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Use of Real-Time Dust Monitoring and Surface Condition to Evaluate Success of Unpaved Road Treatments

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Abstract

Fugitive dust from unpaved roads creates human health hazards, degrades road surfaces, and increases the cost of road maintenance. As a result, many different chemical treatments are applied to unpaved roads in an attempt to control dust and stabilize the wearing course. However, investigations of the effectiveness of these treatments have often been poorly planned or executed. The objective of this study was to use a combination of real-time dust monitoring and objective road condition evaluations to assess the success of two chemical treatments for a period of 19 months post-application, to provide quantitative information in support of road management decisions. Dust production from road sections treated with calcium chloride-based durablend-C™ or the synthetic fluid EnviroKleen® was monitored on five dates using a vehicle-mounted particulate matter meter. Both products reduced dust by up to 99% relative to an untreated control section during the monitoring period, and quantitative data from the meter were consistent with qualitative observations of dust conditions. Linear models of dust production indicated that road treatment and humidity explained 69% of the variation in dust over time. Road sections treated with either product developed less rutting and fewer potholes than the untreated control. Overall, the combination of real-time dust monitoring and surface condition evaluation was an effective approach for generating quantitative data on endpoints of interest to road managers.

Fugitive dust from unpaved roads decreases visibility for drivers and can represent a health hazard for those traveling on or living near roads. Not surprisingly, unacceptable levels of dust are one of the most common complaints of the public to road managers. The loss of fine material from the road surface also contributes to the development of surface distresses and increases costs for road maintenance. For these reasons, various chemical stabilizers (e.g., chlorides, lignosulfonates, synthetic polymer emulsions, and synthetic fluids) have been applied to unpaved roads since at least the 1960s (*1*).

Although there have been numerous product trials and research studies on unpaved road chemical treatments in the past 50 years, many of these efforts have suffered from insufficient monitoring, a lack of untreated controls for comparison, and a lack of reporting (*1, 2*). Even well-planned and executed studies show great variability in methods of evaluating performance. Some studies have focused solely on engineering endpoints (dynamic cone penetrometer and falling-weight deflectometer measurements among others [e.g., *3*]), whereas other studies have reported only subjective observations. Neither of these categories is ideal for informing road management decisions and justifying those decisions to the public. In order to maximize the value of field trials and research studies, performance endpoints should reflect the major concerns of road managers—dust production and surface distresses that lead to aggregate loss and increased maintenance (*4*).

Many previous studies of road dust production have employed visual ratings of dust. Although such ratings can generate useful comparisons, they cannot estimate mass concentrations of particles to which road users or roadside organisms might be exposed. From a research standpoint, quantitative measurement of dust is a much more powerful approach. Measuring road dust in the field, however, can be problematic. Passive methods such

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as dust collection pans tend to suffer from extreme variability, as well as interference from humans and animals (*5*). Active methods such as vehicle-mounted techniques (*2, 6, 7*) have been used successfully, but these methods also face challenges, including lack of widespread access to custom-built equipment.

A quantitative, yet relatively simple and economical approach is needed to evaluate the success of chemical treatments for unpaved roads. Such an approach would allow road managers to assess in a reliable way whether or not a particular treatment is appropriate for their road setting, and to effectively justify their road management decisions. The objective of this project was to provide a rigorous, systematic assessment of the success of two unpaved road chemical treatments for 19 months post-application. Success was evaluated through a combination of real-time dust monitoring using a commercially available meter and an objective road condition rating procedure. Together, these methods allow road managers to quantitatively assess two of the most important endpoints for unpaved roads—dust production and surface distresses.

Methods

Test Site

The Loess Bluffs National Wildlife Refuge (NWR), formerly Squaw Creek NWR, is a 3,011-ha (7,440-acre) complex of wetlands, grasslands, and forest in northwest Missouri. Designated a Globally Important Bird Area by Birdlife International, Loess Bluffs hosts more than a million snow geese, waterfowl, and shorebirds each year. The primary road on the refuge is a 16-km (10-mi) auto tour loop that runs adjacent to managed wetland units. Historically, the refuge has had moderate to severe issues with dust on the auto tour loop, particularly associated with special events that can bring thousands of visitors to the refuge on a single day. Dust on the auto tour loop creates problems for wildlife viewing and photography, which are priority refuge uses. Refuge management has also received complaints from recreational bikers and visitors with respiratory issues.

In an effort to reduce dust and stabilize the road surface on the auto tour loop, two dust control products were applied: durablend-C™, a polymer-enhanced calcium chloride (EnviroTech Services, Greeley, CO), and EnviroKleen®, a synthetic fluid with binder (Midwest Industrial Supply, OH). Each of these products had demonstrated low aquatic toxicity in previous laboratory tests, and was expected to pose minimal risk to the aquatic habitats along the road. Prior to application, product vendors were provided a summary of road geometry, traffic patterns, weather conditions, and aggregate composition and gradation to ensure that the selected products were appropriate for installation at the refuge.

