIO reports, this new article asserts that the ODSVRA (and associated vehicular impacts) are a relatively minor contributor to total $PM_{2.5}$ and PM_{10} concentrations measured at sites immediately downwind of the ODSVRA. This assertion is based on XRF analyses indicating only a small fraction of total gravimetric mass is directly associated with an assumed elemental profile of "mineral dust" originating from the ODSVRA. This assumed elemental profile does not consider the actual mineralogy of ODSVRA dust; for example, the XRF-identified potassium component is assumed to be related to biomass burning despite evidence that Oceano sand contains roughly 50% feldspar (Huang et al., 2019), much of which is rich in potassium. In addition, the article characterizes roughly two-thirds of the gravimetric mass as "unidentified components," and the authors assert (without direct evidence) that these unattributed components are primarily associated with semi-volatiles rather than an ODSVRA-related source. Given these strong assumptions underlying the assertion of minimal ODSVRA contribution to $PM_{2.5}$ and PM_{10} dust, it is clear that further research is needed to better guide interpretation of speciation analyses to inform dust source attribution at the ODSVRA.

The SLOAPCD has considered the SIO reports and SAG reviews of these reports to inform its understanding on the contribution of ODSVRA dune-derived mineral dust to total PM_{10} concentrations, weighing these against other evidence of the role of vehicles on dust emissions (i.e., as described in Chapter II.2 Emissivity and Chapter II.6 Modeling). SLOAPCD is continuing to carry out its own PM_{10} sample collection and analysis. These include speciation results obtained through the Nipomo Mesa Phase 1 and Phase 2 Particulate Matter Studies (SLOAPCD, 2007, 2010), as well as more recent sampling and analysis efforts that are expected to be published soon.

Summaries of several of the studies described above are included in Appendix II.7.A of this chapter.

II.7.3 Description of the Problem at the ODSVRA

It is undisputed that dust of a regulated character (PM_{10}) is emitted from the ODSVRA. The SOA is the framework that is being used to determine how to minimize the health effects of that dust. The SOA originally required that mitigations be put in place such that the mass of dust originating from vehicle riding areas within the ODSVRA be reduced by 50% compared to a baseline year of 2013 (SLOAPCD Hearing Board, 2018). That target can only be attained if the amount of dust measured at the two SLOAPCD monitors at CDF and Mesa2 is in fact generated in large part by vehicle activity affecting the emissivity of the dune sands (Gillies et al., 2022). The 2022 SOA amendment, developed and adopted in response to the SAG's analysis of estimated PM_{10} emissions prior to significant vehicle disturbance (SAG, 2022), acknowledges this issue by clarifying that dust mitigation measures "be designed to eliminate emissions in excess of naturally occurring emissions from the ODSVRA that contribute to downwind violations of the state and federal PM_{10} air quality standards" (SLOAPCD Hearing Board, 2022). If the dust is emitted due to other factors, or in the absence of vehicle activity, implementation of dust control measures focused on stabilizing the dunes to mitigate the effects of vehicle activity (as discussed in Chapter II.3 Dust Controls) would not be expected to attain the target of the original SOA, much less to attain State and Federal PM_{10} standards. Therefore, the challenges of understanding air quality at the ODSVRA are linked to accurate documentation of both quantity and quality of the dust that is captured by the monitors.

The problem of air quality at the ODSVRA, then, is being addressed with studies that seek to determine accurately ***what*** is emitted from the area (the nature of the particles captured in monitors), ***how much*** dust is produced, and whether the dust can be ***attributed*** to vehicle effects on surface emissivity at the ODSVRA. In the chapters and sections above, the background science has been reviewed, and notation made of what problems face managers relating to how these three factors can be addressed. Moving forward, the issues of quality, quantity, and attributability will continue to be in the forefront, requiring patient and rigorous implementation and interpretation of science-based studies.

II.7.4 How the Science is Being Applied to the Problem

Analysis to characterize the quality, quantity, and attributability of air quality violation criteria is ongoing. The studies cited in the Background section of this chapter (Section II.7.1) will no doubt be continued until the end of the SOA period in 2025. As the stakes are high (riding advocates seek one set of conclusions, and air quality advocates and downwind residents seek another), it is important that the best science be applied. Some key considerations for decisions regarding air quality at the ODSVRA are provided below.

II.7.4.1 Qualifying the Chemical Nature of the PM_{10} Collected in the SLOAPCD Filters

Because the SLOAPCD is the entity responsible for documenting attainment of the SOA targets, the methodology for analyzing the chemical characteristics of the dust collected in the Mesa2 and CDF monitoring stations must be standardized. The SAG and the SLOAPCD should clearly articulate standards of analysis consistent with State and Federal regulatory guidance, and firmly reject other strategies and methodologies that may be suggested or demanded by others. Having such regulatory guidance is an important foundation for this discussion and should be used rigorously.

