MUNICIPAL WATER USE AND DUST IMPACTS ON SOYBEANS

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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

As human extraction of earth's natural resources continue to impact the surrounding environment, such effects are compounding and may affect the quantity and quality of other natural resources. Natural resources in oil-developed regions that may be feeling these effects are water quantity and agricultural food production. Therefore, two different studies were conducted to determine if municipal water use was altered from oil and gas development and if soybean production fields were impacted due to increased dust accumulation. Municipal water use increased from 2014 to 2015 in Bismarck, North Dakota and may be attributable to increased population and increased air temperatures and a departure from normal total annual rainfall. Dust impacts on soybean leaf temperature and yield were found to be not significant ($p > 0.05$), but chlorophyll content was significantly different ($p < 0.05$) for a couple dust treatments that may have been due to observed chlorosis in the field.

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Amy Frances Gnoinsky

PREFACE

This thesis contains two very different chapters. This is due to the fact that two different grants paid for the projects and my stipend. The first was a grant from the North Dakota State Water Commission and the United States Geological Survey for a pilot study to understand municipal water quantity use in North Dakota. The grant for the second project was from the North Dakota Soybean Council and assessed the impact of road dust on soybean physiology and production.

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CHAPTER 1. MUNICIPAL WATER USE

Abstract

Allocation of water supplies for human use is a priority, but many municipalities are unable to predict water use shifts in times of population and economic growth due to a lack of methodology and a known baseline of water use for municipal water users. Therefore, the pilot study with the United States Geological Survey (USGS) and the North Dakota State Water Commission was conducted to determine the availability of municipal water-use data and to define municipal water-use categories based on the water user that could be applied to municipalities of various sizes statewide. Multiple municipalities were contacted, however, Bismarck, North Dakota promptly provided municipal water-use data for 2014 and 2015, presented in hundred cubic feet (HCF). An assessment of Bismarck, North Dakota's available municipal water-use data created 72 municipal water-use categories. The two main categories of water use are residential and commercial, with six sub-categories in residential, and 66 sub-categories in commercial. Total annual water use was determined for residential and commercial categories along with each of the sub-categories. Water-use ranges, and average annual water use were also determined for each sub-category. Total annual water use for Bismarck increased from 2014 to 2015 by 406,808 HCF. The increase in water use corresponded to increased water use in residential water use by 281,024 HCF and in commercial by 125,784 HCF. Major sub-categorical water users in each main category were single-family homes in residential and hotel with pool, office building, and lawn meter in commercial. The overall increase in water use for Bismarck may be attributed to an increase in population, an increase in average monthly air temperatures from 2014 to 2015, and a decrease from normal total rainfall in both years.

Introduction

The ‘Bakken oil boom’, 2005-2015, brought with it a shift and increase in water use that is mostly concentrated in the western half of North Dakota. However, along with the oil ‘boom’ came population and economic growth. From 2010 to 2015 the population of North Dakota increased 12.5% (USCB 2016) and between 2013 and 2014 the state’s gross domestic product (GDP) increased by 6.3%, which was the largest increase in that time frame for all 50 states (USDoC 2015). In terms of population and economic growth due to oil and gas development, it is unknown how such growth impacts municipal water use.

Research on municipal water use shows that water-use data is not always reliable and depends on the source of the data (Averyt et al. 2013), and most research is conducted to improve data systems (Cole and Stewart 2013; Mini et al. 2014), determine trends in water use (House-Peters et al. 2010; Wong et al. 2010), or create future projections (Zhou et al. 2000; Qi and Chang 2011). In North Dakota there has been little effort to collect and assess municipal water quantity-use data, beyond identifying problems in municipalities or general reporting to the North Dakota State Water Commission (NDSWC). In general there is a need to identify water-use categories across municipality sizes and to determine how energy development has impacted municipal water use in the state. This information will be useful in predicting future use needs for all water-use categories in the state; as well as, providing information to water managers on appropriate ways to manage municipal water during times of flood or drought.

The objectives of this project are to: 1) gauge availability of water-use data within a municipality; and 2) generate water-use categories that can be applied to municipalities of various sizes statewide. Once developed this water-use profile methodology will be used to inform water management and be applied to a larger study looking at the impact of oil development on municipal water use statewide.

Literature Review

Water Quantity Assessment

Obtaining water-use data can be done through primary or secondary efforts (USGS 2000). Primary gathering of data is done through the use of direct or indirect methods. Direct methods include reading cumulative water meters and are usually done by public water suppliers, while indirect methods include the use of a certain type of flow meter that is used in conjunction with a measurement of time to calculate water usage. Secondary actions of data collection are done through the use of surveys or reports issued to water users who supply water usage information through primary data collection efforts (USGS 2000).

In collection of water-use data pertinent to water-use groups the more common methods are water use reports and estimation techniques or a combination of both (Morales et al. 2009, Averyt et al. 2013, Mini et al. 2014). Averyt et al. (2013) compared water-use data gathered on thermoelectric water users with the use of both reported and estimated techniques and examined the differences. Significant differences among the reported and calculated water withdrawal data of thermoelectric users were observed on a regional level and were associated with unreported or misreported data, and imperfections in the coefficients and the application of coefficients. Calculations made in Averyt et al. (2013) were done by using national level water-use coefficients that based water usage amounts on per unit of generated electricity and are specific to the technologies and cooling systems used in generating the electricity. Shiklomanov (2000) also used coefficients and estimated domestic water use through a coefficient developed by population dynamics data and per capita water withdrawal. In addition to coefficients used to estimate water use, models can be employed to collect water-use information. For instance, Maidment and Parzen (1984) used transfer function models to illustrate daily urban water use based on air temperature and rainfall.

Analysis of water quantity data can be done on a number of levels from micro, a use level which includes a household or an agricultural field; to mezzo, a service level; and finally a macro level including multiple water uses and service systems within a basin or sub-basin (Molden and Sakthivadivel 1999). Dependent on the level of analysis, managing water-use data to include helpful information to aid in the analysis include identification numbers such as those associated with the North American Industry Classification System (NAICS). The NAICS is a standard used by federal agencies to classify businesses into groups based on their processes of producing products (USCB 2014). A few NAICS groups include utilities, retail trade, and manufacturing. The United States Geological Survey (USGS) utilizes the NAICS codes for these groups to see how water is used and in using these groups can help to desensitize water-use data among water users (USGS 2000).

Geographic information such as longitude and latitude can also be useful if geospatial software is employed, while the rate or volume of water used, and where that water comes from are other important factors in water withdrawal assessments (USGS 2000). Federal agencies such as the USGS use a Hydrologic Unit Code (HUC) to identify a hydrologic unit that depicts a geographic area, hydrologic units separate geographic areas into four levels: regions; sub-regions; accounting units; and cataloging units (Seaber 1987). The HUC identifies at which spatial level the assessment is taking place and what water resource is impacted. Focusing water-use data collection efforts on a municipality scale or mezzo level, Mini et al. (2014) gathered household residential water-use information from the Los Angeles Department of Water and

Power (LADWP), and used it to analyze water billing data methods and a remote-sensing model for quantifying outdoor water use in the residential areas of Los Angeles. To protect customer privacy they aggregated the customer billing data to the census tract level with data they obtained from the United States Census Bureau. Census tracts are small geographical areas that divide counties based on population densities. Boundaries of census tracts fall in line with boundaries of townships, counties, and states. Since LADWP provided water to users outside the city boundary of Los Angeles, Mini et al. (2014) dropped individual water-use data that fell outside city limits and was able to use the census tracts within the city boundaries to desensitize customer water-use data.

When assessing current water use in a municipality, characteristics of the water service area must be determined along with the type of demand for the water use. In doing so customer data from a public water supplier can be aggregated into categories that share common water-use characteristics, such classification of water users into groups with similar water-use characteristics include the NAICS (USCB 2014). The NAICS provides a database in which businesses are lumped together under codes that correlate with an industry production process. Although the NAICS provides standard definitions for water-use groups it lacks certain water-use types, such as recycled water, water reuse, navigational, and reclaimed water as it is geared toward economic activity versus water use (USCB 2014). Water-use groups also vary from state to state; for instance, the USGS presents water-use data for eight categories including: thermoelectric power; irrigation; public supply; self-supplied industrial; aquaculture; mining; self-supplied domestic and livestock water-use groups (Hutson 2007; Maupin et al. 2014). On the other hand, the states include the same eight categories with variations including: power generation as a category that houses thermoelectric power and hydroelectric power; and an agriculture category with aquaculture and livestock as subcategories. However, most states include aquaculture under the livestock category. Additional categories that some states incorporate for water uses include navigation, sewage treatment, recreation and preservation, and miscellaneous (Hutson 2007; Maupin et al. 2014).

Current problems in quality assurance and quality control for determining water use include misreported data, unreported data, wrongful use of coefficients, and lack of inclusion of determinant variables (Averyt et al. 2013). Determinant variables are factors of climate or socioeconomics that dictate changes in water use. A few variables that water use is thought to depend on include rainfall, air temperature, income, and education level (House-Peters et al. 2010). Gleick (2003) highlights inaccurate data as a problem along with the fact that water-use data isn’t readily available for all uses as they are unquantifiable or at least not easily quantified.

The systematic collection of water-use data is not common and the data provided in such collections can be outdated. A case in point is USGS’s compilation of water-use information from all states within the United States every five years (Maupin et al. 2014). Water-use collection methods are not standardized among states and can contribute to inaccuracies in comparisons. Some states lack resources for data collection, like man power or funding, and information may be missing or not included or the water-use data is a year behind the rest of the states’ water-use data. Overall improvements are needed in data collection efforts and further studies can aid in such improvement through new technologies like the concept of smart metering that allows meters to capture water-use information automatically, and electronically transmits that information in real-time (Cole and Stewart 2013). Improved access to certain levels of data can improve already existing coefficients and models. New databases that provide access to up to date information on customer classification and heated building area can be used to better improve coefficients in estimating water use for commercial, industrial and institutional categories (Morales et al. 2009).

Trends in Water Quantity

Looking at water use over time is a good reference to see which sectors have increased, decreased, or stabilized their water use and can illustrate patterns of use for current and future water needs. Furthermore, efforts can be made to determine factors that cause changes in water use. Capturing total water withdrawal among water-use categories over a set time period can illustrate the direct causes of water withdrawal changes. Such is the case with Konieczki (2004) who discovered a trend in total water withdrawal data from 1950 to 2000 that illustrated a proportional increase in withdrawal for domestic use compared to agricultural use.

House-Peters et al. (2010) used statistical analysis to determine significant factors that influenced single family residential water use and found that base use (indoor water use) is dependent on household size, while seasonal use was indicated by the percent of adults with a college degree as well as the size of the outdoor space. Another study by Wentz and Gober (2007) corroborates these findings, but further evaluated household residential water use by number of people, lot size, presence of pools, and vegetation type. In addition they discovered people in adjacent neighborhoods display similar water-use behavior. Wong et al. (2010) also looked at indoor use and seasonal water use at a municipal level in Hong Kong. Their study incorporated calendrical use as well, which looks at the day-of-the-week effect, holiday effect, and how they influence urban daily water use. Using six statistically driven models, the researchers were able to develop a single model that explained how these three aspects of calendrical use affect urban water use. It was found that urban water use was higher during the weekdays than during weekends and decreased during the holidays starting two days before a holiday and until one day after. Another study by Portnov and Meir (2008) compared domestic water use and municipal water use in Israel. They revealed that areas within the residential domain that have low rates of water use and high rates of water use have a tendency to converge over time. The cause of the low rates of water use to catch up to high rates of water use are due to improvements in infrastructure for areas that exhibit low rates of water use. Conversely, in the municipal sector of water use, the tendency between low consumption rates and high consumption rates diverge. The divergence in municipal water rates are due to municipalities that were once agricultural communities and still offer a water supply to agricultural providers, this can lead to excessive consumption of water since municipalities receive water at a discounted price and in turn promotes wasteful water-use practices. The savings from discounted water use can also afford the option to wealthy municipalities to invest in further expansion and maintenance on parks and green space to appeal to newcomers, adding to the increase in water-use rates due to irrigation. Poor municipalities are unable to compete with aesthetic advances due to locations near unsuitable environments, so water-use rates remain the same (Portnov and Meir 2008).

The evolution of water use over time can further provide information on the impact of climate change, such as drought impacts on water rates and the context in which conservation efforts are successful. In Santa Barbara California during the drought years 1986-1992 municipal water use and water rates were a combination of water rate manipulation and water conservation measures and significantly reduced water use, along with increasing environmental awareness in consumer behavior (Loaiciga and Renehan 1997). However, in Athens Greece, through the use of a Stone-Geary utility function water rate manipulation was unsuccessful in altering water use due to increases in consumer income (Kostas and Chrysostomos 2006). This study established that a water savings plan should be based on quantitative restrictions as opposed to qualitative restrictions driven by consumer viewpoints on water use. This would mean restricting the amount of water residents can use and for what, and they propose doing it voluntarily through increased environmental awareness (Kostas and Chrysostomos 2006). Furthermore, in an area where water availability is low due to an over-use situation (ex. irrigated agricultural lands) researchers in the Phoenix Arizona area, hypothesized water availability would increase due to the urbanization of agricultural lands and overall water consumption would decrease since urban land needs half the amount of water per unit area (Wehmeier 1980), however, this was not the case. The failure to reduce consumption was pinpointed to water law, water-use policy, the type of urban development, and the attitudes of people who failed to view water as a limited resource (Wehmeier 1980).

The scope of water-use trends can also be conducted on a national scale and can be evaluated by a structural decomposition analysis. An analysis by Wang et al. (2014) was done this way on the United States industrial sector by comparing water withdrawal data to economic data from 1997 to 2002. The factors that contributed to an increase in water use for numerous industrial sectors were population growth, gross domestic product (GDP) per capita (total production of goods and services within a country divided by population), and water-use intensity; while changes in production structure, and consumption patterns decreased water use. The study found consumption patterns to be the largest net contributor in changing water withdrawals (Wang et al. 2014).

