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Land Transitions and Dust in the San Joaquin Valley

How Proactive Management Can Support Air Quality Improvements

Technical Appendices

CONTENTS

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Appendix A. Estimating Land Cover Emissivity and Dust Risk Geography

Introduction

This report includes two main analytical efforts: estimating the links between land cover type and particulate matter concentrations and mapping the dust risk of rural communities across the San Joaquin Valley. This appendix reports on the data sources and methods used to undertake these analyses and provides some additional results and interpretation.

Estimating Land Cover Emissivity

Inventories of particulate matter emissions in the San Joaquin Valley identify both agricultural operations and fugitive windblown dust as major sources of landscape-based particulates. The extent to which land transitions out of agriculture might represent net increases in particulates was a question raised in a number of stakeholder discussions. Although some previous work has considered the scope and scale of agricultural disamenities (incl. dust; see for example Kuminoff (2009)), limited data available to document emissions rates from the valley floor as well as particulate matter concentrations in rural areas has inhibited finer analysis across land cover and/or crop types. We combine existing data on land cover types with new advances in remote sensing of particulate matter to shed light on these relationships.

Data Sources

We make use of several data sources in this analysis: two main sources to identify land cover, one to extract measures of particulate matter concentration, and one additional source to control for the effect of wildfire on local air quality. Our analysis proceeds at the monthly level, spanning the years 2010–16.

First, we identify land cover acreages across 12 of the valley's subbasins using the USDA Cropland Data Layer (CDL) (USDA 2021), aggregating to six major land cover types: almonds, other orchards (incl. pistachios, citrus, etc.), annual crops, idled or fallowed lands, pastureland, and other unmanaged rangeland.[1] The first three categories encompass active agricultural lands, and the second three represent other land uses to which formerly irrigated lands may transition. We omit nursery and horticultural acreage from the agricultural acreages and break out almonds individually because almond orchards have already been identified by stakeholders and regulatory agencies as uniquely meaningful sources of particulates. We analyze pastureland and unmanaged rangeland separately using a method described below, but because results are very similar for both categories report on them as one in the main report.

While the CDL identifies idled lands, it does not differentiate between actively managed (and potentially partially irrigated) pasturelands and unmanaged rangeland. Areas identified as pasture in the CDL but not marked as actively managed agricultural lands in the 2016 Land IQ crop mapping layers were categorized as unmanaged rangeland. These areas are mostly found in the southern Valley and along its western and eastern edges; review of satellite imagery and discussions with local stakeholders suggest these distinctions may be mostly appropriate, but we note that our approach for differentiating these two land types is likely to result in noise and low accuracy. Indeed, that our results are broadly similar for both categories below suggests that our approach may not adequately distinguish the two—hence our decision

[1] We included the following subbasins: Chowchilla, Delta Mendota, Kaweah, Kings, Kern, Madera, Merced, Modesto, Tulare Lake, Tule, Turlock, and Westside. The analysis excluded two subbasins in the northern valley (Eastern San Joaquin and Tracy), and a small one at the valley's southern edge (White Wolf).

report on them jointly in the main report. As we also note there, more work is needed to understand how these lands are related to particulates since the associations found here are strong.

Second, we use a recently released geospatial dataset from NASA to develop measures of local particulate matter concentrations (Di et al. 2021). The geospatial information provided are modeled particulate matter ($PM_{2.5}$) concentrations at 1-kilometer resolution, based on analysis of satellite imagery paired with monitoring data and additional geographic and meteorological information. In calculating local particulate matter concentrations, we omit modeled concentrations from within urban areas as defined by the Federal Highway Administration (FHWA).

While we are constrained to measures of fine particulate matter, which makes up only a portion of fugitive dust and may therefore not fully capture our outcome of interest for understanding the potential impact of land transitions, we are able to compare our measures derived from the NASA spatial model outputs to observations from local EPA monitoring sites. We find generally high degrees of correlation between monitor readings of $PM_{2.5}$ and model measures from the surrounding rural area (98^{th} percentile measures; ρ ranges [0.47, 0.91] across sites) and between local spatial measures of $PM_{2.5}$ and observed measures of PM_{10} across years (98^{th} percentile $PM_{2.5}$ and 2^{nd}-max PM_{10}, ρ ranges [0.35, 0.64] across sites, with one lower outlier at 0.28). While the spatial data on modeled $PM_{2.5}$ do not perfectly track particulate concentrations from landscape sources, these comparisons suggest they can serve as a reasonable proxy for understanding local associations with land cover type.

Finally, because significant wildfire activity during our period of analysis no doubt had an impact on valley particulate matter concentrations, we attempt to control for idiosyncratic shifts in particulate generation from wildfires using data from Cal Fire's Fire and Resource Assessment Program (FRAP) (Cal Fire 2021). We separate the valley into two subregions defined by the Tulare Lake and San Joaquin River hydrologic regions and sum in each month the total acreage burned within these regions (including in headwater forest areas).