II.7.4.2 Quantifying the Amount of PM_{10} Collected in the SLOAPCD Filters at Mesa2 and CDF

Collection strategies to quantify the mass concentration and the chemical constituents of the particles of dust or other particulate matter emitted from an area are well-understood and are, in some cases, specified by State and Federal regulations. Deviation from these standardized collection strategies should be resisted. Where the SOA spells out the kind of air quality (i.e., size of PM) that is being sought under its terms, these goals should be adhered to without distraction. An exception is the issue of the modification of the SOA goals, which has been suggested by the SAG (SAG, 2022), and which was adopted as part of the SOA amendment in 2022 (SLOAPCD Hearing Board, 2022). This modification is in proportion of reduction, and relates most closely to attributability, considered next.

II.7.4.3 Attributability of Air Quality Impairment to Vehicle Activity on the ODSVRA

Although it is impossible to understand past conditions with complete accuracy, the SAG has concluded a scientifically sound evaluation of attributability of dust emissions contributing to the degradation of air quality that allows for a rational evaluation of the amount of dust attributable to vehicle impacts in the ODSVRA (SAG, 2022). This evaluation is based on a monitoring campaign conducted during the period when vehicles were excluded from operation at the ODSVRA in 2020, and on an evaluation of historical vegetation extent in the ODSVRA regions determined from air photographs. Together, these studies have allowed for a scientifically based estimate of the amount of dust emission affecting air quality that can be attributed to vehicle impacts in the present day by comparing modeled emission rates from surfaces unaffected by heavy vehicle activity and the amount of vegetation present in the area prior to the initiation of heavy vehicle activity. This analysis relies on documentation of differences in emissivity between surfaces impacted by vehicles and surfaces unimpacted in this way, supporting the contention that it is surface modification through vehicle impact that is the dominant factor rather than the direct physical production of dust by the movement of vehicles that contributes to the degradation of air quality (Gillies et al., 2022).

This analysis is covered more thoroughly in the emissivity and modeling chapters of this report (Chapters II.2 and II.6, respectively) and is mentioned here to support the view of the SAG that the SOA can best be implemented for the benefit of air quality by careful adherence to the goal of improving air quality only to the extent that it can be demonstrated that human activity has led to degraded air quality. The inherently dusty nature of sparsely vegetated sand dunes neither can, nor should, be addressed in its entirety through air quality mitigation measures. Rather, science-based determination of the attributability of air quality degradation to human activity should guide implementation of dust control measures.

II.7.4.4 Attributability of Air Quality Improvements to Dust Control Measures at the ODSVRA

In addition to examining how vehicle activity contributes to degradation of air quality, studies have also been performed to understand how dust control measures have improved air quality at the ODSVRA. These studies look at changes in airborne PM_{10} over time, while also controlling for natural variability in wind speed that may confound analyses of PM_{10} trends. Several of these studies have already been described in Chapter II.2. Here, the key results relevant to long-term air quality trends are presented again.

One approach that has been used is to compare total PM_{10} to total “wind power density” (WPD, W m^{-2}) (i.e., TPM_{10}:TWPD), which provides a proxy for changes in PM_{10} that accounts for variations in wind speed. An analysis published by DRI (DRI, 2021, Increments of Progress) showed that there has been a reduction in the TPM_{10}:TWPD ratio over time as an increasing number of dust mitigation treatments have been installed, suggesting an overall reduction in PM_{10} emissivity. Another approach, referred to as “difference-in-differences,” compares the ratio of PM_{10} concentration at the CDF monitoring site (subject to vehicular impacts) to PM_{10} concentration at the Oso Flaco monitoring site (undisturbed). Similar to the TPM_{10}:TWPD analyses, the difference-in-differences analyses provide further evidence for air quality improvements resulting from dust mitigation efforts (SLOAPCD, 2022).

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Appendix II.7.A Summaries of Studies

Summaries are provided in the order in which they are first cited within Chapter II.7 above. The citation format is provided in parentheses in the header for each summary below.

Nipomo Mesa Particulate Study, San Luis Obispo County Air Pollution Control District, 2007 *(SLOAPCD, 2007)*

A year-long particulate matter monitoring study was conducted by the San Luis Obispo County Air Pollution Control District (SLOAPCD) in April 2004 through March 2005 to determine the composition and extent of ambient PM_{10} concentrations measured downwind of the ODSVRA.