In general, the most common method used in analyzing trends in water use is time series regression. A time series regression evaluation of water use compares total water withdrawals with related water-use data such as population to determine per capita use over a specified time period (Mini et al. 2014). Mini et al. (2014) used a time series regression method and conducted a Seasonal Mann-Kendall trend test to gauge a relationship between outdoor water use and evapotranspiration on the landscape. In the study it turned out that over half of household water use was used to irrigate landscapes.

Future Projections

Forecasting water use aids in planning efforts for water supply and security. Forecasting can be done for different periods of time via short-term or long-term data depending on what the intended outcomes are for the projection. Short-term approaches forecast daily and monthly water use, while long-term forecasts in years. Approaches to forecasting water use can be categorized into six categories including: regression analysis; time series analysis; computational intelligence approach; hybrid approach; Monte Carlo simulation; and the system dynamics approach (Qi and Chang 2011). Traditional methods consist of regression analysis and the time series analysis while the following approaches are more advanced modeling techniques.

Regression models have been in use the longest for water-use prediction and are based on a statistical estimated relationship between water demand and the independent variables it depends upon (ex. socioeconomic factors) (Qi and Chang 2011). Maidment and Miaou (1986) developed a regression model using daily water-use data from nine cities from various states to forecast the fluctuations in water usage to precipitation and air temperature variables. Time series analysis is based on a mathematical extraction of numerous trends that naturally alter water use over time (Yevjevich and Harmancioglu 1985). Zhou et al. (2000) used a time series analysis when they forecasted daily water use in Melbourne, Australia for the short term and long term by splitting daily water use into base use and seasonal use.

Computational intelligence models such as artificial neural networks (ANN), fuzzy-logic, and agent based models are geared towards simulating complex systems (Engelbrecht 2007). Cutore et al. (2008) used the Shuffled Complex Evolution Metropolis algorithm (SCEM-UA) to calibrate an ANN model as the model is driven by historical data. Therefore, past data is used to train a learning algorithm to which the ANN model output values are compared. From this model error can be refined by the model (Cutore et al. 2008). Examples of fuzzy-logic models and agent-based models are also illustrated in Altunkaynak et al. (2005) and Yuan et al. (2014). Altunkaynak et al. (2005) used a Takagi Sugeno fuzzy method to forecast monthly water use in Istanbul City in Turkey while Yuan et al. (2014) used a household water demand prediction (HWDP) model to predict urban household water usage in the year 2020.

Hybrid approaches are an extension of computational intelligence models. The hybrid approach is self-explanatory in the fact that it integrates a number of models to gain combined advantages. Examples of models that use this approach are pattern recognition (Shvartser et al. 1993), neural-fuzzy modeling system (Yurdusev et al. 2009), and the M5 modeling tree (Solomatine and Xue 2004). Monte Carlo simulations assign fluctuations in water demand on a per capita basis and simulates the resulting system changes into a structure and further pinpoints uncertainties in the forecasting (Khatri and Vairavamoorthy 2009). Lastly, system dynamic models aid in portraying system behaviors including feedback loops that aid in precise forecasts. Qi and Chang (2011) created a system dynamic model based on the assumption that average annual income is increasing in a linear trend over the years 2003-2009 in Manatee County, Florida, and that this tendency can be assumed to persist in the future. Using such assumptions domestic water use in the context of the current macroeconomic environment can be forecasted.

Methods

Working with the USGS and NDSWC multiple North Dakota municipalities were contacted via email and phone calls to gauge availability of water-use data and gain permission to access municipal water-use billings. Bismarck, North Dakota was the first to grant permission and encourage collaboration with North Dakota State University (NDSU). Therefore, the pilot project is focused on approximately 20,000 customer water-use billings supplied by Bismarck Public Works for the timeframe of 2014-2015.

Monthly customer billing records with water-use information were correlated into specific water-use categories. Correlation of two years of water-use information into water-use categories was done using Microsoft Excel. Breakdown of water-use categories with water-use data was done to determine accuracy and usefulness of categories in determining a water-use profile for the city. For the purposes of this study water-use categories were disaggregated to the lowest level possible, from this level results can be re-aggregated into categories to coincide with North Dakota Century Code and NAICS categories for further analysis.

Analysis of the water-use data includes: trend analysis of seasonal use; estimates of individual category users and the average amount of water used (hundred cubic feet annually or gallons/time period; ex. one carwash bay uses approximately 100 gallons of water per day); and major water users in individual categories. It is assumed that results of this study would be an indication of typical categories for a municipality the size of Bismarck; however, comparisons of other cities of the same size should be conducted to determine typical categories.

Results and Discussion

Annual water usage for Bismarck, North Dakota is presented in hundred cubic feet (HCF), one hundred cubic feet equals 748 gallons. In 2014, the entire City of Bismarck used

3,731,182 HCF of water, and in 2015 the amount increased to 4,137,990 HCF as observed in Table 1.1. This increase is a function of both commercial and residential water use growth. However, residential increased water use from 2014 to 2015 by 281,024 HCF; while commercial increased by 125,784 HCF. This information indicates that during 2014 and 2015 at home water use had more of an impact on public water supplies than commercial use. The increase in water use is attributed to general growth in the City of Bismarck during those years. The United States Census Bureau reports population estimates for the entire state of North Dakota in July 2014 at 739,482 and 756,927 in July 2015 (USCB 2016). Much of this growth took place in the western part of the state in the Bakken region, with Bismarck being a fringe city of this growth. In 2014, the total number of customers billed in the residential category for Bismarck was 20,402 and this increased to 20,911 in 2015. Similarly in the commercial category the amount increased from 2,080 in 2014 to 2,189 in 2015. This means there were 618 new customer billings in the City of Bismarck in 2015.

Table 1.1

Total water usage for the year for the City of Bismarck, North Dakota, 2014 and 2015 in hundred cubic feet (HCF).

Category	**Total Water Use-2014**	**Total Water Use-2015**	**Difference**
Residential	2,566,853	2,847,877	+281,024
Commercial	1,164,329	1,290,113	+125,784
Total	**3,731,182**	**4,137,990**	**+406,808**

Residential

Residential water use was disaggregated into sub-categories including single-family home, duplex, condo, apartment, trailer park, and assisted living. The total water usage for the year for each sub-category in 2014 and 2015 are listed in Table 1.2. The highest water user of sub-categories was single-family homes with assisted living as the lowest. The data illustrates the high number of single family homes in the Bismarck area compared to the lower number of assisted living facilities. The total number of single-family home accounts was 18,554 in 2014 and 19,039 in 2015. The total number of assisted living facilities in 2014 was 12 while in 2015 it was 11. The number of total units for assisted living facilities was 611 in 2014 and 599 in 2015. The large differences in water usage between single-family and assisted living facilities is explained by each categories' number of residential units.

Table 1.2

Annual residential water use sub-categories for 2014 and 2015 and the difference between years in hundred cubic feet (HCF).

Residential Sub-Category	Total Water Use-2014	Total Water Use-2015	Difference
Single-family	1,721,159	1,949,294	+228,135
Duplex	94,865	98,586	+3,721
Condo	164,088	172,867	+8,779
Apartment	319,851	352,391	+32,540
Trailer Park	240,390	245,135	+4,745
Assisted Living	26,500	29,604	+3,104

Annual water use ranges of each residential sub-category are provided in Table 1.3. The highest water use per meter belonged to a trailer park, this is not surprising as one meter in a trailer park supplies a higher number of units than any other residential sub-category. Minimum water use numbers were similar in both years except for an increase of 9 HCF in minimum water used by a single meter in the assisted living category. Single-family, duplex, and condo categories have a minimum of 0 HCF of water use for a single meter and are either due to water usage under the required 1 HCF of water used for charged services or denote the installation of a new meter. The change in maximum water used within a category across the two years are larger than the changes found in minimum water use. The biggest changes occurred in single-family with a drop in maximum water use of 9,998 HCF and in trailer park with an increase of 9,210 HCF, both in 2015.

Table 1.3

Annual water-use ranges for residential water use sub-categories on a per meter basis within 2014 and 2015 in hundred cubic feet (HCF).

Residential Sub-Category	**2014 Water-Use Range** Minimum	Maximum	**2015 Water-Use Range** Minimum	Maximum
Single Family	0	19,998	0	10,000
Duplex	0	1,462	0	1,456
Condo	0	1,292	0	3,319
Apartments	5	4,892	1	7,252
Trailer Park	707	44,458	696	53,668
Assisted Living	4	7,387	15	8,338

Note. A minimum of 0 HCF can either denote a new meter or water usage under the required 1 HCF of water used for charged services.

Average water use per residential sub-category is listed in Table 1.4. Averages were obtained by dividing total water use in a sub-category by number of accounts. A few of the accounts have more than one meter and show up as two accounts with the same name; however, it was difficult to distinguish between accounts with the same name as one entity with two meters for the same building or for two separate buildings. Less than one percent of residential accounts fell into this category while about five percent of commercial accounts fell into it. Looking across both years all sub-categories increased water use between 2014 and 2015. The highest annual water usage per water meter/account were trailer parks with an average of 12,020 HCF in 2014 to 14,420 HCF in 2015 per trailer park as illustrated in Table 1.4. The range of trailers or units in a trailer park vary from 12 to 458. As a single trailer park distributes water from a single meter, large amounts of water use from larger trailer parks may skew the average water use per trailer park. In this case, looking at average water use per trailer per park may be more beneficial. Furthermore, Table 1.4 illustrates average water use by sub-category while a follow up of average water use per residential unit (i.e. per trailer, per household, per assisted living patient room, per apartment unit) is illustrated in Table 1.5.

The second highest residential water use sub-category was assisted living facilities (Table 1.4). Water use in this category was higher, again due to the number of units each water meter/assisted living facility serves. For example, an assisted living facility has around 53 units. Apartments in Bismarck have about on average 23 units and therefore, have lower water use volumes. As increases occur in units the amount of water used per meter or per account increases. Overall, the trend in average water use is increasing across all residential sub-categories.

Table 1.4

Average of residential categorical water use per account per year in hundred cubic feet (HCF).

Residential Sub-Category	**Average Water Use-2014**	**# of Accounts**	**Average Water Use-2015**	**# of Accounts**
Single-family	93	18,554	102	19,039
Duplex	105	904	107	919
Condo	260	631	277	625
Apartment	1,138	281	1,175	300
Trailer Park	12,020	20	14,420	17
Assisted Living	2,208	12	2,691	11
Total	**-**	**20,402**	**-**	**20,911**

Note. The number of units within a residential sub-category account vary from 1 to 458. One trailer park has one water meter and supplies water to a range of 12 to 458 trailers or residential units.

Table 1.5

Average annual residential water use per residential unit in hundred cubic feet (HCF).

Residential Sub-Category	2014 Average Water Use	# of Residential Units	2015 Average Water Use	# of Residential Units
Single-Family	93	18,554	102	19,039
Duplex	53	1,808	54	1,838
Condo	52	3,169	55	3,147
Apartment	52	6,162	51	6,923
Trailer Park	87	2,784	91	2,687
Assisted Living	43	611	49	599

Note. Total annual water use for a sub-category was divided by the total number of residential units within sub-category.

Average water use per residential unit (i.e. apartment unit, trailer, single unit in assisted living) for each residential sub-category are listed in Table 1.5. Average water use per unit was determined by taking the total annual water use per sub-category in Table 1.2 and dividing by the total number of units in each sub-category. For example in a duplex the total annual water use was 94,865 HCF in 2014 (Table 1.2), this number was then divided by 1,808 as there are a total of 1,808 residential units in the duplex sub-category; therefore, per unit water use for a duplex was 53 HCF in 2014 as illustrated in Table 1.5.

There was an increase in average water use per unit in every sub-category except apartment. However, looking at Table 1.2 there is still an increase of 32,540 HCF between 2014 and 2015 water use in apartments. This demonstrates that as the number of apartments increases, the per unit average of water use decreases which could be due to empty apartments not using water or potentially other factors such as installation of water-conserving appliances and delivery systems. In general the largest sub-category water user per unit in both 2014 and 2015 was single family homes and the second largest was trailer homes. Interestingly the average size single-family home in 2015 was 2,745 ft^2 while the average size trailer home was 1,430 ft^2 (MHI 2016). This would indicate that while homes may be larger or smaller they are still utilizing close to the same amount of water for inside use (washing dishes and clothing, showering, etc.) and outdoor use (watering lawns and gardens, pools, etc.). The average water use amongst the other sub-categories of duplex, condo, apartment, and assisted living are similar in amount and less than the single family home and trailer home. This could potentially indicate one of two things: 1) there are less people on average living in each of these sub-categories using water for indoor use; or 2) there is water savings on not having as many outdoor water-use functions. This study did not look into additional factors such as home size, number of individuals living in a home, and water-use habits; therefore, it would be impossible based on current data to pinpoint the changes in water use.

Water use in Bismarck is increasing across all categories and per capita. Comparing the data found in Bismarck to both the United States and other municipal water-use data is useful to gauge where the city is in comparison to other municipal and national averages. The City of Santa Fe, New Mexico (2001) reports that a single-family in Santa Fe uses on average 108 HCF of water per home annually, while Bismarck in 2014 only used 93 HCF. Assisted living facilities in Santa Fe used on average 61 HCF annually, while those in Bismarck used 43 HCF; and multi-family dwellings such as, condominiums and apartments typically use 91 HCF annually while those in Bismarck used 52 HCF (CoSF 2001). Santa Fe, New Mexico on average used more water per category than Bismarck. Santa Fe is in a drier area of the United States and this may account for at least a portion of the higher water use per category.