Test Design and Product Applications

The two products were each applied to two different 0.8-km (0.5-mi) sections of the Loess Bluffs NWR auto tour loop in July 2014, and an additional 0.8-km (0.5-mi) section was left untreated as a control (Figure 1). These road sections were selected for consistency of conditions that could influence dust production, namely, canopy cover, orientation relative to prevailing winds, and drainage. Based on discussions with refuge staff, several sections of the auto tour loop were excluded from consideration because of planned construction projects or vulnerability to flooding. These limitations precluded the inclusion of a second untreated control section. Because traffic on the loop is one-way and there are no entrances/exits between the selected sections, all sections should have experienced the same traffic (predominantly light passenger vehicles, with occasional heavy equipment use by refuge staff). During the test period, refuge traffic counters recorded average daily traffic of 71 vehicles, with seasonal peaks of up to 505 vehicles per day.

Prior to product applications, all sections including the untreated control received new crushed limestone surface aggregate (Missouri Department of Transportation [MoDOT] Type I Base) to ensure uniform road conditions. Both products were applied according to vendor specifications, with on-site supervision from vendor technical advisors. For durablend-C™, the road was pre-wet with a water truck, cut with the grader, and then the product was incorporated into the top ~7 cm (~3 in.) of the road surface (i.e., a mixed-in application) at a rate of 2.26 L/m^2 (0.5 gal/yd^2). The road was then shaped and compacted, and a topical application of product at 1.81 L/m^2 (0.4 gal/yd^2) was applied. For EnviroKleen®, the road was pre-wet, cut, shaped, and compacted in the same way, and EnviroKleen® was applied topically at 1.36 L/m^2 (0.3 gal/yd^2). Twenty-four hours later, the EnviroKleen section received final compaction. Applications of both products were performed by specialized trucks with computerized spray systems provided by the vendors. The EnviroKleen® section also received a lighter maintenance application (0.68 L/m^2; 0.15 gal/yd^2) 10 months after initial application. All road preparation steps, application procedures, and maintenance application procedures (or lack thereof) were specified by the product vendors to represent a "typical" application scenario. Therefore, applications of the two products were not standardized, but should be representative of conditions as used in the field.

Dust Measurement

Dust production on each treated and untreated road section was measured at 2, 3, 6, 11, and 19 months after the initial product applications with a DustTrak DRX Aerosol Monitor (Model 8533, TSI Incorporated,