South County Phase 2 Particulate Study, San Luis Obispo County Air Pollution Control District, 2010 *(SLOAPCD, 2010)*

The contribution of vehicle activity at the ODSVRA to downwind PM_{10} concentrations was evaluated by monitoring for sand flux on the riding area using a Sensit, a Cox sand catcher, and a BSNE sand trap. The study also examined ambient PM_{10} concentrations measured downwind of the riding area, both at a clean air control site south of the riding area and downwind of the ConocoPhillips petroleum refinery adjacent to the ODSVRA. These measurements and soil sample data were collected within and near the ODSVRA between January 2008 and March 2009. These studies, conducted by three independent research groups, found that (1) ambient PM_{10} downwind of the ODSVRA did not originate from an offshore source, (2) neither the ConocoPhillips facility nor agricultural fields were significant sources of ambient PM_{10}, (3) ambient PM_{10} impacting the Nipomo Mesa on high wind episode days consisted of fine material of geological origin transported from upwind areas, (4) the primary source of high PM_{10} concentrations on the Nipomo Mesa was open sand sheets in the dune areas of the coast, (5) open sand sheets exposed to vehicle activity emitted significantly greater amounts of PM_{10} than undisturbed sand sheets, and (6) vegetated dune areas do not emit wind-blown particles. However, the finding regarding lack of particulate matter emissions from vegetated surfaces was based on sampling only within fully vegetated areas; the study did not address whether partially vegetated areas produce particulate emissions.

Evaluation of the San Luis Obispo County Air Pollution Control District report, "South County Phase 2 Particulate Study," dated February 2010, California Geological Survey, 2010 *(CGS, 2010)*

This critique of the South County Phase 2 Particulate Study raised questions regarding several reported correlations. Among the questions raised, the critique expressed doubt about the comparability of wind speeds measured at different instrument heights at the California Division of Forestry (CDF) and Oso Flaco monitoring stations, which in turn led to concerns about attempts to compare the actual threshold wind speeds for the onset of saltation at the riding area relative to the onset of saltation upwind of Oso Flaco. The critique mentions that fine silt collected on fence wires on the upwind side of the dune preserve near the shoreline suggest an offshore source of PM_{10}, which was not investigated in the Phase 2 Study.

Comments on Meteorological Data Used for the South County Phase 2 Particulate Study, Illingworth and Rodkin, Inc., 2010 *(Illingworth and Rodkin, Inc., 2010)*

This analysis reviewed the wind data collected at the CDF, Oso Flaco, Mesa2, and Grover Beach monitoring sites during the South County Phase 2 Particulate Study. In the Phase 2 Study, CDF wind data were used to compute sand flux within the beach and interior dunes of the ODSVRA riding area. The Illingworth and Rodkin analysis criticizes the use of CDF wind data for this purpose, because the CDF monitoring site is 2.5 miles downwind of the shoreline. Instead, the analysis recommends using the Oso Flaco wind data for this purpose, because this site is only 1.5 miles from the water's edge. The analysis also questions the selection of the roughness height based on literature values instead of attempting to quantify the roughness height in the area where sand flux measurements were actually taken.

Re: Published Phase 2 Report data does not support claims of association between Oceano Dunes State Vehicular Recreation Area visitor numbers and PM_{10} downwind, TRA Environmental Sciences, Inc., 2010 *(TRA Environmental Sciences, Inc., 2010)*

This analysis focuses on a statement made by the SLOAPCD Air Pollution Control Officer in a 2010 letter to the CDPR Oceano Dunes Superintendent that "a statistically significant average of over 30% in PM_{10} levels at Mesa 2 [occur] on the 50 highest visitation days compared to the 50 lowest visitation days (PM study, Table 3.2)." The analysis, using visitor day data supplied by CDPR and 24-hour PM_{10} data provided by the SLOAPCD, concluded that (1) the statistical analysis performed by SLOAPCD was incorrect, and (2) a corrected statistical analysis performed by TRA Environmental Sciences resulted in no statistical correlation between visitation levels and 24-hour average PM_{10} levels.

South County Community Monitoring Project, San Luis Obispo County Air Pollution Control District, 2013 *(SLOAPCD, 2013)*

This study was designed to identify the area impacted by windblown PM_{10} emissions from the ODSVRA. In the study, a saturation monitoring network downwind of ODSVRA was installed and operated for a three-month period beginning in March 2012. The network consisted of 19 semi-portable PM_{10} monitors (E-BAMs) covering the Mesa area, bounded by Highway 1 on the west, Highway 101 on the east, Halcyon Road on the north, and agricultural fields on the south. This monitoring campaign was preceded by short-term PM_{10} monitoring at 4 public schools within and outside the study domain in 2011. Data from the public schools monitoring was used to inform the boundaries of the study domain. A second smaller saturation monitoring campaign was also conducted in 2012 in the Pier Avenue area with four E-BAMs to better define the area impacted by re-entrained street sand on adjacent neighborhood air quality.

Study data demonstrated a relatively consistent pattern for the path of the dust plume from ODSVRA that impacts the Nipomo Mesa on high wind days. The approximate centerline of the plume typically followed a path inland through the CDF site following the prevailing northwesterly winds. Wind directions turned slightly southward beyond the CDF site and diverged as winds passed over Nipomo. Peak PM_{10} concentrations were greatest at the upwind edge of the Mesa and declined slowly with distance beyond the CDF site. In the Pier Avenue area, PM_{10} concentrations were highest near Pier Avenue, lower at a site adjacent to the beach, and declined to background levels within 0.4 miles downwind of Pier Avenue.

