ENERGY-RELATED TRAFFIC INCREASES FUGITIVE DUST, WITH MIXED EFFECTS ON BAKKEN CROPLAND TROPHIC LEVELS

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

We investigated how anthropogenic landscape industrialization affects croplands through increased emissions of fugitive dust along unpaved roads with energy-related traffic. We reviewed literature regarding plants and increased dust deposition and exposure and found that increased dust deposition and exposure negatively affected photosynthetic activity, chlorophyll content, and stomatal conductance. We measured: traffic, the amount and spatial extent of dust deposition, and plant physiological parameters in annual cereal crop fields adjacent to unpaved roads in western North Dakota. We found that increased traffic along an unpaved road influenced the amount and spatial extent of fugitive dust deposited in fields adjacent to an unpaved road. Increased dust deposition negatively affected plant photosynthetic activity. We measured bird activity using trail cameras and invertebrate abundance using sweep-netting in annual cereal crop fields adjacent to unpaved roads. Distance from an unpaved road or the measured deposition rates did not negatively affect bird activity and invertebrate abundance.

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Abstract

With increased dust emissions from unpaved roads driven by traffic-intensive energy development becoming a growing concern for rangeland and cropland plants, we review the experimental design of recent literature focusing on increased dust deposition or exposure, and perform a meta-analysis using studies that measured plant physiological parameters: photosynthetic activity, chlorophyll content, and stomatal conductance. Increased dust deposition or exposure had a significant, overall negative effect on photosynthetic activity, chlorophyll content and stomatal conductance.

Introduction

With hydraulic fracturing and horizontal drilling allowing for development of unconventional petroleum resources, working landscapes including rangelands and croplands in several regions of North America have undergone widespread industrialization for oil and gas development (Allred et al. 2015). While over an estimated 5 million animal unit months and 120 million bushels of wheat were lost to the discrete footprint of energy infrastructure from 2000-2012 in North America (Allred et al. 2015), traffic associated with the use of hydraulic fracturing potentially increases the impact of energy-driven landscape industrialization through increased fugitive dust emission from unpaved roads (US EPA 2006; Felsburg Staff 2013).

Fugitive dust is a common concern across the globe for its effect on various biotic and abiotic ecosystem components. Air quality and human and animal health are negatively affected by high concentrations of suspended particulate matter, including dust, and especially high concentrations of fine (2.5 – 10 µm) and ultra-fine (< 2.5 µm) particle sizes (Kampa and

Castanas 2008; Cambra-López et al. 2010; Huang et al. 2013; Van Leuken et al. 2015). While suspended dust particles are of concern to human and animal health, deposited dust particles are also an issue for plants (Farmer 1993).

Increased dust deposition can negatively affect plant physiological parameters including: photosynthetic activity, stomatal activity, chlorophyll content, leaf temperature, and yield through either a leaf shading effect or interfering with stomatal functioning (Farmer 1993; Hirano et al. 1995). The amount of dust that a plant is exposed to depends on the source of emission and the distance dust is dispersed prior to being deposited (Lawrence and Neff 2009). For natural sources like salt lakes or exposed soil, the primary determining factors are wind speed and surface characteristics like particle size and moisture content (Reheis 1997; Lawrence and Neff 2009). For unpaved roads, vehicle speed, weight, and amount of traffic also governs dust emissions (US EPA 2006).

Since the last comprehensive review of research regarding dust and plants was published (Farmer 1993), technological advancements have increased the capacity to measure relevant plant physiological responses like photosynthetic activity, stomatal conductance, and chlorophyll content in field settings with handheld or easily portable equipment. Furthermore, an analytical review has not yet been applied to this topic.

With the use of traffic-intensive energy development techniques like hydraulic fracturing expanding globally, researchers need to be aware of potential complications increased dust exposure can have on plants, and how they can evaluate dust-affected plants. The objective of this review is to determine how plant scientists investigate increased dust exposure and plants, and then assess trends across studies that measure photosynthetic activity, stomatal conductance, and chlorophyll content through a meta-analysis.

Methods

Literature Search

We searched for peer reviewed literature in Spring of 2016 using Google Scholar (Google, Mountain View, California). We sought studies that investigated the effects of dust or particulate matter on plants, but focused on those that measured plant physiological parameters. We narrowed the search to studies that investigated the effects of increased dust deposition or exposure on vascular plants (**Table 1.1**).

Table 1.1. The search terms used in Google Scholar in February and March of 2016, and the number of studies each search returned.

Search Terms	Studies Returned
"Chlorophyll content" OR "quantum yield" OR "photosynthesis" OR "photosynthetic activity" "dust" OR "fugitive dust" OR "particulate matter"	215
Articles citing Farmer 1993+dust emission deposition	180
Farmer 1993 dust emission deposition "photosynthetic" OR "stomatal" OR "chlorophyll" – lichen	70

Inclusion Criteria and Data Extraction

We searched the abstract and methods of studies found through the literature search for specific references to dust or particulate matter and plants or vegetation. We excluded studies that did not actually evaluate dust-affected vegetation. We focused on studies presenting original data and did not include reviews. We included studies in the experimental design portion of the review that did not measure the physiological parameters evaluated in the meta-analysis, because we were also interested in how research in the broader topic of dust-affected vegetation is conducted. For the meta-analysis, we focused on papers that investigated how increased dust deposition or exposure affected plant physiological parameters, specifically photosynthetic activity, stomatal conductance, and chlorophyll content. We excluded studies from the meta-analysis for either not measuring at least one of the physiological parameters or not reporting or showing sample size and/or variation for results.

We classified experimental design initially as either experimental or observational based on how dust contacted the plants, and then as either gradient or treatment/control based on how the study evaluated dust affected plants. We define experimental as the researchers applying dust to plants and observed as the plants receiving dust from the environment. In studies deemed observational, we used gradient to describe studies that compare dust affected plants across distances from a source or from similar distances over time, and treatment/control to describe studies that compare dust affected plants to a control or undusted plants. In studies deemed experimental, gradient is used to describe studies that used varying application rates, and treatment/control to describe studies that compare dust affected plants to a control or undusted plants.

For the meta-analysis, we extracted physiological parameter measurement type, species studied, mean, sample size, and standard deviation or standard error from studies when given in text, table, or graphs. We extracted means and variance from graphs using a plot digitizer (Rohatgi 2017). When not specified, we assumed variance shown was standard error. For distance gradient studies, we used data from the area with the highest amount of dust exposure as the treatment and the lowest amount as the control if a control was not used. For seasonal gradients, we used the season with the highest amount of dust exposure and then used the treatment/control data from that season. For experimental gradient studies, we used the highest application rate as the treatment and the lowest application rate as the control if a control was not used. We extracted multiple sets of data from studies that had multiple species or unique experiments.

Analysis

We used the extracted treatment and control means, sample size, and standard deviation from studies to calculate a Cohen's d effect size and 95% confidence intervals (Cohen 1988). We calculated standard deviation from the given standard error and sample size when standard deviation was not given. We calculated a summary effect mean and 95% confidence interval for each physiological parameter using the calculated effect sizes. We used the R Statistical Environment (R Core Team 2016) to run the Cohen's d analysis.

Results

Review of Experimental Procedures

We found 62 studies that met the inclusion criteria regarding experimental design (**Figure 1.1., Appendix A**). We classified 47 studies as observational and 15 as experimental (**Appendix B**). Within observational studies, we classified 18 as having a distance gradient, 10 as having a seasonal gradient, and 14 as treatment/control comparisons. We classified five studies as observational that did not fit into another secondary category. Within experimental studies, we classified 11 studies as varying application rates and four as treatment/control comparisons.

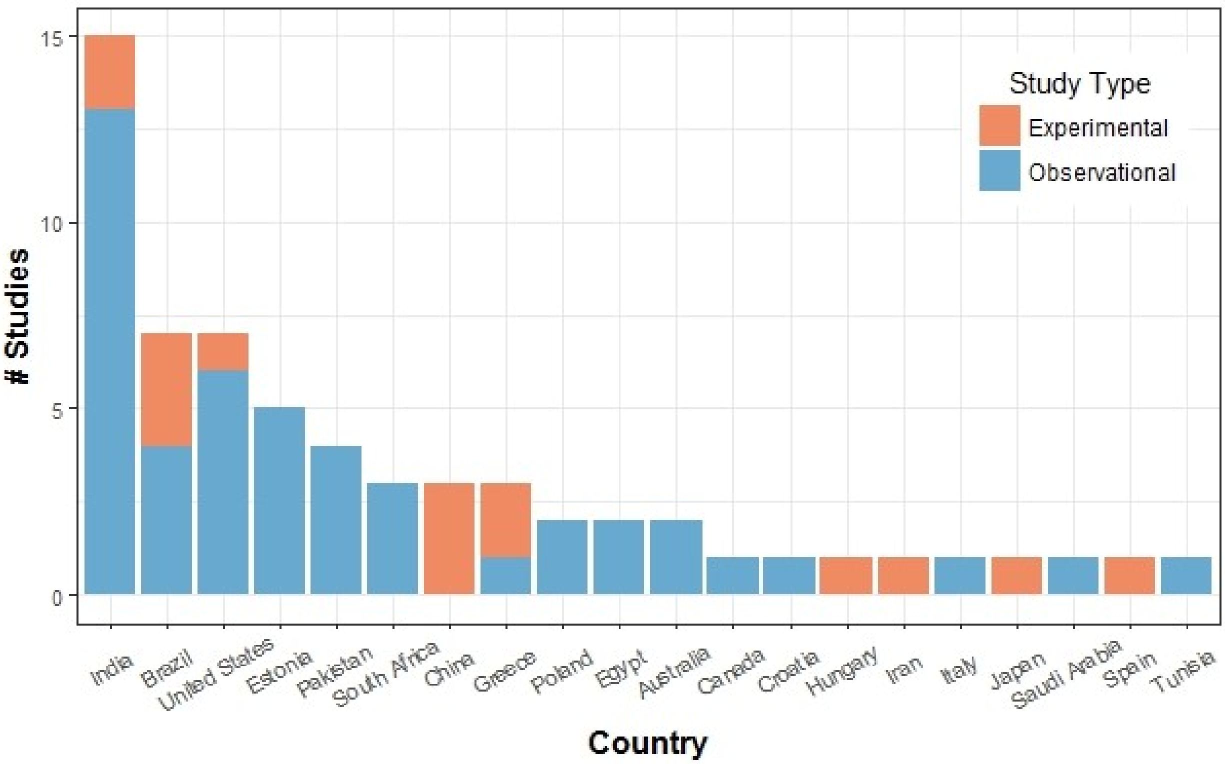

Figure 1.1. Country of origin for studies sorted by study type. We evaluated 62 studies for experimental design. India, Brazil, the United States, and Estonia account for 55% of the evaluated studies.

Within observational, distance gradient studies, 14 focused on emissions from a point source and four from roads. Within observational, seasonal gradient studies, six of the seasonal gradient studies focused on emissions from industrial or multiple sources and four focused on emissions along roadways. Within observational, treatment/control studies, 10 focused on emissions from a point source and four from roads.

Studies most frequently used a leaf wash method to quantify the amount of dust or particulate matter that a plant was exposed to (**Figure 1.2.**). Not quantifying the amount of dust or particulate matter was the second most common method. All but two experimental studies used the application rate to quantify the amount of dust or particulate matter that plants were exposed to.

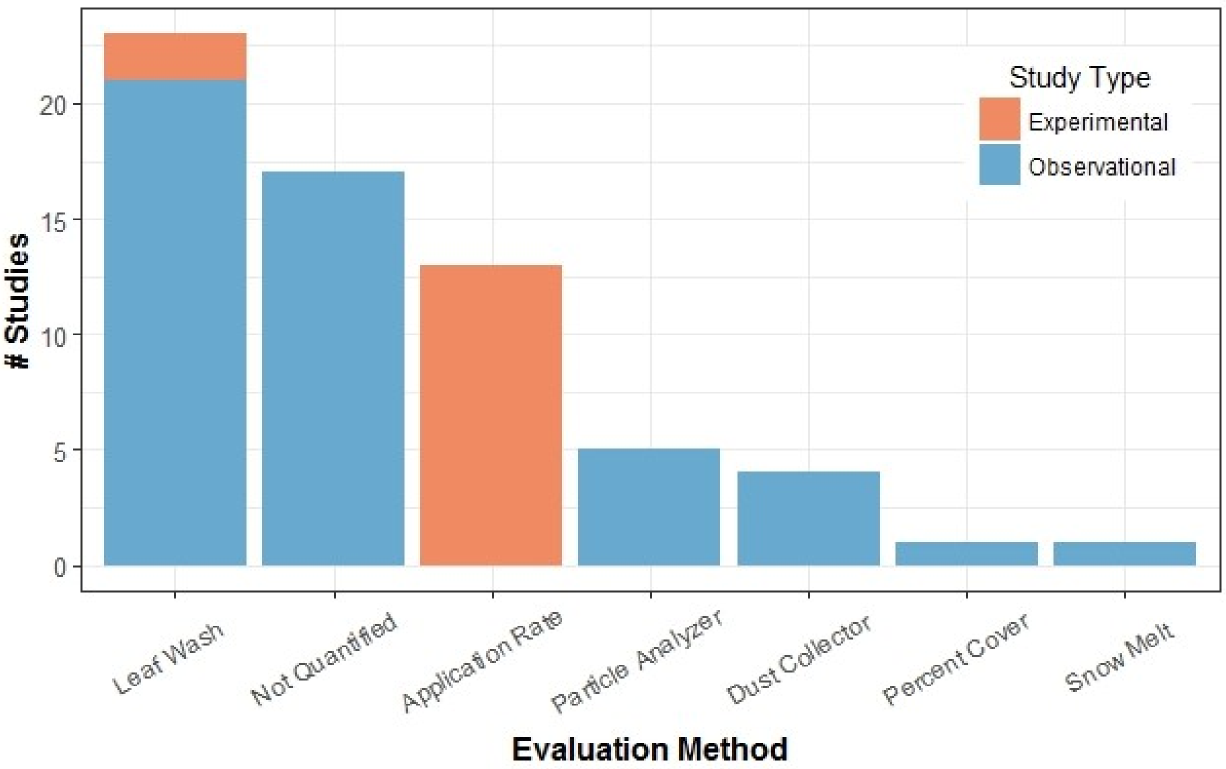

Figure 1.2. How studies evaluated dust or particulate matter. When quantified, most studies used either a leaf wash method or application rate to determine the amount of dust or particulate matter that plants were exposed to. All but two experimental studies used application rate.

Meta-Analysis

24 studies met inclusion criteria for the meta-analysis (**Appendix B**). Increased dust deposition or exposure had an overall negative effect on photosynthetic activity (calculated mean effect size = -2.23, lower confidence interval bound = -3.60, upper confidence interval bound = -0.86, **Figure 1.3.**). We extracted 37 observations from 12 studies, which covered 24 species from 17 families. There was a near-even split between fluorescence and gas exchange methods for evaluating photosynthetic activity (**Figure 1.4.**).

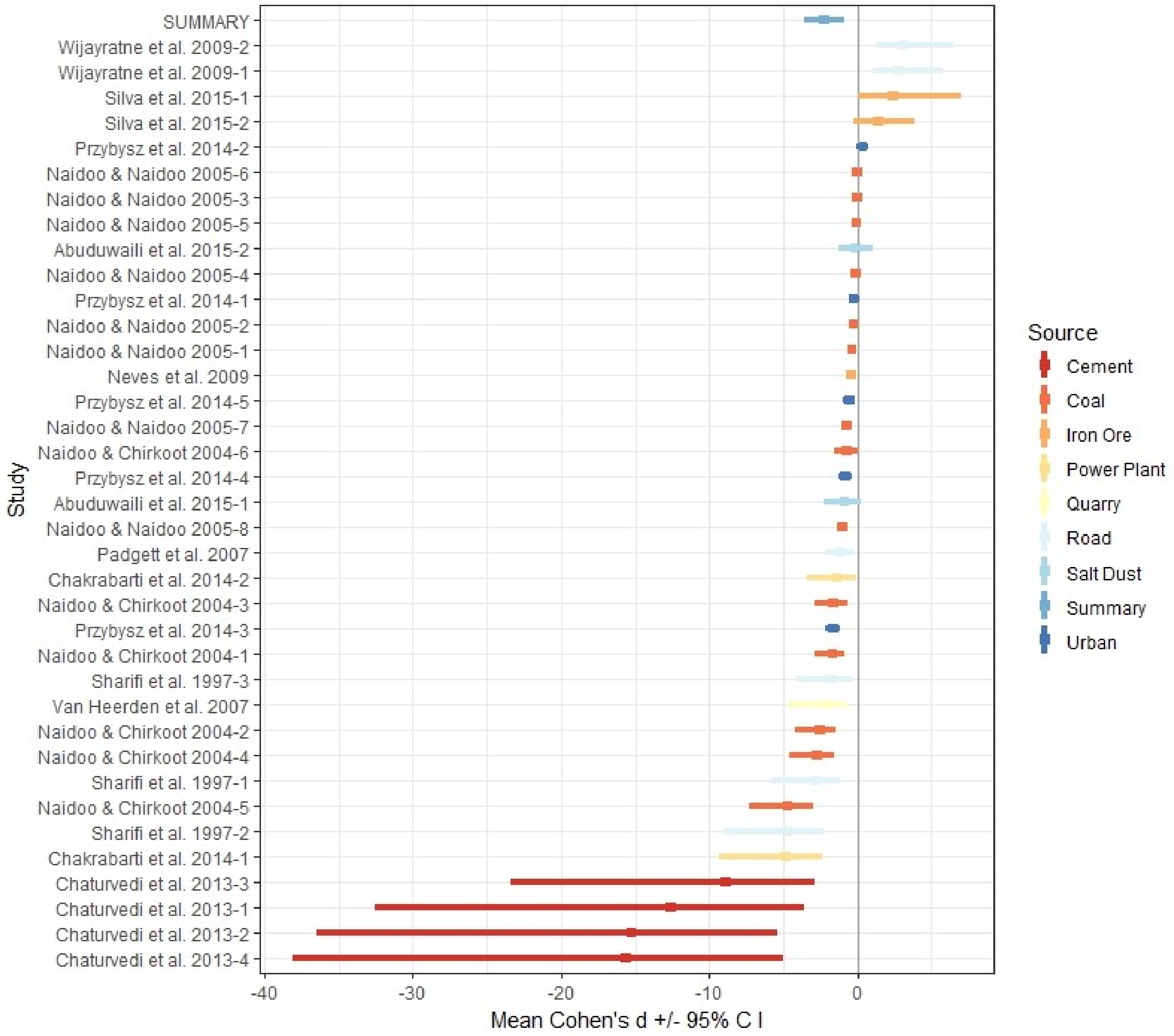

Figure 1.3. The mean Cohen's d effect sizes and 95% confidence intervals for extracted photosynthetic activity data. We extracted 37 observations from 12 studies. Confidence intervals that do not cross the zero line are deemed significant. As indicated by the Summary statistic, top, increased dust deposition has an overall negative effect on photosynthetic activity.

