A UC DUST REPORT ON THE CAUSES, IMPACTS, AND FUTURE OF DUST STORMS IN CALIFORNIA

BEYOND THE HAZE

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Beyond the Haze: A UC Dust Report on the Causes, Impacts, and Future of Dust Storms in California
December 2024

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Photo: A Haboob Traveling Across Death Valley National Park, December 2014, courtesy of Fred Moore

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EXECUTIVE SUMMARY

When strong winds sweep across deserts, fallow fields, and other landscapes prone to erosion, they can lift tiny soil particles—commonly known as dust—into the atmosphere. This phenomenon, known as wind-blown erosion, escalates into a dust storm when it occurs on a sufficiently large and sustained scale. Dust storms are clearly visible to observers on the ground, and can grow in size and intensity to be visible from space. The map in Figure 1 shows the main locations in California where dust storms occur, broken up into five main regions, including Mono Lake through Owens Valley (yellow), the vast Mojave Desert (blue), the northwestern corner of the Sonoran Desert (green), the Salton Trough, which includes the Coachella and Imperial Valleys (pink), and the San Joaquin Valley at the center of the state (orange). These regions where dust storms occur encompass an area greater than 55,000 square miles and are home to nearly five million Californians. To put these numbers in perspective, this is an area and a population greater than nearly half of the states in the US.

This report is intended to be a comprehensive summary of the current state of knowledge of dust storms in California, including where dust storms occur, the features contributing to their geographic distribution, factors driving historical and likely future changes in dust, the impact dust storms have on human health, the economy, and environment of the state, and an assessment of what is needed to mitigate or adapt to those impacts. The purpose of this report is to be a resource to the public, community-based organizations, state agencies, and policy makers on dust storms in California. The information here is intended to help guide future adaptation and mitigation efforts and identify critical gaps in understanding that impede those efforts. This report is organized by the sections described below.

Sources of Dust: A description of how dust storms are generated, the historical changes in dust, and the human activities that cause an increase in dust in the state's air. A large fraction of the inland portions of the state are arid and consist of topographic depressions where fine sediment accumulates, and are thus potential locations for wind-blown dust. However, human activity has degraded many of these landscapes, resulting in an increase in dust emission beyond what would otherwise naturally occur. These human influences on the dust landscape include diversion of water for human use, off-road recreational activity, and drought conditions and wildfires associated with climate change.

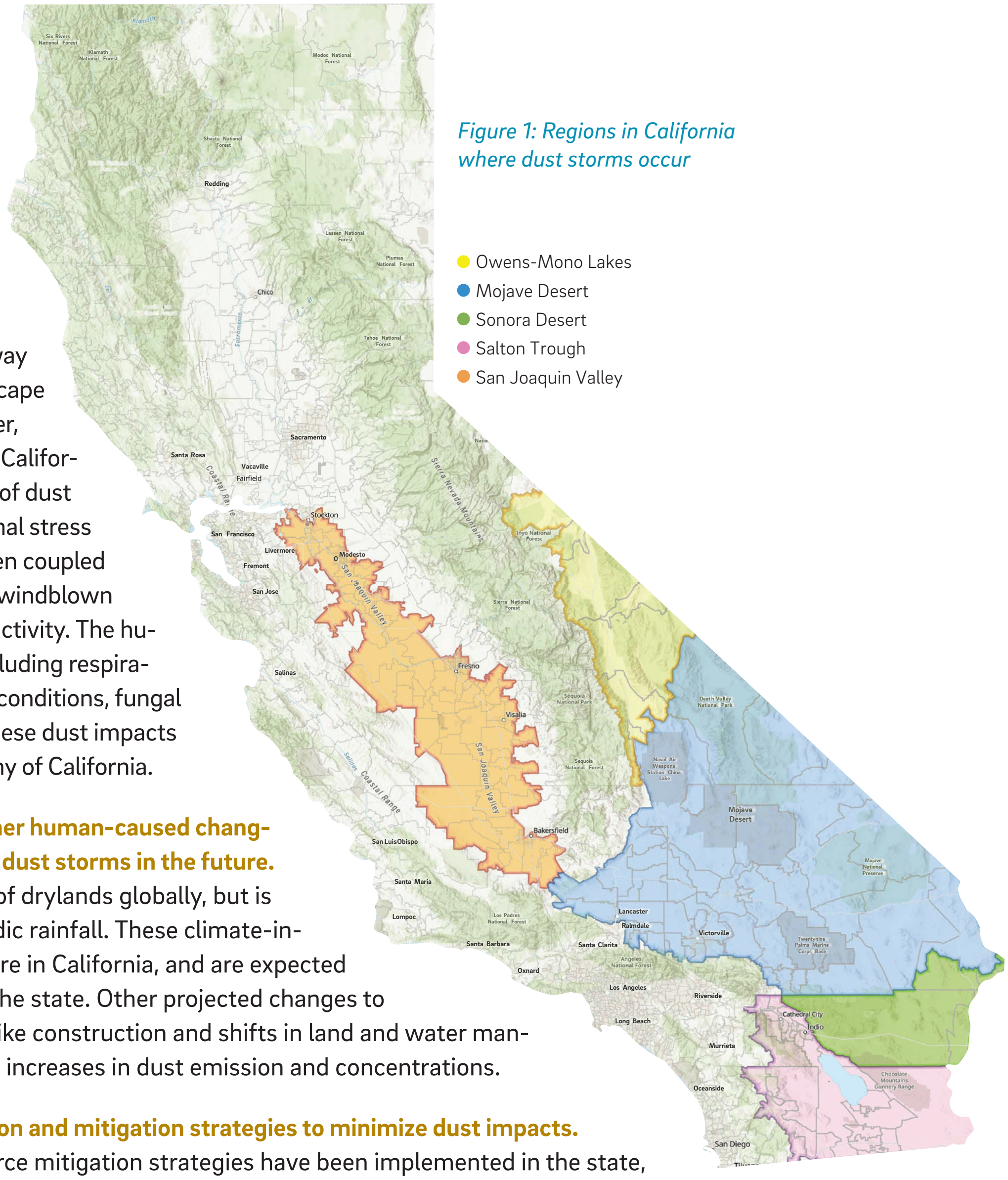


Figure 1: Regions in California where dust storms occur

Dust Impacts: The effects of dust storms on the state's natural and human environment, ranging from desertification to the production of renewable energy to human health. There is a two-way linkage between dust emission and landscape degradation, with one reinforcing the other, leading to potentially irreversible shifts in California's dryland ecosystems. The deposition of dust onto mountain snowpack creates additional stress on the state's water resources which, when coupled to the loss of soil fertility associated with windblown soil erosion, can reduce agricultural productivity. The human health impacts of dust are broad, including respiratory and cardiovascular diseases, allergic conditions, fungal infections, and traffic accident injuries. These dust impacts also have a negative effect on the economy of California.

Future Changes: Climate change and other human-caused changes to the landscape are likely to increase dust storms in the future. Global warming is increasing the aridity of drylands globally, but is also resulting in more intense and sporadic rainfall. These climate-induced changes have already occurred here in California, and are expected to increase future dust emission across the state. Other projected changes to the landscape, including from activities like construction and shifts in land and water management policy, may also result in future increases in dust emission and concentrations.

Strategic Solutions and Needs: Adaptation and mitigation strategies to minimize dust impacts. While a small number of costly dust source mitigation strategies have been implemented in the state, little investment has been made in the area of dust impacts mitigation. To best address current and likely future adverse impacts from exposure to dust, there is a need to 1) make key measurements of the environment and use these to develop a dust forecasting and early warning capacity, 2) generate effort integration among affected communities, researchers, and state agencies, and 3) and dedicate consistent and sustainable resource support for mitigation and adaptation work.

SOURCES OF DUST IN THE STATE

Dust is generated from a variety of landscapes that have sparse vegetation, contain fine sediments, and experience strong winds. This includes large parts of California, including Owen's Lake, the San Joaquin Valley, and the Salton Sea (Figure 1). Emissions from these and other landscapes have been enhanced by human actions, such as water diversion, agriculture, and off-road vehicle use. In addition, climate-change enhanced drought and wildfires have likely increased dust emissions over levels before the arrival of settlers in the 19th century.

HOW DUST IS GENERATED

The suspension of soil particles by winds is commonly referred to as dust emission and is an important influence on climate, weather, water resources, ecosystems, and human health (Field et al., 2010). Smaller scale dust events such as dust devils, blowing dust, or haboobs can last minutes to hours and affect areas as small as a few square meters (Gillette and Sinclair, 1990; Neakrase et al., 2016), whereas major dust storms can last for days and be large enough to affect multiple states. Both smaller and larger dust storms can result in millions of dollars in damage as well as damage to human health, including loss of life (Bhattachan et al., 2019; Jones and Fleck, 2020; Livingstone and Warren, 2019). Typically, large-scale dust events are initiated by synoptic-scale weather systems, such as a cold front which results in strong turbulent winds driving dust emissions (Duniway et al., 2019) while local scale dust events are commonly the result of smaller circulations, such as convective weather systems, which can produce thunderstorms with downward drafts of air (Middleton, 1986). It is estimated that globally, approximately 2000 millions tonnes of PM_{10} dust (particulate matter with an aerodynamic diameter < 10 μm) is emitted and transported annually (Kok et al., 2021; Shao et al., 2011).