Overview of Scientific Concerns Regarding Rule 1001 by the San Luis Obispo County Air Pollution Control District, California Geological Survey, 2012 *(CGS, 2012)*

This memo critiques the SLOAPCD *South County Phase 2 Particulate Study* upon which Rule 1001 is based. The memo highlights four deficiencies in the Phase 2 study:

1. The relationship between wind speed and sand movement is incorrect, as wind speeds in the study were measured at the CDF monitor, where wind speeds are lower than those measured within the ODSVRA.
2. The study reports that there is not less vegetation on the dunes than prior to vehicle recreation on the dunes, whereas aerial photographs of the area in the 1930s show 20% less vegetation than exists currently in the riding area.
3. The study reports that protective crusts on the dunes have been destroyed by vehicle use, whereas no such crusts exist such as are found at Owens Lake, an analogue cited in the study.
4. The study shows a slight correlation between high ODSVRA attendance days and elevated PM_{10} days when no correlation existed.

Review of Stipulated Order of Abatement 17-01 as It Applies to the Development of the Particulate Matter Reduction Plan and Airborne Dust Detected on the Nipomo Mesa, San Luis Obispo County, California, California Geological Survey, 2019 *(CGS, 2019, PMRP Review)*

This critique focused on the policies proposed in the SOA Particulate Matter Reduction Plan (PMRP). Primary criticisms of the SOA PMRP centered on the lack of a definition of the baseline period in 2013 for use in quantifying progress toward emission reduction, and deficiencies in the DRI modeling approach used to calculate ODSVRA emissions and resulting PM_{10} impacts at the CDF monitoring station. Identified deficiencies included the lack of a PM_{10} monitoring station near the center of the Nipomo Mesa against which to validate model performance and the lack of quantification and inclusion of PM_{10} emissions sources other than sand saltation on ODSVRA lands.

Determination of Airborne Crystalline Silica (Quartz) Exposure at Oceano Dunes State Vehicular Recreation Area, San Luis Obispo County, California, John W. Kelse, Industrial Hygienist, 2017 *(Forensic Analytical Lab, 2017)*

This paper presents results from filter samples collected by CDPR staff at the ODSVRA, along with filter samples presumed to have been collected by SLOAPCD staff at the CDF monitoring station. In the first sampling campaign, personal samplers meeting Occupational Health and Safety Administration workplace requirements were used to collect PM_4 samples from a worker and a recreationist performing typical activities within the riding area, and from stationary personal monitors operated at the S1 monitoring site, also within the riding area. These samples, collected over 6- to 7-hour periods on a low wind day in November 2017, were analyzed by X-ray diffraction (XRD) and found to contain crystalline silica below a 15 $\mu g/m^3$ detection level. In a second sampling campaign, samples presumed to have been collected by SLOAPCD at the CDF monitoring site on four days in April through June of 2017 were analyzed by infrared and XRD analysis. The sampling duration on these days was not reported. Three of the samples were found to contain from 10 to 20 µg/m^3 crystalline silica (quartz) and the fourth sample contained crystalline silica below an 8 µg/m^3 level of detection.

Determination of Airborne Crystalline Silica (Quartz) Exposure at Oceano Dunes State Vehicular Recreation Area and CDF Air Monitoring Site, 2391 Willow Road, Arroyo Grande, California, San Luis Obispo County, California, John W. Kelse, Industrial Hygienist, 2018 *(Forensic Analytical Lab, 2018)*

This study replicated the collection of airborne particulates for crystalline silica analysis that was performed in 2017 with the addition of filter samples being collected at the CDF monitoring station. Samples of total particulate and respirable (<4 micron) particulate were collected on March 8, 2018, over an 8-hour interval with moderate to high wind conditions, with personal samplers carried by a CDPR worker and a vehicle recreationalist, and with personal samplers mounted on the S1 tower and a tower at the CDF monitoring station. All filter samples were analyzed gravimetrically, and the respirable particulate samples were analyzed by XRD. None of the respirable quartz values was found to be above the level of detection which varied from 12 to 15 µg/m^3.

2019 Ambient Crystalline Silica Monitoring, San Luis Obispo County Air Pollution Control District, November 2019 *(SLOAPCD, 2019, Crystalline Silica)*

Building on results from a previous sampling campaign (SLOAPCD, 2018, Crystalline Silica), this report presents analyses of 26 PM_{10} filter samples from CDF that were analyzed for crystalline silica. This is the most comprehensive silica sampling campaign performed to date at the ODSVRA. This study showed that crystalline silica was present in most samples, but that concentrations of respirable crystalline silica did not exceed the Occupational Safety and Health Administration (OSHA) 8-hour workplace health-based standard nor the California chronic Reference Exposure Level (REL).