The USGS identified the national average of public-supplied domestic water use in 2010 as 89 gallons per day per person; while North Dakota’s estimated public-supplied domestic water use was 80 gallons per day per person in 2010 (Maupin et al. 2014). Additionally in 2010, the United States Census Bureau identified that a United States household contains on average 2.58

people (Lofquist et al. 2012). Taking the average annual water use for single-family home in Bismarck (Table 1.5) for 2014 and multiplying it by 748 gallons (per one HCF) equals 69,414 gallons of water used per year for a single-family home. Taking the USGS estimate for the state of North Dakota (80 gallons/person/day), and multiplying it by 2.58 people estimated to be in a single family household and multiplying that by 365 days in a year equals 75,336 gallons per household per year. This estimate is slightly above the average 69,414 gallons observed in Bismarck, and would be well below the averages estimated in the rest of the nation at 89 gallons/person/day in 2010.

Trailer parks and assisted living per unit water use were determined by dividing total annual water use by total number of residential units in that category (Table 1.5). For instance, the total water use of trailer parks for 2014 was 240,390 HCF and there were a total of 2,784 trailers within the category; therefore, the resulting per unit water use is 86 HCF per year per trailer. In 2015 there was a drop in the number of trailer parks; as well as, the number of trailers, but the annual water use still increased by 4,745 HCF. Meaning per trailer on average water use is increasing (Table 1.5). In Santa Clara Valley, California the average annual water use per trailer is 115 HCF with a one water meter system per trailer park (SCVWD 2007). Interestingly enough, when a pilot program implemented sub-meters for each trailer in a park the average annual water use dropped to 90 HCF per trailer, which is a more similar water use to the results of water use found in Bismarck (SCVWD 2007).

Assisted living has the second highest difference in water-use per unit between 2014 and 2015 with an increase of 6 HCF in water use (Table 1.5). This increase also came with a loss of 12 assisted living units from 611 in 2014 to 599 in 2015. The 6 HCF change in the year period would equate to approximately 31 gallons more water used per day across all assisted living units combined. While this is a small number the trend does add up over time. Apartment is the only category with a decrease in per unit water use from 2014 to 2015. This may be attributed to newly available residential units that have yet to be filled as number of units increased by 761 units in 2015. Overall within Bismarck, water use for each sub-category are increasing.

Commercial

The total annual commercial water use was disaggregated into sub-categories and is displayed in Table 1.6. In 2014, commercial facilities used a total of 1,164,329 HCF of water annually and 1,290,113 HCF in 2015, leading to a 125,784 HCF increase between the two years. Total water use between years increased in most commercial sub-categories; however, there were a few sub-categories with decreased total water use from 2014 to 2015 including: auto part/supply; auto repair; bar; beverage maker (Coca-Cola bottling company); butcher; concrete batch; construction supplies; entertainment; fast food; funeral home; manufacturer; nursing home; public pool; spa; and veterinarian. The largest decrease was observed with concrete batch plants decreasing 4,201 HCF for the year; while construction supplies had the second biggest decrease at 3,067 HCF (Table 1.6). The largest increase in water use was by lawn meters with an increase in water use of 28,464 HCF from 2014 to 2015.

Annual water-use ranges per commercial sub-category on a per meter basis for each year are presented in Table 1.7. Water-use ranges were determined based on the lowest meter reading and the highest meter reading in each sub-category. The annual water use maximum for lawn meters increased from 2014 by 7,374 HCF in 2015. The two sub-categories behind lawn meters with large increases in maximum water use for a meter were the golf course and the waste water treatment plant categories; with golf courses increasing by 8,528 HCF and waste water treatment plant by 5,493 HCF of water for the highest meter reading. Overall, 43 of the 66 commercial sub-categories had an increase in maximum water use for a single meter, which is representative of the rise in total water usage between the years for the category. Inflation of maximum water-use ranges is likely due to increases in average monthly air temperatures from 2014 to 2015 and a shortage of rainfall from the normal total rainfall of 17.97 inches, with 2014 receiving 14.10 inches and 2015, 15.37 inches (NDAWN 2015; NDAWN 2014).

Decreases in maximum water use readings occurred across the other 23 commercial sub-categories. The largest decrease occurred in the beverage maker sub-category, with a drop in water use of 7,517 HCF for one meter. Subsequent decreases in maximum water use per meter occurred for the concrete batch and nursing home categories. Although the declines for concrete batch and nursing home were not as strong as the beverage maker sub-category, the water use decreased by 1,752 HCF and 1,616 HCF, respectfully.

Average commercial water use per sub-category was calculated by taking total water use in a sub-category and dividing by the number of accounts within the sub-category. Average commercial water use per category per year are listed in Table 1.8. In the case of high and low water users amongst sub-categories, the number of lawn meters only increased by five accounts between the two years while average water use per account increased on average by 380 HCF from 2014 to 2015 (Table 1.8). Lawn meter increases in water use per account could be attributed to the rise of monthly average air temperatures in 2015 from 2014 (NDAWN 2015; NDAWN 2014). As for concrete batch plants and construction supply the number of businesses did not decrease, there was only a decrease in average water use per account.

Sub-categories with a decrease in total annual water use from 2014 to 2015 were also decreasing their average water use per account. The exceptions include bars which lost one account, but kept increasing average water use per bar; as well as fast food which lost several accounts, but water usage continued to increase per account on average.

Table 1.6

Total annual commercial water use per sub-category in hundred cubic feet (HCF) in 2014 and 2015 as well as the difference in water use between the two years.

Commercial Sub-Category	**Total Water Use-2014**	**Total Water Use-2015**	**Difference**
Airport	2,118	2,865	+747
Auto Part/Supply	511	497	-14
Auto Repair	4,663	4,335	-328
Bank	10,924	11,513	+589
Bar	5,816	5,462	-354
Bev Maker	41,948	39,092	-2,856
Big Box Store	12,666	13,380	+714
Body Shop	1,126	1,283	+157
Butcher	453	424	-29
Car Dealer	5,742	7,414	+1,672
Car Wash	39,346	49,302	+9,956
Cemetery	2,536	5,091	+2,555
Church	5,267	7,059	+1,792
Clinics	23,187	26,306	+3,119
College	40,489	48,464	+7,975
Concrete Batch	12,020	7,819	-4,201
Construction Supply	10,676	7,609	-3,067
Contractors	8,436	9,817	+1,381
Dentist/Optical	2,860	3,306	+446
Entertainment	17,466	16,126	-1,340
Fast Food	26,067	24,317	-1,750
Fire Station	1,501	1,895	+394
Food Processing	15,997	16,072	+75
Funeral Home	1,382	1,232	-150
Gas Station	11,331	13,735	+2,404
Golf Course	23,141	31,669	+8,528
Government Offices	26,377	29,887	+3,510
Grocery Store	7,285	9,268	+1,983
Gym	1,790	1,843	+53
Hair Salon	1,080	1,096	+16

Table 1.6. *Total annual commercial water use per sub-category in hundred cubic feet (HCF) in 2014 and 2015 as well as the difference in water use between the two years (continued).*

Commercial Sub-Category	**Total Water Use-2014**	**Total Water Use-2015**	**Difference**
Hospital	46,306	52,663	+6,357
Hotel	19,620	22,423	+2,803
Hotel/Pool	122,148	121,232	-916
Jail/Prison	48,570	55,626	+7,056
Kennels	520	593	+73
Landscapers	1,595	1,553	-42
Large Mall	16,891	17,981	+1,090
Laundromat/Laundry Service	53,288	59,248	+5,960
Lawn Meter	48,830	77,294	+28,464
Machine Shop	975	1,123	+148
Manufacturer	23,831	22,591	-1,240
Military	7,463	10,503	+3,040
Nursing Home	46,852	46,709	-143
Office Building	84,509	88,486	+3,977
Parking Lot	766	1,017	+251
Parks	20,490	28,018	+7,528
Public Pool	3,655	2,757	-898
Restaurant	23,625	24,629	+1,004
Restaurant/Bar	48,069	48,966	+897
Retail	28,470	28,843	+373
Public Schools	29,793	35,591	+5,798
Private Schools	7,183	9,120	+1,937
Service	30,105	31,858	+1,753
Shop Condo	2,788	3,386	+598
Small Mall	1,292	1,308	+16
Spa	1,391	1,194	-197
Sport Complex	14,014	20,984	+6,970
Storage Units	369	546	+177
Strip Mall	17,289	17,591	+302
Truck Parts/Service	3,405	3,903	+498
Trucking Company	689	1,345	+656
Utility	7,489	8,720	+1,231
Veterinarian	1,110	1,018	-92
Warehouse	8,528	9,924	+1,396
Waste Water Treatment Plant	23,538	29,395	+5,857
Zoo	4,672	3,797	-875

Table 1.7

Annual water-use ranges for commercial sub-categories on a per meter basis within 2014 and 2015 in hundred cubic feet (HCF).

Commercial Sub-Categories	**2014 Water-Use Range**		**2015 Water-Use Range**	
	Minimum	Maximum	Minimum	Maximum
Airport	3	1,443	0	2,136
Auto Part/Supply	2	85	2	95
Auto Repair/Service	0	2,340	0	1,466
Bank	0	2,435	1	2,903
Bar	25	1,316	29	1,351
Bev Maker	112	41,836	0	34,319
Big Box Store	185	3,061	79	3,476
Body Shop	2	459	4	353
Butcher	58	395	55	369
Car Dealer	4	1,501	3	1,642
Car Wash	12	7,470	1	7,585
Cemetery	0	2,530	0	3,158
Church	2	818	20	1,048
Clinics	2	8,546	4	9,879
College	397	19,519	3	21,117
Concrete Batch	116	6,270	54	4,518
Construction Supply	0	2,801	0	2,364
Contractors	0	2,769	0	1,934
Dentist/Optical	11	665	26	675
Entertainment	0	4,325	0	5,095
Fast Food	25	1,526	63	1,911
Fire Station	142	416	116	543
Food Processing	6	5,466	5	6,037
Funeral Home	334	579	325	533
Gas Station	20	3,243	7	3,286
Golf Course	23,141	23,141	31,669	31,669
Government Offices	0	5,350	0	5,921
Grocery Store	348	1,676	0	1,752
Gym	36	848	22	982
Hair Salon	22	490	27	380
Hospital	0	12,965	0	14,241
Hotel	340	3,480	740	3,486
Hotel/Pool	37	16,150	297	15,746
Jail/Prison	12	27,857	86	32,971
Kennels	141	379	202	391
Landscapers	18	1,518	16	1,451

Table 1.7. *Annual water-use ranges for commercial sub-categories on a per meter basis within 2014 and 2015 in hundred cubic feet (HCF) (continued).*

Commercial Sub-Categories	**2014 Water-Use Range**		**2015 Water-Use Range**	
	Minimum	Maximum	Minimum	Maximum
Large Mall	0	3,654	0	4,013
Laundromat/Laundry Service	38	29,104	34	33,475
Lawn Meter	0	9,183	0	16,557
Machine Shop	3	290	3	338
Manufacturer	0	9,069	0	8,607
Military	0	2,119	0	2,377
Nursing Home	1,173	13,803	1,568	12,187
Office Building	0	3,047	0	2,791
Parking Lot	10	621	5	725
Parks	0	6,512	0	8,213
Public Pool	268	2,557	303	1,189
Restaurant	152	3,539	0	3,194
Restaurant/Bar	328	5,322	224	5,535
Retail	0	3,113	0	3,513
Schools-Public	0	4,925	0	5,202
Schools-Private	186	2,102	185	3,228
Service	0	1,495	0	1,463
Shop Condo	0	542	0	435
Small Mall	0	693	0	547
Spa	46	1,049	37	873
Sport Complex	7	5,719	0	6,889
Storage Units	1	120	2	181
Strip Mall	0	3,050	0	3,661
Truck Parts/Service	23	769	0	1,119
Trucking Company	3	425	2	345
Utility	25	3,185	11	4,058
Veterinarian	8	489	2	349
Warehouse	0	2,042	0	2,750
Waste Water Treatment Plant	1	20,774	1	26,267
Zoo	4,672	4,672	3,797	3,797

Note. Ranges are determined based on the lowest meter reading and the highest meter reading in a sub-category. A minimum of 0.0 HCF can either denote a new meter or water usage under the required 1.0 HCF of water used for charged services.

Table 1.8

Average commercial water use per account per year in hundred cubic feet (HCF) in 2014 and 2015.

Commercial Sub-Category	2014 Average Water Use	2015 Average Water Use
Airport	212	238.8
Auto Part/Supply	44	41.4
Auto Repair	173	154.8
Bank	266	274.1
Bar	485	496.6
Beverage Maker	41,948 *	39,092.0 *
Big Box Store	1,407	1,338.0
Body Shop	94	80.2
Butcher	227	212.0
Car Dealer	287	285.2
Car Wash	2,315	2,739.0
Cemetery	634	848.5
Church	188	261.4
Clinics	610	674.5
College	13,496	16,154.7
Concrete Batch	6,010	2,606.3
Construction Supply	134	93.9
Contractors	136	160.9
Dentist/Optical	238	275.5
Entertainment	546	474.3
Fast Food	606	657.2
Fire Station	300	379.0
Food Processing	5,332	5,357.3
Funeral Home	461	410.7
Gas Station	708	763.1
Golf Course	23,141*	31,669.0*
Government Offices	628	729.0
Grocery Store	1,214	1,158.5
Gym	358	368.6
Hair Salon	135	156.6
Hospital	1,781	2,025.5
Hotel	2,180	2,491.4
Hotel/Pool	5,552	5,271.0
Jail/Prison	8,095	11,125.2
Kennels	260	296.5
Landscapers	399	388.3
Large Mall	445	438.6

Table 1.8. *Average commercial water use per account per year in hundred cubic feet (HCF) in 2014 and 2015 (continued).*

Commercial Sub-Category	2014 Average Water Use	2015 Average Water Use
Laundromat/Laundry Service	6,661	7,406.0
Lawn Meter	828	1,208
Machine Shop	89	125
Manufacturer	1,702	1,506
Military	1,866	2,626
Nursing Home	3,124	3,114
Office Building	241	259
Parking Lot	153	203
Parks	820	1,078
Public Pool	1,218	919
Restaurant	1,181	1,173
Restaurant/Bar	1,602	1,689
Retail	156	153
Public Schools	1,295	1,424
Private Schools	1,197	1,520
Service	154	157
Shop Condo	33	27
Small Mall	646	654
Spa	348	299
Sport Complex	934	1,399
Storage Units	37	61
Strip Mall	258	267
Truck Parts/Service	170	186
Trucking Company	98	192
Utility	1,248	1,453
Veterinarian	159	145
Warehouse	152	168
Waste Water Treatment Plant	23,538*	29,395*
Zoo	4,672*	3,797*

* = Same water usage as total as there is only one water user in category.