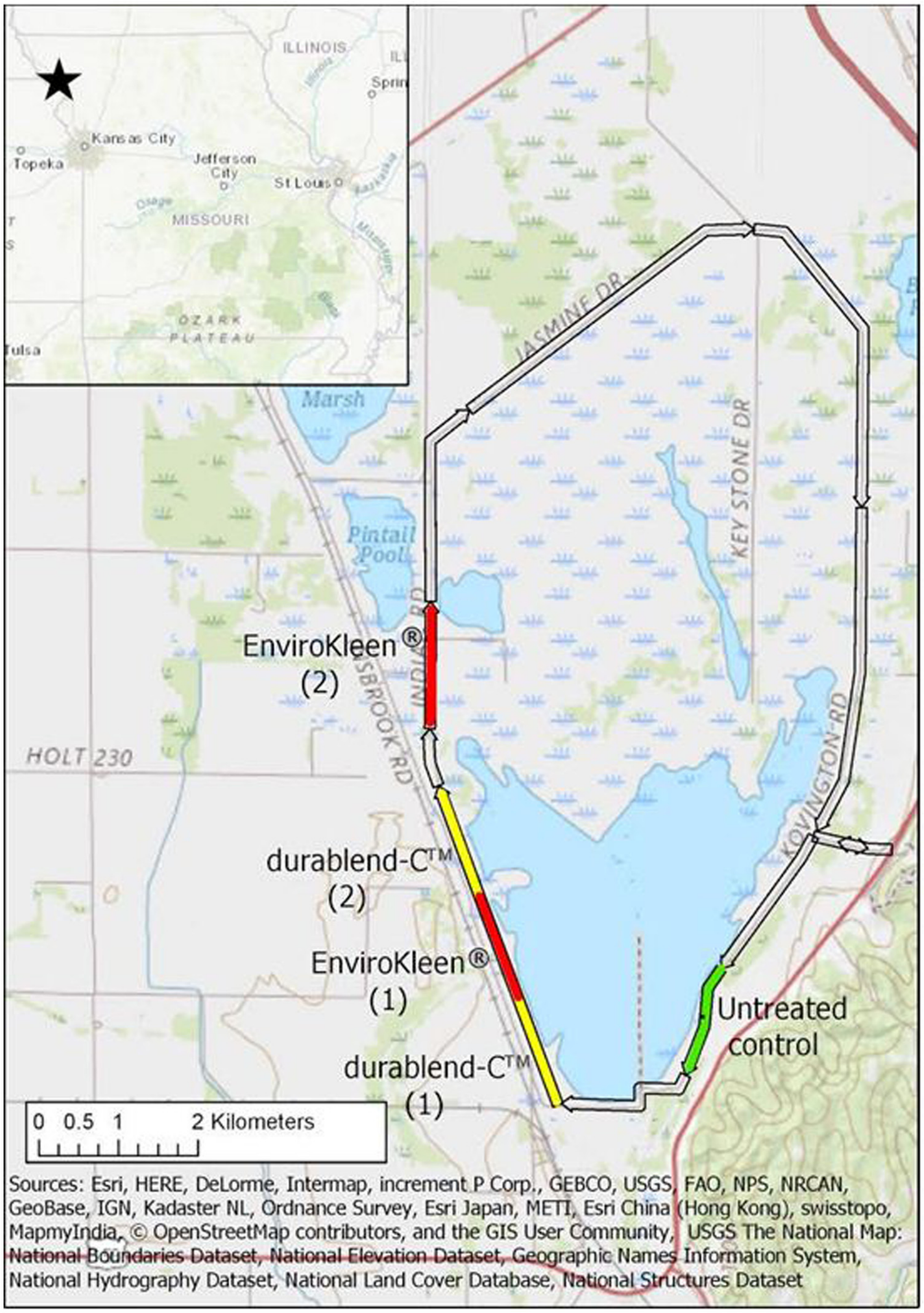

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Figure 1. Layout of experimental treatment sections on the Loess Bluffs NWR one-way auto tour loop. Traffic enters from the east side and arrows show direction of travel. Each treatment section = 0.8 km (0.5 mi).

Shoreview, MN). The DustTrak DRX was chosen because of its portability, the ease with which it could be vehicle-mounted, and its ability to simultaneously infer the mass concentration (mg/m^3) of particulate matter in five size ranges from PM$_1$ to total particulate matter (Table 1). The same or similar models of laser photometers have been used successfully in both vehicle-mounted applications (*7–10*) and stationary applications (*7*). The DustTrak DRX was mounted on the tailgate of a refuge truck inside a weatherproof Storm Case™

Table 1. Size Ranges of Particles Reported by the DustTrak DRX Meter

Size	Particle diameter (μm)
PM_1	0.10–1.0
$PM_{2.5}$	0.10–2.5
PM_{resp}	0.10–4.0
PM_{10}	0.10–10.0
PM_{total}	0.10–15.0

(iM2450, Pelican Products, Inc., CA) with holes drilled for the intake and exhaust lines. The intake line was secured horizontally 1 m (3.28 ft) above the road surface, which is the height at which peak PM10 exposure is expected (*11*). On each sampling date, each road section was driven three times with a DustTrak sampling rate of 1 sample/second, yielding three dust profiles per section. All measurements were taken with the DustTrak mounted on the same refuge truck, with the same driver for all measurements on a sampling date. All sections were driven in the direction of prevailing traffic on the one-way tour loop. All measurements were taken at a speed of 40 kph (25 mph) according to previous recommendations (*8, 12*), with smooth accelerations and decelerations at boundaries between treatment sections. Any passing cars or other potential influences on dust measurements were recorded in field notes for each sampling run. On each sampling date, the project team also made qualitative observations and took digital photographs of dust production on each section.

Data were plotted and compared with field notes to determine quality assurance and control. In two cases, data points were removed from the beginning or end of a run to reflect delays mentioned in the field notes. On the 29 October, 2014, sampling date, the measurements from one run of two sections (one durablend-C™ and one EnviroKleen®) were excluded from analysis because of a meter error. Measurements from each run within a section were averaged to yield a value representing the run. Then, the run-level means from within each sampling date were averaged to yield a value representing that section and sampling date. Because dust data from all five particulate size ranges were strongly right-skewed, all data were $\log_{10}$-transformed prior to analysis to improve normality.

Weather Data

Weather data for the monitoring period (1 June, 2014 to 29 February, 2016) were downloaded from the closest National Oceanic and Atmospheric Administration weather station, which was located at Brenner Field Airport, Falls City, NE (WBAN:94957), 27.5 km (17.1 mi) west of the refuge. To explore the possible influence of weather conditions on dust production, three weather variables representing precipitation, wind speed, and humidity were selected. For each sampling date, precipitation was characterized by days since precipitation >0.03 cm (0.01 in.). Wind speed was characterized as the daily mean wind speed (km/h) for each sampling date, and humidity was characterized as the daily mean relative humidity (%) for each sampling date.