Landscapes That Give Rise to Dust Emission

The primary sources of dust emission in California (Figure 2) are arid - defined as receiving less than 250 mm of annual precipitation - open landscapes that experience strong winds (Bullard et al., 2011; Kolesar et al., 2022). Playas, which are oftentimes dry lakebeds, are responsible for the majority of dust emissions from these landscapes (Gillette et al., 2004; Maffia et al., 2020). Sand dunes and active sand fields contain much less fine sediment and hence make a smaller contribution (Huang et al., 2019), whereas landforms that consist of loose erodible material, such as fluvial (stream erosion) and alluvial (stream deposition) systems contain large amounts of erodible materials and are some of the most productive sources of dust emission (King et al., 2011; Kolesar et al., 2022).

An example of the types of landscapes that give rise to dust emission in California is the Owens Dry Lake, which prior to mitigation efforts was estimated to have generated 72,000 metric tons of PM_{10} throughout the 2000 – 2001 windy season (Ono, 2006). There are additional regions in California that, as a result of shifting precipitation patterns, are vulnerable to generating similar events in the years to come, including the Salton Sea and Tulare Lake Basin (Chow et al., 2003; King et al., 2011). Thus it is of critical importance to better understand the mechanisms and drivers of dust emission in California, as well as how wind-driven dust emission in California has changed throughout the last century.

HAS DUST IN CALIFORNIA AND THE U.S. SOUTHWEST CHANGED OVER TIME?

Records of dust deposition from ice cores and other sedimentary records indicate that, globally, atmospheric dust has increased by approximately 55 ± 30 % since the 1840's (Kok et al., 2023). In the southwestern U.S. and California, dust emission has likely increased since the arrival of settlers in the 19th century (Neff et al., 2008; Tong et al., 2017). California has experienced a significant increase in anthropogenic development and activities that began in the 19th century (Ngai, 2015; Olmstead and Rhode, 2017), and lake records in the Rocky Mountains in Colorado show an increase in dust emission that corresponds to accelerated settlement of the region. The resulting dust emission was 500% higher than any other era during the last 5,000 years (Neff et al., 2008). These increases in dust emission occurred during a relatively wet period in comparison to the recent "mega drought" that California is facing (Williams et al., 2022). This suggests that anthropogenic activities in an increasingly arid environment will result in enhanced dust emission throughout California during the 21st century (Achakulwisut et al., 2019; East and Sankey, 2020).

One of the primary drivers of increasing dust emission at the state level has been the general decrease in soil moisture content, which has resulted in drier soils that are more susceptible to wind-driven erosion (Duniway et al., 2019). Atmospheric circulation patterns (such as the El Niño/La Niña-Southern Oscillation, ENSO, and Pacific Decadal Oscillation, PDO) have also been identified as meteorological

Figure 2: Typical landforms that emit dust in California. Shown are (clockwise from top-left) the Owens (dry) lake (source: Brian Russell and the Great Basin Unified Air Pollution Control District), a dry wash, sand dunes, and barren cropland.

controlling factors of dust emission (Achakulwisut et al., 2017). In addition to local dust emissions, another prominent source of dust to California is cross-Pacific transport (CPT), where dust from Asia and North Africa is transported across the Pacific ocean and deposited throughout the Pacific coast of the U.S. (Huang et al., 2022b).

ANTHROPOGENIC DUST EMISSIONS

In addition to identifying the natural sources of dust emission, it is also of critical importance to ascertain and quantify California's anthropogenic sources of dust emission; some of which could be reduced or mitigated by changes in policies or practices (Ginoux et al., 2012a). In general there are two categories of anthropogenic dust emissions; emission from changes in land cover or land use, and emission that is the result of changes to the climate (Zender et al., 2004).

Environmental Engineering

One of the primary anthropogenic drivers of dust emission within California is the diversion of flowing water for agricultural and urban development (Pelletier, 2006). This has occurred throughout the state at various locations, such as the Owens Valley-Mono Basin (Owens Valley) (Gillette et al., 2004; Ono et al., 2011), Salton Sea (Jones and Fleck, 2020; King et al., 2011), and Tulare Lake (Chow et al., 2003). There has been some initial success during the 21st century in reducing dust emission from these regions (Gutrich et al., 2016), although more recent data indicates that dust emission in the Owens Valley is increasing again as a result of the ongoing and increasing aridity of the region (Borlina and Rennó, 2017).

Arid landscapes, which are the primary dust emitting regions within the state of California, have also started to experience shifting vegetation patterns due to anthropogenic activities such as the development of infrastructure and agriculture, as well as due to the effects of climate change (Finch, 2012; Webb and Pierre, 2018). There are projections that many of California's deserts, such as the Mojave, are expected to experience an expansion of scattered woody vegetation (shrubs) at the expense of relatively more continuous grass cover, as the climate continues to warm and precipitation becomes increasingly irregular (Bachelet et al., 2016). As these landscapes become increasingly dominated by woody vegetation, there is a corresponding increase in soil surface heterogeneity (Bestelmeyer et al., 2018; Ravi et al., 2010b). This causes an overall increase in the amount of bare soil that is susceptible to wind events and is expected to result in an overall increase in dust emission throughout these regions.

Agriculture

Agricultural fields are a prominent source of anthropogenic dust that has ecological implications for the environment as well as serious medical consequences for local community members (Cahn and Phillips, 2019; Wang et al., 2019). California is home to the San Joaquin Valley, where over 340,000 people work in the agriculture industry, which produces more than $24 billion in annual revenue (Escriva-Bou et al., 2023). However, the San Joaquin Valley is also home to the most polluted air within the United States (Billings et al., 2016), which results in excessive rates of respiratory and cardiovascular diseases (such as asthma, atherosclerosis, myocardial infarction, and various forms of cancer) (Meng et al., 2010; Mills et al., 2019). In a 2014 – 2015 survey of community members within the San Joaquin Valley, 91.8% of respondents were concerned with the air quality there (Veloz et al., 2020). Dust emission is likely to get worse as the region continues to become increasingly arid and the amount of water available for irrigation decreases (Williams et al., 2022). The San Joaquin Valley is also facing the possibility of fallowing approximately 900,000 acres (17.7% of the San Joaquin Valley's agricultural fields) of cropland by 2040 as a result of shifting climatic conditions and the Sustainable Groundwater Management Act, which will likely increase the amount of dust emitted from agricultural fields (Escriva-Bou et al., 2023). These changes in land use and land cover have resulted in the creation of novel dust sources in California that previously were less susceptible to aeolian processes (Ayres et al., 2022).

The activities surrounding the maintenance and development of agricultural fields is also a critical source of dust emission in arid and semi-arid environments such as California (Tanner et al., 2016). Arid agricultural soils can emit up to 6 times more PM_{10} than if left undisturbed in their natural state, due to the disturbances that are necessary for the maintenance of these agricultural fields (Katra, 2020). These activities can have significant implications for the health of the agricultural workers that are maintaining these fields and to the members of the surrounding communities (May et al., 2012; Wall et al., 2015).

Vehicles

In the United States, off-road vehicle (ORV) driving is one of the fastest growing recreational activities, and California is the largest ORV market in the country, accounting for 10% of sales nationally (Global Market Insights, 2019). ORV driving results in extensive damage to the landscape (soil, flora, and fauna), and is one of the most destructive uses of land (Goossens et al., 2012). The damage from ORVs can require decades without disturbance to recover, and that is if recovery is even possible (Ploughe and Fraser, 2022). The ORV market is projected to see sustained annual growth of almost 6% (Global Market Insights, 2019), which will likely result in increasing ORV activity as well as an increase in the amount of soil susceptible to aeolian dust emission.

In addition, ORVs are capable of producing large amounts of dust, particularly at the local scale where it can pose a significant hazard to human health (Candeias et al., 2020; McKenna Neuman et al., 2009). Research has shown the dust concentrations around an ORV can be up to 10,000 times (up to 1,000,000 μg m^{-3}) higher than ambient dust levels (Goossens and Buck, 2009). The soil particles that ORVs emit will frequently contain components that would otherwise remain attached to the soil surface and not become suspended, even during strong wind events (Ploughe and Fraser, 2022). This can be particularly dangerous if the soil is contaminated with chemical or organic compounds (Goossens et al., 2012). In conjunction with California's increasing aridity, ORVs have the potential to accelerate the degradation of important ecosystems and thereby drive increased dust emissions.

Wildfire

California's climate is becoming increasingly vulnerable to the effects of climate change, and one of the consequences has been an intensification in both the frequency and intensity of wildfires (Khorshidi et al., 2020). Over the last four decades, over 8.5 million hectares have burned throughout California, and these fires have been increasing in size and severity over time (Xu et al., 2022). In addition to the immediate ecological impacts and human cost, there is a significant and immediate effect on air quality and dust emission as a result of wildfires (Bowman et al., 2017; Sankey et al., 2010; Schlosser et al., 2017).