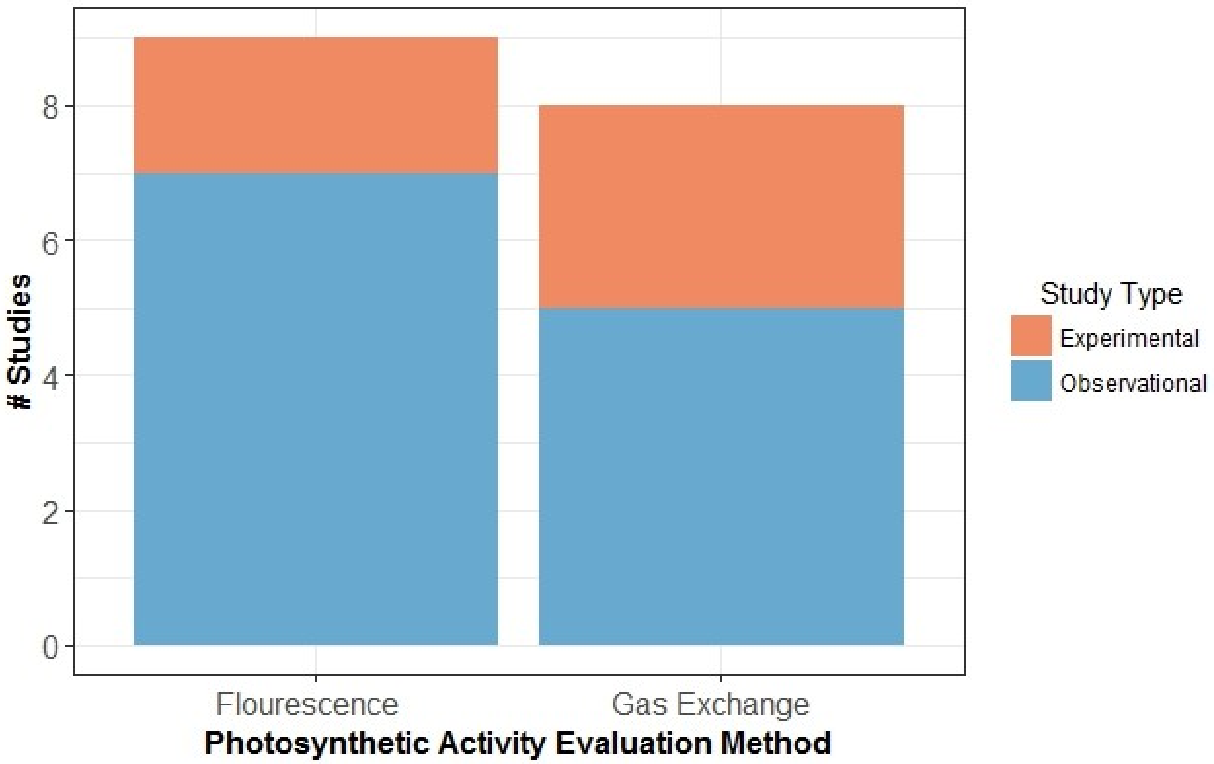

Figure 1.4. How studies evaluated photosynthetic activity. There was a near-even split among studies included in the meta-analysis between evaluating photosynthetic activity using fluorescence measurements or gas exchange chambers.

Increased dust deposition or exposure had an overall negative effect on chlorophyll content (calculated mean effect size = -4.77, lower confidence interval bound = -7.32, upper confidence interval bound = -2.22, **Figure 1.5.**). We extracted 49 observations from 16 studies, which covered 45 species from 24 families. Most studies used an extraction method to evaluate chlorophyll content (**Figure 1.6.**).

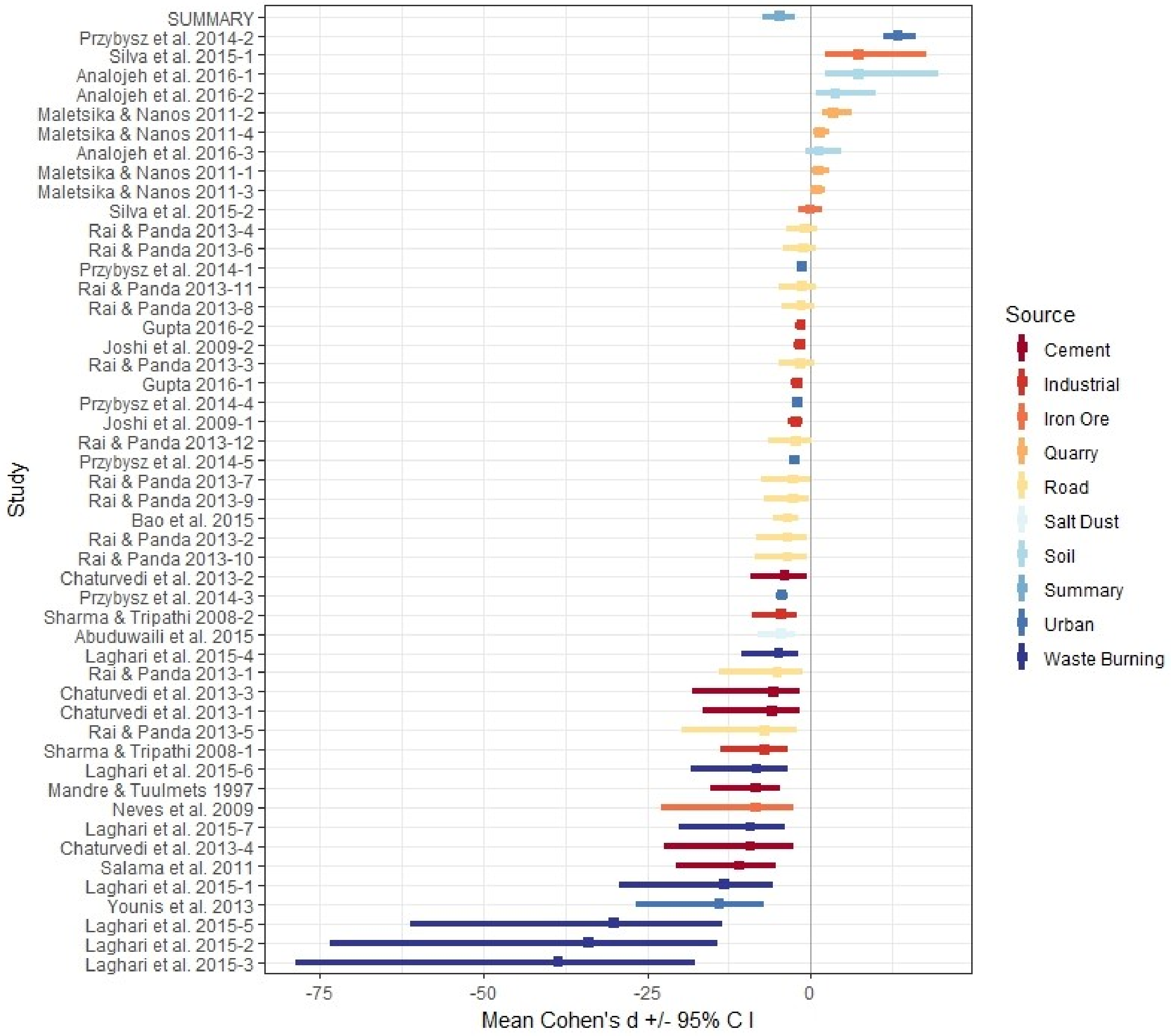

Figure 1.5. The mean Cohen's d effect sizes and 95% confidence intervals for chlorophyll content in dust affected plants. We extracted 49 observations from 16 studies. Confidence intervals that do not cross the zero line are deemed significant. As indicated by the Summary statistic, top, increased dust deposition has an overall negative effect on chlorophyll content.

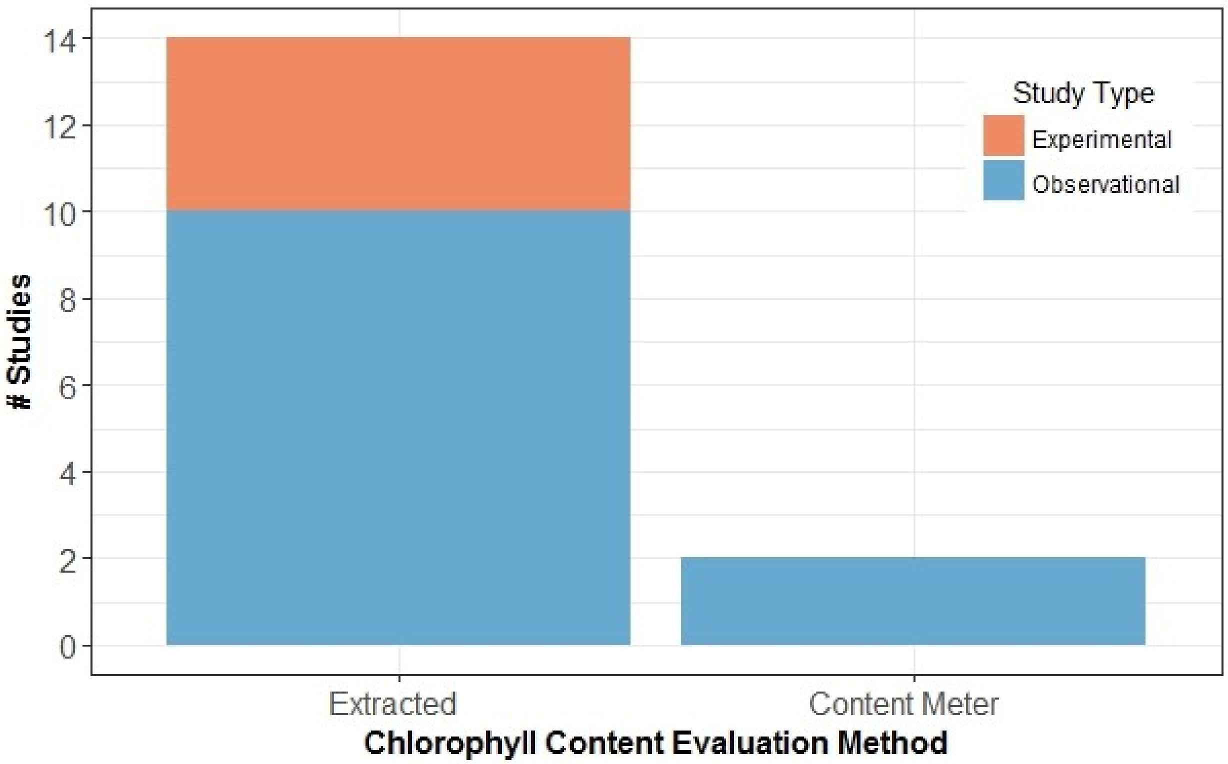

Figure 1.6. How studies evaluated chlorophyll content. The majority of studies in the meta-analysis used an extraction method to evaluate chlorophyll content.

Increased dust deposition or exposure had an overall negative effect on stomatal conductance (calculated mean effect size = -1.70, lower confidence interval bound = -2.96, upper confidence interval bound = -0.43, **Figure 1.7.**). We extracted 38 observations from 11 studies, which covered 33 species from 22 families. Most studies used a gas exchange chamber to evaluate stomatal conductance (**Figure 1.8.**).

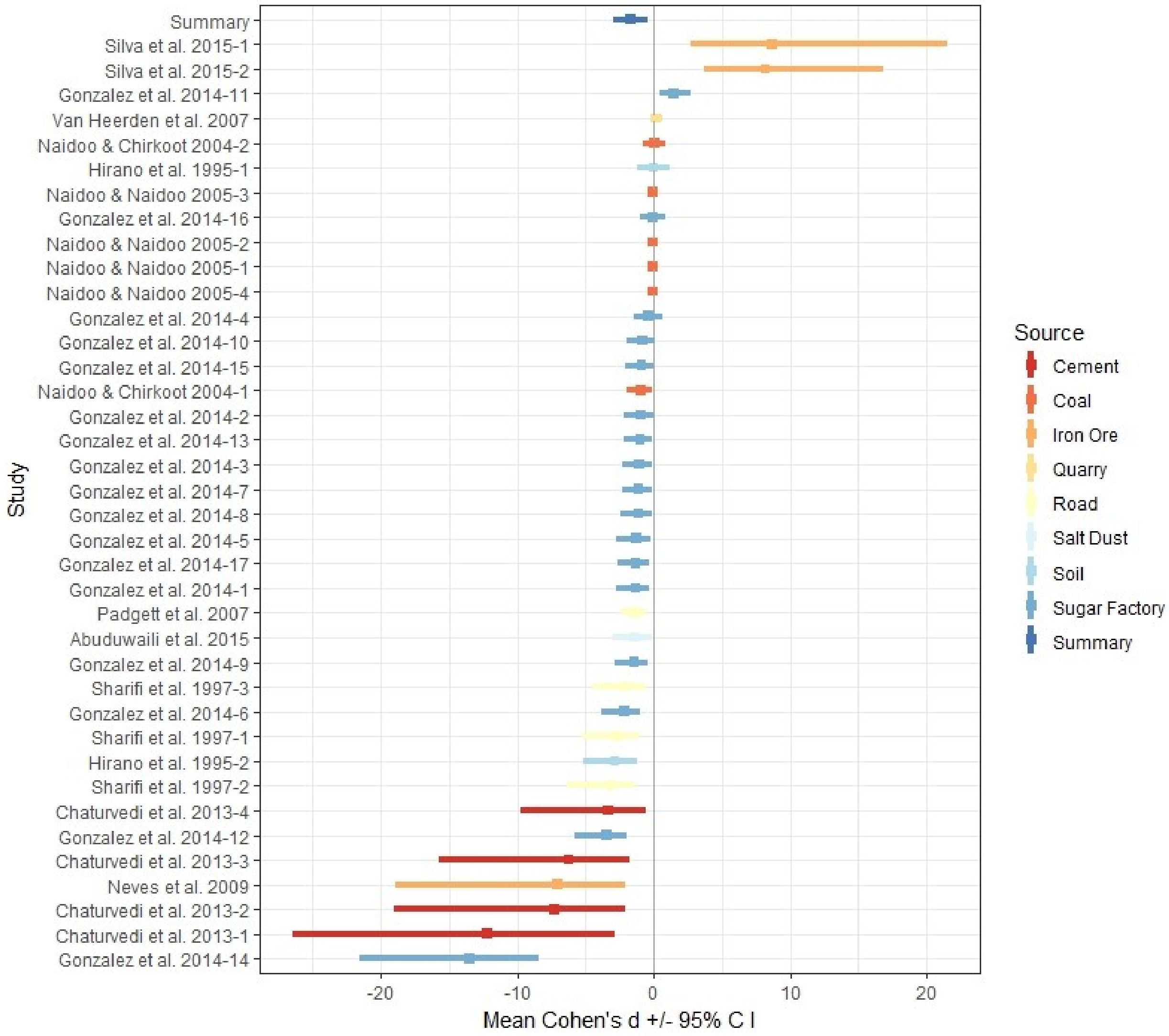

Figure 1.7. The mean Cohen's d effect sizes and 95% confidence intervals for stomatal conductance in dust affected plants. We extracted 38 observations from 11 studies. Confidence intervals that do not cross the zero line indicate significance. As indicated by the Summary statistic, top, increased dust deposition has an overall negative effect on stomatal conductance.

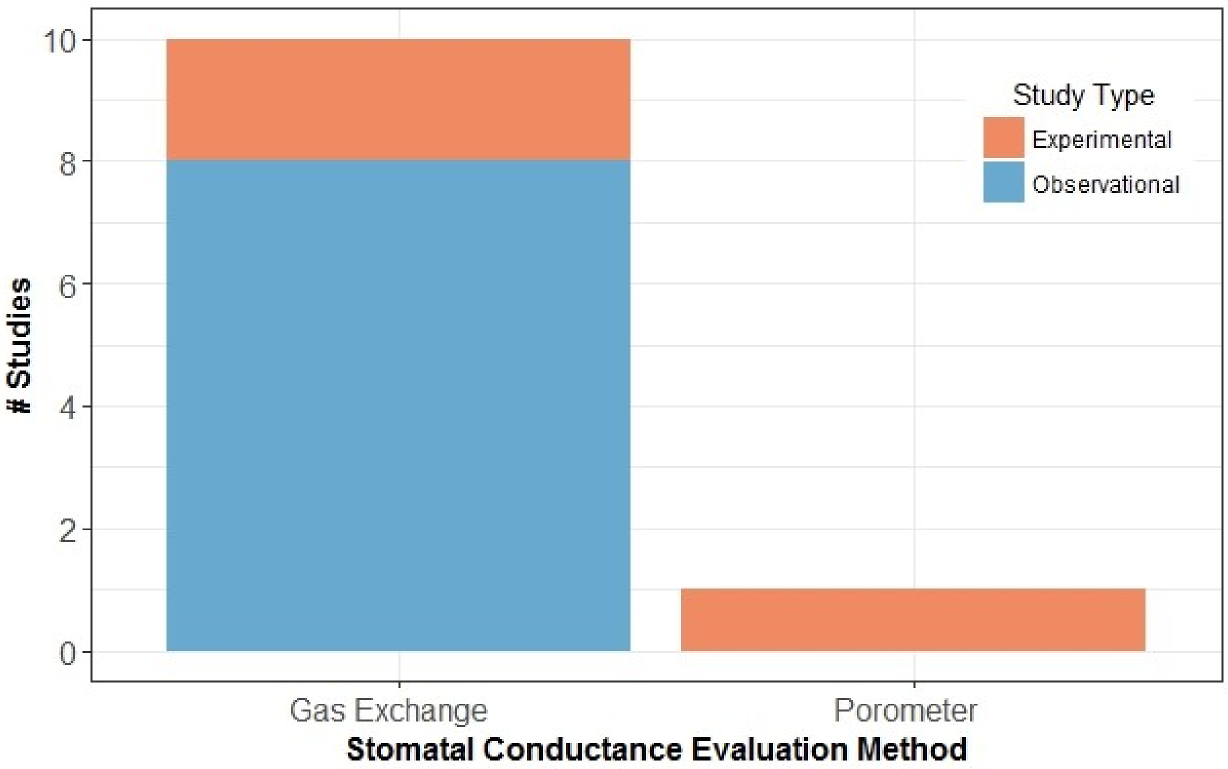

Figure 1.8. How stomatal conductance was evaluated. The majority of studies in the meta-analysis evaluated stomatal conductance using gas exchange chambers.

Discussion

None of the included studies focused on energy development-related traffic on unpaved roads, which are unique among other road emissions because: 1) the amount and type of traffic associated with development techniques like hydraulic fracturing substantially increase traffic; and 2) development of unconventional energy resources is rapidly expanding worldwide. New extraction technologies -specifically, hydraulic fracturing- increase traffic levels associated with energy production. For a single oil well, 1,753 of the 2,206 vehicles passes during the development phase are attributed to carrying the sand, water, and equipment for hydraulic fracturing (Felsburg Staff 2013). The increased weight and frequency of vehicles should increase the amount of dust emitted from an unpaved road and deposited across a landscape (US EPA 2006). We can use the included studies to address two of the broader questions regarding traffic-intensive energy development, dust emissions, and plants: 1) the spatial extent and amount of dust deposited across a landscape; and 2) how increased dust deposition and exposure affects plants in the rangelands and croplands adjacent to unpaved roads with increased traffic.