The State of Indiana defines large commercial water users as significant water withdrawal facilities and classify them as such based on their capability of withdrawing over 134 HCF per day or 48,797 HCF annually (IURC 2013). Based on this definition of large water users, Table 1.9 displays total annual water usage of Bismarck's commercial water users with large water withdrawals of 48,797 HCF or more for either 2014 or 2015, or for both years. There are a total of nine large water users within Bismarck and through water use, illustrate their intrinsic value to commercial business within a city of this size. The largest water user of commercial sub-categories are hotels with pools. On average, a hotel with a pool utilizes 5,412 HCF annually in the City of Bismarck (average of 2014 and 2015, Table 1.8). However, other sub-categories have higher annual water usage per facility, but lack the sheer number of facilities (23 in 2015) to compete with hotel/pool total annual water use (121,690 HCF average of 2014 and 2015, Table 1.9) as a sub-category. A few examples are college, jail/prison, and laundromat/laundry service.

Table 1.9

Total annual commercial water use by large water users Bismarck in hundred cubic feet (HCF) for 2014 and 2015 (listed largest user to smallest).

Commercial Sub-Category	**Total Water Use-2014**	**Total Water Use-2015**	**Difference**
Hotel/Pool	122,148	121,232	-916
Office Building	84,509	88,486	+3,977
Lawn Meter	48,830	77,294	+28,464
Laundromat/Laundry Service	53,288	59,248	+5,960
Jail/Prison	48,570	55,626	+7,056
Hospital	46,306	52,663	+6,357
Car Wash	39,346	49,302	+9,956
Restaurant/bar	48,069	48,966	+897

Note. Large commercial water users are water-use categories that withdraw over 48,797 HCF annually (IURC 2013).

In New Mexico, a hotel with a pool utilizes an average of 24,757 HCF annually, which equates to a total annual water use of 74,270 HCF among the three hotels that are full service (CoSF 2001). According to City of Santa Fe (2001), a full service hotel contains swimming pools, saunas, restaurants, and cocktail bars. For the City of Bismarck, hotels were only assessed on whether or not they had a swimming pool; and therefore, the pools and water features of the hotels in Bismarck were likely smaller than the full service hotels in New Mexico. This is likely why Bismarck's hotel/pool sub-category has a lower average annual water use per facility. Additionally, the City of Bismarck range of total annual water use per hotel with pool was anywhere from 479 HCF to 16,150 HCF in 2014 and 1,618 HCF to 15,746 HCF in 2015; which shows that hotels with larger water facilities use more water and would be closer to the amount used in New Mexico.

The largest difference or change in commercial water use between 2014 and 2015 in Bismarck was lawn meters, with an increase of 28,464 HCF from 2014 ending with a total annual water use of 77,294 HCF in 2015. While lawn meters have the largest change (increase) in water use between 2014 and 2015, they are actually the third largest water user in the City of Bismarck, with a total annual water use of 77,294 HCF in 2015. The second largest water user is office building with a total annual water use of 88,486 HCF in 2015 (Table 1.9). In New Mexico, average annual water use for office building is 19,514 HCF (CoSF 2001). In comparison, the City of Bismarck had an average annual office building water use of 86,498 HCF which is vastly higher than that of New Mexico's office building water use. The difference is likely due to the business functions that occupy the office buildings.

For 2014 the total annual water use for the commercial sub-category car wash was 39,346 HCF and 49,302 HCF in 2015, with an increase of 9,956 HCF within one year. Further disaggregation of total annual water use by facility was done to discern areas of increased water use. The total annual water use by car wash facility and average annual water use per bay a facility held in HCF can be found in Table 1.10.

Table 1.10

Total annual car wash facility water use and average water use per bay in hundred cubic feet (HCF).

ID Number	Number of Car Wash Bays	2014 Total Annual Water Use	2014 Average Annual Water Use/Bay	2015 Total Annual Water Use	2015 Average Annual Water Use/Bay
Car Wash #1	1	736	736	5,494	5,494
Car Wash #2	1	1,268	1,268	1,215	1,215
Car Wash #3	1	254	254	137	137
Car Wash #4	1	7,470	7,470	7,585	7,585
Car Wash #5	5	1,157	231	4,211	842
Car Wash #6	1	7,701	1,446	1,5450	1,348
Car Wash #7	1	1,496	1,496	4,133	4,133
Car Wash #8	3	6,618	2,206	6,225	2,075
Car Wash #9	1	3,600	3,600	3,758	3,758
Car Wash #10	1	2,036	2,036	1,859	1,859
Car Wash #11	1	43	43	54	54
Car Wash #12	1	2,696	2,696	2,848	2,848
Car Wash #13	2	2,011	1,006	2,059	1,030
Car Wash #14	1	3,335	3,335	3,115	3,115
Car Wash #15	1	1,047	1,047	1,246	1,246
Car Wash #16	1	4,813	3,766	1,398	1,245
Car Wash #17	1	17	17	2,419	1,983
Car Wash #18	2	-	-	1	1

Note. Differences in total annual water use and average water use per bay are due to separate water meters and separate buildings for the convenience store and car wash bay.

Overall, the amount of water used per car wash facility and even per bay varies within the City of Bismarck. A few of the car washes were recently built and are just beginning to establish a customer base, among them include Car Wash #17 and Car Wash #18. From 2014 to 2015 two more car wash bays were added to the data set, but added little water use due to timing of development. However, car wash as a sub-category still increased water use; as well as, average water use per bay. In 2014, the total average water used per bay annually was 1,639 HCF, with a total of 24 car wash bays in service. In 2015, the total average water used per bay was 1,896 HCF, as the total annual water use was 49,302 HCF and the number of car wash bays increased to 26. In comparison to residential water use, condominium and apartment water use closely resemble water used per car wash bay annually.

A study done by Brown (2002) for the International Carwash Association examined three types of car washes in three regions of the United States. Gallons of water used per vehicle depended on type of wash for the in-bay car wash and varied between car washes due to owner preference on equipment set up (i.e. nozzle attachments, number of nozzles, etc.). At one car wash in Phoenix, Arizona the gallons per vehicle was 111.5 and during the one week observation period about 178 vehicles were washed (Brown 2002). These numbers were adjusted to annual water use in HCF to compare to Bismarck. To get monthly gallons used per bay, 178 vehicles a week was multiplied by four weeks in a month equaling 712 vehicles. Additionally, multiply by 111.5 gallons per vehicle equals 79,388 gallons a month/bay. Multiplying by 12 months equals 952,656 gallons/car wash bay/year. Divide by 748 gallons equals 1,274 HCF of water used/car wash bay. In comparison to Bismarck, North Dakota with a total average water use of 1,639 HCF per car wash bay in 2014 and 1,896 HCF in 2015 both findings are similar but higher than the water use per car wash bay as found by Brown (2002).

Average annual water use per hotel room for Bismarck, North Dakota in 2014 and 2015 are presented in Table 1.11. Average water use per hotel room was determined by dividing total annual water use for each hotel by the hotel’s number of rooms. Water use in hotels with pools were segregated from hotels without pools. As hotel characteristics such as property size, amenities, and occupancy rates were found to determine the amount of water a hotel would use (Scanlon 2007). In both years (2014 and 2015), the highest average water use per hotel room belonged to hotels without pools. However, the overall average for water use per room for hotels without pools fell below the average of hotels with pools in both years.

In 2014, hotels without pools had an average of 32 HCF of water use per hotel room, while water use per room at hotels with pools used on average 52 HCF. The following year (2015) the trend was similar in that hotels without pools had an average 37 HCF water use per room and hotels with pools had an average of 49 HCF per room. The smaller difference in overall average water use per room between the two hotels in 2015 can be tied to the development of a new hotel with a pool that wasn’t present in 2014, but was still being established in 2015. Although differences in hotel characteristics make it difficult to compare water usage (Scanlon 2007) the numbers give a strong indicator of trends in water use for hotels with and without pools.

In the city of Santa Fe, New Mexico water use trends were similar between hotels without pools and hotels with pools. For instance, hotels without pools used on average 57 HCF of water per room while hotels with pools used 139 HCF of water on average per room (CoSF 2001). Although the evident increase in average water use per hotel room due to climatic differences (Scanlon 2007) between Santa Fe and Bismarck, the trends between both types of hotel are similar and can be related back to hotel characteristics such as property size, occupancy rate, and amenities.

Table 1.11

Annual average water use per hotel room for 2014 and 2015 in hundred cubic feet (HCF).

ID Number	2014 Water use/Room	2015 Water use/Room	Difference
Hotel/Pool #1	35	42	+7
Hotel/Pool #2	70	64	-6
Hotel/Pool #3	63	57	-6
Hotel/Pool #4	44	34	-10
Hotel/Pool #5	69	71	+2
Hotel/Pool #6	42	37	-5
Hotel/Pool #7	65	54	-11
Hotel/Pool #8	48	47	-1
Hotel/Pool #9	85	52	-34
Hotel/Pool #10	45	42	-3
Hotel/Pool #11	5	50	+44
Hotel/Pool #12	48	57	+8
Hotel/Pool #13	43	48	+5
Hotel/Pool #14	63	52	-11
Hotel/Pool #15	29	30	+1
Hotel/Pool #16	61	65	+4
Hotel/Pool #17	31	24	-7
Hotel/Pool #18	55	40	-15
Hotel/Pool #19	43	38	-5
Hotel/Pool #20	52	57	+5
Hotel/Pool #21	18	24	+6
Hotel/Pool #22	46	48	+2
Hotel/Pool #23	75	73	-2
Hotel/Pool #24	*	15	+15
Hotel #1	104	65	-39
Hotel #2	33	35	+2
Hotel #3	54	34	-21
Hotel #4	36	39	+3
Hotel #5	39	80	+42
Hotel #6	20	25	+5
Hotel #7	29	31	+2
Hotel #8	9	34	+25
Hotel #9	26	25	-1

* = Not established in 2014. Note - Hotels with pools were distinguished from hotels without pools.

Annual average water use per patient bed for hospitals and nursing homes in Bismarck are presented in Table 1.12 for 2014 and 2015. Overall, the total annual average water use per hospital bed for both hospitals in 2014 was 85 HCF and 98 HCF in 2015. Between the two years the biggest change in water use was an increase of 17 HCF per hospital bed for Hospital #1, almost twice the amount of increase for Hospital #2 (Table 1.12).

Table 1.12

Annual average water use per bed in hospitals and nursing homes in Bismarck, North Dakota for 2014 and 2015 presented in hundred cubic feet (HCF).

ID Number	2014 Water use/Bed	2015 Water use/Bed	Difference
Hospital #1	64	80	+16
Hospital #2	107	116	+9
Nursing Home #1	65	60	-5
Nursing Home #2	24	31	+7
Nursing Home #3	63	46	-16
Nursing Home #4	56	62	+6
Nursing Home #5	48	49	+1

Both hospitals in Bismarck are considered large hospitals, meaning they have more than 200,000 square feet (ft^2) (USEIA 2012). According to the 2007 Commercial Buildings Energy Consumption Survey (CBECS), hospitals that have a building floor space of 200,001 to 500,000 ft^2 consume on average 158 HCF of water per bed (CBECS 2007). In the case of Bismarck's hospitals, both fall below this average with Hospital #1 using 64 HCF per bed in 2014 and 80 HCF in 2015 and Hospital #2 using 107 HCF and 116 HCF per bed in 2014 and 2015, respectively. Even though Hospital #1 has a floor space of 494,265 ft^2 and Hospital #2 has a square footage of 575,000 ft^2. For Hospital #2, the typical average water use per bed for hospitals with a building floor space of 500,001 to 1,000,000 ft^2 was 199 HCF (CBECS 2007). Overall, hospitals located in the Midwest were found to average 204 HCF of water use per bed (CBECS 2007), in which both hospitals in Bismarck fall short of this regional average.

The overall annual average of water use per bed for nursing homes in Bismarck was 51 HCF in 2014 and decreased to 50 HCF per bed in 2015 (Table 1.12). The greatest change in water use between the two years was for Nursing Home #3 with a decrease in water use per bed of 16 HCF, double the change of any other nursing home in Bismarck. The highest water use per bed for a nursing home varied between the years but the nursing home with the lowest water use per bed stayed the same. Nursing Home #2 had the lowest water use, even though they had the second highest number of beds (140).