Wildfires leave a completely altered and disturbed landscape with reduced vegetation. Since vegetation acts as a windbreak and covers the surface (Duniway et al., 2019), wildfires leave the landscape vulnerable to aeolian and fluvial erosion (Duniway et al., 2019; Ravi et al., 2007b). Wildfires also have the potential to modify both the physical and chemical properties of soil, which can induce soil-water repellency and decrease the threshold wind velocity needed for wind driven dust emission to occur (Ravi et al., 2011). As such, there is a significant increase in wind driven dust emission following wildfires, suggesting an increase in dust emission as climate change continues to increase fire risk (Wagenbrenner et al., 2013; Yu and Ginoux, 2022).

Drought

Since the beginning of the 21st century, California has experienced unprecedented drought conditions that have resulted in the driest period (2000–2021) the state has experienced over the last 1200 years (Williams et al., 2022). Current forecasts are that this drying trend will continue throughout the state and the southwest as a whole (Seager and Vecchi, 2010; Ting et al., 2018). This increase in overall aridity as well as the corresponding decrease in soil moisture has already resulted in a significant (240%) increase in aeolian activity over the last 30 years throughout the southwestern U.S. (Tong et al., 2017). As the region continues to experience increasing levels of aridity, there will likely be corresponding increases in aeolian activity and wind driven dust emission (Field et al., 2010; Neff et al., 2008; Webb and Strong, 2011). Since the beginning of the 21st century, California has experienced unprecedented drought conditions that have resulted in the driest period (2000–2021) the state has experienced over the last 1200 years (Williams et al., 2022). Current forecasts are that this drying trend will continue throughout the state and the southwest as a whole (Seager and Vecchi, 2010; Ting et al., 2018). This increase in overall aridity as well as the corresponding decrease in soil moisture has already resulted in a significant (240%) increase in aeolian activity over the last 30 years throughout the southwestern U.S. (Tong et al., 2017). As the region continues to experience increasing levels of aridity, there will likely be corresponding increases in aeolian activity and wind driven dust emission (Field et al., 2010; Neff et al., 2008; Webb and Strong, 2011).

DRYLAND VEGETATION-DUST INTERACTIONS

Deserts exhibit a distinctive patchy landscape with a mosaic of vegetated areas interspersed with bare ground across various spatial scales, often tied to specific microtopographic features. This patchiness reflects a close interplay between vegetation distribution and surface transport processes of water, water-borne sediment, and wind-blown soil and dust, highlighting important interactions between geomorphic processes and dryland vegetation (Ravi et al., 2011). Thus, understanding the complex interactions between wind erosion, vegetation dynamics, and soil processes is crucial for effective management and conservation of arid and semi-arid ecosystems, as well as addressing desertification challenges and predicting changes in dust sources and dust emission rates.

In grasslands, bare and grassy patches alternate over small distances, especially on sloping terrain, creating a stepped topography (Dunkerley and Brown, 1999; Nash et al., 2004; Parsons et al., 1996). Similarly, in shrublands patchiness extends over a few meters, with bare swales and vegetation-covered mounds. Larger shrubs and trees contribute to a landscape characterized by alternating concave-upward intergroves and flatter groves (Berg and Dunkerley, 2004). In some cases, on sandy soils vegetated patches are associated with more elevated geomorphic features consisting of soil mounds, typically at most 1-2 m tall. Often known as 'coppice dunes' or 'nebkas', these landforms are induced by the ability of shrubs to trap aeolian sediment and therefore are preferential sites for dust deposition and accumulation (Ravi et al., 2007a). These features can be observed across the arid and semiarid landscapes of California in the south-eastern part of the State.

Bare soil patches play a crucial role in aeolian erosion and dust emission (Li et al., 2007; Okin, 2008), water erosion rates (Wainwright et al., 2002), and biogeochemical processes (Schlesinger et al., 1990). Furthermore, bare soil patches typically form a network of conduits (or "streets"), allowing for the movement of water, soil, and dust, via wind or water-borne processes (Okin et al., 2009). Studies suggest that changes in functional and structural connectivity due to rapid vegetation shifts can lead to dryland degradation, with accelerated erosion and dust emission rates. Such rapid changes in vegetation composition have historically occurred as an effect of exotic grass invasions or native shrub encroachment induced by climatic variations or human activities (D'Odorico et al., 2012; Van Auken, 2000). Shrub encroachment is occurring worldwide, including the coastal and inland arid grasslands of California (Huang et al., 2020), and has been related to global drivers (such as climate warming, nitrogen deposition, increased atmospheric CO_2 concentration) as well as local land use practices (e.g. grazing and fire management) (D'Odorico et al., 2012; Turnbull et al., 2008; Van Auken, 2000). Indeed, woody plant encroachments in drylands typically occur with the replacement of a relatively continuous grass cover with scattered shrub vegetation bordered by bare soil patches. The larger fraction of bare soil typically observed in shrub encroached landscapes (with respect to the grasslands they have replaced) allows for an increase in dust emissions and wind erosion, a phenomenon often known as "land degradation" because of the loss of nutrient-rich fine soil particles (D'Odorico et al., 2012). The dependence of dust emissions on vegetation cover is only incompletely captured by the fraction of ground surface area covered by vegetation because it also strongly depends on patch size, orientation of bare soil "streets" with respect to wind direction, as well as vegetation height (Okin et al., 2009).

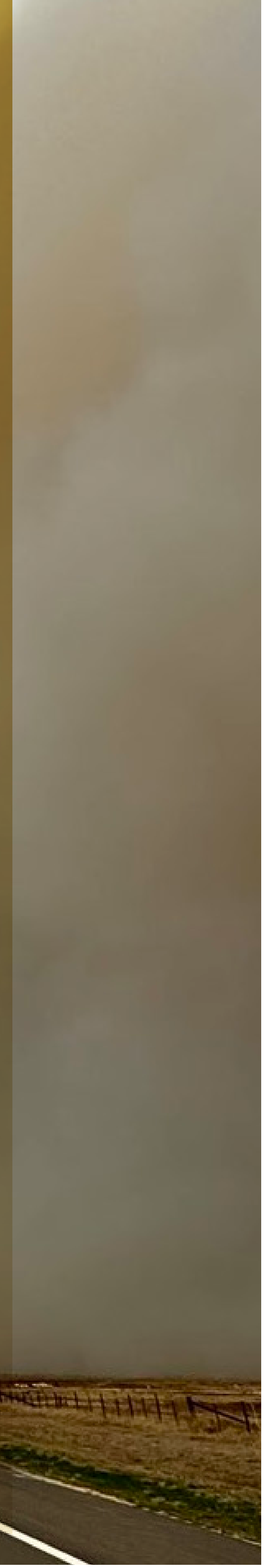
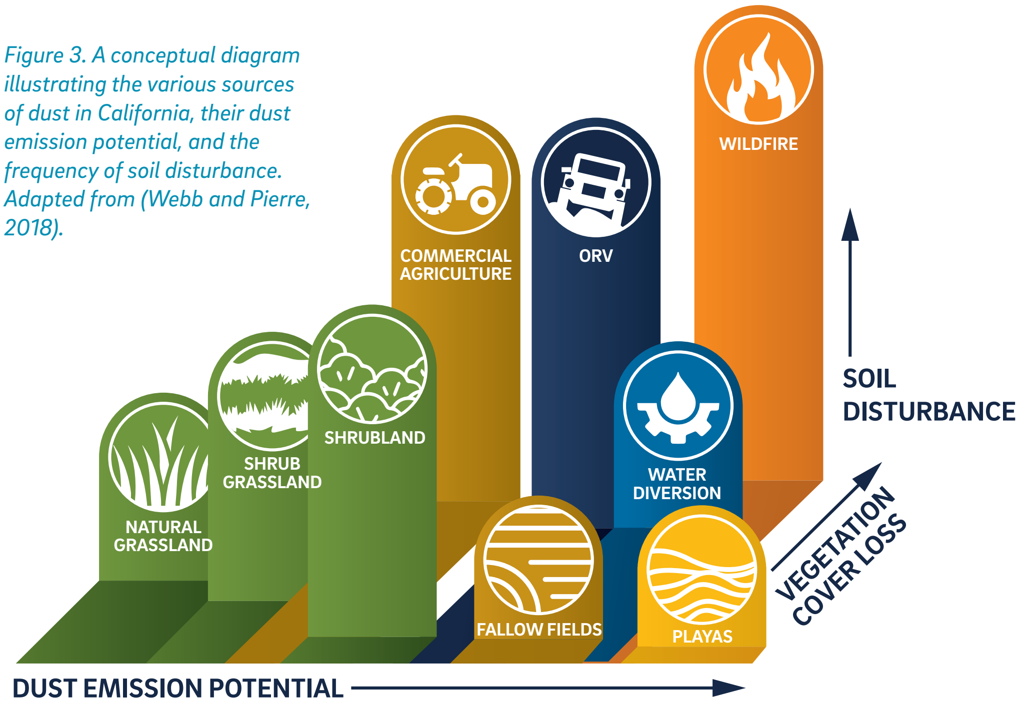


Figure 3. A conceptual diagram illustrating the various sources of dust in California, their dust emission potential, and the frequency of soil disturbance. Adapted from (Webb and Pierre, 2018).