In the context of traffic-intensive energy development along unpaved roads, researchers could use an observational, distance gradient approach to quantify the spatial extent and amount of dust deposited at increasing distances from the road. The amount of dust deposited at a distance could be quantified using passive dust collectors (Padgett et al. 2007; Matsuki et al. 2016) or a leaf wash method (Prusty et al. 2005). The total airborne concentration of suspended particulate matter at a distance could be quantified with a particle analyzer (Joshi et al. 2009; Mori et al. 2015).

With increased dust deposition or exposure causing a significant, overall negative effect on each physiological parameter measured across multiple species, the question becomes how much does dust deposition or exposure is too much for rangeland and cropland plants along unpaved roads. Researchers measuring physiological responses or other plant health indicators in an observational study would need to pair plant responses with a dust deposition or exposure measurement where the plant is located. In an experimental study, researchers might apply dust to plants at rates comparable to those found in an observational study or increasing rates to determine a threshold amount of dust for a species.

Advancements in plant physiological response monitoring technology like flourometers, chlorophyll content meters, and porometers have increased opportunities for researchers interested in plant stressors, including increased dust deposition and exposure. We provide evidence of increased dust deposition or exposure having a significant, overall negative effect on plant physiological parameters including photosynthetic activity, chlorophyll content, and stomatal conductance across multiple species and emission sources. Areas currently receiving or about to receive increased dust deposition or exposure like rangelands and croplands along unpaved roads with traffic-intensive energy development should expect a similar negative effect.

References

Allred, B. W., W. K. Smith, D. Twidwell, J. H. Haggerty, S. W. Running, D. E. Naugle, and S. D. Fuhlendorf. 2015. Ecosystem services lost to oil and gas in North America. *Science* 348: 401–402.

Cambra-López, M., A. J. A. Aarnink, Y. Zhao, S. Calvet, and A. G. Torres. 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environmental Pollution* 158: 1–17.

Cohen, J. 1988. *Statistical power analysis for the behavioral sciences*. 2nd. Hillsdale, NJ: Lawrence Earlbaum Associates.

Farmer, A. M. 1993. The effects of dust on vegetation—a review. *Environmental Pollution* 79: 63–75.

Felsburg Staff. 2013. *Boulder County Oil and Gas Roadway Impact Study*. FHU Reference No. 12-109-01. Felsburg, Holt, and Ullevig.

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

Huang, Q., L. L. McConnell, E. Razote, W. F. Schmidt, B. T. Vinyard, A. Torrents, C. J. Hapeman, R. Maghirang, et al. 2013. Utilizing single particle Raman microscopy as a non-destructive method to identify sources of PM10 from cattle feedlot operations. *Atmospheric Environment* 66. Agriculture and Air Quality: Emission Measurement and Modeling: 17–24.

Joshi, N., A. Chauhan, and P. C. Joshi. 2009. Impact of industrial air pollutants on some biochemical parameters and yield in wheat and mustard plants. *The Environmentalist* 29: 398–404.

Kampa, M., and E. Castanas. 2008. Human health effects of air pollution. *Environmental Pollution* 151. Proceedings of the 4th International Workshop on Biomonitoring of Atmospheric Pollution (With Emphasis on Trace Elements): 362–367.

Lawrence, C. R., and J. C. Neff. 2009. The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition. *Chemical Geology* 267. Combined Ecological and Geologic Perspectives in Ecosystem Studies: 46–63.

Matsuki, M., M. R. Gardener, A. Smith, R. K. Howard, and A. Gove. 2016. Impacts of dust on plant health, survivorship and plant communities in semi-arid environments. *Austral Ecology* 41: 417-427.

Mori, J., A. Saebo, H. M. Hanslin, A. Teani, F. Ferrini, A. Fini, and G. Burchi. 2015. Deposition of traffic-related air pollutants on leaves of six evergreen shrub species during a Mediterranean summer season. *Urban Forestry & Urban Greening* 14: 264–273.

Padgett, P. E., W. M. Dobrowolski, M. J. Arbaugh, and S. A. Eliason. 2007. Patterns of Carbonate Dust Deposition: Implications for Four Federally Endangered Plant Species. *Madroño* 54: 275–285.

Prusty, B. a. K., P. C. Mishra, and P. A. Azeez. 2005. Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. *Ecotoxicology and Environmental Safety* 60: 228–235.

R Core Team. 2016. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria.

Reheis, M. C. 1997. Dust deposition downwind of Owens (dry) Lake, 1991–1994: Preliminary findings. *Journal of Geophysical Research: Atmospheres* 102: 25999–26008.

Rohatgi, A. 2017. *WebPlotDigitizer*. http://arohatgi.info/WebPlotDigitizer/app/. Accessed March 16.

US EPA. 2006. Miscellaneous Sources: Unpaved Roads. In *AP 42, Compilation of Air Pollutant Emission Factors*, 5th ed., 1:20.

Van Leuken, J. P. G., A. N. Swart, A. H. Havelaar, A. Van Pul, W. Van der Hoek, and D. Heederik. 2015. Atmospheric dispersion modelling of bioaerosols that are pathogenic to humans and livestock – A review to inform risk assessment studies. *Microbial Risk Analysis* 13.

CHAPTER 2: ENERGY-RELATED TRAFFIC INCREASES FUGITIVE DUST, DISRUPTS CROP PHYSIOLOGY IN THE BAKKEN OIL PATCH OF WESTERN NORTH DAKOTA

Abstract

Hydraulic fracturing and horizontal drilling have driven development of unconventional petroleum deposits under grasslands and croplands across North America and worldwide. Often, hydraulic fracturing is associated with substantial increases in energy-related traffic and fugitive dust emissions from unpaved roads, which have in turn been linked to negative impacts on surrounding vegetation. We investigated the acute and chronic effects of traffic associated with this unconventional oil production in the Bakken region of western North Dakota. We measured traffic frequency on unpaved roads, and in crop fields adjacent to these roads, we measured dust deposition rates, plant physiology (as an indictor of acute dust deposition impacts), and soil elemental concentrations (as a potential indicator of chronic impacts in fields along roads sprayed with dust suppressants). We found the spatial extent of dust deposition and amount of dust deposited, or dustload, for fields along unpaved roads with high traffic (range 130-186 mean daily vehicle passes) to be higher through 90 meters from an unpaved road than fields with low traffic (range 18-71 mean daily vehicle passes). Increased dust deposition had mixed effects on plant physiological parameters: photosynthetic quantum yield was reduced, chlorophyll content increased, and stomatal conductance was unchanged. We did not find evidence of magnesium or chloride increasing beyond expected levels as deposition increased, suggesting that some amount of dust suppressant use is tolerable. This is the first study in the region to link specific traffic counts with dustload and plant physiological parameters. As development of unconventional petroleum resources expands in use, we expect the associated infrastructure footprint of

widespread hydraulic fracturing to have a perceptible negative impact on plants surrounding unpaved roads in rural landscapes affected by industrialization and energy sprawl.

Introduction

Energy sprawl is a category of land use change that focuses on the surface footprint of renewable and non-renewable energy development, and is projected to overtake urban expansion and agricultural conversion as the largest driver of land use change in the United States through 2040 (Trainor et al. 2016). Importantly, land-use impacts associated with energy sprawl can have compounding effects on natural resources and biodiversity through the industrialization of working rangelands and croplands. Much of this recent development is driven by hydraulic fracturing and horizontal drilling, which facilitate access to petroleum resources inaccessible through conventional methods (Allred et al. 2015; Gaswirth et al. 2013).

Due to the high water demands of hydraulic fracturing, specifically, traffic associated with a single well is estimated at 2,206 vehicle passes during the development phase alone; 1,753 of which are attributed to carrying the equipment, fresh water, sand and flowback water needed for hydraulic fracturing (Felsburg Staff 2013). Such activity substantially alters the type and amount of traffic on roads in energy-production areas, which in turn substantially increases fugitive dust emissions from unpaved roads (US EPA 2006) with potentially problematic, but largely unknown, impacts when deposited across the landscape.

The emission of fugitive particulate matter, dust, is a naturally occurring event that can be exacerbated by anthropogenic activity. Anthropogenic sources of dust emission vary in scope, but include point sources like quarries or factories (Paling et al. 2001; Van Heerden et al. 2007) and continuous, non-point sources like roads (Sharifi et al. 1997; Wijayratne et al. 2009; Maletsika and Nanos 2011; Rai and Panda 2014; Matsuki et al. 2016). Once airborne, dust particles are deposited along a distance gradient from the emission point with courser particles deposited closer to the source and finer particles travelling further (Tegen and Fung 1994; Lawrence and Neff 2009). Atmospheric conditions like relative humidity, wind speed, and wind direction also influence transmission distance (Lawrence and Neff 2009).

The spatial extent of anthropogenic dust emissions varies with the source. Observational studies focused on massive point sources generally operate on a broader scale (0.5 km - ≥ 1 km from a source) (Van Heerden et al. 2007; Chakrabarti et al. 2014) than those focused on roads (15-100 m perpendicular from a source) (Goodrich et al. 2009; Padgett et al. 2007). On unpaved roads, additional factors affecting the amount of fugitive dust include vehicle speed, vehicle weight, amount of traffic, and road surface conditions (US EPA 2006).

Both fugitive dust and its control can impact several aspects of the human and natural environment. Increased dust emissions are a concern for human and livestock respiratory functions as well as visibility (Kampa and Castanas 2008; Cambra-López et al. 2010). Evidence suggests dust deposition can negatively affect plants through leaf shading or interference with stomatal activity (Farmer 1993; Hirano et al. 1995), but research on high-traffic continuous sources like unpaved roads in industrialized rural landscapes is lacking (Chapter 1). Meanwhile, chemical dust suppressants like magnesium chloride salt solutions are sometimes sprayed on unpaved roads to mitigate dust effects on air quality. If these chemicals are transported into fields through dust emission, the use of dust suppressants can increase the magnesium and chloride concentrations in surrounding soils to levels detrimental to plants (Goodrich et al. 2009).

Due primarily to the development of the Bakken oil patch, western North Dakota is currently at the intersection of natural grasslands, croplands, and landscape industrialization. While oil production has occurred in western North Dakota since the 1950's (LeFever 1991), development of the Bakken and Three Forks shale formations rapidly increased with the introduction of hydraulic fracturing and horizontal drilling between 2005-2007 (Miller et al. 2008; Gaswirth et al. 2013). Since 2012, North Dakota trails only Texas and the entirety of offshore rigs in the Gulf Coast for oil production in the United States (US Energy Information Administration Staff 2017). But unlike Texas, oil production in North Dakota is largely confined to a cluster of four rural counties (Dunn, McKenzie, Mountrail, and Williams) that account for 75% of the state's active wells and over 90% of oil and gas production (North Dakota State Industrial Commission 2016). This combination of techniques and production scale has pushed traffic levels past those recorded in the region prior to 2007 with projections ranging from 100-350+ mean daily truck passes into 2030 (Upper Great Plains Transportation Institute Staff 2012). Despite these projections, the relationship between traffic and fugitive dust—and between dust and vegetation—in this principally agricultural region remain unknown.

While dust effects on annual crops are confined to a growing season, and thus constitute acute impacts of fugitive dust, chronic impacts might develop from the long-term accumulation of chemicals associated with dust control. To mitigate detrimental air quality effects near urban areas and rural residences, dust suppressants like magnesium chloride salt solutions are commonly applied to some unpaved roads in the region (Graber 2016). Repeated use of such chemicals could alter the elemental concentrations of surrounding soils over time.

Despite the above concerns, research in the second-highest oil producing state is lacking: Creuzer et al. (2016) compared dust deposition in an area assumed to have high traffic based on well density to one assumed to have low traffic, but did not specifically measure traffic or account for environmental variables such as wind speed direction. The state of North Dakota routinely monitors traffic counts throughout this region on paved and unpaved roads, but does not have an active fugitive dust emission and deposition monitoring program (NDDOT Staff 2017). Furthermore, economically-important crops of the North American Great Plains are largely absent from studies focused on the effects of increased dust deposition and plants (Farmer 1993).

With oil and gas development using hydraulic fracturing and horizontal drilling projected to continue in the Bakken through 2030, the increased traffic associated with hydraulic fracturing is going to remain a continuous source of dust emissions with potentially acute and chronic effects. The overall objective of this study was to relate traffic counts to dust emissions and determine how fugitive dust deposition affects cereal crops in the Bakken region. We sought to evaluate: 1) the amount of traffic on unpaved roads adjacent to crop fields; 2) fugitive dust emissions and spatial extent of dust deposition as a function of traffic; and 3) acute effects of dust deposition on crop physiology and potentially chronic accumulation of magnesium chloride in soils.

Methods

Study Area and Site Selection

We conducted this study from June to early August of 2015 and 2016 in western North Dakota. The study area experienced a mean air temperature of 20° C during both June-August study periods. The study area experienced 17-25 cm of precipitation in study period 2015 and 9-17 cm of precipitation in study period 2016 (NDAWN - North Dakota Agricultural Weather Network 2017: Dunn, Watford, and Williston stations).

Across the two years, we used cereal crop fields from Dunn, McKenzie, and Williams counties that have consistently had the highest amount of oil and gas development since the recent boom began in 2005 (North Dakota State Industrial Commission 2016). For both years, we selected fields for proximity to active energy development and monitored traffic, dust deposition, and plant physiological parameters (5 wheat, 1 corn in 2015; 4 wheat, 1 barley in 2016).

Dust Deposition and Traffic

To determine the amount and spatial extent of dust deposition, we installed three transects of modified passive dust collectors that measure vertical deposition (Reheis and Kihl 1995) at increasing distances (15, 30, 60, 90, 180, and 360 m) from the center of an unpaved road. We installed dust collectors at a height of 1.5 m. We deployed the dust collectors in early June, following planting, and removed them in late July or early August, prior to harvest. We rinsed the dust from a dust collector into a liter bottle for transport from the field, and then obtained the dry mineral weight by drying the rinse water in an oven at 105° C for 24 h before weighing. We added 30% hydrogen peroxide to the rinse water during the drying process to remove organic material including bird fecal matter and leaf or stem material. In 2015, we composited dust across a given distance for each field when collecting and drying. In 2016, we collected and processed each dust collector individually.

To monitor road traffic, we buried wireless TRAFX counters (TRAFx Research Ltd., Canmore, Alberta), which detect vehicles using a magnetometer, in waterproof PVC boxes within 0.5-1 meters from an unpaved road and set them to record individual vehicle trips. We checked each traffic counter with visual counts over an hour period at least three times and found them to be accurate (> 99%, within 1-5 vehicle passes). We installed Decagon (METER Group, Pulllman, Washington): Davis cup anemometers to record wind speed and wind direction; VP-4 sensors to record relative humidity and air temperature; and ECRN-50 rain gauges to record every 15 minutes using an Em50 datalogger.

Plant Physiological Parameters

We measured in-field stomatal conductance, photosynthetic activity, and chlorophyll content along the dust collection transects under ambient conditions. We measured the top leaf from 3-4 randomly selected plants surrounding each dust collector. We measured each field 2-3 times in 2015 and once in in 2016.

To measure stomatal conductance, we used a Decagon SC-1 porometer with a desiccant chamber (METER Group, Pullman, Washington). Stomatal conductance was measured as the rate water exits the stomata (mmol/m^2/s). We measured quantum yield to evaluate photosynthetic activity using an Opti-Sciences OS1p Chlorophyll Fluorometer (Opti-Sciences, Inc., Hudson, New Hampshire). Quantum yield is the photochemical efficiency of photosystem II. We measured total leaf chlorophyll content using an Opti-Sciences CCM-300 (Opti-Sciences, Inc., Hudson, New Hampshire).

Environmental Fate of Dust Suppressants

To determine if magnesium or chloride were being transported into fields along unpaved roads, we looked at the elemental composition of soils along the dust collection transects in 2016. We took soil samples from 4 of the fields (3 wheat, 1 barley). We took soil samples at depths of 0-15 and 15-30 cm surrounding each dust collector using soil probes with a 2 cm diameter. Soil samples were analyzed by AgVise Laboratories (AgVise Laboratories Inc., Northwood, North Dakota) for elemental concentrations of magnesium and chloride (ppm).

Data Analysis

We calculated dust deposition rates by dividing the amount of dust collected by the surface area of the collection surface and then by the number of days the dust collector was deployed to account for variation in sampling effort. When comparing the deposition rates at a distance with deposition rates from other distances within the same field, we can approximate the flux of dust deposition as distance from the road increases. We use the term dustload to refer to the amount of fugitive dust deposited across a field.

We categorized traffic amounts for fields as high or low based on the mean daily vehicle passes recorded by the traffic counter and the lower bound of the high traffic projections from the Upper Great Plains Transportation Institute (2012). Fields with mean daily vehicle passes greater than 100 were categorized as 'high traffic', and fields with mean daily vehicle passes less than or equal to 100 were categorized as 'low traffic'.

We compared the response variables for each plant physiological parameter against the deposition rate corresponding to the distance and field in which the parameter was measured, where the deposition rate is the amount of dust to which plants at a given distance from unpaved roads were exposed. Likewise, we compare the elemental concentrations to the deposition rates corresponding to where they were collected.

We tested for statistical significance by comparing mixed-effect models for each response variable against a null model with analysis of deviance. We fit generalized linear mixed-effect models to account for the gamma distribution with dust deposition when using distance from an unpaved road as a predictor of deposition rate, and linear mixed effect models for response variables with normal distributions. We applied a 'log+1' transformation to chlorophyll content to fit a normal distribution for analysis. We analyzed dust deposition with a logscale transformation. We used field as a random effect variable in all models and nested year as a random effect variable with field for data with multiple years and repeated fields. The inclusion of crop type did not significantly influence models for any of the physiological parameters, thus we tested all crops together in models. Mixed-effect regression models were fit with functions glmer and lmer in package lme4 (Bates et al. 2015) for the R Statistical Environment (R Core Team 2016).

Results

Dust Deposition and Traffic

Fields adjacent to unpaved roads with higher traffic (range 130-186 mean daily vehicle passes) had higher dustloads along the logscale distance gradient than fields adjacent to unpaved roads with lower traffic (range 18-71 mean daily vehicle passes) ($\chi^2 = 38.56$, $p < 0.001$). The dustload for fields adjacent to an unpaved road with high traffic was greater than fields adjacent to an unpaved road with low traffic through 90 meters from an unpaved road (**Figure 2.1.**). Differences in dustload were especially pronounced 15 m from the road — 2.40 (± 0.25 s.e.) $g/m^2/day$ vs. 0.78 (± 0.12 s.e.) $g/m^2/day$ for the high-traffic and low-traffic, respectively — and diminished through 90 m from the road, after which dustloads along both high- and low-traffic roads were perceptible but not different. The dustload for fields adjacent to unpaved roads with low traffic did not vary with distance from the road. In paired fields adjacent to an unpaved road with 71 mean daily vehicles passes, wind direction altered the dustload for two adjacent fields (**Figures 2.2.**).