Estimating Equation

Relationships between the extent of land cover (in acres) and local particulate matter concentrations are estimated for each month separately. (In the following equations, subscript t refers to years but values vary at the month level.) For each month, the following model is estimated:

$$y_{it} = \beta_0 Burn_{jt} + \beta_{1-6} Acres_{it} + \gamma_i + \tau_t + \varepsilon_{it}$$

- y_{it} is the local monthly particulate matter concentration, measured for rural areas only;
- $Burn_{jt}$ is the acreage burned in region j in month-year t;
- $Acres_{it}$ is a vector of crop acreages in subbasin i in year t;
- γ_i is a set of subbasin fixed effects;
- τ_t is a set of year fixed effects;
- and ε_{it} is an error term.

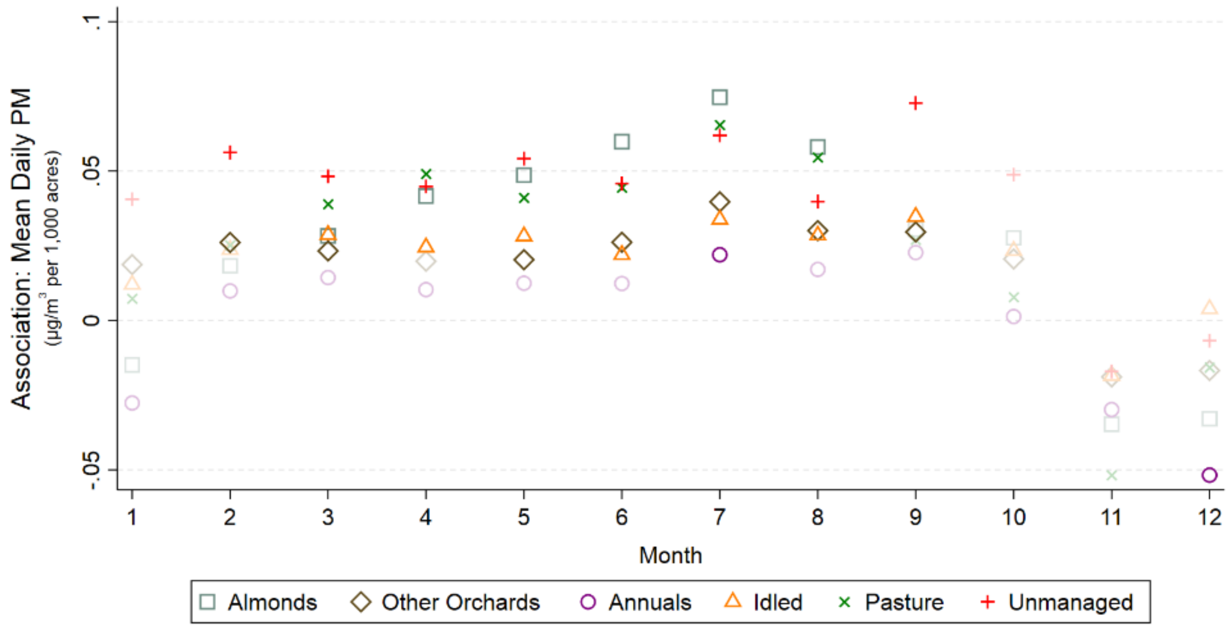
The coefficients of interest are β_{1-6}, relating differences in land cover acreages—relative to long-term baselines and common idiosyncratic annual shocks—to local particulate matter concentrations. The model conditions local particulate matter concentrations on observed wildfire activity as well, in order to help take account of idiosyncratic wildfire activity that may associate with land cover decisions (such as regional drought conditions). One set of six relevant coefficients is produced for each month of the year, resulting in 72 total coefficient estimates to interpret.

Figure A1 plots these estimated acreage coefficients for each monthly regression. Estimates that are statistically significant at the 10 percent level are displayed in fully saturated color; others are displayed in faded colors. Estimated relationships are scaled by the impact on particulate matter per 1,000 acres of the relevant land cover type. The magnitudes suggest mostly moderate to large impacts: for example, looking at associations between almond acreage and local particulate concentrations in the summer (one of the stronger relationships), an increase of 10,000 acres in almonds would imply roughly a 0.5-0.6 $\mu g/m^3$ change in average $PM_{2.5}$ concentration.[2] This reflects an approximately 5–7 percent change in the mean summer average daily $PM_{2.5}$ concentration for the 2010–16 period, depending on location in the valley.[3] It is also important to note that the regional air district began its low-dust nut harvester program in 2018--after our study period ends. The equipment modifications supported by this program have reduced dust emissions from harvest substantially and likely weakened this relationship.