Objective Road Condition Evaluation

In addition to dust production over time, road condition was used as a measure of success for the chemical treatments. Road condition was assessed on 21 December, 2015, approximately 18 months after the initial product applications. At the time of evaluations, no maintenance had been required on any treated section since the product applications. On the untreated control section, approximately one-third of the section length had recently required grading. Objective road condition evaluations followed those used by the Central Federal Lands Highway Division at a road stabilization project at Seedskadee NWR (*13*). These evaluations focused on the same categories of surface distresses as other established unpaved road assessment systems, such as the U.S. Army Corps of Engineers' unsurfaced road condition index (URCI [*14*]) and Wisconsin's gravel pavement surface evaluation and rating (PASER) system (*15*), but used a rating scale optimized to distinguish among roads in relatively good condition, rather than across the full spectrum of "failed" to "excellent."

Each treated and control road section was sampled using three stops, at the 0.1-, 0.2-, and 0.3-mi mark (0.16-, 0.32-, and 0.48-km mark), measured from the beginning of each section. At each stop, a team of two observers measured the depth and extent of four categories of surface distresses—washboarding, raveling, rutting, and potholes—present in a 7.6-m (25-ft) length of road. Washboarding was measured as the depth (in mm) of six consecutive troughs. Raveling was measured as the depth (mm) of loose material at four locations across the width of the road—on the outside and inside edges of each wheel path. Rutting was measured as the depth of depression (mm) in the right and left wheel paths, and potholes were measured as the number and average depth (mm) of potholes in the 7.6-m (25-ft) length. In addition, the total number of potholes observed in each 0.8-km (0.5-mi) road section was recorded. All measurements were subsequently averaged and converted into ratings (0 to 10, with 10 = best condition) to provide an intuitive basis for comparison of sections, according to scales in Appendix B of Woll et al. (*13*). For example, a section with an average washboarding trough depth of 23 mm (0.9 in.) would be assigned a rank of 5.

Statistical Analyses

Dust monitoring data from the five sampling dates were used to generate linear models of dust production. The purpose of these models was to evaluate whether variation in dust measurements over time was associated with application of chemical treatments, with weather conditions on each day of sampling, or with some combination thereof. The analysis also allowed a rigorous assessment of whether chemically treated sections differed from each other and from the untreated control section in dust production.

Correlations. Linear correlation (Pearson's product moment correlation coefficient, *r*) was used to test for correlations between the five measures of dust production (PM_1, $PM_{2.5}$, PM_{resp}, PM_{10} and PM_{total}; Table 1), and between continuous weather covariates. Correlations between dust particle sizes were tested because if two dust production variables were highly correlated with each other (correlation coefficient near 1 or -1), separate analyses of both measures would be redundant. Correlations between potential predictor variables were also tested to ensure that models did not include redundant predictor variables.

Dust Production. Linear models were used to test for a relationship between dust production (response variable) and road treatment (control vs. treated), and four additional predictor variables: time, precipitation, wind speed, and relative humidity. Random intercept models were considered to account for variability between individual sections (*16, 17*); however, preliminary tests showed that the random effect due to section was zero and therefore random effects were excluded. All models with more than one predictor included treatment as a factor ($X_{treatment}$) and either days since 1 June, 2014 (X_{time}), days since precipitation (X_{since}), mean daily wind on sampling date in km/h (X_{wind}), or mean relative humidity on sampling date ($X_{humidity}$) as a continuous covariate (Table 2). The model with the lowest Akaike information criterion value corrected for small sample sizes (AICc [*18*]) was selected as the most parsimonious (i.e., best-fitting) model. Type-III analysis of variance (ANOVA) was used to assess model significance to ensure that comparisons were made in light of other model terms, rather than sequentially (*19*). The use of the linear model with Type-III sums of squares also accounted for the unbalanced sampling design with respect to road treatment (one untreated control section versus two treated sections for each product). Tukey's honest significant difference (HSD) post hoc test was used to test which road treatments differed from each other.