Both wind and water erosion play crucial roles in maintaining the spatial heterogeneity of vegetation cover and soil resource distribution in arid and semi-arid environments. Particularly, wind erosion can remove nutrient-rich particles from the soil surface, irrespective of relief features (Larney et al., 1999; Ravi et al., 2010a, 2009) and plays a crucial role in the formation and dynamics of patchy distributions of vegetation and soil resources (Okin et al., 2001). Indeed, it has been observed (Charley and West, 1975; Schlesinger and Pilmanis, 1998) that shrub encroachment is associated with the formation of nutrient-rich shrub patches (known as "fertility islands") bordered by nutrient-poor bare soil areas. The transition from relatively uniform grass cover to a heterogeneous shrub-dominated landscape with fertility islands is driven by wind-borne transport of nutrient rich fine aeolian sediment from bare soil to vegetated patches, where it settles and remains sheltered by vegetation. These dynamics have an inherent positive feedback, whereby bare soils areas become increasingly nutrient depleted, thus impeding vegetation growth therein and rendering them more susceptible to wind erosion, while shrubby patches accumulate and stabilize nutrient rich soil particles (Okin and Gillette, 2001; Ravi et al., 2007a).

Enhanced wind erosion leads to the removal of organic carbon and nitrogen from the soil surface, altering soil fertility patterns and reinforcing landscape conditions that are suitable to wind erosion. These dynamics have been well-documented and explained by vegetation removal experiments in Southern New Mexico, where soils saw losses of nitrogen (up to 82% over a decade) and of plant available phosphorus (up to 62%) (Okin et al., 2006). Other studies highlighted major losses of soil organic carbon, as well as of total soil nitrogen (Li et al., 2009, 2008a, 2008b, 2007).

SUMMARY

The goal of this chapter is to identify the various sources of dust emission within the state of California and how they could be affected by anthropogenic activities and climate change. Figure 3 contains a schematic indicating both natural and human-impacted sources of dust in the state, and the types of activities that affect their dust emission potential. For example, natural grasslands and shrub grasslands are some of the least emissive landscapes in the state's arid regions, whereas dry playas are very effective sources of dust into the atmosphere. Agriculture, OHV, and wildfire all produce changes to the landscape that reduce the cover of native vegetation and increase its emission potential. Fallowing and water diversion also increase susceptibility to wind erosion.

IMPACTS OF DUST STORMS

Dust storms create a range of hazards with far-reaching social and economic implications for California and its residents (Figure 4). These include impacts of dust on the environmental services that support the state, like water and agriculture, and on the state's expanding solar photovoltaic infrastructure which provides energy services to millions. More directly, dust storms create acute public safety hazards through reduced visibility, lead to reduced recreation and other avoidance behaviors that can have important economic and welfare consequences, and – most important – pose direct threats to human health through both inhalation of the particles themselves and increased exposure to toxins or pathogens that are lofted into the air along with soil particles. Here we discuss these dust impacts as a first step towards quantifying the damages attributable to dust in California. This type of estimate forms the backbone of standard benefit-cost analyses, enabling policymakers to decide how to optimally deploy mitigation resources for maximum benefit.

Figure 4. Types of dust impacts across environmental, health, and economic domains.

DIRECT EFFECTS OF DUST

Human Health

Airborne dust is transported over long distances and contributes to adverse health outcomes for populations near and far from its sources (Morman and Plumlee, 2013). Inhaled dust poses a significant health risk, as fine particulate matter penetrates deep into the lungs, and the smallest particles, those having diameter less than 2.5 microns, can enter the bloodstream, causing oxidative stress, inflammation, and immune response issues (Fussell and Kelly, 2021; Lwin et al., 2023; Tong et al., 2023). Epidemiological evidence links dust exposure to respiratory illness (e.g., difficulty breathing, coughing, decreased lung function, exacerbated asthma, chronic obstructive pulmonary disease) and cardiovascular disease (e.g., heart attacks, strokes) (Johnston et al., 2019; Jones and Fleck, 2020; Kanatani et al., 2010; Khammar et al., 2023; Lwin et al., 2023). Dust may also contribute to allergic and atopic conditions, including eye diseases, by acting as an allergic adjuvant and enhancing allergic responses (Khammar et al., 2023; Lwin et al., 2023). Emerging research also associates dust exposure with adverse birth outcomes, potentially affecting infant health and development and contributing to increased infant mortality risk (Altindag et al., 2017; Heft-Neal et al., 2020; Jones, 2020; Kanatani et al., 2014; Moreira et al., 2020; Viel et al., 2020). It is important to note that a majority of studies linking dust exposure to adverse health outcomes have used data from populations in Asia, Africa, and Europe, with few studies focusing on US or California populations. *Epidemiological studies in California are needed to clarify the relevant health impacts of dust and identify the highest risk communities.*

A key worry in California is that dust often contains more than geogenic minerals. Dust – particularly from sources heavily impacted by human activity – often carries chemicals, including neurotoxic pesticides and heavy metals like lead, arsenic, and cadmium, that can lead to chronic toxicity, endocrine disruption, and increased cancer risks (Fu and Xi, 2020; Kim et al., 2017). These contaminants can accumulate in the body, affecting neurological development, immune function, kidney health, and blood cell production (Chen and Lippmann, 2009; Jia et al., 2018; Lentini et al., 2017; Mahurpawar, 2015; Sall et al., 2020). In addition to metals, dust can carry biologic species (fungi, bacteria, viruses) that directly cause illness or lead to enhanced inflammatory responses that increase the risk of pulmonary disease (Chellam et al., 2023; Vergadi et al., 2022; Yang et al., 2020; Yarber et al., 2023). In California (and across similar climates in the U.S. and Mexico), dust exposures drive incidence of coccidioidomycosis (Valley Fever) (Johnson et al., 2014; Weaver et al., 2025). This infection is caused by inhaling dust containing the fungi *Coccidioides* spp. Although the majority of symptomatic cases resolve for individuals with robust immune systems, symptoms may last for many months. Moreover, 5-10% of cases will develop chronic pulmonary disease and 1-4% develop disseminated disease, the most severe outcome that is characterized by the infection spreading to other organs of the body such as the nervous or skeletal systems ("Symptoms of Valley Fever | Coccidioidomycosis | Types of Fungal Diseases | Fungal | CDC," 2021). Incidence of Valley Fever is on the rise in California ("Valley Fever in California Dashboard," 2024), and more regions are expected to become endemic under changing climate (Gorris et al., 2019; Head et al., 2022; Heaney et al., 2024; Partlow et al., 2024).

The Environmental Protection Agency (Region 9) has been working in California to identify the health risks associated with the distribution of naturally occurring asbestos (NOA) that are easily suspended in the air as dust. Asbestos is a known human carcinogen that causes cancers in the lungs and lining of internal organs in addition to asbestosis and respiratory diseases that constrain lung function (Hanley, 2001). NOA occurs as long, thin, separable fibers derived from asbestiform minerals in rocks and soil formed through natural geological processes in the coastal ranges and foothills of the Sierra Nevada mountains (Van Gosen and Clinkenbeard, 2011). The subsequent mining of NOA throughout California has exacerbated the human-induced disturbance of NOA-containing soils and rocks, but the full range of NOA distribution and associated human health effects remain underrecognized.

Public safety

Beyond direct and mediated health impacts, dust is also an important contributor to broader public safety concerns in California (Tong et al., 2023). Airborne dust poses a significant risk to transportation safety by impairing visibility on highways and thereby increasing the risk of car accidents (Li et al., 2018; Van Pelt et al., 2020). National Highway Traffic Safety Administration (NHTSA) records from 1994-2011 indicate that dust / blowing sand, soil or dirt contributed to 17% of weather-related U.S. highway fatalities (which were themselves around 17% of total traffic fatalities) (Ashley et al., 2015).

In California, researchers linked public transportation incident records (from the Statewide Integrated Traffic Records System, SWITRS) with data on weather and visibility, and satellite observations of aerosol optical depth, and found that wind-related weather accidents have double the fatality rate of other weather related accidents, and are associated with low visibility and high dust optical depth, pointing to dust as a major contributor to road travel risk (Bhattachan et al., 2019). Literature exploring the relationship between dust and aviation or sea travel is more sparse, but reviews of aviation reports have revealed dust devils as a source of equipment damage (Baddock et al., 2013; Lorenz and Myers, 2005).