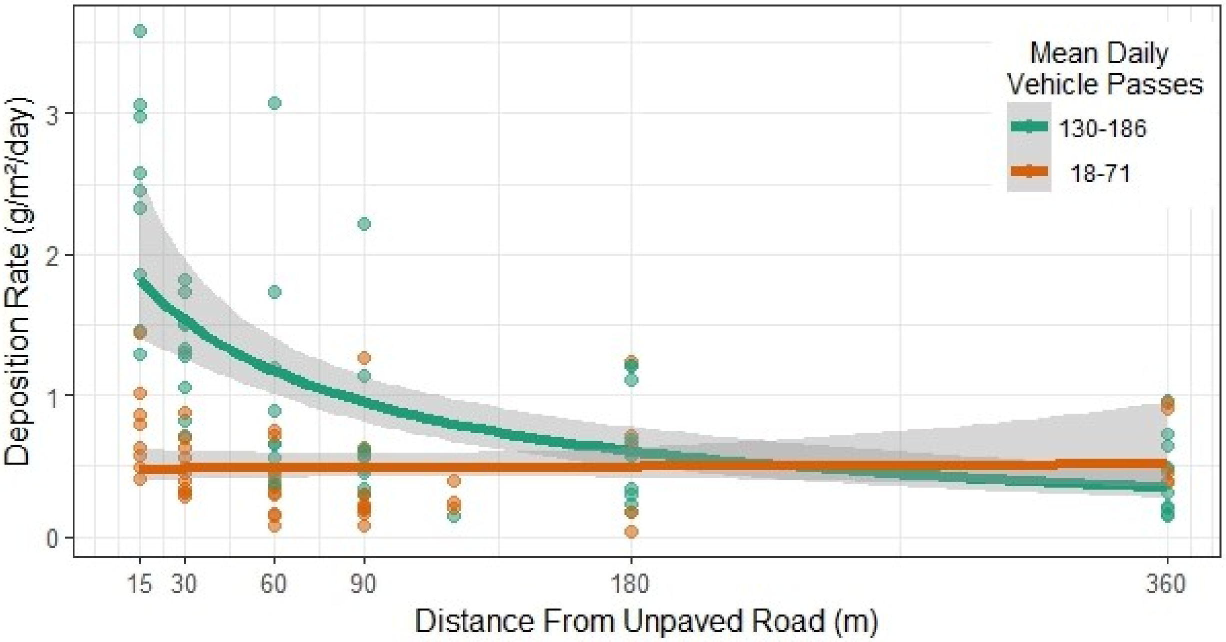

Figure 2.1. Fields adjacent to unpaved roads with high traffic (range = 130-186 mean daily vehicle passes) had a higher dustload than fields adjacent to unpaved roads with low traffic (range = 18-71 mean daily vehicle passes) through 90 m from an unpaved road. We zeroed distances on the center of the road adjacent to a field. Deposition rate is the dry mineral weight of dust collected at a point divided first by the surface area of the dust collector and then by the number of days the dust collector was deployed. Darkened points indicate overlapping deposition rates.

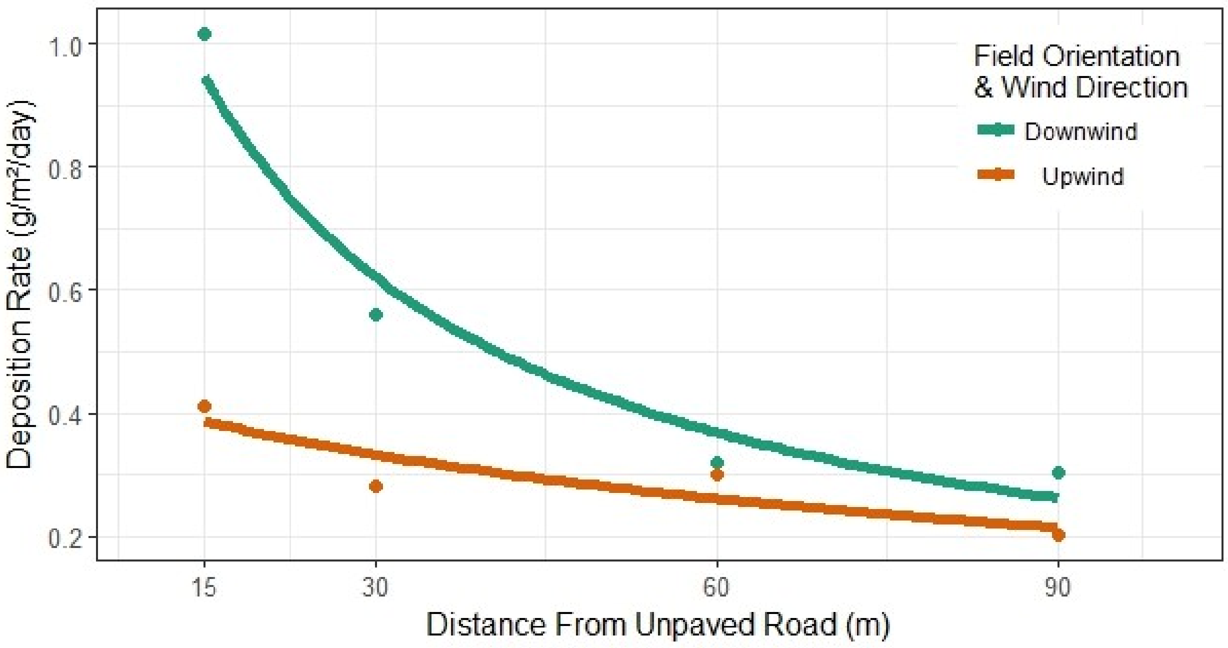

Figure 2.2. The deposition rates for two fields on opposite sides of an unpaved road with 71 mean daily vehicle passes during the 2015 field season. The field on the downwind side of the road had a higher initial dustload than the field on the upwind side of the road.

Evidence of Acute and Chronic Impacts

Photosynthetic activity, measured as quantum yield of photosystem II, gradually decreased with increasing dust deposition (χ^2 = 5.19, p = 0.02, 95% CI: -0.04 – -0.002) (**Figure 2.3.**). Stomatal conductance was not influenced by increased dust deposition (χ^2 = 0.48, p = 0.53, 95% CI: -0.04 – 0.08). (**Figure 2.4.**). Chlorophyll content increased with increasing dust deposition (χ^2 = 6.47, p = 0.01, 95% CI: 2.02 – 15.56) (**Figure 2.5.**).

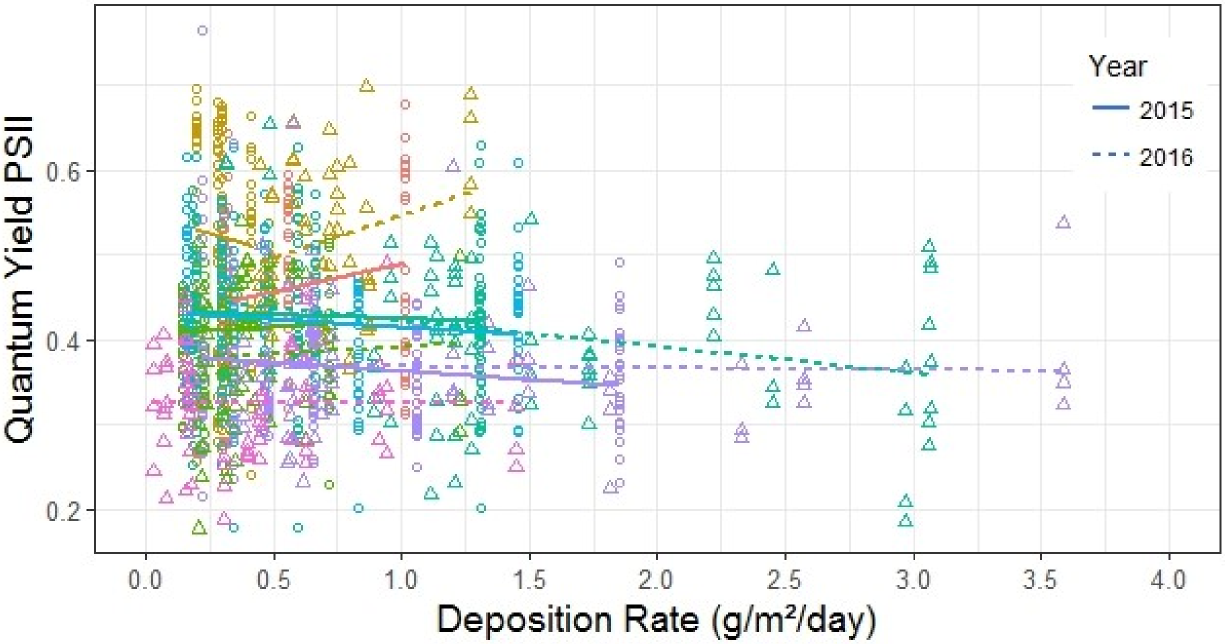

Figure 2.3. Photosynthetic activity, measured through quantum yield of photosystem II, decreased along the deposition gradient in annual cereal crop fields adjacent to unpaved roads in western North Dakota. Symbol colors differentiate sampled fields, while shapes differentiate years. Darkened points indicate overlapping measurements.

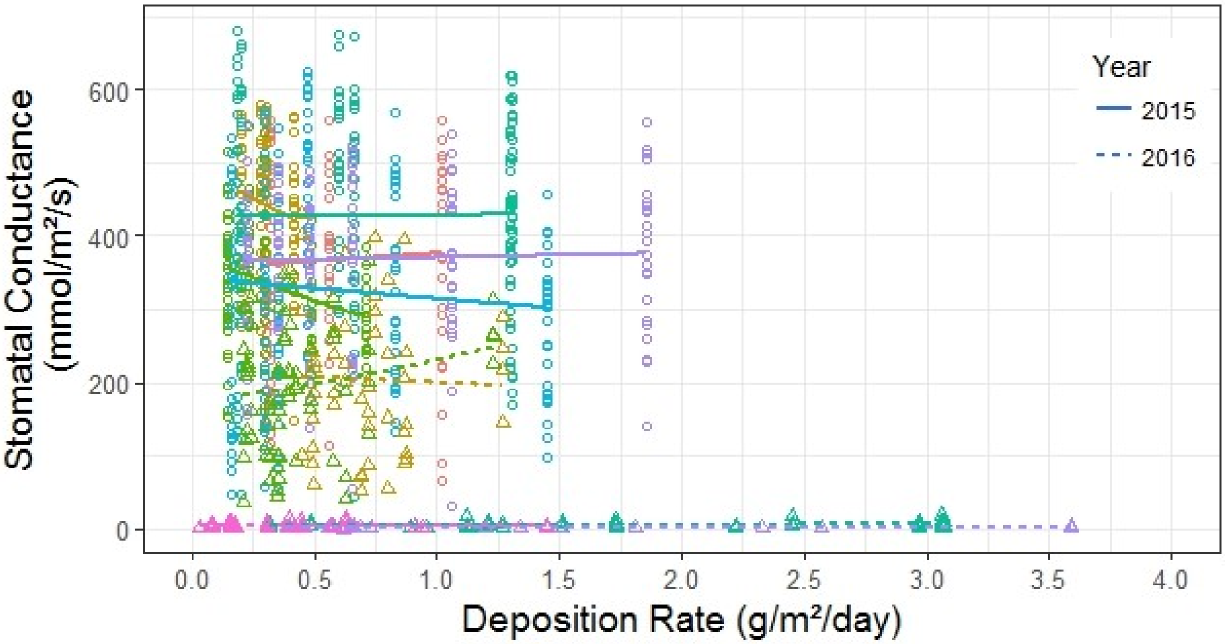

Figure 2.4. Stomatal conductance did not change across the deposition gradient in annual cereal crop fields adjacent to unpaved roads in western North Dakota. Symbol colors differentiate sampled fields, while shapes differentiate years. Darkened points indicate overlapping measurements.

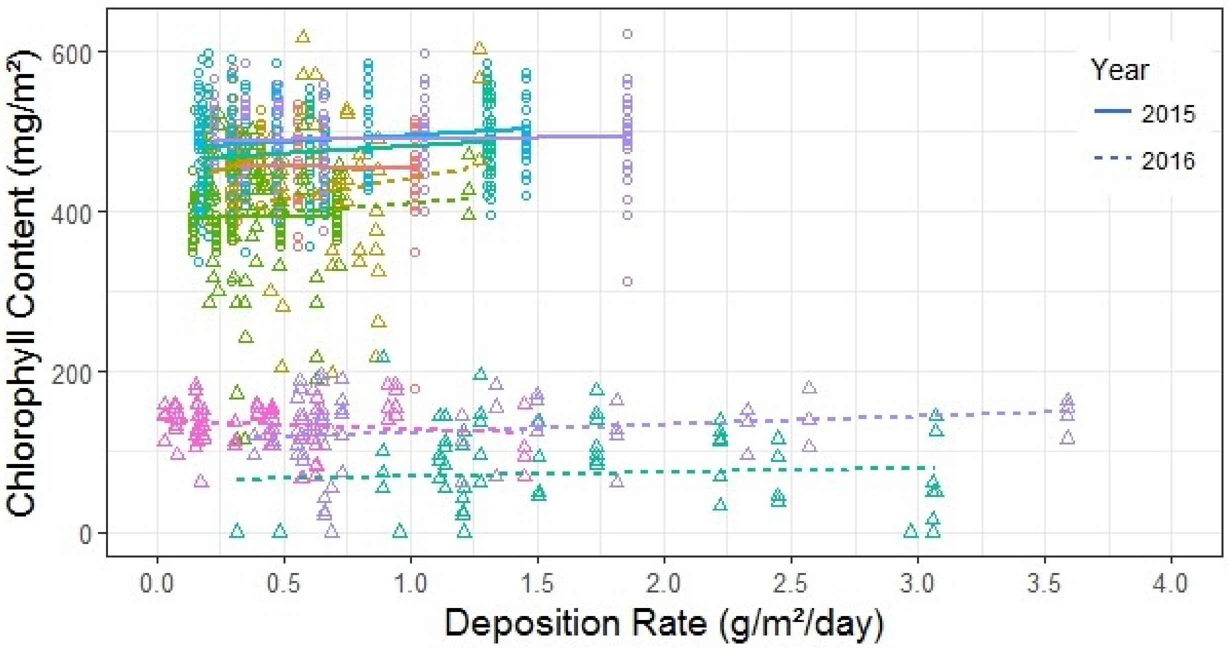

Figure 2.5. Leaf chlorophyll content increased across the deposition gradient in annual cereal crop fields adjacent to unpaved roads in western North Dakota. Symbol colors differentiate sampled fields, while shapes differentiate years. Darkened points indicate overlapping measurements.

The concentration of magnesium did not change across the deposition gradient (χ^2= 1.04, p = 0.31, 95% CI: -298,622.36 – 938,883.61) (**Figure 2.6.**). Samples from the 15-30 cm depth had higher concentrations of magnesium than samples from 0-15 cm (χ^2 = 39.19, p < 0.001, 95% CI: -282.38 – -155.12). The mean magnesium concentration from 0-15 cm samples was 735.05 ppm (± 26.48 s.e.) and 952 ppm (± 24.71 s.e.) in 15-30 cm samples. The concentration of chloride slightly increased across the deposition gradient (χ^2= 4.42, p = 0.04, 95% CI: 170.22 – 5,070.51) (**Figure 2.7.**). Chloride concentrations did not differ between the sampling depths (χ^2 = 0.36, p = 0.86, 95% CI: -0.27 – 0.33). The mean chloride concentration from 0-15 cm samples was 1.62 ppm (± 0.12 s.e.) and 1.59 ppm (± 0.10 s.e.) in 15-30 cm samples.

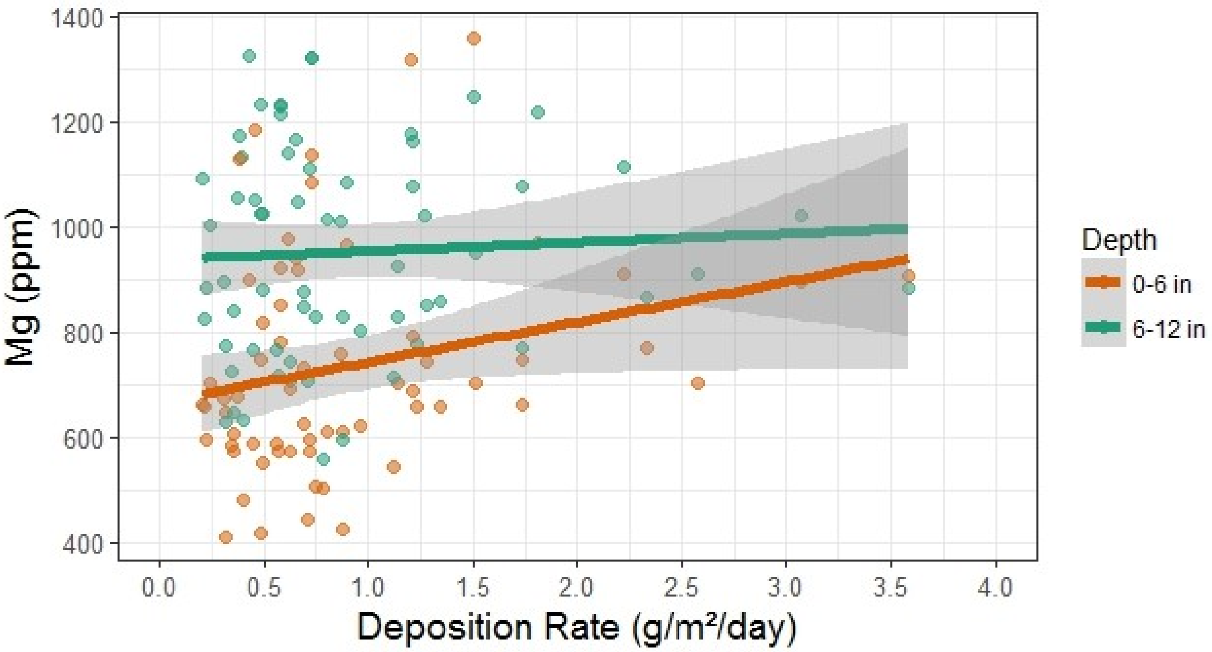

Figure 2.6. Soil magnesium concentrations did not increase with dust deposition rate in annual cereal crop fields adjacent to unpaved roads in western North Dakota. Samples from the 15-30 cm depth had higher magnesium concentrations than the 0-15 cm samples.