The following section explores relationships between land cover and mean daily maximum concentrations, which are likely more sensitive to outlier fugitive dust events caused by high winds.

FIGURE A1

Estimated links between land cover and particulates reveal important differences and seasonality



SOURCE: Developed by the PPIC Water Policy Center using data from NASA (particulate matter), Land IQ (land cover), and Cal Fire (wildfire burn acreage).

NOTES: Plotted points reflect estimated coefficients for relationships between land cover and local particulate matter concentrations. Points displayed in full color saturation reflect estimate statistically significant at the 10 percent level.

[2] A change of 10,000 acres reflects roughly 3 percent of the average irrigated acreage in a valley subbasin.

[3] This value represents the average effect of increasing almond acreage, given other existing land uses in the subbasin. Relative to the other land uses considered in this analysis, replacing annual crops with almond acreage would likely have the largest impact on PM concentrations in the summer months, for example.

Wind Speed Scaling

While not all landscape-based particulate emissions are driven by wind processes, many are. To investigate what role wind plays, we use wind speed data provided by Iowa State University for a number of monitoring sites throughout the valley. In particular, we calculate for each month in each subbasin the proportion of time that recorded wind speeds exceeded 7 miles per hour. (Robustness tests reveal similar results for other wind speed thresholds.) These calculations are based on averages across years with available data, which vary by monitoring site.[4] Such data limitations prevent us from controlling for wind speed directly, but we are able to test whether the relationship between land cover types and particulate depends on wind speeds.

The model specification for this additional estimation exercise is given by:

$$y_{it} = \beta_0 Burn_{jt} + \beta_{1-6} Acres_{it} + \beta_{7-12} Acres_{it} * WindSpd_i + \gamma_i + \tau_t + \varepsilon_{it}$$

This estimating equation includes interaction terms for each land cover type with wind speed averages in subbasin i, and accordingly expands the number of estimated coefficients of interest by 6. In addition, the outcome variable in our preferred specification is now the average maximum (as opposed to mean) daily particulate matter concentration, as we are interested in uncovering the role of wind in driving large dust events based on emissions from these landscapes. The interpretation of these new coefficients is—conditional on all other controls, as in the baseline specification—the degree to which the relationship between land cover type and local particulate matter concentrations depends on wind speed. A positive coefficient estimate would be consistent with higher wind speeds strengthening the relationship between that land cover type and local particulates (i.e., wind kicking up more dust from that particular landscape type).

[4] For many stations, this includes the period 2010-2016; for subbasins lacking monitoring sites that cover this period, we use other years to establish a long-term representative average.

FIGURE A2

Trends across land cover types and seasons remain mostly similar when accounting for wind speed interactions

SOURCE: Developed by the PPIC Water Policy Center using data from NASA (particulate matter), Land IQ (land cover), Cal Fire (wildfire burn acreage), and Iowa State University (wind speed).

NOTES: Plotted points reflect combined estimated coefficients for wind-speed-scaled relationships between land cover and local particulate matter concentrations; calculated values are representative and based on cross-sectional average wind speeds. Full-color points reflect estimate statistically significant at the 10 percent level.

We compute representative relationships using valley-wide average wind speeds, and these are plotted in Figure A2. In part because these relationships reflect a combination of multiple estimated coefficients, fewer are reliably statistically significant; nonetheless, the estimated signs follow similar trends to our baseline specification. In spring, late summer, and fall, exposed landscapes like pastures, idled lands, and unmanaged rangelands have large point estimates, and associations are generally weak in winter. During harvest, larger almond and other orchard acreages are associated with greater particulate matter measures, although the relationship associated with almond acreages is no longer typically the strongest in those months.

Mapping the Valley's Dust Risk Geography

While landscape-based dust particles can travel long distances from their source after being introduced to the air, this distance largely depends on the particle size and the prevailing wind speed. Particulates from the soil tend to be larger and not travel more than a few miles except during extreme dust storms—for the most part the impact is local. In addition, the proclivity of a landscape to produce dust—and dust of different sizes—depends on its soil characteristics. Soil type can have an important influence on how much fugitive dust might be generated from a given area, and what human health impacts it may have.

Accordingly, there is value in understanding what soil conditions characterize the land surrounding the valley's rural communities.

Data Sources

Most spatially explicit mapping of cities does not include small communities of several hundred—or as few as several dozen—residents, which are common in the valley. Absent a general, precise mapping of rural communities, we rely on the State Water Board's mapping of community water systems to identify rural settlements throughout the valley.[5] Of the more than 350 community water systems located in the valley, many are co-located in one area where a single settlement may be served by multiple systems; we identify just under 150 unique rural locations surrounded by significant expanses of agricultural land.