Recreation

Recreation, opportunities for adventure, and enjoyment in the natural environment can sometimes be disrupted by atmospheric dust through its impacts on both the environment and the individuals engaging in recreational activities.. The potential impacts on recreation vary depending on the amount of dust, its composition and the specific recreational activity involved (Griffin and Kellogg, 2004; Hand et al., 2016; Jung et al., 2019). Exposure to airborne dust can have a range of effects, from irritation of the eyes, nose, and throat, to more severe consequences, such as the exacerbation of respiratory conditions. Inhaling dust can lead to a range of respiratory symptoms that diminish the enjoyment of recreational activities like hiking, biking, or picnicking, and individuals are less inclined to spend time in recreational activities when high concentrations of PM_{10} are present (Jung et al., 2019).In addition to health impacts, anthropogenic dust emissions also have broader environmental repercussions that affect the overall recreational experience by disrupting the natural beauty of recreational landscapes. Haze from airborne dust can significantly reduce visibility, obstructing scenic vistas and natural landscapes, thereby detracting from the aesthetic appeal of outdoor recreational areas (Mace et al., 2004; Miri et al., 2009; Poudyal et al., 2013). Furthermore, particle pollution of water bodies can carry contaminants in aquatic environments, compromising water quality and diminishing opportunities for recreational activities like fishing or swimming (Gokul et al., 2023).

INDIRECT EFFECTS OF DUST ON ECOSYSTEM SERVICES

Snowpack

Mountain snowpack is a critical resource in the western US for the supply of freshwater to irrigation, urban areas, and industrial developments. Despite recent years exhibiting record snow in the Sierra Nevadas (e.g. winter 2022/2023) there is a long-term decreasing trend in snowpack across the state (Mote et al., 2018). One factor affecting the amount of mountain snowpack is the deposition of dust. Dust settling on snow surfaces influences a range of environmental processes and systems. From altering albedo to affecting the water balance, dust plays a role in shaping natural ecosystems and human environments (Seidel et al., 2016). Snow presents the highest albedo of any natural surface, but the presence of impurities like dust decreases snow albedo, especially in the visible wavelengths, thereby increasing absorption of solar energy. This darkening effect of dust accelerates snowmelt, altering the montane hydrological cycles and regional energy balances (Conway et al., 1996; Kaspari et al., 2015; Painter et al., 2007; Seidel et al., 2016; Warren and Wiscombe, 1980). Moreover, snowmelt acceleration reduces the natural storage of winter precipitation in snowpack with important socioeconomic implications for regions reliant on snowmelt for agriculture, hydropower generation, and municipal water supplies. In the case of California, snowmelt plays a crucial role in sustaining water availability during the rainless months of the growing season (Dettinger and Cayan, 1995; Harpold and Molotch, 2015). Changes in the timing of snowmelt also disrupt ecosystems that rely on consistent water availability, change plant phenology, control forest fire regimes, alter wildlife habitat suitability, species migration, and biogeochemical cycling, with important impacts on species distributions, community composition, biodiversity and ecosystem functioning and services (Westerling et al., 2006).

photo: Desert Sunlight Solar Farm courtesy of the Bureau of Land Management

Agriculture

California is the nation's largest agricultural producer, growing nearly 100% of some of the country's most treasured fruit and nut crops, and serving the state, country, and beyond with its vegetable and dairy production. In addition to agricultural activities enhancing dust emissions (see above), dust itself has myriad impacts on the agricultural sector (Ahmadzai et al., 2023; Farmer, 1993; Stefanski and Sivakumar, 2009). Dust storms can directly cause physical damage to plants, and dust deposition on leaves negatively impacts photosynthesis, including by blocking chlorophyll from absorbing incoming radiation (Meravi et al., 2021). Even in the absence of direct damage or dust deposition, suspended dust leads to reduced crop yields as reduced downward solar radiation leads to reduced photosynthesis, which is not offset by any benefits from increased scattered light use efficiency (Hemes et al., 2020), or surface temperature impacts (Burney and Ramanathan, 2014; Lobell and Burney, 2021; Proctor et al., 2018). Beyond crops, dust storms can injure and kill livestock, resulting in asset as well as income loss for producers (Middleton, 2024). Moreover, the health impacts of dust exposure are more acute for the agricultural labor force who work outdoors (Rodriquez et al., 2014; Schenker, 2000; Schenker et al., 2009; Stoecklin-Marois et al., 2015). Furthermore, even at low levels of ambient pollution small changes in PM exposure are associated with decreases in agricultural labor productivity, suggesting that small dust events may exert a negative impact on California's economy (Chang et al., 2016; Graff Zivin and Neidell, 2012).

Photovoltaic systems

Solar energy systems have experienced a notable rise in recent decades thanks to a combination of technological advancements, reduced costs, and increased awareness of environmental concerns. In the United States alone the U.S. Energy Information Administration has forecasted a 75% increase in solar power generation from 2024–2026 (US EIA, 2024). Many of these installations are situated in arid regions, as they are particularly suitable for solar energy production mainly due to intense sunlight, clear skies, and availability of unused land.

In recent years there has been a growing interest in understanding the potential impacts of dust settling onto these energy systems. Wind tunnel experiments and field data have demonstrated that dust deposition onto photovoltaic (PV) panels reduces cell performance (Goossens et al., 1993; Goossens and Kerschaever, 1999). Laboratory studies have demonstrated that the reduction in PV output efficiency is approximately proportional to the dust mass deposition (Jiang et al., 2011), with modeling and observational work suggesting that the reduction in efficiency can be as high as 25% (Bergin et al., 2017). Measurements at a large commercial site suggest that even when averaged over long time periods, PV output in areas where dust storms occur can be reduced by approximately 10% due to deposition (Mejia et al., 2014). Addressing dust deposition requires regular maintenance and cleaning of panels with water (Mani and Pillai, 2010), which is typically limited in these arid environments. Furthermore, the water requirements to address dust deposition onto PV panels may be so large that alternative forms of energy production, like biofuels, may be equally feasible in arid regions (Ravi et al., 2014).

ENVIRONMENTAL JUSTICE

Dust impacts are not felt evenly across the population of California. Sources (e.g., exposed playa of the Salton Sea and Owens Lake, or fallow farmland in the Imperial and San Joaquin Valleys) tend to be more proximate to lower-income communities, communities with higher Hispanic/Latino population shares, and greater fractions of undocumented immigrants (US Census Bureau, 2023). This is reflected in increased asthma aggravations nearby: for example, Imperial County has the highest rate of pediatric asthma hospitalization in the state, and unlike other regions,

demographics explain a small portion of this outcome; most of it is driven by dust (Farzan et al., 2019, 2024.; Goodyear, 2015; Johnston et al., 2019). Further afield, dust emissions and dust storms are more likely to impact southern and central California. Because outcomes from PM exposures have long been known to vary by income and access to health care, significant environmental justice concerns exist in the management of California dust emissions.

Within the San Joaquin Valley and Los Angeles Basin, occupational dust exposures likely put agricultural, construction, and fieldworker at high risk for coccidioidomycosis infection (Nicas, 2018), and solar energy field expansion puts solar panel construction workers at risk for dust exposures and *Coccidioides* infection (Wilken et al., 2015). Legislative efforts in California have mandated *Coccidioides* risk education and safety protective equipment for at-risk workers in endemic areas (e.g., the 2019 California Assembly Bill-203, Occupational safety and health: Valley Fever). Disease impact is further complicated by socioeconomic constraints of many field workers. In California's SJV, Hmong and Latino minorities make up a large percentage of field workers and soil-based laborers (Struglia et al., 2003). These populations tend to fall into the lowest wealth bracket with little to no access to healthcare, thus representing those with the least availability and opportunity to seek medical care, and the most exposed to *Coccidioides* (Mobed et al., 1992).

Moreover, we note that environmental justice consists of both exposure equities and procedural justice; that is, all community members regardless of income or protected class status, should have equal access to environmental services as well as the ability to participate in the governance process. It has long been a concern that both proximate and more distant communities affected by dust have not had due input into the regulatory process. Increased effort by researchers and regulators to work with Californians to understand their own exposures, advocate for optimal mitigation strategies and remediation protocols, and benchmark progress is critical to a more just future for our state.

SUMMARY

The dust impacts described here represent an important but non-comprehensive list. Many plausible impact pathways have not been estimated due to relative paucity of data (for example, direct impacts of dust on crop yields). The domains addressed above nevertheless clearly illustrate that dust is closely connected with human health and welfare in California. Because dust emissions impact key ecosystems that mediate human health (e.g., via water for agriculture) and directly negatively affect morbidity and mortality through physical (e.g., PM inhalation, road accidents), pathogenic (e.g., coccidioides), and mental health (e.g., outdoor recreation) pathways, it is a prime target for cross-sector policy innovation. Particularly when the state's environment and climate sustainability goals into the future are considered, there are likely large co-benefits to human wellbeing from effective and efficient mitigation of dust emissions within the state.

THE FUTURE OF DUST IN CALIFORNIA

The impacts of dust on health, agriculture, ecosystems, recreation, and so on, will extend into the future with influence from climate change and land and water management policy. However, due to the complex dynamics underlying dust generation and transport, our understanding of how dust storms will change in the future remains limited. Here, we discuss how environmental drivers and natural resource management are likely to shape dust in California over the coming years to decades.