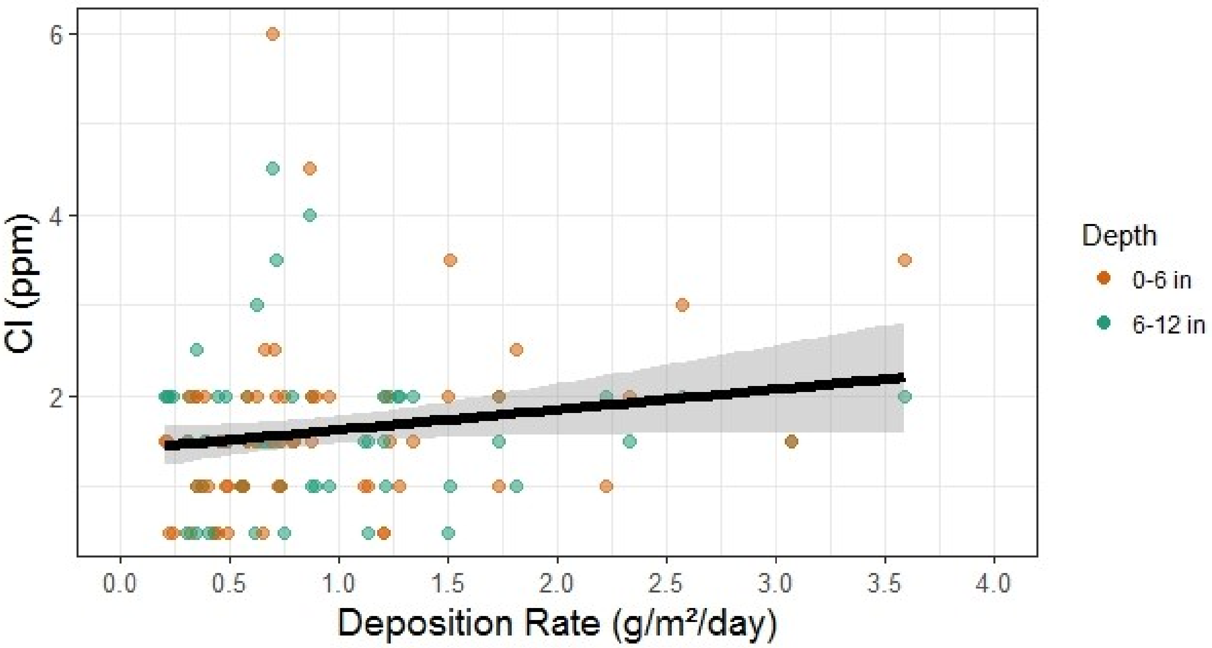

Figure 2.7. Soil chloride concentrations gradually increased with dust deposition rate in annual cereal crop fields adjacent to unpaved roads in western North Dakota, but are below the 20-70 ppm Cl concentration found in similar soil series. Concentrations did not differ between sampling depths.

Discussion

Conceptually, dust emission along unpaved roads and deposition on the surrounding area behaves like a disturbance regime in that it varies in frequency, intensity, and spatial extent. As such, arid and semi-arid regions naturally experience dust emission from exposed soil surfaces; these dust emissions are largely driven by wind velocity (Reheis 1997; Lawrence and Neff 2009). In general, the spatial extent of dust deposition is minimal as seen in the lack of distance influencing the deposition rates in our fields along unpaved roads with low traffic (range 18-71 mean daily vehicle passes). But when energy activity substantially increases traffic activity, quantifying traffic—or at least categorizing it appropriately—matters: A previous study from federal conservation lands in western North Dakota simply categorized traffic by proximity to active oil and gas development, and reported an increased dustload was limited to 10 m from an unpaved road (Creuzer et al. 2016), with high traffic compared to low traffic, but traffic was not actually measured. In contrast, we found dustloads in agricultural fields were significantly greater up to 90 m from unpaved roads with high traffic frequencies quantified here as 130-186 mean daily vehicle passes. North Dakota Department of Transportation can confirm the potential for spatially-broad impacts of increased dustload throughout the Bakken region, with records of mean daily vehicle passes exceeding 300 and 400, and even up to 940 mean daily vehicle passes on unpaved in Dunn and McKenzie counties in 2015 and 2016 (NDDOT Staff 2017).

The increased traffic amount and subsequent dust emission are a byproduct of oil and gas development using hydraulic fracturing. Of the estimated 2,206 vehicle trips to a well with a single well, single pad configuration, 1,753 vehicle trips are attributed to carrying the equipment, fresh water, sand, and flowback water required for hydraulic fracturing (Felsburg Staff 2013). While we have some information about how increased dust deposition affects various plants, there is a dearth of research focused on how this might affect other trophic levels like birds, small mammals, and insect communities. As this technique expands in use throughout the United States and countries looking to develop shale formations, so will the impact on infrastructure (Gregory et al. 2011; U.S. Energy Information Administration Staff 2013).

Apart from photosynthetic quantum yield, plant physiological parameters were inconsistent with similar studies. In an observational study, the leaves of wheat plants exposed to increased particulate matter had lower chlorophyll content than plants in the control (Joshi et al. 2009). In another observational study, increased deposition of particulate matter reduced photosynthetic rate and biomass yield in wheat and rice (*Oryza sativa*) (Chakrabarti et al. 2014). In experimental applications of fly ash onto rice foliage, photosynthetic rate, stomatal conductance, and yield declined as application rates increased (Raja et al. 2014).

The variability in our stomatal conductance and chlorophyll content readings between years could be a factor of increased rainfall in 2015 rinsing dust from leaves and mitigating any detrimental effects. Our study area received 9.0 cm of precipitation above the 30-year average during 2015 and 9.9 cm below average during 2016. An experimental gradient study in a greenhouse could use the deposition rates found here to control for this variation in precipitation and test an array of plant species.

It does not appear that the application of magnesium chloride solutions as a dust suppressant affected the concentrations of magnesium or chloride in the sampled fields. While we found that chloride concentration increased across the deposition gradient, the range of values are substantially lower than the expected 18-70 ppm Cl range from similar soil series (National Cooperative Soil Survey 2017; Soil Survey Staff 2017). Similarly, when the use of magnesium chloride solutions on unpaved roads has increased the chloride concentrations of roadside soils, the mean concentration was over 200 ppm Cl compared to 20-30 ppm Cl in control soil (Goodrich et al. 2009). Unlike Goodrich et el. (2009), we were unable to obtain access to sites with specific application frequency and application rates which limited our ability to fully encapsulate the variety of dust suppressant use in western North Dakota. Further investigation into dust suppressants in this region should focus on sites where this information is available to ascertain which application frequencies or application rates could detrimentally affect vegetation.

Conclusion

We found that crop fields in the Bakken region of North Dakota adjacent to unpaved roads with high traffic (range 130-186 mean daily vehicle passes) had a higher dustload through 90 m from an unpaved road than fields in the low traffic grouping (range 18-71 mean daily vehicle passes). Across plant species, increasing deposition influenced photosynthetic quantum yield negatively, chlorophyll content positively, but did not influence stomatal conductance. We did not find evidence that magnesium or chloride concentrations were elevated beyond normal levels. We expect these dust deposition trends to continue in the region if development continues at the current projected pace. Landscapes about to undergo traffic-intensive energy development of this kind should expect a similar infrastructure footprint.

References

Abdel-Rahman, A. M. 2012. The effect of cement dust pollution on the yield and quality of Ficuscaria L. fruits. Journal of Life Sciences.

Allred, B. W., W. K. Smith, D. Twidwell, J. H. Haggerty, S. W. Running, D. E. Naugle, and S. D. Fuhlendorf. 2015. Ecosystem services lost to oil and gas in North America. *Science* 348: 401–402.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effect Models Using lme4. Journal of Statistical Software, 67-1.

Cambra-López, M., A. J. A. Aarnink, Y. Zhao, S. Calvet, and A. G. Torres. 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. Environmental Pollution 158: 1–17.

Chakrabarti, B., R. Singh, A. Bhatia, S. D. Singh, and B. Singh. 2014. Impact of aerial deposition from thermal power plant on growth and yield of rice (Oryza sativa) and wheat (Triticum aestivum). Indian Journal of Agricultural Sciences 84: 602–606.

Creuzer, J., C. L. M. Hargiss, J. E. Norland, T. DeSutter, F. X. Casey, E. S. DeKeyser, and M. Ell. 2016. Does Increased Road Dust Due to Energy Development Impact Wetlands in the Bakken Region? Water, Air, & Soil Pollution 227: 1–14.

Farmer, A. M. 1993. The effects of dust on vegetation—a review. Environmental pollution 79: 63–75.

Felsburg Staff. 2013. Boulder County Oil and Gas Roadway Impact Study. FHU Reference No. 12-109-01. Felsburg, Holt, and Ullevig.

Gaswirth, S. B., K. R. Marra, T. A. Cook, R. R. Charpentier, D. L. Gautier, D. K. Higley, T. R. Klett, M. D. Lewan, et al. 2013. Assessment of undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota, 2013. USGS Numbered Series 2013–3013. Fact Sheet. Reston, VA: U.S. Geological Survey.

Goodrich, B. A., R. D. Koski, and W. R. Jacobi. 2009. Condition of Soils and Vegetation Along Roads Treated with Magnesium Chloride for Dust Suppression. Water Air and Soil Pollution 198: 165–188.

Graber, K. M. 2016. Effectiveness and simulated impacts of produced water as a dust abatement in western North Dakota. Natural Resource Program, North Dakota State University.

Gregory, K. B., R. D. Vidic, and D. A. Dzombak. 2011. Water Management Challenges Associated with the Production of Shale Gas by Hydraulic Fracturing. Elements 7: 181–186.

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

Joshi, N., A. Chauhan, and P. C. Joshi. 2009. Impact of industrial air pollutants on some biochemical parameters and yield in wheat and mustard plants. The Environmentalist 29: 398–404.

Kampa, M., and E. Castanas. 2008. Human health effects of air pollution. Environmental Pollution 151. Proceedings of the 4th International Workshop on Biomonitoring of Atmospheric Pollution (With Emphasis on Trace Elements): 362–367.

Lawrence, C. R., and J. C. Neff. 2009. The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition. Chemical Geology 267. Combined Ecological and Geologic Perspectives in Ecosystem Studies: 46–63.

LeFever, J. A. 1991. History of Oil Production from the Bakken Formation, North Dakota*: 3–17.

Maletsika, P. A., and G. D. Nanos. 2011. Effects of particulate matter contamination on apple, peach and olive tree leaf characteristics and olive leaf inorganic element composition. Ann. Agric. Valahia University 6: 9–14.

Matsuki, M., M. R. Gardener, A. Smith, R. K. Howard, and A. Gove. 2016. Impacts of dust on plant health, survivorship and plant communities in semi-arid environments. Austral Ecology 41: 417–427.

Miller, B. A., J. M. Paneitz, M. J. Mullen, R. Meijs, K. M. Tunstall, and M. Garcia. 2008. The Successful Application of a Compartmental Completion Technique Used To Isolate Multiple Hydraulic-Fracture Treatments in Horizontal Bakken Shale Wells in North Dakota. In . Society of Petroleum Engineers.

National Cooperative Soil Survey. 2017. NCSS Soil Characterization Database. National Cooperative Soil Characterization Database. https://ncsslabdatamart.sc.egov.usda.gov/querypage.aspx. Accessed March 6.

NDAWN - North Dakota Agricultural Weather Network. 2017. https://ndawn.ndsu.nodak.edu/. Accessed February 9.

NDDOT Staff. 2017. Interactive Transportation Information Map. North Dakota Department of Transportation. https://gis.dot.nd.gov/external/ge_html/?viewer=ext_transinfo. Accessed March 8.

North Dakota State Industrial Commission. 2016. Oil and Gas Production Report: December 2016. Monthly Production Report. North Dakota State Industrial Commission.

Paling, E. I., G. Humphries, I. McCardle, and G. Thomson. 2001. The effects of iron ore dust on mangroves in Western Australia: Lack of evidence for stomatal damage. Wetlands Ecology and Management 9: 363–370.

Padgett, P. E., W. M. Dobrowolski, M. J. Arbaugh, and S. A. Eliason. 2007. Patterns of Carbonate Dust Deposition: Implications for Four Federally Endangered Plant Species. *Madroño* 54: 275–285.

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rai, P. K., and L. S. Panda. 2014. Leaf dust deposition and its impact on biochemical aspect of some roadside plants in Aizawl, Mizoram, North-East India. International Research Journal of Environmental Sciences 3: 14–19.

Raja, R., A. K. Nayak, K. S. Rao, C. Puree, M. Shahid, B. B. Panda, A. Kumar, R. Tripathi, et al. 2014. Effect of Fly Ash Deposition on Photosynthesis, Growth and Yield of Rice. Bulletin of Environmental Contamination and Toxicology 93: 106–112.

Reheis, M. C. 1997. Dust deposition downwind of Owens (dry) Lake, 1991–1994: Preliminary findings. Journal of Geophysical Research: Atmospheres 102: 25999–26008.

Reheis, M. C., and R. Kihl. 1995. Dust deposition in southern Nevada and California, 1984–1989: Relations to climate, source area, and source lithology. Journal of Geophysical Research: Atmospheres 100: 8893–8918.

Sharifi, M. R., A. C. Gibson, and P. W. Rundel. 1997. Surface Dust Impacts on Gas Exchange in Mojave Desert Shrubs. Journal of Applied Ecology 34: 837–846.

Soil Survey Staff. 2017. Web Soil Survey. Natural Resource Conservation Service, United States Department of Agriculture. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. Accessed March 5.

Tegen, I., and I. Fung. 1994. Modeling of mineral dust in the atmosphere: Sources, transport, and optical thickness. Journal of Geophysical Research: Atmospheres 99: 22897–22914.

Trainor, A. M., R. I. McDonald, and J. Fargione. 2016. Energy Sprawl Is the Largest Driver of Land Use Change in United States. PLOS ONE 11: 1–16.

Upper Great Plains Transportation Institute Staff. 2012. An assessment of county and local road infrastructure needs in North Dakota. Upper Great Plains Transportation Institute, North Dakota State University.

U.S. Energy Information Administration Staff. 2013. Technically recoverable shale oil and shale gas resources: an assessment of 137 shale formations in 41 countries outside the United States.

US Energy Information Administration Staff. 2017. Crude Oil Production. US Department of Energy.

US EPA. 2006. Miscellaneous Sources: Unpaved Roads. In AP 42, Compilation of Air Pollutant Emission Factors, 5th ed., 1:20.

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

Wickham, H. 2009. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wijayratne, U. C., S. J. Scoles-Sciulla, and L. A. Defalco. 2009. Dust Deposition Effects on Growth and Physiology of the Endangered Astragalus Jaegerianus (fabaceae). Madrono 56: 81–88.

CHAPTER 3: BIRD ACTIVITY AND INVERTEBRATE COMMUNITIES NOT AFFECTED BY INCREASED TRAFFIC IN WESTERN NORTH DAKOTA CROPLANDS

Abstract

The introduction of hydraulic fracturing and horizontal drilling has driven an increase in traffic-intensive oil and gas development throughout the grasslands and croplands of western North Dakota. We investigated how the traffic associated with energy development influences bird and invertebrate communities in croplands along unpaved roads through increased dust emissions. We monitored bird activity using trail cameras and invertebrate communities using sweep-netting at increasing distances from unpaved roads along dust collection transects in croplands. We found that distance from an unpaved road and dust deposition did not negatively influence relative bird abundance or invertebrate abundance. We found greater invertebrate abundance in July compared to June and dissimilarity in the types of invertebrates collected between months. This suggests that bird and invertebrate communities utilizing croplands are not bothered by increased dust deposition, and might be more resilient to increased anthropogenic activity in the surrounding landscape.

Introduction

Globally, temperate grasslands are among the terrestrial biomes most threatened by land use change with 10 times as much land being converted for agricultural use and urbanization than placed under protection (Hoekstra et al. 2005). Land use change, the conversion of one type of land cover or use to another, has a detrimental effect on biodiversity through habitat loss, degradation, and fragmentation (Hoekstra et al. 2005; Krauss et al. 2010; Newbold et al. 2015). As a set of anthropogenic activities impacting the environment, land use change is often discussed in terms of native grassland conversion to agricultural production, especially in North America (Laycock 1988; Samson et al. 2004; Wright and Wimberly 2013). But energy sprawl, a specific type of anthropogenic land use change that consists of renewable and non-renewable energy development, is projected to be the largest driver of land use change in the United States through 2040 (Trainor et al. 2016).

An effect of energy sprawl is the industrialization of grasslands and croplands through oil and gas development, which has recently increased due to access to shale petroleum resources provided by new technologies such as hydraulic fracturing and horizontal drilling (Gaswirth et al. 2013; Allred et al. 2015). From 2000-2012, the agricultural land area lost to oil and gas development in North America accounted for an estimated 5 million animal unit months and 120+ million bushels of wheat in grasslands and croplands, respectively (Allred et al. 2015). With widespread use of hydraulic fracturing, there is also a reasonable expectation for a strain on road infrastructure through increased traffic: a national summary found traffic serving a single well developed via hydraulic fracturing and horizontal drilling required an estimated 2,206 vehicle passes prior to production (Felsburg Staff 2013).

A major consequence of increased traffic in agricultural landscapes affected by energy sprawl is increased dust emissions from rural, unpaved roads, and the effects of such dust on wildlife are unclear. On unpaved roads, dust emission is related to the amount, weight, and speed of vehicles using the road as well as road surface conditions (US EPA 2006). Once emitted, dust particles are transmitted and deposited along a distance gradient from the source with courser particles deposited closer to the source and finer particles travelling further (Tegen and Fung 1994; Lawrence and Neff 2009). Increased dust emission is already a known concern for human and livestock respiratory health (Davidson et al. 2005; Cambra-López et al. 2010) and known to impair plant growth and physiology (Farmer 1993; Hirano et al. 1995), but to our knowledge little work has focused on dust impacts on wildlife communities in energy-production landscapes. Birds are known to avoid anthropogenic structures and infrastructure, which potentially compounds habitat loss to land use change (Benítez-López et al. 2010). Bird avoidance along roads with increased traffic has been attributed to factors such as traffic noise or collisions (Summers et al. 2011; Polak et al. 2013). But energy-related traffic along rural, unpaved roads could potentially directly increase avoidance through the nuisance of increased dust emission and/or indirectly reduce habitat quality through negative impacts on invertebrate prey communities.

Western North Dakota is a landscape at the intersection of grasslands, croplands, and landscape industrialization through development of unconventional shale resources. As of 2012, the state of North Dakota trails only Texas and the entirety of offshore rigs in the Gulf Coast for oil production in the United States with a cluster of four counties accounting for over 90% the state's production. (North Dakota State Industrial Commission 2016; US Energy Information Administration Staff 2017). This combination of techniques and production scale has pushed traffic levels past those recorded in the region prior to 2007 with projections ranging from 100-350+ mean daily truck passes into 2030 (Upper Great Plains Transportation Institute Staff 2012).

During an ongoing investigation into the spatial extent of dust deposition in croplands adjacent to unpaved roads with varying levels of traffic and its effects on plant physiological parameters (Chapter 2), we observed more bird fecal material and miscellaneous invertebrate parts in dust collectors at 180 and 360 m from the road than those at 60 and 90 m from the road where dust deposition was higher. In a previous study of grassland birds in the region, birds avoided the area within 150 meters from a road with assumed high traffic (Thompson et al.