To understand the propensity of soil to produce dust from either agricultural disturbance or wind processes, we rely on the Wind Erodibility Index (WEI), defined by USDA's Natural Resources Conservation Service (NRCS) and mapped for California by Walkinshaw et al. (2021). This index relies itself on categorical delineations of soil types based, among other things, on the prevalence of different mineral compounds and the proportion of particle sizes, which it translates into expected erosion in terms of tons/acre/year.

We characterize baseline air quality conditions using the same NASA data referenced above.

Finally, we consider as a proof-of-concept a comparison of high-dust-risk areas to areas likely to see fallowing under SGMA implementation. To do so, we rely on preliminary estimates of fallowing from hydro-economic modeling being undertaken as part of PPIC's broader work on agricultural land transitions; this work represents an extension of the modeling from Hanak et al. (2019). This modeling produces estimates of fallowing for several dozen modeling subregions throughout the San Joaquin Valley. The expected fallowing for a given community is the area-weighted average of fallowing proportions for all modeling subregions that intersect the community's buffer (described below).

We use modeling results from a scenario assuming inflexible water management options: little additional water is available for application and recharge, and water trading is not permitted between districts. Results should be interpreted as illustrative and not definitive with respect to the ultimate risk facing Valley communities; additional future work will shed additional light on the geography of fallowing under SGMA.

For each of the soil, air quality, and fallowing metrics, we construct our measures based on the lands that fall within a circular buffer with a 1.5-mile radius around each community. In addition, for calculating average WEI and area-weighted average fallowing we also estimate and account for the size of each community's developed footprint by cropping out a central circular area with a radius sized by the location's population—the buffer radius is extended 1.5 miles beyond the cropped edge.[6] We produce an additional set of metrics based on buffers with a 3-mile radius and find broadly similar results.[7]

[5] This method will not capture the locations of all rural valley residents; in particular, those who depend on domestic wells for drinking water and are located outside of the boundaries of a community system are not mapped in this exercise.

[6] We use a representative household size of 4 persons/household to convert population to households; thereafter, we rely on local development planning documents to convert households to acres at an average rate of 2 households per acre (for example, San Joaquin County (2022)). Deriving the radius of an equally sized circular area is straightforward.

[7] Using the 3-mile buffer distance, the distribution of dust risk collapses somewhat, as buffers including relatively extreme values in the 1.5-mile buffer are expanded. Twelve additional locations are in the "low" dust risk category compared to under the 1.5-mile buffer. In contrast, some areas saw increased estimated fallowing as the larger buffer incorporated some lands from neighboring modeling subregions with non-zero expected fallowing; twelve locations that expected zero fallowing with a 1.5-mile buffer now expect some fallowing within the 3-mile buffer. Overall, 35 of the 147 locations shifted at least one category, but our qualitative conclusions do not change significantly.

Categorization Approach

Our categorization approach is based on threshold distinctions in soil characteristics (as measured by WEI) and baseline particulate matter exposure rates. These high and low risk distinctions follow meaningful breakpoints in physical or regulatory processes, as described below. Delineating communities as high or low risk on both margins results in four combinations, which we term high (high risk on both metrics), high medium (high WEI and low PM), medium low (low WEI and high PM), and low (low risk on both metrics).

We follow the categorical foundations of the WEI and consider soil types with greater than 86 tons/acre/year erosion potential as high risk; this represents a breakpoint in the index values, above which soil mixes become more erosive with high proportions of fine and very fine sands and silt particles.

Because some health impacts occur or are exacerbated at high concentration levels, we also distinguish elevated risk for areas with higher baseline particulate matter concentrations. In particular, we categorize areas with average daily mean $PM_{2.5}$ greater than 12 $\mu g/m^3$ over 2010-2016 period as high risk. This threshold is the California annual average ambient air quality standard (CAAQS), so areas not regularly in attainment are considered to have higher baseline risk and as such warrant additional consideration. This distinction is secondary to the distinction between areas with highly erosive nearby soils.

Results of this categorization exercise are displayed spatially in the main report's Figure 4. Communities on the west side of the valley see lower particulate matter levels and soil conditions less susceptible to erosion via wind; highly erosive areas are mostly spatially concentrated along the central-east side of the valley as well as the north-central area. Table A1 below quantitatively summarizes the distribution of communities across these risk categories; it also breaks down the distribution according to the extent of expected fallowing in the communities' surrounding areas. Most communities (92) face high baseline particulate matter concentrations, while a lower number (63) are at elevated risk of dust problems due to surrounding soil types.