Table 2. Models of Dust Production Tested

Model	Form
0	$y = Constant$
1	$y = \beta_0 + \beta_1 X_{treatment}$
2	$y = \beta_0 + \beta_1 X_{time}$
3	$y = \beta_0 + \beta_1 X_{since}$
4	$y = \beta_0 + \beta_1 X_{wind}$
5	$y = \beta_0 + \beta_1 X_{humidity}$
6	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{time}$
7	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{since}$
8	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{wind}$
9	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{humidity}$
10	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{time} + \beta_3 X_{treatment} X_{time}$
11	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{since} + \beta_3 X_{treatment} X_{since}$
12	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{wind} + \beta_3 X_{treatment} X_{wind}$
13	$y = \beta_0 + \beta_1 X_{treatment} + \beta_2 X_{humidity} + \beta_3 X_{treatment} X_{humidity}$

Note: In these models, y = total dust production (mg/m^3); $X_{treatment}$ = treatment (control, durablend-C™, or EnviroKleen®); X_{time} = days since June 1, 2014; X_{since}= is days since precipitation $\geq$0.03 cm (0.01 in.); X_{wind} = mean wind speed on sampling date (km/h); $X_{humidity}$ = mean relative humidity on sampling date (%). β_0 = model intercept; β_1, β_2, and β_3 = regression coefficients.

Software. All analyses were performed using R version 3.3.3 (R Core Team 2017). Within R, package "MuMIn" (*20*) was used to calculate AICc values, package "car" version 2.1-4 (*19*) was used for Type-III ANOVAs and package "multcomp" version 1.4-6 was used for Tukey tests (*21*).

Results and Discussion

Dust Measurement

Overall, quantitative dust monitoring data indicated that treatment with either product reduced dust by up to 99% for the first 11 months of the study relative to the untreated control (Figure 2). Although absolute dust levels varied by sampling date, the reductions associated with treatment were relatively consistent over time, with greater dust suppression by durablend-C™ than EnviroKleen® on most dates (Figure 2). By the final monitoring visit (19 months after initial applications), dust levels on EnviroKleen® sections were 71% lower than the control, and those on durablend-C™-treated sections were 93% lower than the control. The fact that control efficacy did not decline in a consistent manner over the course of the study precludes plotting of deterioration curves (*22*) or drawing definitive conclusions about the effective lifespan of the two products. However, based on dust reductions at the end of the monitoring period and the difference in application history (one initial application for durablend-C™ versus an initial application and a maintenance dose for EnviroKleen®), durablend-C™

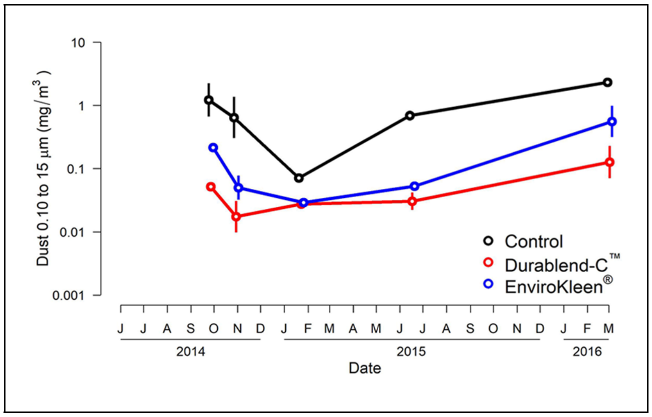

Figure 2. Dust production (PM_{total}; 0.10 to 15 μm) over time on untreated and treated road segments. Points represent means; error bars represent 95% confidence intervals. Note that the y-axis scale is logarithmic. For clarity, points for control treatment are offset 3 days to the left and points for EnviroKleen® are offset 3 days to the right.

provided longer-lasting dust control under the conditions of the current study.

Importantly, the results for dust production based on real-time dust monitoring with the DustTrak DRX are consistent with qualitative observations of dustiness by project researchers. Reductions in dust associated with road treatment were clear when driving the auto tour loop (Figure 3). Improvements in driving conditions were even more evident when compared with an adjacent section of the auto tour loop that did not receive new aggregate or chemical treatment as part of the study (i.e., business-as-usual conditions).

Objective Road Condition Evaluation

The mean depths of each type of surface distress (washboarding, raveling, rutting, and potholes) and the associated ratings are presented in Table 3. Each road section is listed individually to highlight any variation between replicate sections of the same treatment. Overall, all sections, including the untreated control, performed relatively well, with minimal washboarding and limited raveling. Relative to the treated sections, the untreated control exhibited moderately more rutting and substantially more potholes. The untreated section was characterized by both greater numbers and greater depths of potholes, as reflected in the pothole rating. In general, condition ratings for replicate sections of the same treatment were consistent. One exception was the EnviroKleen® (2) section, which developed less rutting and more potholes than the EnviroKleen® (1) section.