CLIMATE CHANGE

Climate change is expected to increase dust storms in the southwestern parts of the United States, including California (Achakulwisut et al., 2019; Brey et al., 2020; White et al., 2023). This is because dust emissions are affected by environmental drivers, such as precipitation, soil moisture, surface temperature, and surface winds, which are projected to change as the planet continues to warm (Pu and Ginoux, 2017; Zha et al., 2021). For example, precipitation extremes are projected to intensify, along with more frequent and extreme dry-to-wet events, increasing the risk of both flood and drought in California (Diffenbaugh et al., 2015; Swain et al., 2018). Future drought conditions could result in changes in soil characteristics, such as reducing soil moisture, potentially leading to changes in dust emissions in California's arid and semi-arid regions. For example, drought-induced changes in soil characteristics was attributed to recent increases in dust concentration around Owens Lake between 2013 and 2015 (Borlina and Rennó, 2017). Flooding can enhance the transport of dust-sized sediment downstream and over dry lakes, which may increase the susceptibility of dust emissions after they become dry (Zender and Kwon, 2005). Elevated surface temperatures due to greenhouse gases can greatly amplify seasonal dryness and moisture loss in the atmosphere and soil, resulting in increased severity of drought conditions, degradation of protective desert soil crust, and increases in associated dust activities (Cheng et al., 2016; Dai, 2013, 2013; Diffenbaugh et al., 2015; Kok et al., 2023). Changes in the near-surface wind speeds that drive dust emissions are projected to be small and variable, depending on the season and location (Wang et al., 2020).

Shifts in global-to-regional circulation patterns caused by the changing climate are also likely to influence dust emission in the future. For example, the increasing frequency of strong El Niño/Southern Oscillation events due to the warming climate (Cai et al., 2014) is likely to result in more frequent periods of below average rainfall across the Western US that are associated with La Niña-like conditions, and thus an increase in dust in the year following these dry periods (Okin and Reheis, 2002). In southeastern California projections of a weakening North American Monsoon (Pascale et al., 2017) imply a potential reduction in summertime dust storms there, although these results are in seemingly in contradiction to historical increases in the intensity of monsoonal precipitation (Luong et al., 2017), suggesting a high level of uncertainty in the connections between climate change, regional circulation patterns, and dust.

LANDSCAPE DISTURBANCE

In addition to these environmental factors that may dominate future dust emissions from natural desert sources like dry lakebeds and dry washes, human-induced factors may also influence dust emissions from so-called anthropogenic sources, such as construction, off-road vehicle use, and agriculture. The California Air Resources Board's California Emissions Projection Analysis Model (CEPAM) (California Air Resources Board, 2019) projects that dust from these anthropogenic sources will increase by approximately 45% in 2050, relative to the 2017 baseline (Figure 5). This increase in dust emission is projected to mostly come from construction, demolition, and resuspensions from paved roads. In contrast, CEPAM suggests that dust emissions from unpaved roads, fugitive windblown dust from croplands and pasturelands, and farming operations, such as tilling and harvest, will remain approximately the same or decrease by less than 7% in the coming decades (Fig. 4). Because these future dust emission projections depend on the 2017 base year emission inventory and emission factors model (Propper et al., 2015), they are subject to substantial uncertainties. While CEPAM may project minimal changes in anthropogenic dust from agricultural croplands, historically, poor agricultural management and practices have been linked to major wind-blown dust or dust storms. For Example, the dust event of November 1991 that led to a collision of 164 vehicles and 17 fatalities on Interstate 5 in the San Joaquin Valley was thought to be wind-blown dust from agricultural sources likely aided by inadequate land management (Pauley et al., 1996). Therefore, changes in agricultural land management and practices could alter future changes in anthropogenic dust emissions, particularly in California's Central Valley where a majority of the state's agricultural sources are located (Ginoux et al., 2012b). For example, changes in tillage, fallowing, and grazing could expose vast swathes of farm cropland to wind erosion and contribute to desertification and dust production (Zobeck et al., 2013), echoing some of the conditions that lead to the Dust Bowl (Lee and Gill, 2015). Because the contribution to dust emission from anthropogenic sources is likely substantial (Chen et al., 2019; J. P. Huang et al., 2015), understanding the large uncertainties in the projection of anthropogenic dust emission is key to estimate the future of dust in California.

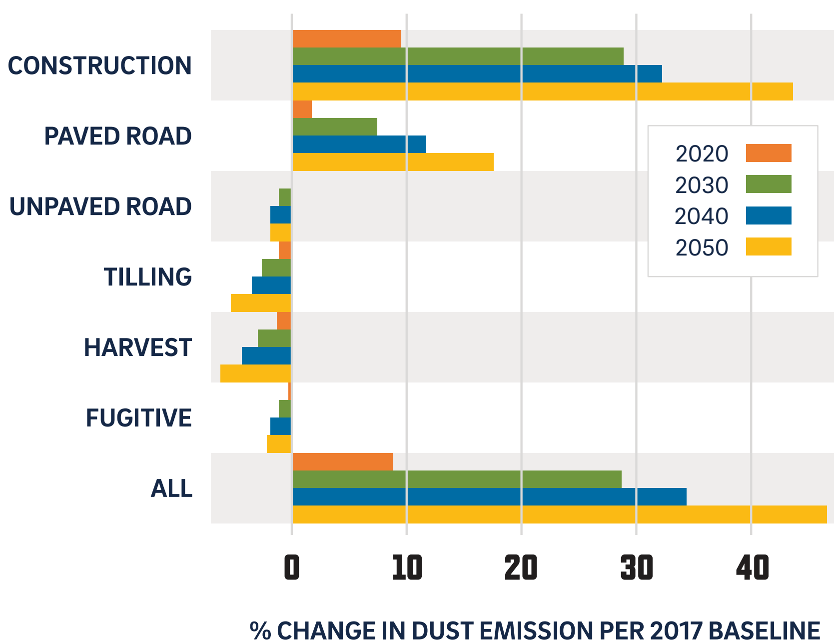


Figure 5. Percentage change in state-wide summer dust emission from the California Air Resources Board's California Emissions Projection Analysis Model. Dust emission is approximated as the coarse particulate matter (PM), which is estimated as the difference between PM_{10} and $PM_{2.5}$ for emission sources that include dust.

OTHER CHANGES IN NATURAL RESOURCES MANAGEMENT

In addition to factors that can affect dust emissions, changes in government policies can also influence agricultural land-use management practices with direct consequences for wind erosion. A report from the Public Policy Institute of California suggested that to achieve the goals of the state's 2014 Sustainable Groundwater Management Act, instituted to bring groundwater basins into balance in the next two decades, between 0.5-1 million acres of irrigated land will need to be fallowed (Hanak et al., 2019). Such fallowed cropland could become new dust sources that may increase dust emission and surface concentrations particularly in the Central Valley. Additionally, Southern California dustiness is susceptible to climate-change driven policies in water transfer and storage. For example, global warming drives the long-term decline in Colorado River levels by aridifying the basin's snowpack regions (Bass et al., 2023). Climate models project that this drying will intensify toward the end of this century (AghaKouchak et al., 2014). This will exacerbate pressure on agricultural users, who consume more than two-thirds of California's Colorado River allocation, to increase fallowing and to reduce irrigation (Richter et al., 2024). Both of these actions tend to increase dust emission. Irrigation runoff has been the only source of water to the Salton Sea since the Quantification Settlement Agreement of 2003 ended the direct transfer of Colorado River water to the Sea in 2017 (Cohen, 2014). The Sea's level has since transitioned from a period of gradual decline to a new era of rapid decline that is estimated to expose about 40% of the year 2000 lakebed to wind erosion by 2030, reaching about 100,000 acres of exposed lakebed by 2050 when levels may stabilize. Dust deflated from the exposed playa may increase PM_{10} in the surrounding region by about 10% by 2030, and by much more in localized source areas (Parajuli and Zender, 2018).

Broadly over California, a projected increase in dust emissions and activities is expected to have significant impacts on the Sierra Nevada snowpack, hydrology, air quality, and public health. As previously discussed, dust deposition onto the Sierra Nevada snowpack can accelerate snowmelt by reducing surface albedo (Huang et al., 2022a), particularly in spring and summer, when dust activities are high across major sources that transport dust to the Sierra Nevada (Huang et al., 2022b). Such a decrease in Sierra Nevada snowpack could, in turn, exacerbate California's water scarcity, negatively impacting crucial water reservoirs that feed into the state's water supply system, particularly during future drought years. In addition, an increase in future dust storms can significantly degrade air quality by elevating fine particulate matter concentrations that could trigger more respiratory illnesses and increase hospital admissions for asthma and chronic obstructive pulmonary disease, especially for underserved communities in California's Central Valley (see the Impacts of Dust Storms Section of this report for more detail). Understanding future changes in sources, transport pathways, and composition of dust aerosols will be crucial for mitigating impacts on Sierra Nevada snowpack, air quality and regional climate across California.

SUMMARY

The future of dust in California is expected to worsen under climate change. This is because common environmental drivers that influence dust emission, such as precipitation, soil moisture, surface temperature, and surface winds, are all projected to change under climate change in a way that is likely to drive an increase in dust emissions. In addition, changes in land use management, influenced by climate change, current or future government policies may also have indirect impacts on future dust emission in California. In particular, water management initiatives like the 2014 California's Sustainable Groundwater Management Act, could necessitate the fallowing of million acres of irrigated land, potentially creating new dust sources. Overall, understanding the complex dynamics behind dust generation and likely occurrence of new emission sources is crucial for developing effective mitigation strategies.