Among communities with high-risk soils, approximately 75 percent would see some degree of nearby fallowing under the modeling scenario described above; within the highest-risk category, the proportion is roughly 80 percent. However, most of these communities are in areas expecting relatively low fallowing (<20%, the lowest non-zero fallowing category considered here). This could nonetheless represent a significant departure from the current extent of irrigated agricultural land cover. These cross-tabulations of risk with expected fallowing are an illustrative example: in future work we intend to calculate and discuss potential risk profiles under multiple different water management and land fallowing scenarios.

TABLE A1

Some areas at high risk for dust may see significant fallowing under inflexible water management scenarios

Dust Risk Category	Fallowing: 0%	0.1-20%	20-40%	40-60%	60-80%	Total
High	7 (18%)	20 (50%)	7 (18%)	6 (15%)	0	40
High Medium	9 (39%)	6 (26%)	8 (35%)	0	0	23
Medium Low	2 (4%)	26 (50%)	20 (38%)	3 (6%)	1 (2%)	52
Low	7 (22%)	16 (50%)	8 (25%)	0	1 (3%)	32

SOURCE: PPIC categorizations based on data from Walkinshaw et al. (2021), Di et al. (2021), and preliminary PPIC fallowing estimates.

NOTES: Numbers indicate the count of locations that belong to each categorization; numbers in brackets are approximate percentages of the locations in each dust risk category. Dust risk categories are as follows: high (WEI>86, ambient PM>12 μg/m^3 over 2010-2016), high medium (WEI>86, PM<12 μg/m^3), medium low (WEI<86, PM>12 μg/m^3), and low (WEI<86, PM<12 μg/m^3). Expected fallowing percentages are based on preliminary PPIC hydro-economic modeling scenarios that reflect full SGMA implementation without new valley water supplies and no trading across water district boundaries. All values are calculated within 1.5-mile buffers, adjusted in the case of WEI and fallowing percentages to account for the footprint of the community.

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Appendix B. Dust Mitigation Strategies

The purpose of this appendix is to document the varied interventions that can be applied to control dust emissions on formerly irrigated agricultural lands. The ongoing implementation of SGMA in the San Joaquin Valley will present a risk of significant increases in dust from these lands, creating numerous negative downstream health and economic effects for community members throughout the region. This appendix can serve as a guide for land managers as they begin to navigate the process of transitioning farmlands out of production, in addition to providing a common source of information for other parties who may encounter new land management challenges.

Data on cost, description, and purpose were retrieved from a number of agency document and other primary research sources. First, we consulted the USDA Natural Resources Conservation Service (NRCS) "Guide to the Control of Windblown Dust on Agricultural Lands in Nevada" [1] & "California Practice Scenarios - Fiscal Year 2022" [2], as well as the 2016 Salton Sea Air Quality Mitigation Program Annual Report [3], *Economic Comparison of the Undercutter and Traditional Tillage Systems for Winter Wheat-Summer Fallow Farming* from the Washington State University Extension [4], and *Restoring Mojave Desert Farmland with Native Shrubs* from the U.S. Department of Agriculture, Forest Service, Intermountain Research Station [5], hereby referred to as documents [1], [2], [3], [4], and [5] respectively. A sixth source, [6], refers to additional research conducted by PPIC on some practices—particularly on costs. This work included consultation with experts familiar with the practices.

Cost estimates were mainly retrieved from documents [2] and [3]—both relatively recent sources—and from our additional research on costs [6]. Where relevant, older estimates were adjusted for inflation (to 2021 US dollars). As such, the estimates provided here reflect relatively recent implementation costs; although we note that costs may be higher today, particularly in light of current inflationary pressures. Information on description and purpose was retrieved from document [1]. Data from documents [1] and [2] were originally retrieved by their authors from the 2012–2020 Financial Management Modernization Initiative (FMMI), and the National Planning and Agreements Database (NPAD). Additionally, researchers at the Bren School of Environmental Science & Management at the University of California, Santa Barbara, retrieved data for their report through personal communications with project implementers. Data from the Washington State University Extension were gathered from a case study in Adams Count, Washington. Lastly, researchers from the U.S. Department of Agriculture, Forest Service, Intermountain Research Station retrieved their data from the USDA Soil Conservation Service (today's Natural Resources Conservation Service).