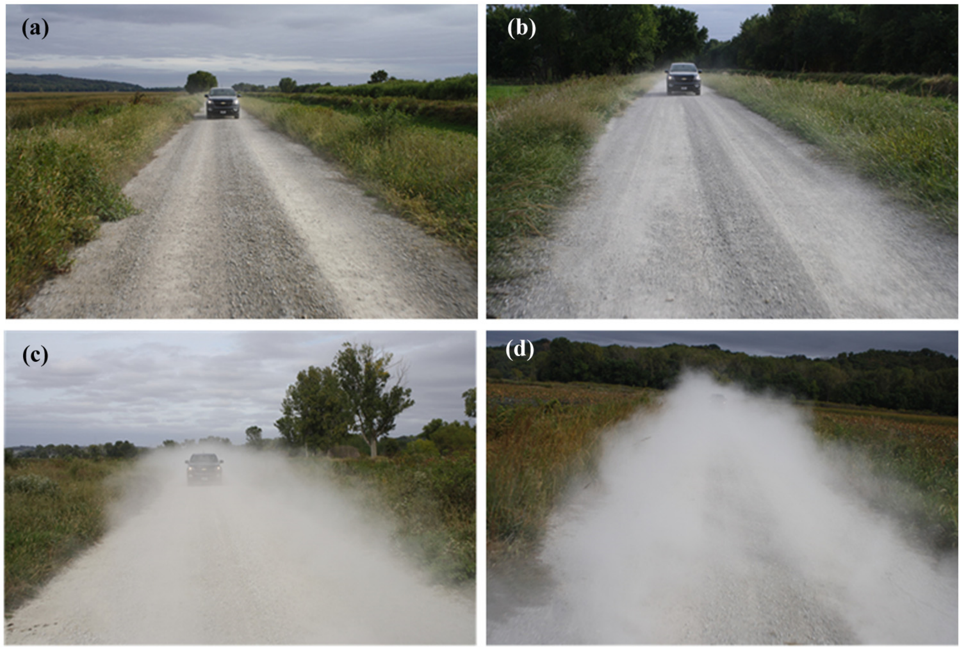

Figure 3. Representative dust levels 15 months after original product applications (5 months after maintenance application of EnviroKleen®): (*a*) durablend-C™- treated section; (*b*) EnviroKleen®-treated section; (*c*) untreated control section; (*d*) an adjacent road section on the auto tour loop that did not receive new surface aggregate or chemical treatment as part of the study, shown for reference. Photographs were taken from the back of a passenger truck traveling 40kph (25mph). Photo credit: B. Kunz, USGS.

Table 3. Objective Road Condition Evaluation

Section	Washboarding mean depth (mm)	Washboarding rating^{a}	Raveling mean depth (mm)	Raveling rating	Rutting mean depth (mm)	Rutting rating	Pothole mean depth (mm)	Number of potholes in overall section	Pothole rating	Overall rating
Untreated control	2.4	9	8.9	8	17.0	6	36.7	19	5	7.0
durablend-C™ (1)	0.6	9	6.3	8	7.3	8	0	3	9	8.5
durablend-C™ (2)	0	10	8.8	8	7.5	8	0	4	9	8.8
EnviroKleen® (1)	0	10	9.2	8	11.0	7	0	4	9	8.5
EnviroKleen® (2)	0.7	9	4.2	9	4.3	9	70^{b}	13	7	8.5

Note: 25.4 mm = 1 in.

[a] All ratings on a scale of 0 to 10, with 10 = best condition.

[b] A single deep pothole in one of the 7.6-m (25-ft) lengths. Because this depth was not characteristic, rating was based on other potholes within the overall section.

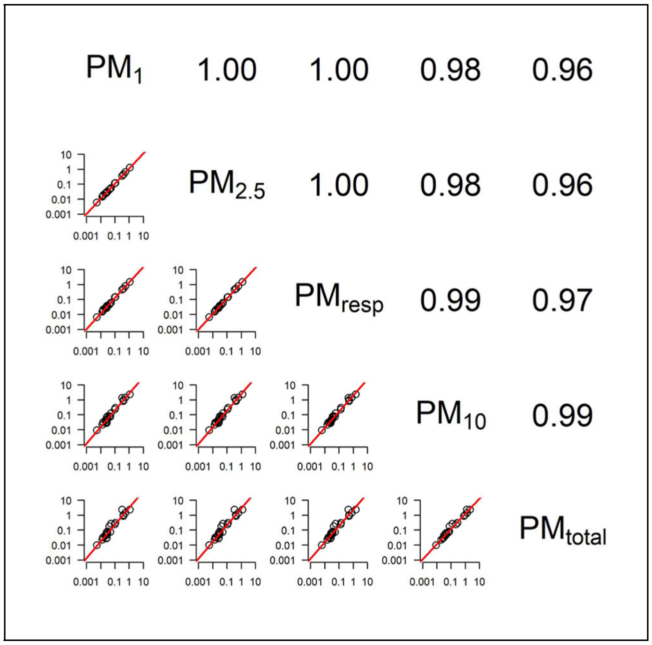

Figure 4. Correlations between five measures of dust production. Variables and associated dust size ranges are as follows: PM_1 (0.1 to 1.0 μm); $PM_{2.5}$ (0.1 to 2.5 μm); PM_{resp} (0.1 to 4.0 μm); PM_{10} (0.1 to 10 μm); and PM_{total} (0.1 to 15 μm). Numbers in panels above the diagonal show Pearson product moment correlation coefficient (*r*). Red lines show linear relationship between the variables. Note that all axes are on a $\log_{10}$ scale.