Scripps Study of Marine Contributions to Aerosol Particulates, Oceano Dunes State Vehicular Recreation Area, San Luis Obispo County, California, Scripps Institution of Oceanography, 2018 *(SIO, 2018)*

The focus of this study was to determine if marine-derived biological materials contributed to ambient particulate matter within the ODSVRA. Thirty-two samples of seawater, beach foam, beach and dune sand, and Environmental Beta Attenuation Mass Monitor (E-BAM) air filters were collected along a windward traverse extending from offshore waters to dunes beyond the boundary of the riding area between 2014 and 2016. Total DNA was extracted from each sample and sequenced for bacterial or eukaryotic community composition. Sequences were then clustered into predicted species based on sequence similarity. DNA from marine microbes in seawater samples was found in onshore samples collected from wind fence accumulations and E-BAM filter strips. No difference in sequences was found in riding area sand versus non-riding area sand. The numbers of biological and eukaryotic species found in E-BAM filter strips varied significantly. Diatoms, containing amorphous silica, were found on near-beach fencing, but not in dune sand samples.

First Year (2019) Summary Report: Investigation of Aerosol Particulates in a Coastal Setting, South San Luis Obispo County, California, Scripps Institution of Oceanography, 2020 *(SIO, 2020, Year 1 Report)*

This study was intended to quantify constituents of $PM_{2.5}$ collected in filter samples, compare $PM_{2.5}$ to PM_1 concentrations, test the efficacy of using Teflon filters for DNA analysis of ambient $PM_{2.5}$, and characterize photosynthetic activity of phytoplankton in waters offshore of the ODSVRA. $PM_{2.5}$ and PM_1 filter samples were collected for periods of several hours on consecutive days in May-June 2019 (20 days) and in September-October 2019 (12 days) at the CDF monitoring station, and at the S1 riding area monitoring site during the September-October campaign. These filter samples were analyzed by Fourier Transform Infrared spectroscopy (FTIR) for organic functional groups and by XRF for elemental constituents. Water samples were collected for DNA analysis of organic filtrate, and sand samples were collected for moisture analysis by an undefined method. Satellite images from the two campaign periods were evaluated for surface chlorophyll-a daily net primary production.

The FTIR analysis found that sea spray and motor vehicle exhaust comprised the majority of organic functional groups found on filters collected at the CDF and S1 monitoring stations. XRF analysis found that mineral dust was present in ambient filter mass and in re-entrained dust from sand. This analysis also found that re-entrained dust from sand samples contained more water than in filter samples. In comparing elemental mass contribution totals to SLOAPCD $PM_{2.5}$ BAM measurements, the study reported that BAM measurements exceeded total elemental mass by 43% to 62%. Elemental analysis also reported that $PM_{2.5}$ filter mass contained 4% to 7% sea salt, 26% to 46% mineral dust, and less than 6% organic matter. PM_1 organic matter mass contributions were found to be about half of those found in $PM_{2.5}$ filter samples. More sea salt and mineral dust were found in $PM_{2.5}$ samples collected at the S1 monitoring station than at CDF. Total mass constituents in S1 filters were found to be about three times those measured at CDF. DNA extraction found biological sequences in seawater samples, but not in air samples. Air samples contained fungal spores from a non-marine source and bacterium typically found in marine sediments. Only one seawater sample contained bacterium. Examination of satellite images showed the offshore waters to have high productivity and high variability of phytoplankton associated with upwelling events.

UCSD Supplemental Report 2020: Preliminary Results from May 2020 Aerosol Measurements, Scripps Institution of Oceanography, 2020 *(SIO, 2020, Year 1 Supplemental Report)*

In this study, PM_{10} filter samples were collected at a "beach" site within the ODSVRA riding area and $PM_{2.5}$ samples were collected at the CDF monitoring station between April 27 and May 17, 2020, during the COVID-19 riding closure period. The beach site was located approximately 100 meters from the mean high tide line to reduce exposure to dune sources, and seven samples were collected primarily during high wind/high PM afternoons due to power and support personnel limitations. Twenty-six samples were collected during afternoon and overnight hours at the CDF monitoring station. During this period, a $PM_{2.5}$ E-BAM was also operated at the CDF monitoring station, and a PM_{10} E-BAM was operated at the beach site. The $PM_{2.5}$ and PM_{10} filters were analyzed gravimetrically and by XRF. The CDF $PM_{2.5}$ filter masses averaged 26% less than the $PM_{2.5}$ E-BAM integrated hourly values recorded during the same run times. During 10 days on which 24-hour PM_{10} BAM measurements exceeded 140 µg/m^3, $PM_{2.5}$ filters averaged 38% less mass than $PM_{2.5}$ E-BAM measurements. XRF analysis of the $PM_{2.5}$ filters reported mineral dust contributed 17% of mass and salt contributed 11%. On high PM_{10} days, mineral dust contributed 33% to gravimetric mass and salt contributed 7%. Dust and $PM_{2.5}$ mass in the filter samples correlated strongly (R^2~0.8), but salt and $PM_{2.5}$ mass were only weakly correlated (R^2~0.3). At the beach site, PM_{10} filter mass was 28% lower than PM_{10} E-BAM measurements on the 7 high wind afternoons sampled. At this site, dust accounted for 16% of PM_{10} filter mass and salt contributed 7%. Both dust and salt were strongly correlated with PM_{10} mass (R^2~0.9).