Table B1 organizes mitigation strategies into categories based on the land they could be adopted on—and includes information on their purpose, time of year used, and estimated cost. Time of use illustrates the ideal time of year for growers to implement the suggested interventions, based on weather and soil conditions. We note here that not all land management strategies are equally appropriate in all conditions. Whereas some interventions are temporary land practices, others entail a permanent approach. Likewise, while some measures are meant only to be implemented on cropped dryland, others are better suited for fallowed drylands or otherwise unmanaged lands.[8] However, there remain a handful of interventions that

[8] "Dryland cropping" refers to cropping that relies solely on precipitation and stored soil moisture for plant water needs, typically in drier areas with less than 20 inches of annual precipitation. See the companion PPIC report by Peterson et al. (2022) (listed as [7] in the references) for a discussion of dryland cropping and other water-limited farming options (including "dryland-plus" cropping with a small amount of supplemental irrigation).

can be applied within both scenarios. In the same vein, it is important to note that time of use delineates the circumstances under which certain interventions would prove most effective (e.g., during the growing season, or year-round). Similarly, estimated cost figures represent the scenario cost per unit, where units are most frequently measured in acres, unless otherwise stated. These data suggest that interventions utilizing wind barriers and strip-cropping are the least costly, whereas strategies that physically cover the land surface or alter it (e.g., concrete, gravel, mulching, surface roughening, etc.) come at a significantly higher cost. Because the latter interventions provide multi-year benefits, however, they may be more cost-effective over time.

TABLE B1

Dust control measures on non-cropland

Non-Cropland / Fallowed Lands				
Management Strategy	**Description [1]**	**Purpose [1]**	**Time of Use**	**Cost Estimate**
Access Restriction	"Access restriction" means restricting or eliminating public access to non-cropland with signs or physical obstruction.	Reducing the number of trips driven on agricultural aprons and access roads can reduce that area's susceptibility to PM_{10}.	Year-round	Varies based on tillage operation
Aerial – Seeding [6]	"Aerial–seeding" means large-scale seeding of vegetative cover via helicopter dispersal.	Designed to introduce vegetative cover that reduces PM by stabilizing the soil and stopping entrainment of particles.	Growing season (late spring - early fall)	$30–$110/acre Depends greatly on scale of seeding operation and prevailing wind conditions. Smaller operations likely not cost-effective relative to direct ground seeding. Additionally, success is reliant on subsequent precipitation. [6]
Aggregate Cover	"Aggregate cover" means gravel, concrete, recycled road base, caliche or other similar material applied to non-cropland.	Applying an aggregate cover to unpaved farm roads, parking areas and canal banks helps reduce the amount of soil particles exposed to the surface, thus helping to reduce the generation of PM_{10}. Aggregate cover acts as a surface barrier to erosive forces like wind or vehicle traffic.	Year-round	$10.17/sqr-ft [2]
Artificial Wind Barrier	"Artificial wind barrier" means a physical barrier to the wind, such as a fence or spare agricultural equipment.	Artificial wind barriers disrupt the erosive flow of wind over unprotected areas, thus helping to reduce PM_{10}.	Year-round	$0.80/ft [6] Treating one edge of an acre at 208 feet costs $166
Chips/Mulches [6]	"Chips and mulches" means application of any application of any heavier stabilizing material not produced on-site to the land surface. Cost varies by material and land slope.	Reduces transport of fugitive dust. Typically applied to lands at high risk for significant soil erosion.	Year-round	$250–9,000/acre [2] Depends on material: straw (low) to netted wood fiber (high)

Non-Cropland / Fallowed Lands				
Management Strategy	**Description [1]**	**Purpose [1]**	**Time of Use**	**Cost Estimate**
Critical Area Planting	"Critical area planting" means using trees, shrubs, vines, grasses, or other vegetative cover on non-cropland.	Critical area plantings help control soil movement and protect the soil surface when adequate cover does not exist. Ground covers reduce dust and wind erosion by shielding the soil with vegetation and anchoring the soil with roots. This practice applies to field aprons, equipment parking areas, turn rows, canal or ditch banks, canal excavation spoil piles and bare areas where vegetation is difficult to establish by usual planting methods. Critical area planting consists of any vegetative cover that maintains more than 60 percent ground cover.	Growing season (late spring - early fall)	$349.93/acre [2]
Cross-Wind Vegetative Strips	"Cross-wind vegetative strips" means herbaceous cover established in one or more strips within the same field.	Herbaceous cover creates a protective windbreak that disrupts the erosive forces of high winds, especially during critical wind erosion periods.	Growing season (late spring - early fall)	Approx. $10/acre [6; modified from 2]
Gravel	"Gravel" means placing a layer of gravel with enough depth to minimize dust generated from vehicle movement and to dislodge any excess debris which can become entrained	To add a layer of washed gravel, rock, or crushed rock, which helps reduce wind erosion and PM_{10}.	Year-round	$38,828.67/acre (2-inches) $51,771.56/acre (4 inches) 0.25% (estim. O&M) [3; older source]
Manure Application	"Manure application" means applying animal waste or biosolids to a soil surface.	Applying manure to maintain or improve chemical and biological condition of the soil can help reduce wind erosion and PM_{10} emissions.	Tillage and harvest operations	$71.57/acre [2]
Reduce Vehicle Speed	"Reduce vehicle speed" means operating farm vehicles or farm equipment on unpaved private farm roads at speeds not to exceed 20 mph.	Reduced speeds can decrease the amount of PM_{10} generated by vehicles or equipment on unpaved farm roads	Year-round	Varies based on tillage operation