Statistical Analyses

Correlations. All five measures of dust production were significantly positively correlated with each other (all $p < 0.0001$; Figure 4). In particular, the correlations between total particulate matter (PM_{total}) and particulate matter $< 2.5\,\mu m$ ($PM_{2.5}$) and $< 10\,\mu m$ in diameter (PM_{10}) were 0.96 and 0.99, respectively. Therefore, at least for the surfacing aggregate and conditions tested in this study, PM_{total} is a useful surrogate for particulate matter in the two size ranges of greatest concern for human health. Because analyzing all five highly correlated size fractions separately would be redundant, only analyses of total dust production are presented.

All combinations of continuous covariates (time and weather variables) were significantly correlated (all $p < 0.0001$; data not shown). Therefore, no model was tested with more than one continuous covariate.

Dust Production. Over the 19 months of the study, the best model of dust production was Model 9, in which dust varied with road treatment and relative humidity on the sampling date (Table 4). In this model, treatment and humidity explained 68.5% of variation in total dust production (Tables 4 and 5). Dust production decreased with increasing humidity (Figure 5). This result is not surprising, given the effect of road bed moisture on dust production (*23*). Models that included days since precipitation were not supported in this study. This result is in contrast with an earlier study that documented a trend of increasing dust for at least 7 days after a rainfall event (*10*). The stronger relationship with humidity than days since precipitation in the current study may have been a function of seasonal differences in sampling or geographic differences in climate.

Dust production was significantly greater on control sections than on durablend-C™ or EnviroKleen® sections. Differences in dust production between durablend-C™ and EnviroKleen® sections over the entire monitoring period were not statistically significant (Table 6).

Benefits and Limitations of the Approach

The greatest benefit of this approach is the quatitative nature of the data generated. For practitioners, these data could be used to set definitive performance measures for chemical treatments (e.g., "80% reduction in average dust production for 6 months"), or make more

Table 4. Dust Production Model Selection Results

Model	*F*	DF_{model}	DF_{res}	*P*	R^2	*AICc*	Δ*AICc*	$AICc_{wt}$
9	20.0988	3	21	<0.0001	0.6852	31.7961	0	0.9223
13	2.2931	5	19	0.0864	0.6640	38.3524	6.5564	0.0348
6	13.0844	3	21	<0.0001	0.5823	38.8688	7.0727	0.0269
1	12.6412	2	22	0.0002	0.4914	41.7939	9.9979	0.0062
8	9.9545	3	21	0.0003	0.5236	42.1561	10.3601	0.0052
7	9.4374	3	21	0.0004	0.5064	43.0439	11.2479	0.0033
10	2.2727	5	19	0.0886	0.5474	45.8032	14.0072	0.0008
12	0.9689	5	19	0.4614	0.4946	48.5586	16.7626	0.0002
11	3.9258	5	19	0.0130	0.4920	48.6876	16.8915	0.0002
5	7.4276	1	23	0.0121	0.1556	52.7248	20.9288	0
2	30.3341	1	23	<0.0001	0.0616	55.3629	23.5669	0
4	8.6603	1	23	0.0073	0.0080	56.7515	24.9554	0
3	31.3855	1	23	<0.0001	−0.0077	57.1447	25.3486	0

Note: F = *f* statistic in omnibus (Type-III ANOVA) test; DF_{model} = degrees of freedom in the model; DF_{res} = degrees of freedom in the residuals; *P* = *p*-value in omnibus test; R^2 = coefficient of determination; *AICc* = Akaike's information criterion corrected for small sample sizes; Δ*AICc* = difference from lowest AICc; $AICc_{wt}$ = AICc weight. Level of significance for *P* = 0.05.

Table 5. Type-III ANOVA Table for Final Model of Dust Production

Source	SS	DF	MS	*F*	*P*
Intercept	0.7424	1	0.7424	5.0537	0.0354
Treatment	5.9788	2	2.9894	20.3497	<0.0001
Humidity	2.1364	1	2.1364	14.5434	0.0010
Residuals	5.0618	25	0.2025	na	na

Note: na = not applicable; SS = sum of squares associated with each term; DF = degrees of freedom associated with each term; MS = mean squared error; *F* = *f* statistic of ANOVA test; *P* = *p*-value. Level of significance for *P* = 0.05.