STRATEGIC SOLUTIONS AND NEEDS

As previously discussed, dust storms are associated with a myriad of negative health, environmental, and economic impacts. Reducing emission of–and exposure to–windblown dust represents a unique challenge, since emissions tend to be less consistent, predictable, and controllable than other common sources of atmospheric particulates. In part as a result of these challenges, windblown dust emissions in California have increased over time, even as other anthropogenic particulates have seen reductions over the years. Thus, developing effective strategies to minimize the negative impacts of dust in California, including adaptation and mitigation, is imperative. Here we present strategies that have proven to be useful in other locations, and discuss implementation challenges.

DUST SOURCE MITIGATION

In cases where the sources of *dust are anthropogenic in nature direct mitigation is an effective approach to minimize dust emission.* As previously described, windblown dust emissions are typically tied to strong surface winds over dry, erodible surfaces. Dust source mitigation strategies generally aim to increase surface roughness over target areas, therefore slowing surface winds and reducing the likelihood of dust particle suspension, or modifying surface properties such as soil moisture to reduce emissions. There is a large body of literature on mitigation techniques designed to minimize erosion in croplands and pasturelands in arid regions, as well as dune stabilization (Middleton and Kang, 2017), which include short term strategies like preserving crop residues (Presley and Tatarko, 2009; Sharratt et al., 2010), and longer-term strategies like planting windbreaks (Wang et al., 2010). Dust source mitigation also requires continuous landscape management to minimize disturbances to the surface like from off-highway vehicle use, which can render efforts ineffective and cause irreversible damage to the environment (Duniway et al., 2019; Goossens et al., 2012).

One example of anthropogenic dust source mitigation is the Owens Lake, which lies just east of the Sierras and was desiccated due to a water diversion project that was constructed in the early 20th Century (Fig. 2). Over the last 25 years billions of US dollars have been spent implementing a variety of dust emission control measures on the now dry lakebed, including surface roughening, controlled flooding, and vegetation enhancement, although the effectiveness of each specific measure is still not completely understood (Owens Lake Scientific Advisory Panel, 2020). Another example of an anthropogenic dust source is the Salton Sea, which is a large lake in the southeastern corner of the state that is rapidly drying due to water diversion. Dust source management activities, similar to those implemented at Owens lake, are currently being tested on the exposed playa there (CNRA, 2020). The long term efficacy of these management techniques is not easy to assess, since environmental changes like drought may render some techniques ineffective or unfeasible (Borlina and Rennó, 2017). Furthermore, evaluating the effectiveness of this work in terms of minimizing the adverse impacts of dust will always be somewhat uncertain since characterizing dust emission from natural sources in the surrounding areas is difficult.

Dust source mitigation is an expensive technique that requires continued investment in application and monitoring that is limited to discrete anthropogenic sources of dust. While minimizing any wind-blown erosion should improve air quality, the exact benefits to human health are difficult to quantify.

DUST IMPACTS MITIGATION: FORECASTING IMPROVEMENTS

While efforts to mitigate dust emissions sources can be helpful for scenarios where emissions are predominantly coming from known, consistent, and spatially limited sources (e.g. unpaved roadways or active construction sites), such work is generally only applied to a small subset of dust events. For most dust storms, robust and reliable forecasting and communication tools can help to minimize impacts, and have been a focus of air pollution research and policy in dust-impacted areas around the world (M. Huang et al., 2015; Niu et al., 2008; Stajner et al., 2012; Walker et al., 2009; Westphal et al., 2009). Although PM_{10} forecast products for various regions of the state exist, their usefulness is limited. For example, five day forecasts of air quality from PM_{10} for the Imperial Valley, a region frequently impacted

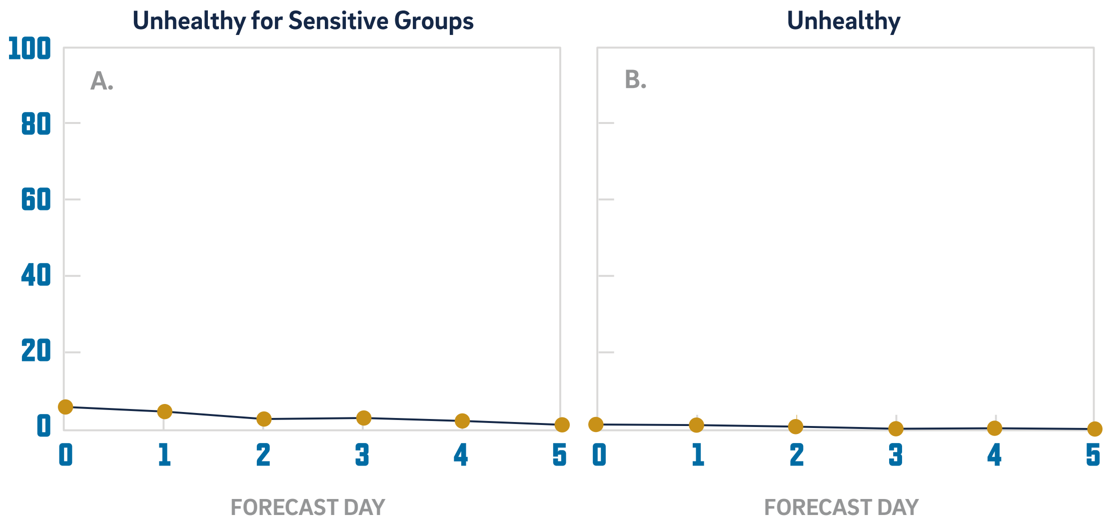


Figure 6. Evaluating Daily PM_{10} Forecasts for the Imperial Valley. Shown are the accuracy of daily PM_{10} forecasts for the Imperial Valley for days when the air quality is unhealthy for sensitive groups (panel A.) and unhealthy (panel B.). The horizontal axis represents the number of days prior to the event that the forecast was issued, where a forecast day of zero indicates a forecast generated the day of the unhealthy air quality. The vertical axis represents the true positive rate, which is the percentage of high PM_{10} events that were correctly predicted.

by dust storms, are available via the Imperial County Air Pollution Control District. Preliminary work conducted by the report authors has identified three main shortcomings of this forecast: 1) the forecast only provides a daily average PM_{10} air quality index (e.g., healthy, unhealthy, extremely unhealthy, etc.) but does not indicate how poor the air quality will be at a given time or the duration of the unhealthy air quality, 2) the forecast shows little skill in actually forecasting unhealthy air quality (Figure 6), and 3) as a result, informal polling of community members in the Imperial Valley indicates that this forecast product is not used by the people most impacted by dust. We note that nearly identical results were obtained when repeating this analysis for PM_{10} forecasts generated for the Coachella Valley, an area also impacted by dust. Providing accurate, high spatiotemporal resolution dust forecasts to impacted communities is an urgent task; a trustworthy forecast can generate community confidence, adoption, and thus actionable information.

Previous modeling work has shown that uncertainties related to surface properties associated with dust emissions are likely a major contributor to overall model error (Evan et al., 2023), making development and evaluation models that correctly reflect the relation between surface properties and dust emissions a high priority for dust forecast improvement. Integrated surface measurements and remote sensing data products have been used previously to identify especially emissive locations, or hotspots, allowing for improved dust event intervention strategies (Li et al., 2018). Using the same approach, dust emissive hotspots in California could be identified. Around California's Salton Sea region, an area of increasing concern for windblown dust levels due to a shrinking lake footprint (Parajuli and Zender, 2018), measurement efforts have also included direct surface observations of emissivities, providing valuable data on surface properties themselves and the relationship between wind speeds and resulting dust emissions (Dickey et al., 2023). These long-term local measurements and focused field campaigns are important steps towards understanding regional dust emissions and identifying areas where further data is needed to answer key air quality questions related to dust emissions and transport. However, since soil surface properties and related dust emissions are highly variable in space, it is necessary to expand the coverage of dust measurements, including into agricultural lands. Furthermore, ongoing assessments of surface conditions and evaluation of forecast model performance are needed since the environmental conditions that give rise to dust storms are dynamic. Coupled comprehensive modeling and measurement efforts are necessary to identify not only how robust and representative current surface property datasets and emissions inventories may be, but also how to continue to improve them.

Robust and effective forecast products are a proven method to mitigate the adverse health impacts of dust. The following three tasks are identified as critical to generate actionable dust forecasting in California: 1) create accurate surface properties for forecast model input datasets, 2) initiate an ongoing effort to measure dust emission across different land use types, such as playas and croplands, to better parameterize dust emissions mechanisms used to produce modeled forecasts, and 3) expand efforts to monitor PM_{10} across the state so that forecast models can be continually tested and improved.