2015). Little is known about the bird community in western North Dakota croplands under these new conditions.

To grasp the full scope of anthropogenic landscape industrialization, we must also determine how wildlife that utilize previously converted grasslands along unpaved roads are affected by increased, energy-associated traffic and subsequent dust exposure. The observation with bird related organic material in the dust collectors led us to multiple questions regarding how birds and potential prey invertebrates might respond to increased dust deposition in crop fields: 1) what species of birds use the dust collectors for perches; 2) how do bird and invertebrate abundance differ across distance and dust exposure gradients; 3) what kinds of behavior do birds exhibit while on dust collectors. To investigate these questions, we used trail cameras to monitor the bird species, activity, and behavior and sweep-netting to monitor insect communities along previously established dust collection transects in crop fields located in the Bakken region of western North Dakota.

Methods

Study Area and Site Selection

We conducted this study in the summer of 2016 from June to early August in the Bakken region of western North Dakota. The main crop grown in this region during the summer is wheat (*Triticum sp.*), but canola (*Brassica napus*), sunflower (*Helianthus sp.*), barley (*Hordeum vulgare*), and corn (*Zea mays*) are also common. The study area experienced a mean air temperature of 20˚ C and 9-17 cm of precipitation during the study duration (NDAWN - North Dakota Agricultural Weather Network 2017).

We used privately owned crop fields from Dunn, McKenzie, and Williams counties which have consistently had the highest amount of oil and gas development since the recent boom began (North Dakota State Industrial Commission 2016). We chose potential fields based on road type and proximity to active energy development. We monitored road traffic, dust deposition, and insect communities on 5 crop fields (4 wheat, 1 barley). We monitored relative bird activity and behavior on 4 of those crop fields (3 wheat, 1 barley).

Sampling Design

Dust Deposition and Traffic

To determine the amount and spatial extent of dust deposition, we installed 3 transects of modified passive dust collectors that measure vertical dust deposition (Reheis and Kihl 1995) at increasing distances from the center of an unpaved road (15, 30, 60, 90, 180, and 360 meters) at a height of 1.5 meters. We deployed the dust collectors in early June, following planting, and removed them in early August, prior to harvest. We rinsed the dust from a dust collector into a liter bottle for transport from the field, and then obtained the dry mineral weight by drying the rinse water in an oven at 105° C for 24 hours before weighing. We added 30% hydrogen peroxide to the rinse water during the drying process to remove organic material.

To monitor road traffic, we buried wireless TRAFx counters (TRAFx Research Ltd., Canmore, Alberta) in waterproof PVC boxes within 0.5-1 meters from unpaved road and set them to record individual vehicle trips. We checked each traffic counter with visual traffic surveys over an hour period and found them to be accurate (> 99% agreement).

Bird Behavior and Activity

To monitor bird activity on dust collectors, we installed Bushnell 14 megapixel Trophy Cam HD trail cameras (Bushnell Outdoor Products, Overland Park, Kansas) in four fields approximately 2 meters from a dust collector. We set the trail cameras to take a 3-photo burst at 14 megapixels when triggered with a 10 second delay before triggering again. We identified birds to the species level. We counted individual observations of birds on a dust collector by starting an observation when a bird contacted a dust collector and then ending that observation when either: a bird no longer appeared in the frame; a different species appeared in the frame without the original bird; or a period greater than 30 seconds occurred between a 3-photo burst with a bird in the frame.

To determine behavior while on dust collectors, we categorized the recorded observations initially by the presence or absence of prey invertebrates from a bird's beak. We then categorized behavior based on head and body movements. We classified observations with prey visible as either bashing (head moving towards rim of dust collector) or holding (all activity not bashing). We classified instances without prey visible as still (little to no head or body movement), surveying (head moves frequently), calling (beak moves open and closed repeatedly), preening (head moving around body in a cleaning manner), or foraging (head moving in dust collector with no prey visible).

Invertebrate Abundance and Community Composition

To inventory the insect community over the growing season, we sweep-netted five fields in June and July along 25 meter transects at each dust collector and parallel to the unpaved road following an existing protocol (Doxon et al. 2011). We froze collected invertebrates and then later identified them to the Order level and counted abundance for each Order from October to December.

Data Analysis

We calculated deposition rates for individual dust collectors by dividing the amount of dust collected by the surface area of the dust collector and then by the number of days that the dust collector was deployed. To account for differences in sampling effort between cameras, we calculated relative bird activity by dividing the number of observations recorded at a camera by the number of days that a camera was deployed and actively recording.

We tested for significance by comparing mixed-effect models for each response variable against a null model using analysis of deviance. We used generalized linear mixed-effect models for three response variables that fit gamma distributions (dust deposition, bird activity per day, and invertebrate abundance), and linear mixed-effect models for the remaining response variables that fit a normal distribution. We analyzed distance with a logscale transformation. We applied an arithmetic transformation to bird activity to fit a normal distribution for analysis. We controlled for site-specific variation by including field as a random effect in all models. To compare the invertebrate communities collected between months, we fit an ordination using month as a predictor of taxonomic order with a Bray-Curtis dissimilarity index. In R Statistical Environment (R Core Team 2016), we used: functions glmer and lmer in package lme4 (Bates et al. 2015) for running the mixed-effect models, package multcomp (Hothorn et al. 2008) for comparing assigned behaviors, and package vegan (Oksanen 2009) for community analysis.

Results

Dust Deposition and Traffic

Fields adjacent to unpaved roads with high traffic (range 130-162 mean daily vehicle passes) had higher dustloads across the logscale distance gradient than fields adjacent to unpaved roads with low traffic (range 18-41 mean daily vehicle passes) ($\chi^2 = 27.39$, $p < 0.001$). On the untransformed distance scale, the dustload for the high traffic grouping was greater than the low traffic grouping through 180 meters from an unpaved road (**Figure 3.1.**). The dustload for the low traffic grouping did not change across the distance or logscale distance gradient. At 15 meters from the road, the high traffic grouping had a mean deposition rate of 2.83 g/m^2/day (0.19 s.e.).

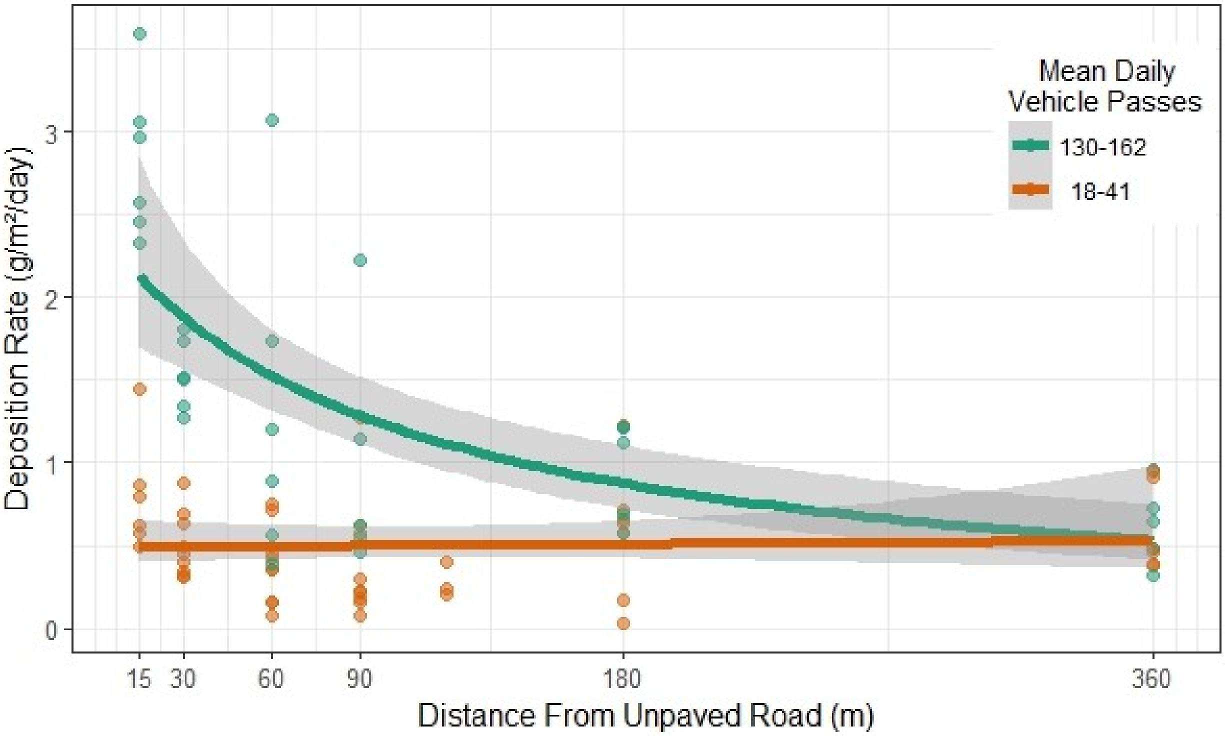

Figure 3.1. Fields adjacent to roads with high traffic (range 130-162 mean daily vehicle passes) had a higher dustload than fields adjacent to roads with low traffic (range 18-41 mean daily vehicle passes) through 180 meters from an unpaved road. We zeroed distance on the center of the road adjacent to a field. Deposition rate is the dry mineral weight of dust deposited on a dust collector at a point divided by the surface area of the dust collector and then by the number of days that the dust collector was deployed. Darkened points indicate overlapping deposition rates.

Bird Abundance and Behavior

Distance from the road did not influence relative bird activity ($\chi^2 = 0.46$, p = 0.52) (**Figure 3.2.**). Relative bird activity was, however, positively influenced by increased dust deposition ($\chi^2 = 4.06$, p = 0.04) (**Figure 3.3.**). We recorded 1048 observations across 13 species of birds across all trail cameras from July 13th to August 3rd. Four species—Brewer's Blackbird (*Euphagus cyanocephalus*), Eastern Kingbird (*Tyrannus tyrannus*), Western Kingbird (*Tyrannus verticallis*), and Loggerhead Shrike (*Lanius ludovicianus*)—accounted for roughly 93% of instances recorded (**Table 3.1.**). While Brewer's Blackbird had the most recorded observations with prey visible, Eastern Kingbird had the largest proportion of recorded observations with prey visible (**Figure 3.4.**). Distance from an unpaved road did not significantly influence the proportion of observations with prey invertebrates visible (Z values range -1.78 – 1.56, p values > 0.22) (**Figure 3.5.**).

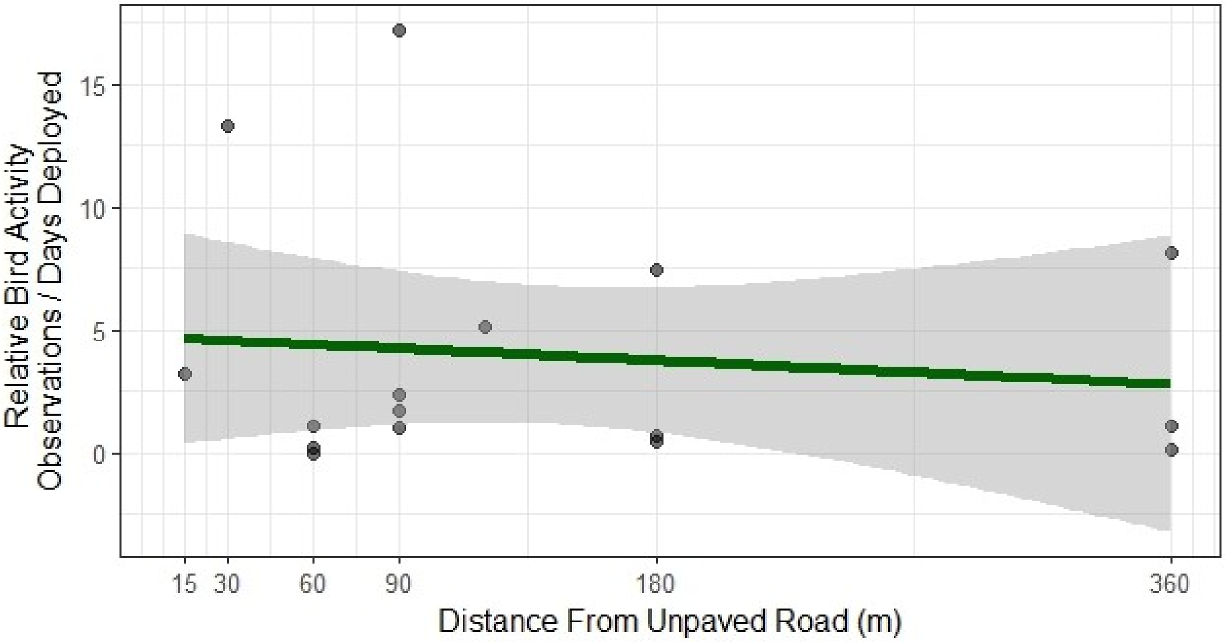

Figure 3.2. Distance from an unpaved road did not influence relative bird activity in annual cereal crop fields in western North Dakota. Relative bird activity is the total number of observations recorded with birds on a dust collector divided by the number of days that a trail camera was deployed and actively recording.

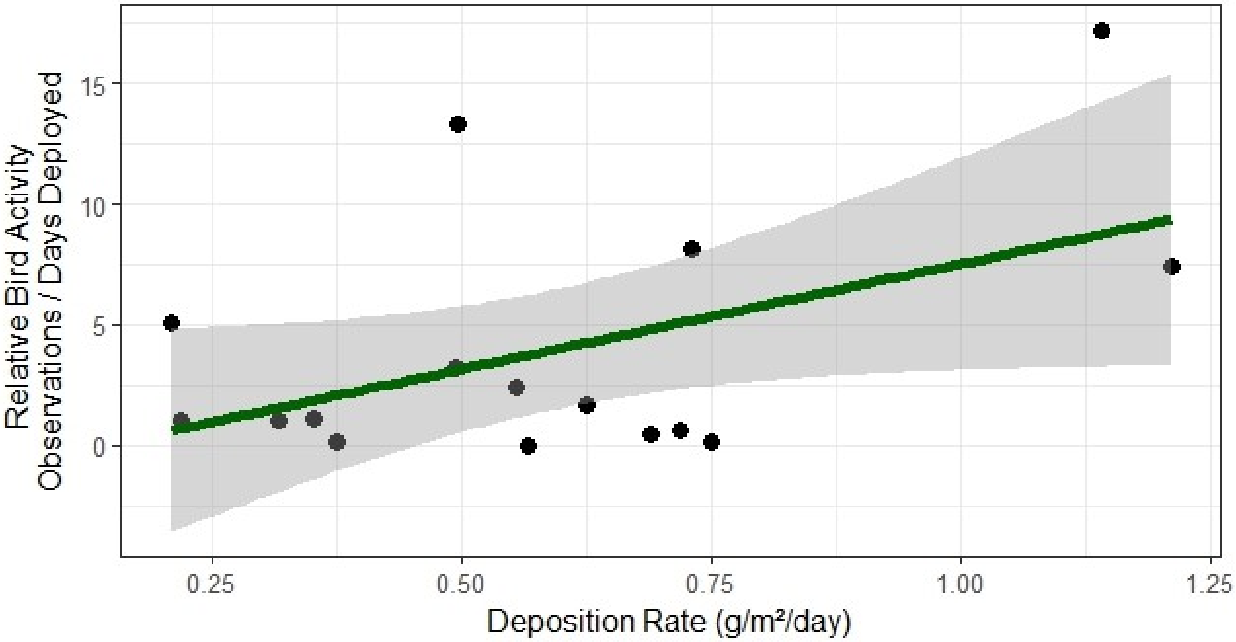

Figure 3.3. Dust deposition did not negatively influence relative bird activity in annual cereal crop fields in western North Dakota. Relative bird activity is the total number of observations recorded with birds on a dust collector divided by the number of days that a trail camera was deployed and actively recording.

Table 3.1. We recorded 1,048 observations across 13 species of birds in annual cereal crop fields in western North Dakota during the monitoring period (July 13th - August 3rd). Time per observation is the total amount of time (seconds) spent on a dust collector divided by the number of instances for a species.

Common Name	**Scientific Name**	**Observations**	**Time (s) Per Observation**
Brewer's Blackbird	*Euphagus cyanocephalus*	462	21
Eastern Kingbird	*Tyrannus tyrannus*	312	15
Western Kingbird	*Tyrannus verticalis*	126	27
Loggerhead Shrike	*Lanius ludovicianus*	72	19
Savannah Sparrow	*Passerculus sandwichensis*	37	8
Red-winged Blackbird	*Agelaius phoeniceus*	16	7
Western Meadowlark	*Sturnella neglecta*	7	23
Vesper Sparrow	*Pooecetes gramineus*	5	5
Bobolink	*Dolichonyx oryzivorus*	4	14
American Robin	*Turdus migratorius*	3	5
Mourning Dove	*Zenaida macroura*	2	5
American Goldfinch	*Spinus tristis*	1	5
Chipping Sparrow	*Spizella passerine*	1	5

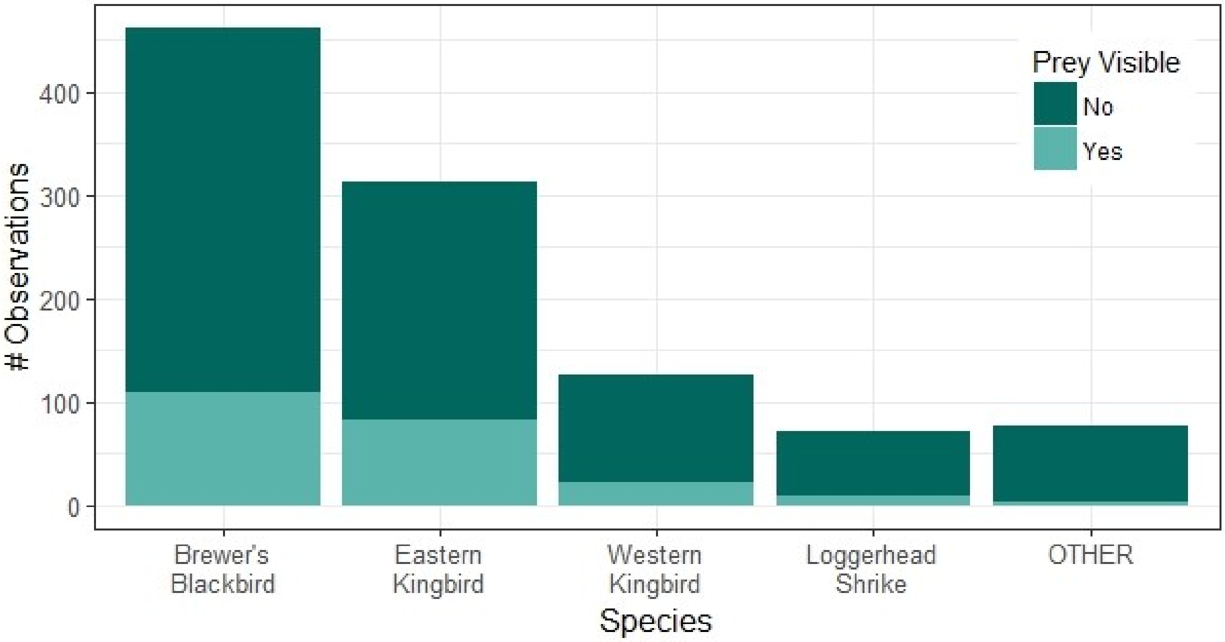

Figure 3.4. Total observations and observations with prey visible recorded for Brewer's Blackbird, Eastern Kingbird, Western Kingbird, and Loggerhead Shrike. The remaining nine species were grouped together as Other. We were interested in which species could have contributed to the bird related organic material in the previous year's dust collectors. Brewer's Blackbird had the most recorded observations with prey visible, but Eastern Kingbird had the largest proportion of its recorded observations with prey visible.