San Luis Obispo County Air Pollution Control District Review of September 2020 Scripps Report, San Luis Obispo County Air Pollution Control District, 2020 *(SLOAPCD, 2020, SIO Review)*

The SLOAPCD operated a filter based $PM_{2.5}$ sampler co-located with a $PM_{2.5}$ BAM at the CDF monitoring station in the spring of 2019 to assess the correlation between these two types of monitors. The SLOAPCD results showed an $R^2 = 0.999$ with least squares slope of 0.999 and an intercept of 1.13. On the basis of these results, the SLOAPCD refutes the conclusion of Scripps that the difference between $PM_{2.5}$ filter and $PM_{2.5}$ BAM measurements is due to moisture and semivolatile mass contributions. The SLOAPCD review also notes that Scripps used a Sharp Cut Cyclone (SCC) inlet of their $PM_{2.5}$ filter sampler at the CDF monitoring station that is designed to be operated at a 16.7 lpm flow rate, whereas Scripps operated their sampler at a 7.5 lpm flow rate, which could alter the size of particles being collected.

III. Outstanding Questions

Efforts to mitigate dust emissions at the Oceano Dunes State Vehicular Recreation Area (ODSVRA) are informed by decades of research on coastal dune processes and air quality impacts, along with years of intensive monitoring and modeling efforts specific to the ODSVRA. However, important knowledge gaps persist, including with regard to the specific effect of vehicles on PM_{10} air quality, the effectiveness of dust control measures, and the long-term evolution of the restored foredune. Continued monitoring and modeling is critical to inform long-term adaptive management for PM_{10} dust mitigation at the ODSVRA. Further scientific study at the ODSVRA could also improve generalized understanding of coastal dunes, their restoration, and associated air quality impacts. This chapter lays out both the "need to know " scientific questions of direct relevance to informing adaptive management at the ODSVRA, as well as the "want to know " scientific questions that would be worthy of investigation with the availability of additional resources.

Geology and History of the Oceano Dunes (Chapter II.1)

The ODSVRA resides in the Callender Dunes, which is part of the Santa Maria dunes complex – the largest active transgressive coastal dune system in California. Previous research indicates that during the Quaternary period the Santa Maria structural basin experienced extensive tectonic deformation, infilling with marine and fluvial sediments, and periods of sea-level transgression (rise) followed by regression (fall) to present levels in the recent Holocene epoch (~11,700 years BP to present). This resulted in significant deposition of sediments that have since been reworked by coastal, riverine, and aeolian processes. Dune surfaces are naturally emissive (see Chapter II.2), with the amount of dust emitted dependent on sand mineralogy, regional precipitation and wind climatology, vegetation cover, and anthropogenic disturbance processes.

At the ODSVRA, it is unknown how emissive dune surfaces were prior to establishment of the park, or even before widespread use of vehicles in the dunes. Vegetation cover is known to have declined since the early aerial imagery in 1939 and distinctly since 1966 through to the early 1980s when the park was established and as vehicle activity increased within the dunes (see Chapter II.5). To quantify and understand progress made toward the Stipulated Order of Abatement (SOA) target, and to specifically inform refinements to the DRI-LPD modeling, a 'pre-disturbance' reference state is required. The Scientific Advisory Group (SAG), in consultation with the California Department of Parks and Recreation (CDPR) and San Luis Obispo County Air Pollution Control District (SLOAPCD), agreed that the 1939 vegetation cover should be used as a pre-disturbance surface condition for further modeling and estimation of what dust emission conditions were prior to vehicular disturbance in the dunes.

Other scientific questions of importance include estimating the interannual variability in onshore sand supply (volume) to beaches fronting the dunes, mapping sand transport pathways within the dunes, and quantifying dune migration rates to better understand the morphodynamics of the dune system as it continues to evolve with the recent restoration treatments. Broader understanding of how active and emissive the Callendar Dunes have been over the Holocene prior to significant human impacts is also important for interpreting the modern emissivity of the dunes at ODSVRA.

Dust Emissions (Chapter II.2)

Existing research establishes the mechanisms by which wind causes the emission of PM_{10} dust from exposed coastal sand dunes. Research at ODSVRA also demonstrates that intensive vehicle activity enhances the rate of PM_{10} dust emissions, and that PM_{10} dust emissions are reduced within months of removing vehicles from impacted areas. However, the specific mechanisms by which vehicle activity affects PM_{10} dust emissions are not yet clear. To inform decisions about how to prioritize vehicle management actions (including the possible deployment of new dust controls), we need to know more about ***what specific changes in PM_{10} dust emissions*** *are expected when vehicle activity is added or removed*. Such information would directly help to determine the dust reduction benefit of areas temporarily or permanently exclosed from vehicle activity. We also want to know more about ***the underlying physical mechanisms by which vehicles enhance PM_{10} dust emissions***. Such mechanistic understanding is not immediately necessary to guide short-term management actions at the ODSVRA, but it could indirectly contribute to developing holistic approaches to managing vehicle activity at ODSVRA and elsewhere over the long term.