DUST IMPACTS MITIGATION: EARLY WARNING OF DUST EVENTS

With windblown dust source regions often distributed over large areas of remote, unmanaged land, reducing the negative impacts of dust events should also include real-time forecasting of significant events when they occur. Timely communications with affected communities plays a crucial role in reducing dust exposure and is considered part of the success of real-time dust forecasts (Henry et al., 2023). For example, between 2007 and 2011, 72% of all vision-obscured fatal crashes occurred when no visibility advisory was in effect (Ashley et al., 2015). For real-time warning of dust events a separate but related modeling strategy must be developed that can produce forecasts on time scales of minutes. Furthermore, developing an application for mobile devices that allows for communication of immediate risks, and for the public to report and monitor dust events based on their locations, is a reasonable strategy to mitigate adverse impacts of dust storms in affected communities.

There is a need to generate an early warning system for dust storms in impacted parts of the state to provide timely and actionable information on significant dust events as they occur.

AWARENESS OF DUST IMPACTS AND OUTREACH

Efforts to raise awareness about dust-related health concerns in California face several challenges, including limited and inconsistent funding, difficulties in reaching rural communities, and the complexities of engaging with diverse populations across the state (Ayres et al., 2022). Language and cultural barriers, along with distrust of researchers and Western medicine, further hinder outreach (Ramírez et al., 2017; Rodriguez et al., 2023). To address these issues, it is essential to promote and facilitate research on climate and health disparities that specifically target rural and vulnerable communities (Cushing et al., 2015). Vulnerable populations—including immigrants, undocumented individuals, and those of low socioeconomic status—are especially difficult to reach for both data collection on dust exposure and the distribution of health information.

High dust exposure, a major factor exacerbating the health of rural communities, is not typically included in the health and risk assessments at the state level. The regions of California most affected by dust storms also tend to house the most vulnerable populations, making it crucial to tackle long-standing environmental inequalities in these underserved areas (Kodros et al., 2022; Schwartz and Pepper, 2009). Achieving success by reducing airborne dust and dust-related health impairments will require collaboration between affected communities, researchers and policy makers, particularly in the San Joaquin, Imperial and Coachella Valleys. These communities are acutely aware of the risks they face and possess valuable local expertise that can enhance efforts to mitigate dust exposure.

A comprehensive strategy encompassing awareness, prevention, and restoration is needed to address the challenges posed by dust in recreational areas. Adopting land management practices that can reduce dust emissions is a crucial step toward mitigating the impact of anthropogenic dust emissions on both human health and the environment, else outdoor recreational activities may witness a "silent spring", one without the "beauty of bird songs" (Carson et al., 1962). Bridging the gap between local concerns and the goals of scientific and policy efforts is key to creating effective, sustainable solutions (Fernandez-Bou et al., 2021).

There is a need to involve community groups in both research and outreach initiatives to both empower impacted communities and ensure the development of culturally relevant strategies for promoting awareness and change.

BUDGET GAPS

Dust storms are pervasive in California, yet despite the large amount of funding for mitigation of a small number of dust sources in the state, there is little investment in developing capacity for dust impacts mitigation. As such, it is not possible to accurately predict when, where, and for how long

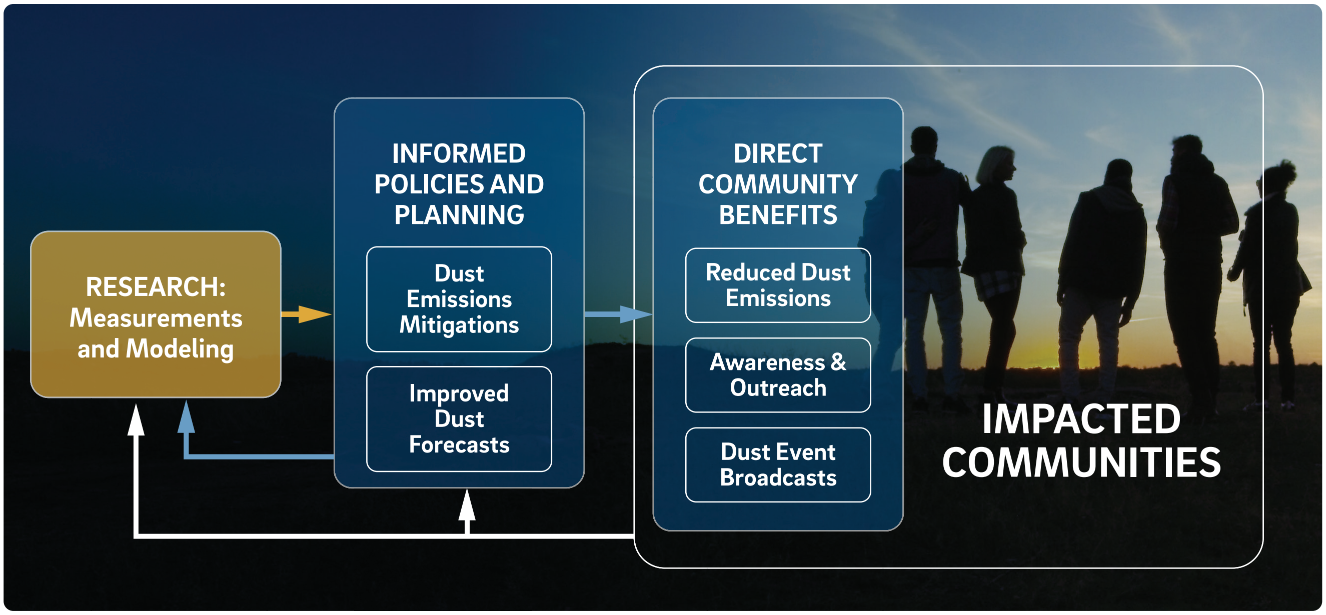


Figure 7. Strategies to minimize negative dust impacts . New research and input from impacted communities generates informed policy and planning, which leads to community benefits. Assessment of these policy and planning activities and community feedback informs new research directions and shapes those policies and planning activities.

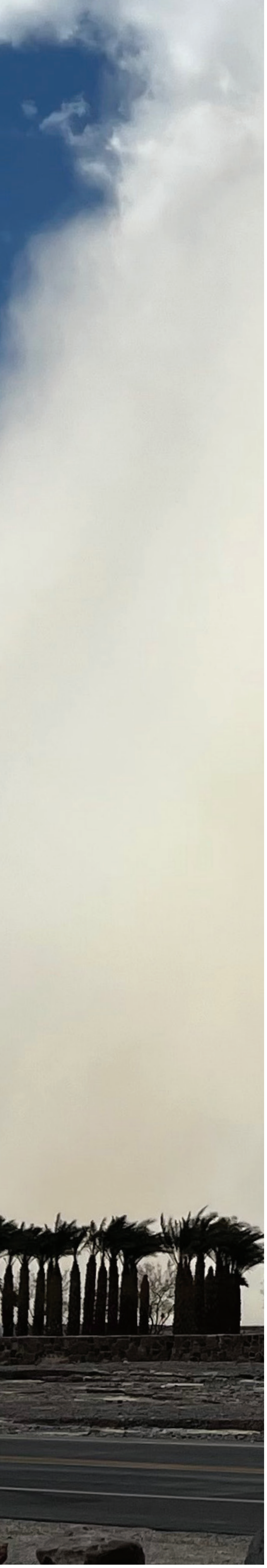
dust levels become unhealthy or unsafe. California has the opportunity to become a leader in dust impacts mitigation, opening up opportunities for collaboration between legislators, state agencies, scientists, and community groups on this important issue. From this foundation, there are significant opportunities to expand these collaborations to other dust-prone regions of the country. Given the numerous adverse health impacts of dust storms and risk to transportation safety by impairing visibility on highways, efforts focused on tracking and forecasting tied to hospitalization data will generate the capacity to improve the health of the people who live and work in the dustiest regions of California (Aguilar-Gomez et al., 2022; Tong et al., 2023; Williams and Chiller, 2022). This work will also help to address long-standing environmental inequalities for these historically underserved communities. The dust-related challenges highlighted here and in prior chapters demonstrate identifiable gaps and areas of need. The collection of data will be necessary to address these gaps.

A long-term commitment to sustainable funding for research and application solutions is required to improve air quality, health, and public safety in communities that are impacted by dust.

SUMMARY

Dust has significant impacts on human safety and health. As dust emissions in California have increased in the past and likely will continue to grow in the future, developing effective adaptation and mitigation strategies to minimize dust impacts needs to be prioritized. Furthermore, the locations in the state with some of the highest concentrations of dust in the air are also home to some of the most vulnerable and underserved populations here. Figure 7 summarizes different strategies and actions to reduce the various negative impacts of airborne dust, including increasing public awareness of dust's effects on human safety and health through outreach, providing accurate and high spatiotemporal dust events forecasts, broadcasting dust events to impacted communities in real-time, and targeted dust emission mitigation work. Research and measurements are the foundations of these strategies and actions, as the rest are extended from these two components. Therefore, they are the backbones of the reduction of negative dust impacts. However, the feedback and interactions between these strategies and actions are critical to the success of these dust adaptation and mitigation strategies. The challenges of awareness stem from inadequate and inconsistent funding, difficulties in reaching rural communities, and the complexities of engaging with diverse populations across the state.

To carry out critical mitigation strategies three equally important activities must be taken: 1) generation of key environmental measurements and development of forecasting capacity, 2) an integrated effort between the communities, researchers, and state agencies, and 3) consistent and sustainable funding support.



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