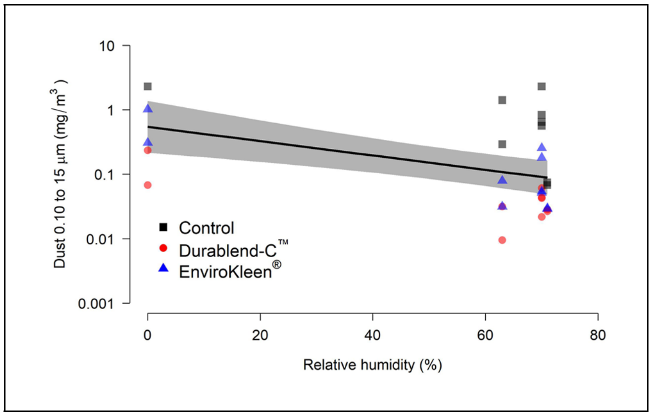

Figure 5. Total dust production (PM_{total}; 0.10 to 15 µm) decreased with increasing relative humidity (%) on untreated and treated road segments. Shaded area indicates 95% confidence interval. Note that the y-axis scale is logarithmic. Points represent samples taken on a particular road segment on a particular date.

compelling decision justifications to the public or funding sources. For researchers, these data could be used to standardize evaluations of relative chemical treatment effectiveness across a range of climatic conditions and geographic locations.

Monitoring with the commercially available DustTrak DRX as described here requires no installation of infrastructure or modification of existing vehicles. The unit can easily be tailgate-mounted and removed at the end of sampling. Although the purchase price is substantial (approx. US$11,000), units can also be rented and shipped to a field site for < US$500/week. It is important to recognize, however, that measurements using this meter provide meaningful comparisons of *relative* dust production on different sections. Because dust production varies with weather, vehicle weight and speed (*23*) among other factors, all sampling for a given set of sites must take place under consistent conditions.

The objective road condition evaluations did require more time than visual (i.e., "windshield") methods. A two-person crew required approximately 10 min to complete each 7.6-m (25-ft) section. However, this measurement-based approach generated more comprehensive data on the severity of surface distresses, while eliminating some of the subjective determinations required by visual methods (e.g., PASER [*15*]). In the

Table 6. Tukey's HSD Post Hoc Test for Differences in Means between Levels of Treatment

Level 1	Level 2	Estimate	SE	T	P
durablend-C™	Control	−1.3376	0.2099	−6.3720	<0.0001
EnviroKleen®	Control	−0.9415	0.2099	−4.4850	0.0006
EnviroKleen®	durablend-C™	0.3961	0.1714	2.3110	0.0756

Note: Estimate = estimated difference in means ($\mu_{level1} - \mu_{level2}$); SE = standard error of estimate; T = t statistic; P = p-value adjusted for multiple comparisons. Level of significance for $P = 0.05$.

current study, this method was sensitive enough to detect differences in surface distresses among road sections that were all in relatively good condition. For a study design in which a greater range of performance is expected, a system such as the URCI (*14*) may be more appropriate.

Conclusion

This paper describes an approach for quantitatively evaluating the success of unpaved road treatments. Based on real-time dust monitoring data, road treatment with one application of durablend-C™ suppressed dust by up to 99%, relative to the untreated control. At 19 months post-application, average dust levels remained 93% lower than those on the control section. Treatment with an initial application and a maintenance dose of EnviroKleen® suppressed dust by a similar magnitude for 11 months, with a smaller reduction (71%) relative to the control by the end of the project. Objective road surface condition evaluations were used to quantify the type and severity of road surface distresses, and determine that sections treated with either product according to the vendors' directions developed less rutting and substantially fewer potholes in the first 15 months after application.

Data generated by this quantitative approach also facilitated modeling to determine whether road treatment, weather, or some combination thereof was the most important influence on dust production. Linear models revealed that chemical treatment and relative humidity on the sampling date were the dominant influences on dust production on the different road sections in this study. Understanding the factors controlling dust is critical for designing effective dust monitoring programs.

Both of the techniques described here are relatively simple to implement, and required minimal equipment and training of staff. Although this approach would not be detailed enough for some research studies and would be too time-consuming for general unpaved road management, it provided a useful balance between ease of use and quality of data in the current study.

Overall, a combination of real-time dust monitoring and road surface condition evaluations was an effective approach for determining success of unpaved road treatments. The approach generated quantitative data for comparisons of treatments over time, while retaining more flexibility than some other quantitative methods. These data could be used to develop more definitive performance measures for chemical treatments and should also facilitate better communication regarding justification for road management decisions.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: BK, EL; data collection: BK, EL; analysis and interpretation of results: NG, JA, MW, BK; draft manuscript preparation: BK, NG. All authors reviewed the results and approved the final version of the manuscript.

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