Dust Controls (Chapter II.3)

A variety of methods exist for controlling PM_{10} dust emissions, among which installation of physical elements and surface modifications that disrupt the emissions process (e.g., straw treatments, dune vegetation) have been most widely adopted at the ODSVRA. The selection and placement of specific dust controls must balance the potential for PM_{10} emissions reductions with other factors, including logistical viability and long-term sustainability of controls. To inform decisions about where to deploy dust controls and how to maintain those that have already been deployed, it will be necessary to continue monitoring such dust controls on a regular basis. For temporary treatments (e.g., straw treatments and wind fences), continuing deployment of sand trap arrays can be used to monitor wind-blown sand flux within treatment areas, which can serve as a proxy for understanding how such treatments reduce PM_{10} dust emissions. For vegetation restoration areas (including foredunes), scientific priorities for monitoring associated PM_{10} emissions reductions are described later in this section (i.e., in reference to Chapters II.4 and II.5). As PM_{10} emissions modeling serves as a key tool to inform ODSVRA dust control management decisions, further refinements to the DRI-LPD model to accurately predict the PM_{10} emissions reduction of installed dust controls is also critically important (see below in reference to Chapter II.6). Beyond the management imperative to understand the effectiveness of specific dust controls, we also more generally want to know how dust controls behave in a system-wide manner at the ODSVRA. For example, how do changes in wind-blown sand flux that result from the presence of the vegetated foredune propagate into changes in the effectiveness of downwind dust controls?

Vegetation Restoration (Chapter II.4)

The following questions are of interest to informing vegetation restoration approaches at the ODSVRA:

- What does an effective restoration look like in an ODSVRA management context?
    - There are two types of dune vegetation projects that have been implemented at ODSVRA: back dune areas and the experimental foredune. The foredune area will be dealt with in the next section.
    - For the back dunes, the goal is to document that the restoration areas are capable of sustainable development such that they will function as vegetated dune areas with a minimum of input from CDPR. The metrics for such development include:
        - **Overall cover.** The cover of these patches should be evaluated with a line intercept method every three (3) years and should be compared to data from Oso Flaco in a similarly positioned dune area that is relatively free of non-native invasive vegetation. Three (3) distinct locations should be chosen at Oso Flaco to be broadly representative of the revegetation areas at ODSVRA in terms of distance from the high tide line, slope, and aspect. The line intercept transects should be aligned with the dominant wind direction so as to take into account leading and trailing edges. A total of 50 m (~150 f) of transect distance should be permanently established at each site, with endpoints documented as GPS coordinates. **Triggers** for adaptive management would be either (1) failure to progress towards a condition described by the Oso Flaco transects; or (2) a decline in cover of over 20% from the previous sampling in any sampled area. **Adaptive management strategies** could include replanting, and/or installation of exclosure fencing outside of the leading edge to restrict disturbance along that edge and allow plants to grow up through the sand. The rationale for these monitoring and management strategies is to sample often enough so as to address any deficiencies soon enough to rectify them but not often enough to cause undue burden on CDPR; and to use management strategies that are already in CDPR's implementation and management "toolbox."
        - **Species Richness.** Associated with the line intercept transects should be a 2m (~6f) wide "belt" transect that is defined as the designated width of a corridor observed to one side or the other of the line transect in both the ODSVRA revegetation parcels and in the Oso Flaco, areas described for cover above. Data for the "belt" is simply a checklist of all species encountered. **Triggers** for adaptive management would be either (1) failure to progress towards a species richness condition described by the Oso Flaco transects; or (2) a decline in species richness of over 20% from the previous sampling in any sampled area. **Adaptive management strategies** could include replanting either as transplants or as native seed, introduced using standard CDPR protocols for revegetation.

- What is the historical evolution of vegetation at the ODSVRA?
    - This question is certainly of interest, but there are probably few ways of understanding the evolution of vegetation besides what has already been accomplished with the air photo analysis. However, there could be value in the observation that the topography as well as vegetation cover will change from decade to decade. In this context, knowing what the emission from a "natural" dune landscape is today (and moving forward) would help to inform understanding of what amount of emission would be considered "excess." It could, then, be of great value to interpret monitoring of PM_{10} concentrations downwind of the ODSVRA and at the Oso Flaco site.

Restoration of Coastal Foredunes (Chapter II.5)

The scope and approach of foredune restoration at ODSVRA is unique globally. Thus, continued monitoring and interpretation of geomorphic and vegetation responses and their impacts on reducing dust emissions is of critical importance both pragmatically, in terms of understanding the contribution of foredune restoration to the goals of the SOA, as well as scientifically. In particular, it remains to be seen which treatment approach is most effective at restoring a sustainable natural foredune. Research on early stage responses (Walker et al., 2022) suggests that a broadcast treatment of native plant and sterile grass seeds has been most effective at promoting incipient dune development in the first two years post-implementation. Evolution of foredunes to their full form in this region from a flat, barren beach could take decades, however, so further monitoring and research is required, including changes in plant community compositions.