Non-Cropland / Fallowed Lands				
Management Strategy	**Description [1]**	**Purpose [1]**	**Time of Use**	**Cost Estimate**
Residue Management	"Residue management" means managing the amount and distribution of crop and other plant residues on a soil surface.	Leaving crop and other plant residues on the soil surface can protect the soil between the time of harvest of one crop and emergence of a new crop, thus helping reduce wind erosion and the generation of PM_{10}.	Year-round	$20.83/acre [2]
Surface Roughening	"Surface roughening" means manipulating a soil surface to produce or maintain clods.	The formation of clods helps disrupt the erosive force of the wind over an unprotected soil surface. Soil clods can be formed by tillage implements under appropriate soil moisture conditions.	Tillage and harvest operations	$300.25/acre 75% (estim. O&M) [3; older source]
Synthetic Particulate Suppressant	"Synthetic particulate suppressant" means a manufactured product such as lignosulfonate, calcium chloride, magnesium chloride, an emulsion of a petroleum product, an enzyme product, and polyacrylamide that is used to control particulate matter.	Synthetic particulate suppressants provide a surface barrier or bind soil particles together to retard PM_{10} on unprotected areas, such as unpaved roads, rights-of-way and abandoned fields.	Year-round	$2,157.15/acre 100% (estim. O&M) [3; older source]
Targeted Burn Treatment [6]	"Targeted burn treatment" means burning land cover as an alternative weed control method.	Reduces PM_{10} emissions that would otherwise result from disking.	Applied as needed, consistent with burning permits	$43-61/acre [6]
Tree, Shrub, or Windbreak Planting	"Tree, shrub, or windbreak planting" means providing a woody vegetative barrier to the wind.	Barriers placed perpendicular to the wind direction can reduce wind speeds by changing the pattern of airflow over the land surface, which helps reduce wind erosion and PM_{10}.	Growing season (late spring - early fall)	$8.46/ft [2] $130 to establish one barrier along a quarter section

TABLE B2
Dust Control on Dryland

Dryland Cropping / Cover Cropping				
Management Strategy	**Description [1]**	**Purpose [1]**	**Time of Use**	**Cost Estimate**
Access Restriction	"Access restriction" means restricting or eliminating public access to non-cropland with signs or physical obstruction.	Reducing the number of trips driven on agricultural aprons and access roads can reduce that area's susceptibility to PM_{10}.	Year-round	Varies based on tillage operation
Artificial Wind Barrier	"Artificial wind barrier" means a physical barrier to the wind.	Artificial wind barriers disrupt the erosive flow of wind over unprotected cropland fields thus helping to reduce PM_{10}.	Year-round	$0.80/ft [6] Treating one edge of an acre at 208 feet costs $166
Chemical Irrigation	"Chemical irrigation" means applying a fertilizer, pesticide, or other agricultural chemical to cropland through an irrigation system.	Chemical irrigation reduces the number of passes across a field with tractors, sprayers, fertilizer applicators, and machinery. Reducing the number of field operations reduces the emissions associated with those activities and the amount of soil disturbed.	Growing season (late spring to early fall)	$56.25/acre [2]
Combining Tractor Operations	"Combining tractor operations" means performing two or more tillage, cultivation, planting, or harvesting operations with a single tractor or harvester pass.	Combining tractor operations reduces the number of passes or trips that a tractor, implement, harvester, or other farming support vehicle makes across a field or unpaved surface, thereby reducing the amount of soil disturbed.	Tillage and harvest operations	Varies based on tillage operation; possibly produces cost savings
Cover Crop [6]	"Cover crop" means plants or a green manure crop grown for seasonal soil protection or soil improvement.	Cover crops help control soil movement and protect the soil surface between crops. Cover crops reduce wind erosion by shielding the soil with vegetation and anchoring the soil with roots. Cover crop effectiveness is in large part determined by surface and canopy coverage.	Growing season (late spring - early fall)	Strip Cover: $6.76–$12.09/acre [2] Extensive Cover: $61–$66/acre [6] Depending on cover species
Cross-Wind Ridges	"Cross-wind ridges" entails the construction of purposefully placed soil ridges during tillage operations.	Ridges formed by tillage operations create protective windbreaks that disrupt the erosive forces of high winds.	Growing season (late spring - early fall)	$26.47/acre [2]