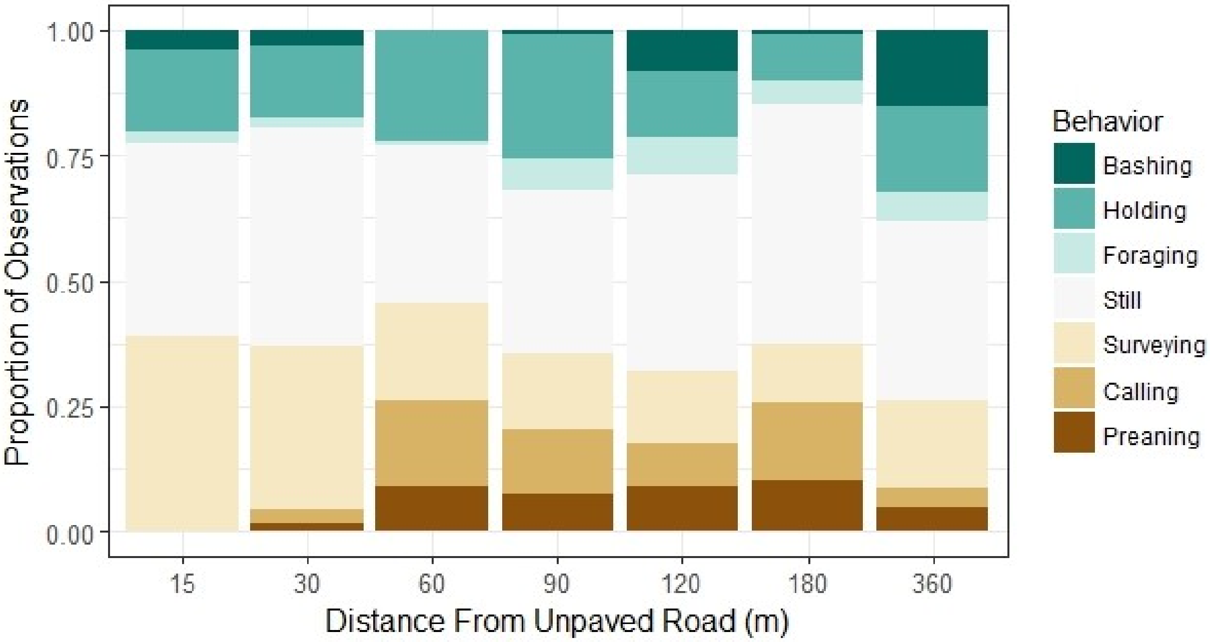

Figure 3.5. Proportional breakdown of assigned behavior for recorded observations of birds on dust collectors across distances from an unpaved road in annual cereal crop fields in western North Dakota. Assigned behaviors with prey visible are bashing and holding. Distance did not influence the proportion of instances with prey visible.

Invertebrate Abundance and Community

Invertebrate abundance varied with neither distance ($\chi^2 = 2.39$, $p = 0.50$) (**Figure 3.6.**) from an unpaved road nor dust deposition ($\chi^2 = 0.04$, $p = 0.84$) (**Figure 3.7.**). Invertebrate abundance was significantly higher in July than June across all distances and deposition rates ($\chi^2 = 92.31$, $p < 0.001$).

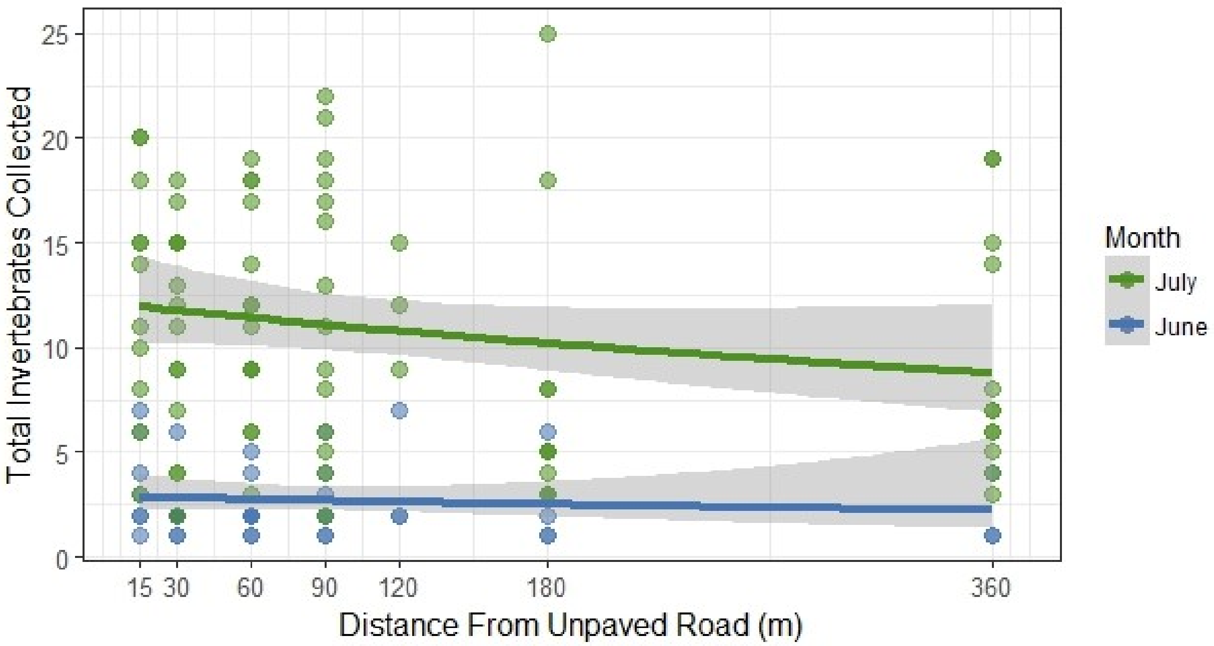

Figure 3.6. Distance from an unpaved road did not influence invertebrate abundance in annual cereal crop fields in western North Dakota for either month. We collected more invertebrates in July than June. Darkened points indicate overlapping samples.

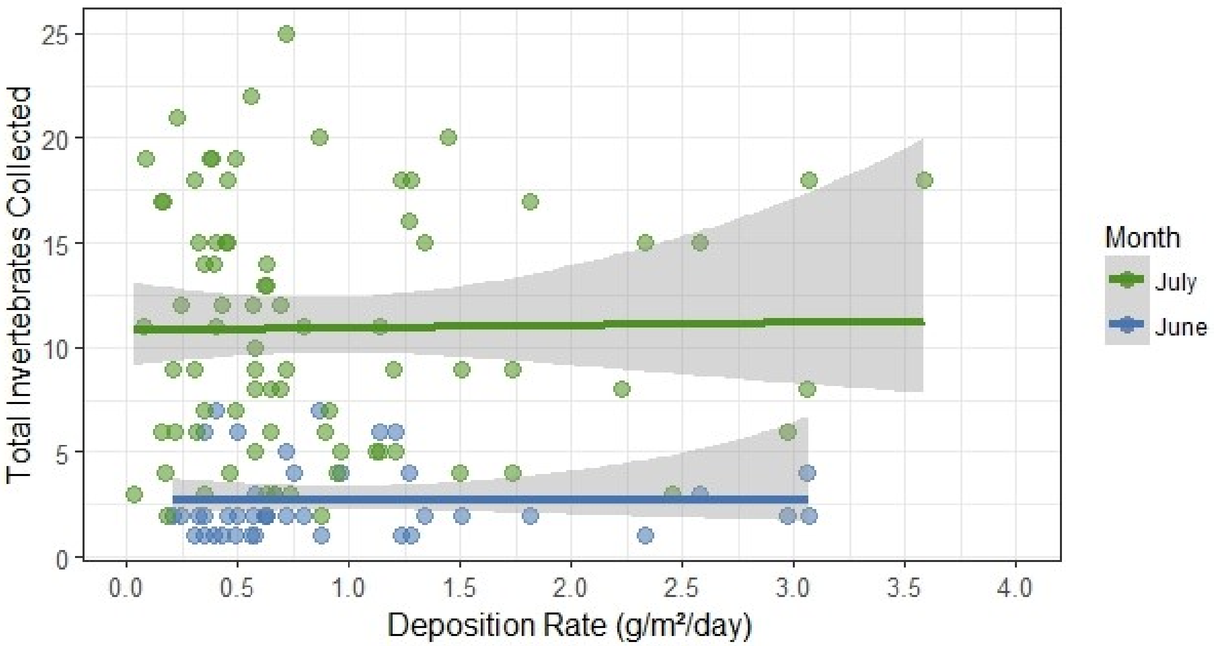

Figure 3.7. Dust deposition did not influence invertebrate abundance in crop fields for either month. We collected more invertebrates in July than June. Darkened points indicate overlapping samples.

We observed dissimilarity among invertebrate communities between months (k = 10, stress = 0.10, $p < 0.01$, $r^2 = 0.272$) (**Figure 3.8.**). While we collected more Orders Hymenoptera (bees, wasps, and ants) and Diptera (flies) in June, we collected more Araneae (spiders) and orders Neuroptera (lacewings), Orthoptera (grasshoppers and crickets), and Lepidoptera (butterflies and moths) in July. We collected Orders Hemiptera (true bugs) and Coleoptera (beetles) in both June and July.

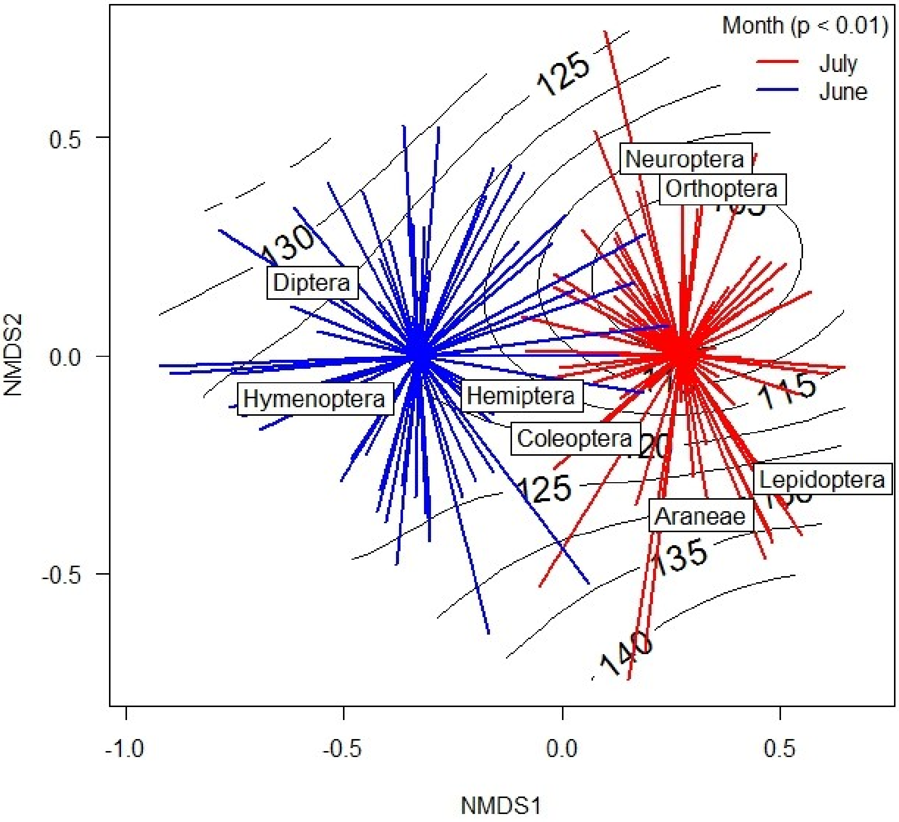

Figure 3.8. There was dissimilarity between the invertebrate communities collected in June and July (k = 10, stress = 0.10). We collected more Orders Hymenoptera and Diptera in June, and more Neuroptera, Orthoptera, Araneae, and Lepidoptera collected in July. We collected Orders Hemiptera and Coleoptera both June and July.

Discussion

Our dust collectors were overwhelmingly used by species associated with artificial perches (Brewer's Blackbird, Eastern Kingbird, Western Kingbird, and Loggerhead Shrike) like power lines or fence posts. These species were not documented in bird surveys in grasslands along unpaved roads in western North Dakota (Thompson et al. 2015), which suggests that these species are more associated with areas previously converted to cropland than natural grasslands and might be more resilient to further anthropogenic impacts. Likewise, Savannah Sparrow do not appear to be negatively affected by increased traffic or oil and gas wells (Bogard and Davis 2014; Ludlow et al. 2015; Thompson et al. 2015).

One potential explanation for the lack of a distance and traffic effect on overall bird activity is that traffic levels may not have been high enough to cause one. Our high traffic grouping (range 130-162 mean daily vehicle passes) is at the lower bound of what the state deems 'high traffic' for unpaved roads the Bakken region (Upper Great Plains Transportation Institute Staff 2012). While 130-162 mean daily vehicle passes were enough to increase the dustload through 180 meters from the road, traffic counts of 300 and even 400 mean daily vehicle passes have been consistently recorded on unpaved roads in the region since the recent boom began in 2007 (NDDOT Staff 2017).

Quantifying and reporting the amount of traffic should be a priority when determining the effects of increased anthropogenic industrialization with traffic-intensive energy development. Bird avoidance of grasslands surrounding unpaved roads with assumed increased, energy-associated traffic has been reported as being both increased and unaffected (Ludlow et al. 2015; Thompson et al. 2015). In an area of sagebrush steppe with traffic-intensive energy development, 300 and 400 daily vehicle passes increased grassland bird avoidance of paved roads (Ingelfinger and Anderson 2004). Future research could clarify the traffic threshold for a species before it will avoid a road.

While not statistically significant, distance from an unpaved road not influencing invertebrate abundance in cereal grain fields is contrary to repeated reports that invertebrate abundance is higher in the edge area of vegetation near the end of a crop field (Vickery et al. 2002; Bianchi et al. 2006). In South Dakota wheat fields, predator invertebrate abundance increased with increasing plant diversity and heterogeneity of the surrounding landscape (Elliott et al. 1999).

Our wheat and barley fields were expansive monocultures sprayed with herbicides to reduce broadleaf weeds. Since we were interested in how the broader invertebrate community might respond to increased dust deposition, we measured general invertebrate abundance only within crop fields. Compared to studies determining the abundance of plant pest and pest-predator abundance within fields and adjacent vegetation types, we measured general invertebrate abundance within fields at a larger scale (Elliott et al. 1999; Bianchi et al. 2006; Haughton et al. 2016). If an edge effect were to occur in our fields, then invertebrate abundance should have decreased as distance from the road increased.

Conclusion

We investigated the link between increased traffic and subsequent dust emissions on bird and invertebrate communities in western North Dakota croplands. We show that although fields adjacent to roads with higher traffic (range 130-162 mean daily vehicle passes) received a greater dustload through 180 meters, the observed deposition rates did not negatively influence bird activity or invertebrate abundance. Likewise, distance from an unpaved road did not influence bird activity or invertebrate abundance. This suggests that bird and insect communities utilizing croplands are more resilient to increased anthropogenic industrialization of rangelands and croplands for energy development using traffic-intensive techniques like hydraulic fracturing.

References

Allred, B. W., W. K. Smith, D. Twidwell, J. H. Haggerty, S. W. Running, D. E. Naugle, and S. D. Fuhlendorf. 2015. Ecosystem services lost to oil and gas in North America. *Science* 348: 401–402.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. *Fitting Linear Mixed-Effect Models Using lme4*. Journal of Statistical Software, 67-1.

Benítez-López, A., R. Alkemade, and P. A. Verweij. 2010. The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis. *Biological Conservation* 143: 1307–1316.

Bianchi, F. J. J. A., C. J. H. Booij, and T. Tscharntke. 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society of London B: Biological Sciences* 273: 1715–1727. doi:10.1098/rspb.2006.3530.

Bogard, H. J., and S. K. Davis. 2014. Grassland songbirds exhibit variable responses to the proximity and density of natural gas wells. *The Journal of Wildlife Management* 78: 471–482.

Cambra-López, M., A. J. A. Aarnink, Y. Zhao, S. Calvet, and A. G. Torres. 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environmental Pollution* 158: 1–17.

Davidson, C. I., R. F. Phalen, and P. A. Solomon. 2005. Airborne Particulate Matter and Human Health: A Review. *Aerosol Science and Technology* 39: 737–749.

Doxon, E. D., C. A. Davis, and S. D. Fuhlendorf. 2011. Comparison of two methods for sampling invertebrates: vacuum and sweep-net sampling: Methods of Sampling Invertebrates. *Journal of Field Ornithology* 82: 60–67.

Elliott, N. C., R. W. Kieckhefer, J.-H. Lee, and B. W. French. 1999. Influence of within-field and landscape factors on aphid predator populations in wheat. *Landscape Ecology* 14: 239–252.

Farmer, A. M. 1993. The effects of dust on vegetation—a review. *Environmental pollution* 79: 63–75.

Felsburg Staff. 2013. *Boulder County Oil and Gas Roadway Impact Study*. FHU Reference No. 12-109-01. Felsburg, Holt, and Ullevig.

Gaswirth, S. B., K. R. Marra, T. A. Cook, R. R. Charpentier, D. L. Gautier, D. K. Higley, T. R. Klett, M. D. Lewan, et al. 2013. *Assessment of undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota, 2013*. USGS Numbered Series 2013–3013. Fact Sheet. Reston, VA: U.S. Geological Survey.

Haughton, A. J., D. A. Bohan, S. J. Clark, M. D. Mallott, V. Mallott, R. Sage, and A. Karp. 2016. Dedicated biomass crops can enhance biodiversity in the arable landscape. *GCB Bioenergy* 8: 1071–1081.

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

Hoekstra, J. M., T. M. Boucher, T. H. Ricketts, and C. Roberts. 2005. Confronting a biome crisis: global disparities of habitat loss and protection. *Ecology Letters* 8: 23–29.

Hothorn, T., F. Bretz, and P. Westfall. 2008. Simultaneous Inference in General Parametric Models. *Biometrical Journal* 50: 346–363.

Ingelfinger, F., and S. Anderson. 2004. Passerine response to roads associated with natural gas extraction in a sagebrush steppe habitat. *Western North American Naturalist* 64: 385–395.