A benchmark for efficient water use in nursing homes was established for the City of Boulder, Colorado at 49 HCF of water use per bed (CoB 2007). The benchmark was established by the Brendle Group, who conducted a water use benchmark study for the City of Boulder Colorado for high water users in the commercial, industrial, and institutional water-use categories. The benchmark was calculated based on indoor water use of nursing homes during the winter months (December to April) and was extrapolated to twelve months of water use. For 2014, only two out of the five (40%) nursing homes in Bismarck fell below the Colorado benchmark of 49 HCF, with 24 HCF and 48 HCF of water use per bed. In 2015, three out of the five (60%) nursing homes met or fell below the benchmark with 31 HCF, 46 HCF, and 49 HCF of water use per bed. The total annual average water use per bed for nursing homes in Bismarck were 51 HCF in 2014 and 50 HCF in 2015, both of which fall above the Colorado benchmark. Although Bismarck’s total annual average of water use per bed for nursing homes fell above or close to the benchmark set for the state of Colorado, the water-use data provided in Table 12 may also include outdoor water use depending on the nursing home; whereas, the benchmark only considers indoor water use. Utilization of such benchmarks would further aid assessments of performance in water use conservation practices within the state of North Dakota and provide information on areas of improvement.

Seasonal/Monthly Water Use

Seasonal water use within the City of Bismarck, along with seasonal water use for residential and commercial categories are displayed in Figure 1.1. Seasonal water use for the City of Bismarck contains both residential and commercial water use; as a summation of averaged water used per category for 2014 and 2015. For each main category of water use (i.e. residential and commercial), seasonal water usage for winter is comprised of December, January, and February water use; spring of March, April, and May; summer of June, July, and August; and fall of September, October and November. Proportions of water used in the different seasons are relatively similar across residential and commercial categories and are represented in the seasonal use for the City of Bismarck. To further disseminate seasonal water use, monthly water usage for residential and commercial use were determined for 2014 and 2015.

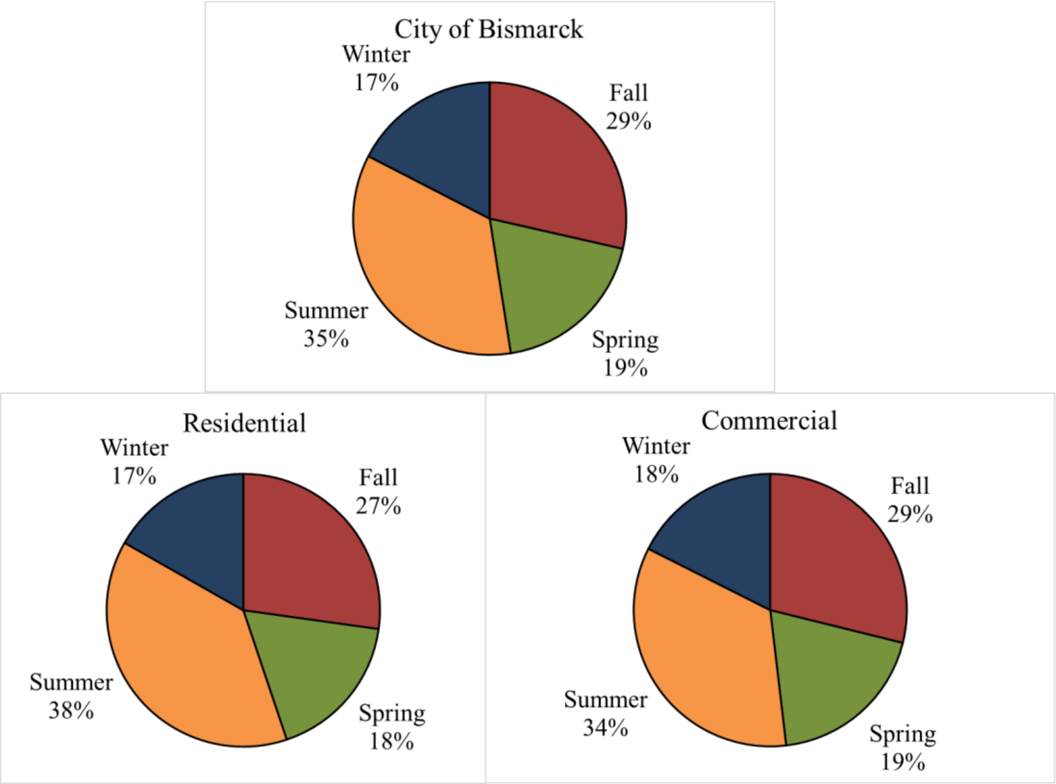

Figure 1.1. Percent seasonal water use for the City of Bismarck and for residential and commercial water use categories.

Monthly residential water use for Bismarck is listed in Table 1.13 and illustrated in Figure 1.2. Total water use per account was added up for the month and divided by number of accounts present in that month. Average monthly water usage within the residential category shows increased water use per account in late spring to late summer. Water use then starts to decrease after August and into November and December and then stays low until late spring.

Table 1.13

Average monthly residential water use in hundred cubic feet (HCF) for 2014 and 2015.

Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
2014	9	8	8	8	9	16	18	23	15	13	9	8
2015	9	8	7	9	12	13	17	25	23	13	8	8

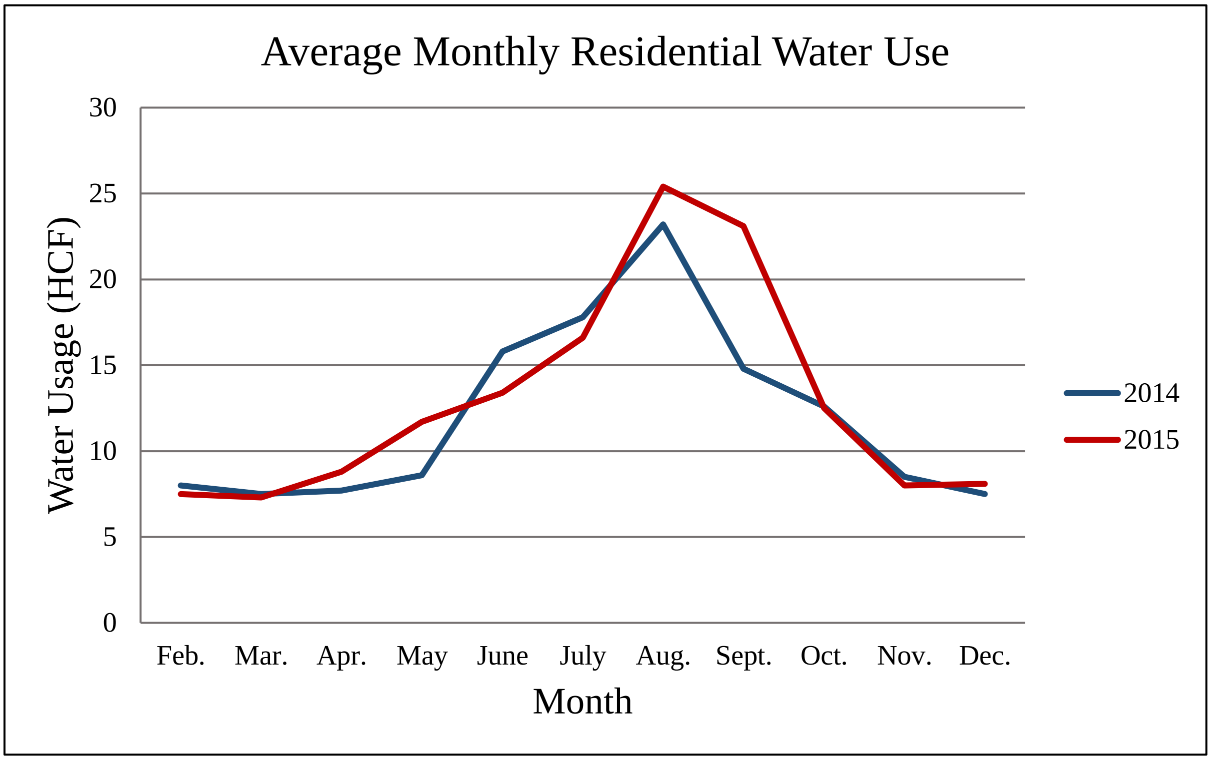

Figure 1.2. Average monthly residential water use in hundred cubic feet (HCF).

A study done by Cole and Stewart (2013) discovered temperature and rainfall are the most influential factors causing fluctuations in residential water use and such influences are heightened when both factors reinforce one another. For instance, when temperatures are high and rainfall is low outdoor water use will increase or when temperatures are low and rainfall is high it is expected that outdoor water use will decrease (Cole and Stewart 2013). Therefore, it is expected that water use would be higher during the summer months as this is when residents' use water to irrigate landscape, use water through outdoor hose bibs, fill or backwash swimming pools, and wash cars and pavement (DeOreo et al. 2016). Mini et al. (2014) found on average, landscape irrigation makes up 54% of total annual single-family water use in Los Angeles, California. But this number varies depending on annual weather patterns and climate. As areas with arid climates have an outdoor water use percentage of 59-67%, while areas with cool/rainy climates have 22-38% outdoor water use (Mayer et al. 1999). The data from the City of Bismarck, when averaged for 2014 and 2015, shows that 67% of residential water used in the city is used between May-October, and the remaining 33% is used between November-April.

Within the residential category outdoor and indoor water use depends on factors such as owner occupied dwellings, income, household swimming pools, number of residents, family structure (single-family, multi-family, etc.), household location, lot size, and age of water using devices (ARCWIS 2002, Mayer et al. 1999). However, it was found that location of household, lot size, rain water tank ownership, household income, and household makeup (number of residents and family structure) were the most influential (Willis et al. 2013). Indoor water use is also affected by seasonal changes, more specifically shower water use. During winter months, shower times are typically longer, while in the summer months showers occur more frequently (Rathnayaka et al. 2015).

Monthly commercial water use is listed in Table 1.14 and is displayed in Figure 1.3. Monthly commercial water use was calculated through summing total monthly water use per account and dividing by the number of accounts, similar to the monthly residential water usage above. Also, similarly to residential water use, commercial water use increases in early spring but drops off after August and September and steadily decreases into December.

Table 1.14

Average monthly commercial water use in hundred cubic feet (HCF) for 2014 and 2015.

Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
2014	37	38	39	38	43	56	78	87	66	64	42	33
2015	41	37	36	40	53	57	68	96	90	67	42	39

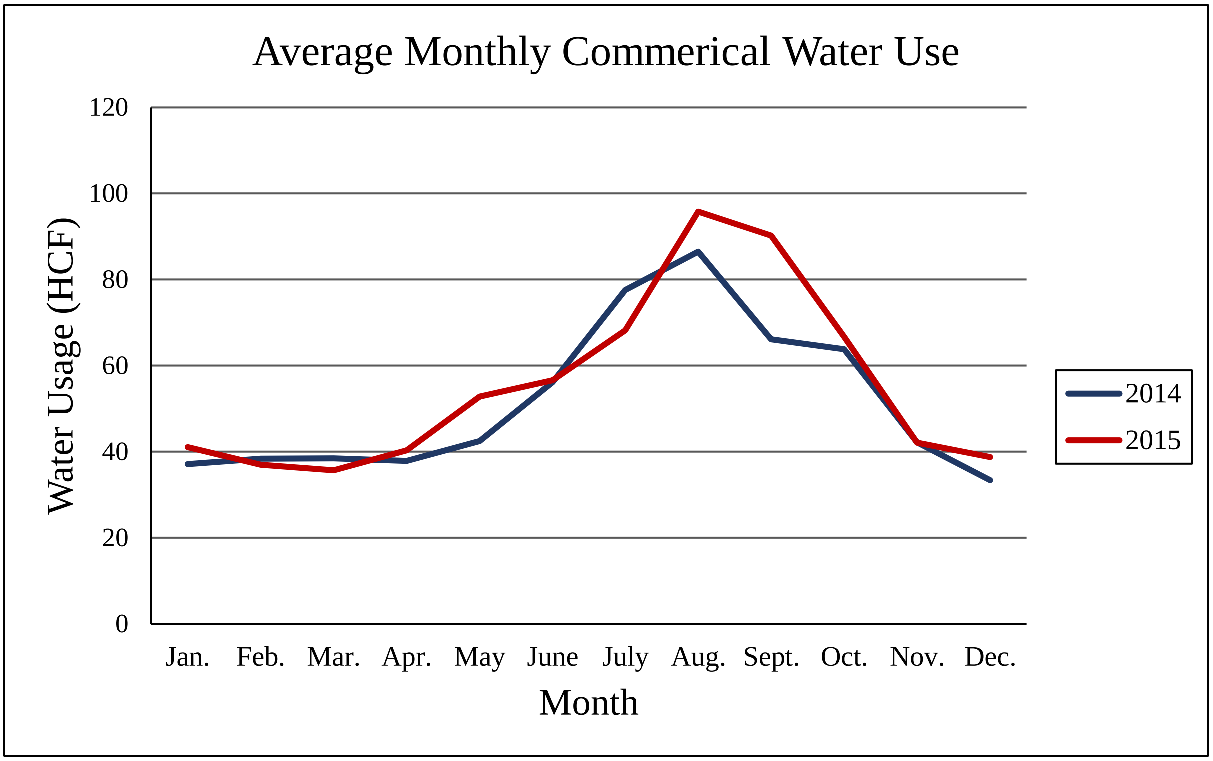

Figure 1.3. Average monthly commercial water use in hundred cubic feet (HCF).

Overall, water use increases considerably during the summer months due to higher temperatures and increased water use for cooling, irrigation, and dust control purposes, among other outdoor activities (Dziegielewski et al. 2000). The high water use in summer months is followed by a subsequent decrease in water use due to lower temperatures and a drop in outdoor irrigation and indoor cooling coinciding with macroclimate. Dziegielewski et al. (2000) discovered that 25% of commercial water use in Southern California is seasonal water use. The direct nature of a business venture also directs the amount of seasonal variation observed in total annual water use by the commercial category. As Dziegielewski et al. (2000) found that sports clubs, which run on seasonal business cycles, utilize 72.4% of their water use during the summer months.