Computational Fluid Dynamics (CFD) simulations over full-stage foredunes at the Oso Flaco reference site (Furtak-Cole et al., 2022) show that roughness effects of foredunes generate appreciable reductions of surface shear stress and dust emissions potential for significant distances downwind of the foredunes. Understanding flow response and shear stress within, and downwind of, the foredune restoration treatments as they evolve is required. This, combined with interpretation of geomorphic, sediment budget, and vegetation cover responses, as above, will provide invaluable information for assessment of which treatment(s) provide the most effective dust emissions control. In turn, this information could be used to inform adaptive management decisions on maintenance or potential modifications to the restoration sites for improved performance.

Seasonal variability in the sand transport regime within the treatments is characterized in a limited sense from single-point measurements of transport activity from Sensits deployed at the monitoring stations at the landward (eastward) boundary in each treatment site. Further insights on transport activity, depositional responses, and plant community change can also be gleaned from imagery from time-lapse cameras deployed on each station. This information is important for enhancing understanding on the effectiveness of the treatments and how these evolve over time.

Modeling of Particulate Matter Emission and Dispersion in the Atmosphere (Chapter II.6)

The DRI-LPD model is commonly used to inform dust control activities at the ODSVRA. The DRI-LPD model is built on established scientific knowledge regarding the mechanisms of PM_{10} dust emissions and the downwind dispersion of airborne PM_{10}. In tandem with ongoing meteorological monitoring, as well as mapping of PM_{10} dust emissivity via PI-SWERL surveys, the DRI-LPD model has proven to be a powerful tool for predicting PM_{10} mass emissions from the ODSVRA and airborne concentrations at downwind receptor sites. The accuracy of DRI-LPD model predictions has been verified via comparison to observed PM_{10} concentrations at receptor sites within and downwind of the ODSVRA. The DRI-LPD model has also been used to quantify PM_{10} mass emissions reductions and concentration changes expected to result from the installation of dust controls. However, a critical management need is to improve the accuracy of DRI-LPD model predictions of PM_{10} dust emissions at the ODSVRA under various management scenarios. This includes refining model predictions for "naturally occurring emissions" associated with ODSVRA conditions prior to significant vehicle disturbance. It also includes refining modeling for the effectiveness over time of various management actions that are meant to provide dust control benefit, including exclosures, temporary treatments, and restoration of foredune and back dune areas with native dune vegetation. Of general scientific interest, but of lower priority for specific management decisions at the ODSVRA, is to improve modeling for extreme wind event days, for which the historical observational record is limited. Further comparisons to verify DRI-LPD model performance under a wide range of wind conditions could improve the applicability of this model to the management of PM_{10} dust emissions and controls at the ODSVRA and other locations.

Air Quality (Chapter II.7)

Studies going back over a decade have established that the area downwind of the ODSVRA (during prevailing onshore wind) regularly experiences degraded PM_{10} air quality conditions in violation of California state ambient air quality standards. The overriding management question is how much of this PM_{10} is "naturally occurring" and how much is associated with "excess" PM_{10} emissions, resulting from vehicle activity at the ODSVRA. Scientific analyses have demonstrated long-term improvements in PM_{10} air quality at the ODSVRA resulting from management actions, including installation of dust controls and removal of vehicle activity. However, the specific attributability of these PM_{10} changes remains subject to some uncertainty. To better inform further management actions, we need to refine understanding regarding the fraction of PM_{10} measured at downwind receptor sites (e.g., CDF and Mesa2) that can be attributed to vehicle activity at the ODSVRA, especially during high wind events. In addition, further speciation analyses would help to distinguish the importance of PM_{10} that is generated from within the ODSVRA relative to "other" sources of PM_{10} that are measured at receptor sites downwind of the ODSVRA, but which originate from outside the ODSVRA. Such studies could help to resolve seemingly conflicting information from different monitoring approaches, including filter traps and Environmental Beta-Attenuation Mass (E-BAM) monitors. Of further scientific interest, but less critical to specific ODSVRA management issues, would be studies to improve the science of PM_{10} attributability. For example, how does the mineralogy of dune sand (including relative fractions of quartz, feldspar, clay coatings, sea salt, and other constituents) affect PM_{10} emissions and ambient PM_{10} concentrations at the ODSVRA? Could this mineralogical profile be leading to enhanced emissions at the ODSVRA relative to other systems? Dust source speciation studies typically depend on assumptions about the source profile of PM_{10} dust relative to elemental analyses of filter samples. Can knowledge about the specific source profile of PM_{10} dust originating from the ODSVRA help to improve these speciation analyses?

Chapter References

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