Dryland Cropping / Cover Cropping				
Management Strategy	**Description [1]**	**Purpose [1]**	**Time of Use**	**Cost Estimate**
Cross-Wind Strip-Cropping [6]	"Cross-wind strip-cropping" means planting interspersed rows of wind-erosion-resistant crops within the same field as conventional crops. (Code 585)	Growing crops or managing residue as a protective cover in strips across the prevailing wind direction can break the effects of high wind events.	Growing season (late spring - early fall)	Approx. $10/acre [6]
Equipment Modification	"Equipment modification" means modifying agricultural equipment to prevent or reduce particulate matter generation from cropland.	Modifying and maintaining an existing piece of agricultural equipment or purchasing new equipment to prevent PM_{10} from becoming airborne during tillage and harvest operations, which helps reduce PM_{10} and soil erosion.	Tillage and harvest operations	Switch to undercutter from traditional tillage can produce cost savings From eastern Washington: $102.15/acre (undercutter) vs. $104.61/acre [4; older source]
Limited Activity During a High-Wind Event	"Limited activity during a high-wind event" means performing no tillage or soil preparation activity when the measured wind speed at 6 feet above the ground is more than 25 mph at the farm site.	Because this management strategy falls within the tillage, planting, and harvest category, it also applies during harvest time. Wind speed, temperature and relative humidity affect the distance that PM_{10} travels and the ability for PM_{10} to be suspended in the air. Limiting activity during a high-wind event will reduce the transport of PM_{10}. Reducing farm operations during a high wind event, as well as when the wind speed is less than 25 mph, can significantly help reduce PM_{10} emissions.	Year-round	Varies based on tillage operation
Manure Application	"Manure application" means applying animal waste or biosolids to a soil surface.	Applying manure to maintain or improve chemical and biological condition of the soil can help reduce wind erosion and PM_{10}.	Tillage and harvest operations	$71.57/acre [2]
Mulching	"Mulching" means applying plant residue or other material that is not produced on site to a soil surface.	Adding a protective layer to the soil surface reduces soil movement in high wind events. This practice also conserves soil moisture, which can reduce surface movement of soil.	Tillage and harvest operations	$262.44/acre [2]
Reduced Tillage System	"Reduced tillage system" means reducing the number of tillage operations used to produce a crop.	Any tillage operation in a field can modify the soil structure and possibly release PM_{10} into the air. Reducing the number of tillage activities can maintain the soil structure and help reduce PM_{10}.	Tillage and harvest operations	$20.83/acre [2]

Dryland Cropping / Cover Cropping				
Management Strategy	**Description [1]**	**Purpose [1]**	**Time of Use**	**Cost Estimate**
Residue Management	"Residue management" means managing the amount and distribution of crop and other plant residues on a soil surface.	Leaving crop and other plant residues on the soil surface can protect the soil between the time of harvest of one crop and emergence of a new crop, thus helping reduce wind erosion and the generation of PM_{10}.	Tillage and harvest operations	$20.83/acre [2]
Sequential Cropping	"Sequential cropping" means growing crops in a sequence that minimizes the amount of time bare soil is exposed on a field. (Code 328)	By reducing the amount of time bare soil is exposed, sequential cropping helps reduce the window of time that the cropland is susceptible to PM_{10} erosion.	Growing season (late spring - early fall)	$790.10–914.89/acre [2]
Timing of a Tillage Operation	"Timing of a tillage operation" means performing tillage operations at a time that will minimize the soil's susceptibility to generate PM_{10}.	Adjusting the time of tillage operations can minimize the amount of time the soil surface is susceptible to wind erosion and generation of PM_{10}. When a field's surface is smooth, dry, and consists of finer grained soil particles, the field is most susceptible to wind erosion, resulting in PM_{10}.	Tillage and harvest operations	Varies based on tillage operation
Tree, Shrub, or Windbreak Planting	"Tree, shrub, or windbreak planting" means providing a woody vegetative barrier to the wind.	Barriers placed perpendicular to the wind direction can reduce wind speeds by changing the pattern of airflow over the land surface, which helps to reduce wind erosion and PM_{10}.	Growing season (late spring - early fall)	$8.46/ft [6] Establishing one 2500-ft barrier along a quarter section (160-acre parcel), results in cost of approx. $130/acre

SOURCE: Information compiled by PPIC researchers from USDA NRCS documents as well as other primary research reports. Citations available in reference section.

NOTES: Footnote citations [1], [2], [3], [4], [5], and [6] refer to sources listed by number in the reference section. O&M refers to ongoing operations and maintenance costs. Some measures are listed twice, where they are applicable for both actively cropped (dry) lands and non-cropped lands. "Tillage and harvest operations" refers to the preparation of soil for planting, the cultivation of soil after planting, and the gathering of the useful part or parts of the plant and clearing of managed lands. The language contained in the "description" and "purpose" columns was retrieved directly from document [1], except where otherwise noted.

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