Conclusions

From 2014 to 2015 Bismarck's total water usage increased across both categories of residential and commercial water use. The water use difference between the two years amounts to 406,808 HCF or 304,292,384 gallons of water. Residential water use increased more than commercial water use by 155,240 HCF; as residential increased water usage from 2014 to 2015 by 281,024 HCF and commercial increased by 125,784 HCF. This would indicate that the population of Bismarck grew between the two years, but the commercial sector water use did not increase as much as the residential water use.

Growth, as observed in recent years (2015 and prior), in this part of the state may be linked to energy development and oil extraction but could also be from normal city growth. Even more, the observed increases in water use between 2014 and 2015 may be linked to a dry weather pattern and an increase in air temperature. The annual rainfall for Bismarck in 2014 was 14.10 inches, while in 2015 the annual rainfall was 15.37 inches (NDAWN 2014; NDAWN 2015). Rainfall in both years fell below the normal total rainfall of 17.97 inches (NDAWN 2014). Furthermore, the area has experienced an increase in average monthly air temperature in 2015 from averages experienced in 2014 (NDAWN 2014; NDAWN 2015). The decrease in rainfall from the annual average and an increase in monthly air temperatures in 2015 may attribute to the observed rise in water use for both categories.

Within the residential water use category, single family homes had the largest water use increase and is by far the category that uses the most water. The number of single family dwellings increased by 485 units from 2014, resulting in 19,039 homes in 2015. The total number of single family homes increased water usage by 228,135 HCF since 2014 with total water use amounting to 1,949,294 HCF in 2015. The second largest category of water use was apartment with a total water use of 319,851 HCF in 2014 and 352,391 HCF in 2015. Although, the number of apartment units increased by 761 units, the total water usage by apartment only increased by 32,540 HCF. Further increases in water usage to match the increase in apartments may still happen.

Within the commercial water use category, lawn meters had the largest change in water usage with an increase of 28,464 HCF. Lawn meters had the largest increase with 48,830 HCF in 2014, and increasing by 28,464 HCF in 2015 to 77,294 HCF. Other commercial water users had changes in total water usage less than 10,000 HCF.

Overall, water use in Bismarck increased across both the residential and commercial categories. Water use also increased within most sub-categories within residential and commercial. As in many areas around the United States water use in both the commercial and residential categories was highest in the summer as this is the time when water is used most frequently to water lawns and gardens, fill swimming pools, and wash cars. It is important to understand these trends long term to make accurate water projections of the water that will be required to sustain a municipality.

The City of Bismarck proved to be an excellent municipality to use as a pilot project of water use information and categories within the state of North Dakota. In this pilot project we were able to obtain all billings from the City of Bismarck for two years. The City of Bismarck informed us that prior to 2014 this type of data would not be available because of limitations in data recordings. The City of Bismarck agreed to do the pilot study as they were interested in the results of the research.

Future research into water use should be flexible in the type of data that is collected. Potential ideas to make future water use research easier include: determine what type of data is available on average from municipalities across the state, collect only certain categories and/or sub-categories of water-use data, and know that research prior to the most recent 5-10 years may not be available.

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CHAPTER 2. DUST IMPACTS ON SOYBEANS

Abstract

Road dust is a common by-product of transportation and it is important to understand the impact of road dust on crop production. Therefore, dust was applied to soybean plants to determine if soybean (*Glycine max*) production (i.e. chlorophyll content, leaf temperature, and yield) and seed quality (i.e. seed composition), were altered by dust. In the 2015 and 2016 growing season Roundup Ready soybeans with indeterminate growth were planted using a randomized block design with eight replicates. Dust was applied weekly to soybean treatment areas at designated rates of 0, 15.8, 78.8, 158 g/m^2, in 2015 and 0, 15.8, 78.8, 158, 2×158, and 315 g/m^2 in 2016. The 2×158 g/m^2 treatment is 158 g/m^2 applied twice a week. Leaf temperature and chlorophyll content of all treatments were taken prior to dust application at the V4, R1, R3, and R6 growth stages. Soybeans were harvested at the R8 growth stage and yield and seed composition data were determined. Results of dust treatments on soybean production and seed quality found no significant differences for leaf temperature and chlorophyll content among treatments ($p > 0.05$). Also, no significant differences were found among treatments in yield, yield components, and seed composition in either year ($p > 0.05$). Therefore, results of the study indicate that weekly and bi-weekly applications of dust has little if any impact on soybean production and seed quality.

Introduction

Agriculture is a major land use worldwide and in the United States, with agricultural fields covering approximately 51% of the land base (Nickerson et al. 2011). Considering unpaved roads surround many of these fields, increased traffic during the growing season can intensify dust deposition on nearby vegetation (Everett 1980; Creuzer et al. 2016; U.S. DOT

2016). Although unpaved roads have been around for decades, an increase in demand for food production worldwide has turned traditional smallholder production into a more mechanized, large-scale commercial approach (Chapoto et al. 2013), such an approach increases the number of trucks and traffic traveling on these unpaved roads, contributing and increasing the overall dust particles in the air and potentially impacting crop growth, physiology, and production.

Research efforts on dust have focused on vegetative impacts by non-inert dust and inert dust. Different types of non-inert dust include industrial dusts such as fly ash (Raja et al. 2014), cement (Anda 1986, Bačić et al. 1999, Borka 1980, Shukla et al. 1990), and ceramic (Ali et al. 2003). The few studies that assessed non-inert dust effects on crops studied rice (*Oryza sativa*) (Raja et al. 2014), olive trees (*Olea europaea* L.) (Nanos et al. 2007), sunflower (*Helianthus annuus*) (Borka 1980), soybean and corn (*Zea mays* L.) (Mishra et al. 1986), and soybean and rosemary (*Rosmarinus officinalis* L.) (Ali et al. 2003). The two studies that looked at soybeans were both in conjunction with ceramic or fly ash dust presence in the soil (Ali et al. 2003; Mishra et al. 1986) and not on the plants themselves. These studies found vegetation to be negatively impacted by these types of dusts; specifically through stomatal conductance, leaf temperature, chlorophyll content, growth and yield.

Studies that have focused on ambient dust have examined its impacts on crops such as cotton (*Gossypium hirsutum* L.) (Zia-Khan et al. 2015), grape (*Vitis vinifera* L.) (Leghari et al. 2014), wheat (*Triticum aestivum* L.) and garden pea (*Pisum sativum* L.) (Jwan Khidhr Rahman 2015), and cucumber (*Cucumis sativus* L.) and kidney bean (*Phaseolus vulgaris* L.) (Hirano 1995). Cotton was found to have increased leaf temperature on dusted leaves and an increase in number of blocked stomata (Zia-Khan et al. 2015). The same results were discovered in cucumber and kidney bean which also, increased transpiration rates and altered the photosynthetic rate corresponding to its response curve with leaf temperature (Hirano et al. 1995). While reduced chlorophyll content was found in grape and in wheat and garden pea (Leghari et al. 2014; Jwan Khidhr Rahman 2015), along with a decrease in carbohydrate content for both wheat and garden pea but an increase in proline content (Jwan Khidhr Rahman 2015). As impacts of ambient dust are apparent on some crops, information on soybeans and whether or not these affects apply is lacking. Additionally, it is unknown if these impacts would still occur if these crops were placed in field settings since most of these studies were conducted indoors. Experimentation in the field would provide information on how road dust impacts soybeans in a natural environment that includes uncontrollable variables such as weather and soil variability, two such variables that agricultural growers experience throughout the growing season. Furthermore, as many studies have examined dust impacts on stomatal conductance, and photosynthesis, understanding how dust impacts overall yield along with seed quality, are crucial in food production systems.

Soybeans are a highly utilized crop and are incorporated into food products (i.e. vegetable oil, margarine, edamame), animal feed (i.e. soybean meal), and industrial applications (i.e. inks, paints, biodiesel fuel, and hydraulic fluids) (Smith 1996; Liu 1996). The quality of soybeans and their derivatives are important, as soybeans are in great demand due to their high protein, oil, and dietary fiber content, along with containing a multitude of vitamins and minerals (Lokuruka 2011). However, it is possible that these factors may be altered due to extenuating circumstances in the field, such as road dust. A case in point includes soybeans in situ exposed to varying levels of pH in acid rain which experienced corresponding reductions in protein and carbohydrate content (Evans et al. 1981). Yet, to date, no studies have analyzed seed composition of soybeans impacted by road dust and what that would mean for soybean yield.

The objectives of this study were to: (1) determine if applied road dust influences soybean physiology, specifically leaf temperature and chlorophyll content; and (2) determine if applied road dust impacts soybean production, specifically yield quantity and quality (i.e., seed protein, oil composition, and amino acids).

Literature Review

Vegetation plays a crucial role in sustaining human life, specifically through generation of oxygen for human consumption, food production, and environmental services. Plant production and the services provided by plants are highly influenced by the surrounding environment (Power 2010); and dust has been found to be a large supplier of air pollution, contributing almost 725,748 metric tons of dust into the air annually (NEI 2014). Vegetation in its natural environment is surrounded by large amounts of dust and it is necessary to determine how such dusts effect vegetation and how much dust is needed to create these effects.

Dust Characteristics

The impact and intensity of the effect of dust on vegetation heavily relies on the characteristics of the dust. Dust characteristics that influence its effect or harmfulness to plants include particle size, deposition rates, and chemical composition (van Jaarsveld 2008; Chaturvedi et al. 2013). Size of dust particulates is one factor of concern in how much dust is deposited and how it impacts vegetative processes. Based on human health research, particulate matter (i.e. dust) with aerodynamic diameters less than or equal to 10 micrometers (µm) (PM_{10}) were found to have significant effects (U.S. EPA 2014). However, in vegetative health research, airborne particulates with diameters of 0.01 to 100 µm, depending on the type of dust, were shown to influence plant physiological processes (Farmer 1993). Contributors of these different types of dust are either natural causes or by anthropogenic activities. Anthropogenic activities that contribute to airborne dust include industrial processes, roads, transportation, agriculture, prescribed burning, and construction, among others (U.S. EPA 2014).

Dust deposition rates also plays a part in the intensity of impacts on plant processes, and dust deposition can be influenced by a number of factors. The amount of dust deposited on vegetation relies on the plant's distance from the dust source (Cruezer et al. 2016, Farmer 1993), as well as the size of the dust particle (Everett 1980, Tamm and Troedsson 1955, Rao 1971). Wind speed, surface roughness, and whether surfaces are wet or dry, are a few other factors that also influence dust deposition rates (Farmer 1993). Even though the amount of dust on leaf surfaces is a crucial component when considering dust impacts on vegetation, such impacts are also influenced by the type of dust deposited and its chemical composition.

Chemical composition of dust differs between types of dust. Chemical components of dust can either be non-inert or inert. Non-inert dusts may be chemically active with various combinations of metals (Cawse et al. 1989, Santelmann and Gorham 1988), alkalinity (Arslan and Boybay 1990), and salinity (Everett 1980). However, some of these chemical attributes can be seen in inert dusts. In agriculture, inert dusts are classified into four different categories based on composition and particle size (Golob 1997). The four groups of inert dusts are non-silica dusts, coarse grain silicates, diatomaceous earths, and silica aerogels (Golob 1997). An example of a non-silica dust is limestone (Golob 1997), limestone is high in carbonates and can attribute to an increase in alkalinity (Kheshgi 1995). Limestone can also be found in different types of cements, which are non-inert dusts (Abu-Romman and Alzubi 2015). However, the difference between non-inert dust and inert dust is that inert dust primarily causes effects through physical means such as hindering the absorption of light energy through a layer of dust on leaf surfaces (Loppi and Pirintsos 2000), whereas, non-inert dust with chemical compositions directly impact plant metabolic processes (Golob 1997). A study done by Manning (1971) discovered limestone (i.e. a combination of lime, slaked lime, and fly ash) dusted leaves of wild grape (*Vitis vulpina* L.) and sassafras (*Sassafras albidum*) were darker in color than non-dusted leaves but were all comparable in size. The darker colored leaves were believed to be beneficial but dusted leaves also experienced an increase in leaf spot disease as it promoted a suitable habitat for fungi at moderate dust levels (Manning 1971). Furthermore, inert dusts may become chemically active under certain conditions (Golob 1997). Chemical elements found in dust mostly occur as small particulates and are likely to form a large percentage of the small fractions portion of dust (Milford and Davidson 1985, Farmer 1993). For vegetative health, this means the impacts of the elemental portion of dust are felt by vegetation at longer distances from the point source (Everett 1980).

History of Research on Vegetative Impacts by Dust

The impacts of dust on vegetation are variable and have the potential to be harmful. Reviewing past and present research, in regards to dust impacts on vegetation, will be helpful to gauge what is known about dust impacts on vegetation and where further research is needed. The study of dusts and their impacts on vegetation have been under investigation since the early twentieth century. Early on most research was guided towards impacts of non-inert dust including industrial particulates of coal (Raja et al. 2014), cement (Borka 1980; Anda 1986; Shukla et al. 1990; Bačić et al. 1999), and ceramic dust (Ali et al. 2003). Jameson and Schiel (1972) even looked at gypsum dust and how it impacted trees near a gypsum processing plant. Even though gypsum is a known beneficial soil amendment (Miller 1990), when deposited on leaf surfaces they found that trees within a half mile of the plant showed more impacts as a result of higher amounts of dust deposition. The reflectance due to the gypsum dust on the vegetation was increased because of the higher amounts and hindered photosynthesis. Growth rate was also impeded and it was evident in tree core samples (Jameson and Schiel 1972). More recent studies have focused on natural causes of dust, specifically dust associated with arid climates (Zia-Khan et al. 2015) and volcanic ash/soot (Hirano et al. 1995), both of which are typically inert dusts.