Krauss, J., R. Bommarco, M. Guardiola, R. K. Heikkinen, A. Helm, M. Kuussaari, R. Lindborg, E. Öckinger, et al. 2010. Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. *Ecology Letters* 13: 597–605.

Lawrence, C. R., and J. C. Neff. 2009. The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition. *Chemical Geology* 267. Combined Ecological and Geologic Perspectives in Ecosystem Studies: 46–63.

Laycock, W. A. 1988. History of grassland plowing and grass planting on the Great Plains. Impacts of the Conservation Reserve Program in the Great Plains: 3–8.

Ludlow, S. M., R. M. Brigham, and S. K. Davis. 2015. Oil and natural gas development has mixed effects on the density and reproductive success of grassland songbirds. *The Condor* 117: 64–75.

NDAWN - North Dakota Agricultural Weather Network. 2017. https://ndawn.ndsu.nodak.edu/. Accessed February 9.

NDDOT Staff. 2017. Interactive Transportation Information Map. North Dakota Department of Transportation. https://gis.dot.nd.gov/external/ge_html/?viewer=ext_transinfo. Accessed March 8.

Newbold, T., L. N. Hudson, S. L. L. Hill, S. Contu, I. Lysenko, R. A. Senior, L. Börger, D. J. Bennett, et al. 2015. Global effects of land use on local terrestrial biodiversity. *Nature* 520: 45–50.

North Dakota State Industrial Commission. 2016. *Oil and Gas Production Report: December 2016*. Monthly Production Report. North Dakota State Industrial Commission.

Oksanen, J. 2009. *vegan: Community Ecology Package* (version 2.4-2).

Polak, M., J. Wiącek, M. Kucharczyk, and R. Orzechowski. 2013. The effect of road traffic on a breeding community of woodland birds. *European Journal of Forest Research* 132: 931–941.

R Core Team. 2016. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria.

Reheis, M. C., and R. Kihl. 1995. Dust deposition in southern Nevada and California, 1984–1989: Relations to climate, source area, and source lithology. *Journal of Geophysical Research: Atmospheres* 100: 8893–8918.

Samson, F. B., F. L. Knopf, and W. R. Ostlie. 2004. Great Plains ecosystems: past, present, and future. *Wildlife Society Bulletin* 32: 6–15.

Summers, P. D., G. M. Cunnington, and L. Fahrig. 2011. Are the negative effects of roads on breeding birds caused by traffic noise? *Journal of Applied Ecology* 48: 1527–1534.

Tegen, I., and I. Fung. 1994. Modeling of mineral dust in the atmosphere: Sources, transport, and optical thickness. *Journal of Geophysical Research: Atmospheres* 99: 22897–22914.

Thompson, S. J., D. H. Johnson, N. D. Niemuth, and C. A. Ribic. 2015. Avoidance of unconventional oil wells and roads exacerbates habitat loss for grassland birds in the North American great plains. *Biological Conservation* 192: 82–90.

Trainor, A. M., R. I. McDonald, and J. Fargione. 2016. Energy Sprawl Is the Largest Driver of Land Use Change in United States. *PLOS ONE* 11: 1–16.

Upper Great Plains Transportation Institute Staff. 2012. *An assessment of county and local road infrastructure needs in North Dakota*. Upper Great Plains Transportation Institute, North Dakota State University.

US Energy Information Administration Staff. 2017. *Crude Oil Production*. US Department of Energy.

US EPA. 2006. Miscellaneous Sources: Unpaved Roads. In *AP 42, Compilation of Air Pollutant Emission Factors*, 5th ed., 1:20.

Vickery, J., N. Carter, and R. J. Fuller. 2002. The potential value of managed cereal field margins as foraging habitats for farmland birds in the UK. *Agriculture, Ecosystems & Environment* 89. The Ecology of Field Margins in European Farming Systems: 41–52.

Wright, C. K., and M. C. Wimberly. 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proceedings of the National Academy of Sciences* 110: 4134–4139.

APPENDIX A: THE LIST OF STUDIES INCLUDED IN THE REVIEW

Author (s)	Year	Title	Publication Title	Issue	Volume
Abdel-Rahman et al.	2012	The effect of cement dust pollution on the yield and quality of Ficuscaria L. fruits.	Journal of Life Sciences	6	3
Abuduwaili et al.	2015	The Disastrous Effects of Salt Dust Deposition on Cotton Leaf Photosynthesis and the Cell Physiological Properties in the Ebinur Basin in Northwest China	PLoS ONE	5	10
Amal and Migahid	2011	Effect of cement-kiln dust pollution on the vegetation in the western Mediterranean desert of Egypt	World Academy of Science, Engineering and Technology		81
Analojeh et al.	2016	Investigating and comparing short period impact of dust on physiological characteristics of three species of Pinus eldarica, Cupressus sempervirens, and Ligustrum ovalifolium	Arabian Journal of Geosciences	4	9
Arrivabene et al.	2015	Effect of pollution by particulate iron on the morphoanatomy, histochemistry, and bioaccumulation of three mangrove plant species in Brazil	Chemosphere		127
Bamniya et al.	2011	Harmful effects of air pollution on physiological activities	Clean Technologies and	1	14

Author (s)	Year	Title	Publication Title	Issue	Volume
		of Pongamia pinnata (L.) Pierre	Environmental Policy		
Bao et al.	2015	Urban dust load impact on gas-exchange parameters and growth of Sophora japonica L. seedlings	Plant Soil and Environment	7	61
Chakrabarti et al.	2014	Impact of aerial deposition from thermal power plant on growth and yield of rice (Oryza sativa) and wheat (Triticum aestivum)	Indian Journal of Agricultural Sciences	5	84
Chaturvedi et al.	2013	Effect of dust load on the leaf attributes of the tree species growing along the roadside	Environmental Monitoring and Assessment	1	185
Dziri and Hosni	2012	Effects of cement dust on volatile oil constituents and antioxidative metabolism of Aleppo pine (Pinus halepensis) needles	Acta Physiologiae Plantarum	5	34
Gill et al.	2014	Cumulative Impacts and Feedbacks of a Gravel Road on Shrub Tundra Ecosystems in the Peel Plateau, Northwest Territories, Canada	Arctic, Antarctic, and Alpine Research	4	46
Gleason et al.	2007	Assessing and Mitigating the Effects of Windblown Soil on Rare and Common Vegetation	Environmental Management	6	40

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Gonzalez et al.	2014	Atmospheric Dust Accumulation on Native and Non-Native Species: Effects on Gas Exchange Parameters	Journal of Environment Quality	3	43
Goodrich et al.	2009	Condition of Soils and Vegetation Along Roads Treated with Magnesium Chloride for Dust Suppression	Water Air and Soil Pollution	4-Jan	198
Gupta	2016	Deposition and Impact of Urban Atmospheric Dust on Two Medicinal Plants during Different Seasons in NCR Delhi	Aerosol and Air Quality Research		16
Gupta et al.	2015	Industrial dust sulphate and its effects on biochemical and morphological characteristics of Morus (Morus alba) plant in NCR Delhi	Environmental Monitoring and Assessment	3	187
Hirano et al.	1995	Physical effects of dust on leaf physiology of cucumber and kidney bean plants	Environmental Pollution	3	89
Jankowski et al.	2015	Content of lead and cadmium in aboveground plant organs of grasses growing on the areas adjacent to a route of big traffic	Environmental Science and Pollution Research	2	22
Joshi et al.	2009	Impact of air quality on physiological attributes of certain plants	Report and Opinion	2	3

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Joshi et al.	2011	Impact of industrial air pollutants on some biochemical parameters and yield in wheat and mustard plants	The Environmentalist	4	29
Kuki et al.	2008	The Simulated Effects of Iron Dust and Acidity During the Early Stages of Establishment of Two Coastal Plant Species	Water, Air, and Soil Pollution	4-Jan	196
Kuki et al.	2008	Iron Ore Industry Emissions as a Potential Ecological Risk Factor for Tropical Coastal Vegetation	Environmental Management	1	42
Lafragueta et al.	2013	Germination of Medicago sativa is inhibited by soluble compounds in cement dust	Environmental Science and Pollution Research	2	21
Laghari et al.	2015	Impact of solid waste burning air pollution on some physio-anatomical characteristics of some plants	Pakistani Journal of Botany	1	47
Lepedus et al.	2003	The annual changes of chloroplast pigments content in current- and previous-year needles of Norway spruce (Picea abies L. Karst.) exposed to cement dust pollution	Acta Botanica Croatica	1	62
Maletsika and Nanos	2011	Effects of particulate matter contamination on apple, peach and olive tree leaf characteristics and olive leaf inorganic element composition	Ann. Agric. Valahia University		6

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Maletsika et al.	2015	Peach leaf responses to soil and cement dust pollution	Environmental Science and Pollution Research	20	22
Mandre and Ots	1999	Assessment of growth and stemwood quality of Scots pine on territory influenced by alkaline industrial dust	Environmental Monitoring and Assessment	3-Jan	138
Mandre and Tuulmets	1997	Growth and Biomass Partitioning of 6-Year-Old Spruces under Alkaline Dust Impact	Water, Air, and Soil Pollution	2-Jan	114
Mandre et al.	2007	Variation in the morphological structure of the crown of Norway spruce in North Estonian alkalised soil	Forest Ecology and Management		278
Mandre et al.	2012	PIGMENT CHANGES IN NORWAY SPRUCE INDUCED BY DUST POLLUTION	Water, Air, and Soil Pollution	4-Mar	94
Matsuki et al.	2016	Impacts of dust on plant health, survivorship and plant communities in semi-arid environments	Austral Ecology		
Mori et al.	2015	Deposition of traffic-related air pollutants on leaves of six evergreen shrub species during a Mediterranean summer season	Urban Forestry & Urban Greening	2	14
Naidoo and Chirkoot	2004	Coal Dust Pollution Effects on Wetland Tree Species in Richards Bay,South Africa	Wetlands Ecology and Management	5	13

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Naidoo and Naidoo	2005	The effects of coal dust on photosynthetic performance of the mangrove, Avicennia marina in Richards Bay, South Africa	Environmental Pollution	3	127
Nanos and Ilias	2007	Effects of inert dust on olive (Olea europaea L.) leaf physiological parameters	Environmental Science and Pollution Research - International	3	14
Neves et al.	2009	Photosynthesis and oxidative stress in the restinga plant species Eugenia uniflora L. exposed to simulated acid rain and iron ore dust deposition: Potential use in environmental risk assessment	Science of The Total Environment	12	407
Osan et al.	1996	Physiological Effect of Accidental Fly Ash Deposition on Plants and Chemical Study of the Dusted Plant Leaves by XRF and EPMA	X-Ray Spectrometry	4	25
Ots et al.	2011	Changes in the canopies of Pinus sylvestris and Picea abies under alkaline dust impact in the industrial region of Northeast Estonia	Forest Ecology and Management	2	262
Padgett et al.	2007	Patterns of Carbonate Dust Deposition: Implications for Four Federally Endangered Plant Species	Madroño	4	54

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Padgett et al.	2007	Monitoring fugitive dust emissions from off-highway vehicles traveling on unpaved roads and trails using passive samplers	Environmental Monitoring and Assessment	3-Jan	144
Paling et al.	2001	The effects of iron ore dust on mangroves in Western Australia: Lack of evidence for stomatal damage	Wetlands Ecology and Management	5	9
Pereira et al.	2008	Photosynthetic changes and oxidative stress caused by iron ore dust deposition in the tropical CAM tree Clusia hilariana	Trees	2	23
Prajapati and Tripathi	2008	Seasonal variation of leaf dust accumulation and pigment content in plant species exposed to urban particulates pollution	Journal of Environmental Quality	3	37
Prusty et al.	2005	Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India	Ecotoxicology and Environmental Safety	2	60
Pryzbysz et al.	2014	Efficiency of photosynthetic apparatus of plants grown in sites differing in level of particulate matter	Acta Sci. Pol. Hortorum Cultus		13
Rai and Panda	2013	Leaf surface structure alterations due to particulate pollution in some common plants	The Environmentalist	1	30

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Rai and Panda	2014	Leaf dust deposition and its impact on biochemical aspect of some roadside plants in Aizawl, Mizoram, North-East India	International Research Journal of Environmental Sciences		3
Rai et al.	2009	Dust capturing potential and air pollution tolerance index (APTI) of some road side tree vegetation in Aizawl, Mizoram, India: an Indo-Burma hot spot region	Air Quality, Atmosphere & Health	1	7
Raja et al.	2014	Effect of Fly Ash Deposition on Photosynthesis, Growth and Yield of Rice	Bulletin of Environmental Contamination and Toxicology	1	93
Saha and Padhy	2011	Effects of stone crushing industry on Shorea robusta and Madhuca indica foliage in Lalpahari forest	Atmospheric Pollution Research	4	2
Salama et al.	2011	Effects of Riyadh cement industry pollutions on some physiological and morphological factors of Datura innoxia Mill. Plant	Saudi Journal of Biological Sciences	3	18
Sharifi et al.	1997	Phenological and physiological responses of heavily dusted creosote bush (Larrea tridentata) to summer irrigation in the Mojave Desert	Flora	4	194

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Sharifi et al.	1999	Surface Dust Impacts on Gas Exchange in Mojave Desert Shrubs	Journal of Applied Ecology	4	34
Sharma and Tripathi	2008	Biochemical responses in tree foliage exposed to coal-fired power plant emission in seasonally dry tropical environment	Environmental Monitoring and Assessment	4-Jan	158
Silva et al.	2015	Differential responses of C3 and CAM native Brazilian plant species to a SO2- and SPMFe-contaminated Restinga	Environmental Science and Pollution Research	18	22
Van Heerden et al.	2007	Dynamic responses of photosystem II in the Namib Desert shrub, Zygophyllum prismatocarpum, during and after foliar deposition of limestone dust	Environmental Pollution	1	146
Wijayratne et al.	2009	Dust Deposition Effects on Growth and Physiology of the Endangered Astragalus Jaegerianus (fabaceae)	Madrono	2	56
Younis et al.	2013	Particulate matter effect on biometric and biochemical attributes of fruiting plants	Global Journal of Environmental Science and Management-Gjesm	2	1
Younis et al.	2015	Variations in leaf dust accumulation, foliage and pigment attributes in fruiting plant species exposed to particulate pollution from Multan	Int. J. Agric. Sci. Res		3

Author (s)	**Year**	**Title**	**Publication Title**	**Issue**	**Volume**
Younis et al.	2013	Dust interception capacity and alteration of various biometric and biochemical attributes in cultivated population of Ficus carica L, IOSR	J. Pharm. Biol. Sci.(IOSR-JPBS),(6)	6	4
Zia-Khan et al.	2014	Effect of Dust Deposition on Stomatal Conductance and Leaf Temperature of Cotton in Northwest China	Water	1	7

APPPENDIX B: INCLUDED STUDIES SORTED BY EXPERIMENTAL TYPE AND META-ANALYSIS INCLUSION

Author (s)	**Year**	**Exp. or Obs.**	**Gradient**	**Treat. Cont.**	**Meta : PA**	**Meta : CC**	**Meta : SC**
Abdel-Rahman et al.	2012	Observational	Distance				
Abuduwaili et al.	2015	Experimental	Application Rate		Yes	Yes	Yes
Amal and Migahid	2011	Observational		Yes			
Analojeh et al.	2016	Experimental	Application Rate			Yes	
Arrivabene et al.	2015	Observational					
Bamniya et al.	2011	Observational	Seasonal				
Bao et al.	2015	Experimental	Application Rate			Yes	
Chakrabarti et al.	2014	Observational	Distance		Yes		
Chaturvedi et al.	2013	Observational		Yes	Yes	Yes	Yes
Dziri and Hosni	2012	Observational		Yes			
Gill et al.	2014	Observational		Yes			
Gleason et al.	2007	Observational	Distance				
Gonzalez et al.	2014	Observational		Yes			Yes
Goodrich et al.	2009	Observational	Distance				
Gupta	2016	Observational	Seasonal			Yes	
Gupta et al.	2015	Observational		Yes			

Author (s)	**Year**	**Exp. or Obs.**	**Gradient**	**Treat. Cont.**	**Meta : PA**	**Meta : CC**	**Meta : SC**
Hirano et al.	1995	Experimental	Application Rate				Yes
Jankowski et al.	2015	Observational	Distance				
Joshi et al.	2009	Observational	Seasonal			Yes	
Joshi et al.	2011	Observational					
Kuki et al.	2008	Experimental	Application Rate				
Kuki et al.	2008	Observational	Distance				
Lafragueta et al.	2013	Experimental	Application Rate				
Laghari et al.	2015	Observational	Distance			Yes	
Lepedus et al.	2003	Observational		Yes			
Maletsika and Nanos	2011	Observational	Distance			Yes	
Maletsika et al.	2015	Experimental		Yes			
Mandre and Ots	1999	Observational		Yes			
Mandre and Tuulmets	1997	Observational	Distance				
Mandre et al.	2007	Observational	Distance				
Mandre et al.	2012	Observational	Distance				
Matsuki et al.	2016	Observational	Distance				
Mori et al.	2015	Observational	Seasonal				
Naidoo and Chirkoot	2004	Observational		Yes	Yes		Yes
Naidoo and Naidoo	2005	Observational		Yes	Yes		Yes

Author (s)	**Year**	**Exp. or Obs.**	**Gradient**	**Treat. Cont.**	**Meta : PA**	**Meta : CC**	**Meta : SC**
Nanos and Ilias	2007	Experimental		Yes			
Neves et al.	2009	Experimental	Application Rate		Yes	Yes	Yes
Osan et al.	1996	Experimental	Application Rate				
Ots et al.	2011	Observational	Distance				
Padgett et al.	2007	Observational	Distance		Yes		Yes
Padgett et al.	2007	Observational	Distance				
Paling et al.	2001	Observational		Yes			
Pereira et al.	2008	Experimental	Application Rate				
Prajapati and Tripathi	2008	Observational	Seasonal				
Prusty et al.	2005	Observational	Seasonal				
Pryzbysz et al.	2014	Observational	Seasonal		Yes	Yes	
Rai and Panda	2013	Observational		Yes		Yes	
Rai and Panda	2014	Observational	Seasonal				
Rai et al.	2009	Experimental		Yes			
Raja et al.	2014	Experimental	Application Rate				
Saha and Padhy	2011	Observational	Seasonal				
Salama et al.	2011	Observational	Distance			Yes	
Sharifi et al.	1997	Observational		Yes	Yes		
Sharifi et al.	1999	Observational		Yes			Yes

Author (s)	**Year**	**Exp. or Obs.**	**Gradient**	**Treat. Cont.**	**Meta : PA**	**Meta : CC**	**Meta : SC**
Sharma and Tripathi	2008	Observational	Seasonal			Yes	
Silva et al.	2015	Observational	Distance				Yes
Van Heerden et al.	2007	Observational	Distance		Yes		Yes
Wijayratne et al.	2009	Experimental		Yes	Yes		
Younis et al.	2013	Observational				Yes	
Younis et al.	2015	Observational					
Younis et al.	2013	Observational					
Zia-Khan et al.	2014	Experimental	Application Rate				