Dust Impacts on Vegetation

The impacts of dust on vegetation typically cause either a physical or chemical effect on the plant and are based on the properties of the dust. Physical effects of dust on vegetation include shading, plugging of the stomata, decreased growth, increased temperature of leaves and canopy cover (Farmer 1993; Hirano et al. 1995). Furthermore, Shukla et al. (1990) discussed the impediment of pollen germination due to cement dust coating the stigmas and this hindrance decreased yield of field mustard (*Brassica campestris* L.). The study also noted a decline in leaf area, number of pods and seeds per pod. With these physical effects also came chemical effects which included negative impacts on photosynthesis, transpiration, oil content and synthesis of chlorophyll (Shukla et al. 1990).

Non-inert Dust Vegetative Impacts

In examining the impacts of non-inert dusts on vegetation, impacts of such dusts were seen on both structural components and structural composition. Dusts with heavy metals, such as nickel, cobalt, and lead, were shown to bio-accumulate in roadside vegetation (Brumbaugh et al. 2011; Baby et al. 2008) and increase pH (Chauhan et al. 2010); while dusts with soluble salts increased alkalinity of soybean and corn at high deposition rates (Mishra et al. 1986). Cement dust induced oxidative stress in Mouseear cress (*Arabidopsis thaliana*) and enhanced protease activity, but decreased total protein content and chlorophyll (Abu-Romman and Alzubi 2015). Furthermore, cement dust was found to reduce vitamin content in Lago Spinach (*Celosia* *argentea*) (Ade-Ademilua and Obalola 2016), increase leaf temperature, evapotranspiration, and decrease fertilization and yield in corn (Anda 1986). Cement dust also plugged stomatal openings, and altered the appearance of surface wax on needles in Aleppo Pine (*Pinus halepensis*) (Bačić et al. 1999), and overtime decreased plant growth, respiration rate, and catalase activity in sunflower (*Helianthus annuus*) (Borka 1980). However, in some instances non-inert dusts have been shown to improve or not effect plant processes or structures. In the case of fly ash, it was shown to increase plant soybean and corn growth, metabolic rate, and chlorophyll content by counteracting a boron deficiency at lower deposition rates (Mishra et al. 1986). Moreover, ceramic dust in clay soils increased soybean and rosemary growth and yield at lower rates of occurrence (Ali et al. 2003).

Inert Dust Vegetative Impacts

Negative impacts of inert dust have been observed in physical structures of plants. Plant physical structures effected by dust include leaves, stomata, and stems. Deposition of inert dust on plant leaves acted as a blanket on leaf surfaces which block stomatal openings and increase leaf temperature (Zia-Khan et al. 2015). As a result of blocked stomatal openings and increased leaf temperature, research has shown that transpiration rates increase and decrease plant water use efficiency, leaf chlorophyll content, and photosynthetic rate decreased (Hirano et al. 1995, Sharifi et al. 1997, Prusty et al. 2005, Jwan Khidhr Rahman 2015). Furthermore, particulate deposits without harmful materials have been shown to decrease plant growth in cotton (*Gossypium hirsutum* L.), but were determined to not be a major problem for cotton production due to naturally low deposition rates (1.5 µg/m^2/day) and high removal of particulates by wind and rain (Armbrust 1986). Another study by Chaturvedi et al. (2013) found teak (*Tectona grandis*) to have higher dust loads of inert dust due to its rough and hairy leaf texture, along with a greater leaf area, compared to the relatively smooth leaf textures of the other three studied tree species (*Anthocephalus cadamba*, *Syzygium cumini*, and *Madhuca indica*). Declines in chlorophyll content, leaf area, photosynthetic rate, and intrinsic water-use efficiency were also the greatest in *T. grandis* and was determined to be more sensitive to dust (Chaturvedi et al. 2013). Based on research to date we understand that dusts, whether inert or non-inert, are likely to impact all vegetative types. However, it is still unclear how these different dusts impact different plants types and specific species under certain environmental conditions and at different deposition rates.

Road Dust Vegetative Impacts

Although most air pollution research focuses mainly on human health, the impacts of dust on vegetation, namely agricultural crops, is a cause for concern in achieving an economic food crop that will sustain future generations (Greening 2011). Not all vegetation and ecoregions have to deal with arid climates and volcanoes; however many terrestrial areas on the planet deal with dust deposition caused by unpaved roads. Fine particulate matter or dust is known to be directly connected to the quantity of dust emitted by unpaved roads (Sanders et al. 1997). In a study done by Creuzer et al. (2016) dust deposition between highly trafficked and low trafficked unpaved roads was most significant within 40 meters adjacent to the road. As most agricultural fields are surrounded by unpaved roads, the traffic-generated dust that lands on roadside vegetation and nearby crops are thought to have negative impacts (Greening 2011).

In a study by Thompson et al. (1984) researchers went beyond road dust and studied motor vehicle exhaust dust. They found that exhaust dust with a particle size of 1-10 µm can reduce photosynthesis on upper leaf surfaces and impede diffusion on the lower leaf surfaces if the observed leaf surface held 5-10 grams of dust per meter squared (g/m^2). However, the maximum load of exhaust dust seen on leaves of shrubs on the roadside of the motorway was about 2g/m^2 (Thompson et al. 1984). Meaning that the impact on photosynthesis through shading or hindrance of diffusion are likely to be minimal.

Of current research only a handful of studies address the impacts of gravel road dust on crops. Gravel road dust impacts have been evaluated on grape (Leghari et al. 2014), cotton (Zia-Khan et al. 2015), wheat and garden pea (Jwan Khidhr Rahman 2015), and on cucumber and kidney bean (Hirano et al. 1995). Overall, road dust has reduced plant growth in grape (Leghari et al. 2014), blocked stomatal openings and increased leaf temperature in cucumber and kidney bean (Hirano et al. 1995), reduced chlorophyll and carbohydrate content in wheat and garden pea (Jwan Khidhr Rahman 2015), and decrease yield in cotton (Zia-Khan et al. 2015). However, there has typically been only one study addressing road dust and a particular species, and only certain species have been evaluated.

Impacts on Crop Physiology

Influences on plant physiology by gravel road dust have been shown to impact major plant structural components. Structural components that have been impacted in vegetation include leaves, stomatal openings, and shoots or stems. Number of leaves and leaf area have been found to decrease due to dust deposition (Jwan Khidhr Rahman 2015) along with a decrease in total plant biomass in cotton (Zia-Khan 2015). Leghari et al. (2014) found a negative correlation between the amounts of dust accumulated and plant growth parameters such as plant length, plant cover, and number of leaves. In general as the amount of dust increased on grape plant growth decreased (Leghari et al. 2014). Plant height, shoot, pod, and seed length are other physiological structures that have been found to be negatively influenced by dust (Leghari et al. 2014; Jwan Khidhr Rahman 2015; Zia-Khan et al. 2015). Dust accumulations on leaf surfaces have also been found to increase leaf temperatures and decrease total chlorophyll content (Hirano et al. 1995; Zia-Khan et al. 2015), both of which factor into a plant's photosynthetic rate.

Impacts on Crop Processes

Plant processes that have been impacted by dust include transpiration, photosynthesis, and respiration. Zia-Khan et al. (2015) found a 30% decrease in stomatal conductance of cotton with dust treatment in comparison to the control. The dust treatment included the application of 100 g/m^2 of dust every ten days while the control group received no application of dust and no cleaning of leaves. Further implications of the findings are attributed to blocking of the stomata on the upper leaf surface and increased canopy temperature of dust-applied leaves by 2-4˚C compared to the control (Zia-Khan et al. 2015), both of which increase the rate of transpiration (Hirano et al. 1995). Differences in transpiration rates between dusted plants and non-dusted plants increased as air temperature increased (Hirano et al. 1995).

Leaf temperature is known to be directly related to photosynthetic rate through a response curve in which dust shifts the response curve to the left (Hirano et al. 1995). Where, an increase in leaf temperature corresponds to an increase in photosynthetic rate at a lower air temperature, but will decrease photosynthetic rate at a higher air temperature (Hirano et al. 1995). Moreover, as leaf temperature rises enzymes that catalyze the light independent reaction of photosynthesis are denatured as the optimum temperature range is surpassed, decreasing the photosynthetic rate (Eller 1977). Therefore, as photosynthetic rate decreases so does plant respiration. Other limiting factors for photosynthesis besides temperature include carbon dioxide concentration and light intensity.

Light intensity at the leaf surface can be hindered by dust and can cause the plant not to reach the light saturation point needed for optimum photosynthetic rate (Gaastra 1959; Hirano et al. 1995). Additionally, chlorophyll is required to capture light energy to be used in photosynthesis, but a reduction in chlorophyll content can further limit the plant's ability to reach an optimum photosynthetic rate (Evans 1989). A dusted leaf surface can increase leaf temperature and cause a shading effect that can hinder or degrade chlorophyll synthesis (Shukla et al. 1990; Mark 1963) and decrease a leaf's total chlorophyll content (Abu-Romman and Alzubi 2015; Singh and Rao 1981). Chlorophyll content has been shown to decrease in response to road dust in crops such as grape (Leghari et al. 2014), cotton (Zia-Khan et al. 2015), wheat and garden peas (Jwan Khidhr Rahman 2015). Pollutants have also been shown to decrease production of chlorophyll and further its degradation (Chauhan et al. 2010; Sandelius et al. 1995), and chlorophyll content has been highly utilized as a qualitative measurement for vegetative health in plant research (Chauhan et al. 2010; Pawar and Dubey 1985; Gilbert 1968).

Vegetative health is highly influenced by plant surroundings, and the environmental stress which a plant experiences has the ability to alter the functional capacity of plant processes. These plant processes are vital to overall vegetative health and give a plant the ability to produce fruit and seed as a means of reproduction. In terms of food production, the quality and quantity of such fruits and seeds are paramount in achieving a sustainable yield for human consumption.

Impacts on Crop Production (nutrient content/yield)

The importance of plant production is highlighted in terms of yield and yield composition, and it is important to understand how these factors are impacted by dust. Nutrient content of plants have been shown to decline in some crops due to dust deposition on leaf surfaces (Jwan Khidhr Rahman 2015). In wheat, total carbohydrate, total chlorophyll, and water content were decreased while proline content increased on dusted treatments (Jwan Khidhr Rahman 2015). In the same study, total carbohydrate, and total chlorophyll content decreased in garden pea, as water and proline content increased (Jwan Khidhr Rahman 2015). The decrease in carbohydrate content was associated with harmful metals within the dust and reduced the amount of accessible food resources to the plants (Jwan Khidhr Rahman 2015). The increase in proline content was tied to a plant defense response towards environmental stress (Jwan Khidhr Rahman 2015). A similar response was shown in wheat and mustard, but with a decrease in ascorbic acid and carotenoids, both of which are antioxidants (Chauhan et al. 2010). In the study, ascorbic acid was consumed due to oxidative stress and the decline in carotenoids was attributed as a protection mechanism from photo-oxidative stress on chlorophyll-protein complexes (Chauhan et al. 2010). Other nutrients in crops that have been shown to be affected by dust include protein, total sugars, starch, lipids, and amino acids, but these impacts were triggered by non-inert dusts such as cement (Raajasubramanian et al. 2011).

Road dust impacts on yield have been shown in grape (Leghari et al. 2014), cotton (Zia-Khan et al. 2015), and wheat and garden pea (Jwan Khidhr Rahman 2015), along with wheat and mustard growing near urban and industrial areas (Chauhan et al. 2010). Yield in cotton was reduced by an average of 28% in dusted plants and seemed to impact growth and yield during the flowering period due to an observed decrease in flowering and fruiting potential (Zia-Khan et al. 2015). A significant decrease in growth of grape occurred and was apparent through number of leaves, plant length, and plant cover (Leghari et al. 2014). Furthermore, a negative correlation was determined between dust amount and growth rate (Leghari et al. 2014). Other observed reductions in yield have been shown in plant height, and leaf area of wheat and garden pea, along with a decrease in wheat spike length, and pea pod length in comparison to non-dusted plants (Jwan Khidhr Rahman 2015). In wheat and mustard growing near urban and industrial areas, number of grains per plant, grains weight per plant and weight of 100/1000 grains were significantly reduced (Chauhan et al. 2010). With a number of physiological characteristics of plants being affected by road dust, a decrease in yield is inevitable. Such yield losses have been ascribed to decreases in photosynthetic rates in which plants revert supplies to ensure reproductive development and seed growth (Chauhan et al. 2010; Krupa and Kickert 1989).

Methods

Study Area

The experimental site was located in Cass County, North Dakota near Prosper (47.001306^o N, 97.0198^o W) (Figure 2.1). Weather data on maximum wind speed, rainfall, maximum and minimum air temperature, average air temperature, and total solar radiation were collected onsite by the North Dakota Agricultural Weather Network (NDAWN) throughout the duration of the 2015 and 2016 growing seasons. Data for each weather variable during each growing season can be found in Appendixes A and B. Intensity and timing of rain were variable over both years but factored into the accumulation and duration of dust on leaf surfaces. Maximum daily wind speed along with timing and amount of rainfall between dust applications and soybean measurements are illustrated for both years in Appendixes C and D. Between dust applications it rained 30.5% and 28.7% of the time in 2015 and 2016, respectively (NDAWN 2015; NDAWN 2016). Wind speeds were another factor that played a role in dust accrual and time length on plants. Wind speeds above 5 m/s occurred 95% of the time between dust applications in 2015 and 94% in 2016 (NDAWN 2015; NDAWN 2016).Wind speeds were accounted for before each dust application in an attempt to minimize dust deposition disturbance. Mild to moderate average wind speeds occurred per month for each growing season and most days with mild to moderate wind were utilized for dust applications when possible.

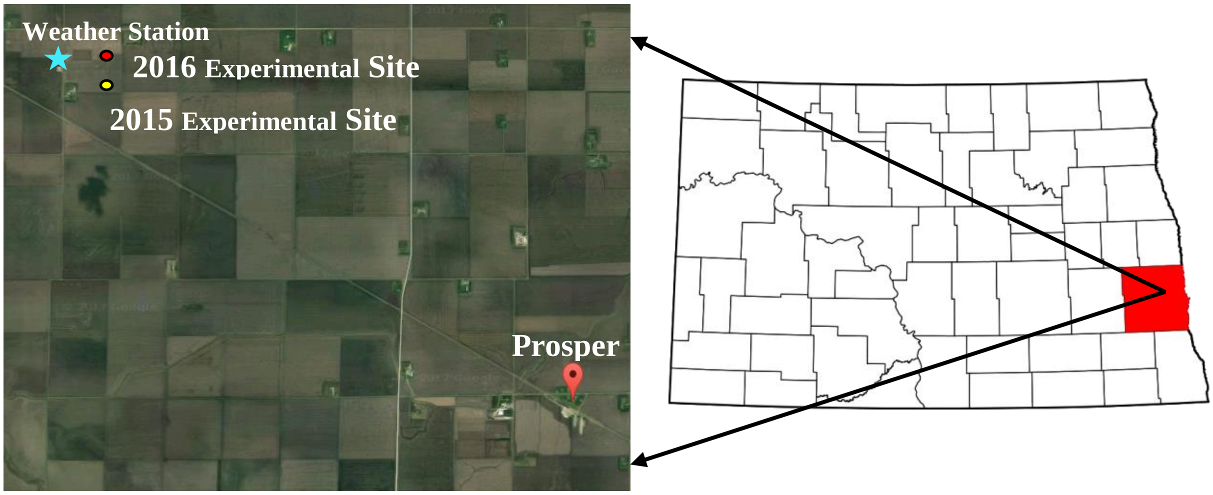

Figure 2.1. Location of experimental sites in Cass County, North Dakota.

Experimental Design

In the growing season of 2015 a 73.2 m × 45.7 m field plot was planted with a single variety of Roundup Ready soybeans, while a 61.0 m × 45.7 m plot was planted in 2016. Soybean variety RG607RR from Howe Seed Farm (Casselton, North Dakota) was used in 2015 while soybean variety 16RO9N from Peterson Farms Seed (Harwood, North Dakota) was used in the 2016 growing season due to a decrease in germination of the 2015 soybean variety. In accordance with Thompson et al. (1984) both fields were controlled for ambient road dust by being surrounded by other fields as a buffer and with the nearest gravel road being a quarter mile to a half mile away. Annual grass (Sonalan) and broadleaf (Sharpen) pre-emergence herbicides were applied in 2015 and 2016, while annual and perennial grass and broadleaf (Buccaneer Plus) post-emergence herbicide was sprayed twice on the 2015 field to combat weed abundance and prevent competition (Table 2.1). All herbicides were applied at the labeled rates. When soybeans reached the V1 stage (i.e. first trifoliate unrolled) of vegetative growth, flags were placed to mark treatment areas within replicates and dust applications began.

Table 2.1

Herbicides applied on experimental sites with dates applied, growth stage of soybeans at time of application, and application rate of herbicide.

Herbicide	**Date Applied**	**Growth Stage of Soybeans**	**Application Rate**
Sonalan[1]	5/20/2015	Not planted	2.92L/187.1 L of water/ha
Sharpen[2]	5/24/2015	Planted on 5/23/2015	109.61mL/187.1 L of water/ha
Buccaneer Plus[3]	6/18/2015	V1	4.10L/187.1 L of water/ha
Buccaneer Plus	7/14/2015	V6	4.10L/187.1 L of water/ha
Sonalan	5/16/2016	Not planted	2.92L/187.1 L of water/ha
Sharpen	5/24/2016	Not planted	109.61mL/187.1L of water/ha

[1] = Ethalfluralin, Dow Agro Sciences LLC, Indianapolis, Indiana, USA
[2] = Saflufenacil, BASF, Triangle Park, North Carolina, USA
[3] = Glyphosate, Tenkoz, Inc., Alpharetta, Georgia, USA

To determine how dust interacts with soybean physiology and growth, treatments were based upon rates of applied dust. Average rates of dust loading from normal traffic gravel roads from Cruezer et al. (2016) were 1-4 g/m^2/day depending on distance from the road, while dust loads during times of high traffic were 3-4 g/m^2/day. Based on these findings the treatments were 0, 4, 20, and 40 g/m^2/day which equated to 15.8, 78.8, and 158 g/m^2, respectively.

In 2015 eight randomized replicates of each treatment occurred within the block. Plot sizes were 7.62 m × 7.62 m and the dust application areas were located within the middle of the plots and were 0.75 m × 0.75 m (Appendix E). Application of dust took place on the specified treatment area on a weekly basis; therefore, daily dust amounts were compiled to equalized weekly amounts. Further information on the application process is discussed in the dust application section.

Based on low differences seen among treatments in 2015, two treatments were added for the 2016 growing season. These two treatments included an increase in frequency of dusting at the 158 g/m^2 rate which occurred twice per week versus just once, while the second treatment doubled the highest dust amount to 315 g/m^2, applied once a week. The experimental field design for the 2016 growing season is provided in Appendix F.

Dust Application

Fine particulate matter was obtained from standard class 5 road gravel (North Dakota standard for class 5 includes; 90-100% of aggregate that pass through 1.9 cm sieve, 35-70% < 4.76 mm, 16-40% < 0.595 mm, 4-10% < 75 µm) (NDDoT 2014). A sample of dust was sent to the NDSU Soil Testing Laboratory (Fargo, North Dakota) for mechanical analysis and chemical composition. For standardization, road gravel was sieved with a No. 40 mesh sieve (425 µm) based on Sanders et al. (1997). Dust was then weighed into 37 mL plastic cups (PL125 37, Solo®, Lake Forest, Illinois, USA), capped, and transported to the field. Application of dust occurred using a 1.2 L stainless steel flour sifter with a spring-action hand trigger and a three layer mesh $\geq$ 0.425 mm (080468-006-000, Starfrit, Longueuil, Quebec, Canada) (Figure 2.2a) modified with a slow release apparatus (Figure 2.2b) cut from wax paper into a 5 cm^2 area with four 5 cm wide attachments elongating from each side of the square area to attach to the outside of the sifter with tape (Figure 2.2c). The slow-release apparatus allowed the dust applicator to hold dust before dispensing and aid in a more uniform application of dust within the treatment area.

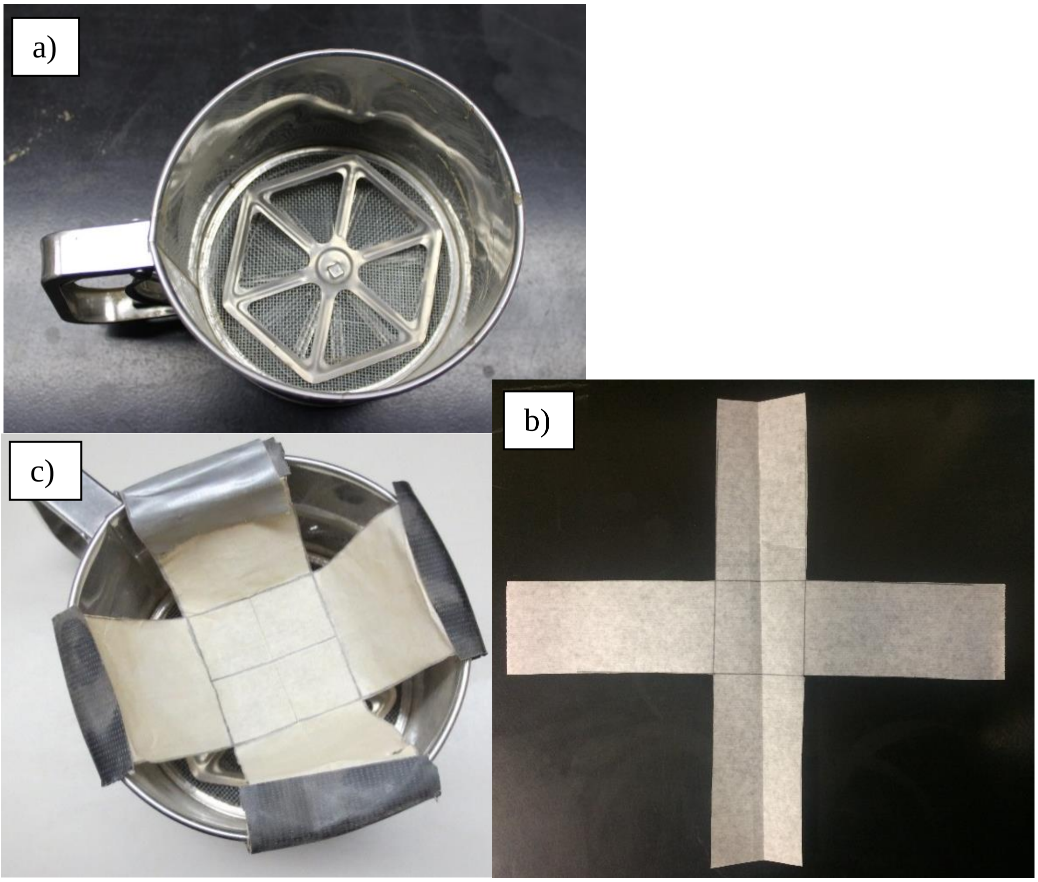

Figure 2.2. Method used for dust application includes: a) stainless steel flour sifter; b) slow-release apparatus; c) sifter with slow-release apparatus attached.

To decrease disturbance by wind during application and to ensure that dust is applied evenly within the treatment area, a spray booth was constructed from 19.1 mm polyvinyl chloride (PVC) pipe, 8-19.1 mm 3-way PVC elbows, polyethylene tarp, and tape. The frame (1.31m × 0.75m × 0.75m) was constructed with 11.24 m of PVC pipe and fittings, the polyethylene tarp was secured on the inside of the structure with tape (Figure 2.3). Trial experiments confirmed that dust was not adhering to the sides of the tarp.

Figure 2.3. Dust spray booth during dust application.

Leaf Dust Quantification

To determine the amount of dust deposited on plant leaves in each treatment, a separate study was conducted in summer 2016 where 15.8, 78.8, 158, and 315 g/m^2 was applied to soybeans adjacent to the study area, three replications each. After application three leaves located towards the top of the plant were sampled from each repetition, with a total of nine leaves per treatment. Leaves were clipped and put into individually packaged 120 mL specimen containers (M4928, GENT-L-KARE®, Medical Action Industries Inc., Gallaway, Tennessee, USA). To quantify dust from specimen containers, 9 cm filter paper (Qualitative, 413, 28310-048, VWR, Chicago, Illinois, USA) was weighed before filtration using a 4 decimal analytical balance (GH-300, A&D Weighing, San Jose, California, USA), then placed in an 87 mL capacity Buchner funnel (COORS™, 60240, Coorstek Inc., Golden, Colorado, USA) which was situated into a 250 mL Erlenmeyer filter flask (KIMAX™, Kimble™ 27060250, 10-181D, Fisher Scientific Co. L.L.C., Pittsburgh, Pennsylvania, USA). The filter flask was connected to a vacuum outlet using 0.79 cm × 1.11 cm × 0.16 cm plastic tubing (Nalgene™ 180 Clear Plastic PVC Tubing, Thermo Scientific™ 80000090, 14-176-30, Fisher Scientific Co. L.L.C., Pittsburgh, Pennsylvania, USA) cut to 60.96 cm. Dust was rinsed from a leaf and specimen container with deionized (DI) water and captured onto filter paper. Once dust was filtered, the filter paper with dust was placed into a desiccator to assimilate samples to the same relative humidity. After a minimum of 24 hours in the desiccator, filter paper with dust was re-weighed to quantify the mass per leaf. Leaf area data of sampled leaves was also collected via a Leaf Area Meter (LI-COR Environmental Portable Area Meter LI-3000C, Lincoln, Nebraska, USA) with the transparent belt conveyor accessory (LI-COR Environmental Conveyor Accessory LI-3050C, Lincoln, Nebraska, USA). The quantification of leaf dust was then used to determine how much dust per treatment actually ended up on a square area of a leaf.

Soybean Measurements

Chlorophyll Content

Measurements were taken during the 2015 and 2016 growing season to assess impacts of dust applications on soybean physiology. Soil plant analysis development (SPAD) readings were taken to measure the amount of chlorophyll in soybean plants (Konico Minolta Chlorophyll Meter SPAD-502 Plus, Aurora, Illinois, USA). The amount of chlorophyll in a leaf correlates to leaf nitrogen status and is also proportional to photosynthetic rate (Evans 1983; Seeman et al. 1987). Furthermore, chloroplast development is based on light availability, plant nutrition, and water stress (Buetow et al. 1991; Sundqvist et al. 1980). To measure chlorophyll a leaflet (leaf) from a selected plant was clipped from the uppermost fully expanded trifoliate. The leaflet was then rinsed thoroughly with DI water to remove any residual dust that may interfere with the SPAD reading and air-dried for 5 sec. Three places on the leaflet were measured with the SPAD meter and averaged to give an overall reading for the leaflet which represented the given plant. Three plants were selected within each treatment area for all replicates. SPAD readings were taken throughout the growing season during the V4, R1, R3, and R6 growth stages. Measurements were taken prior to the dust application for that week. Previously measured leaflets were below that of subsequent leaflets as both soybean varieties are indeterminate in growth and continued to produce leaves on the main stem, as well as on branches throughout the flowering period. Shade and irradiance effects were minimized for SPAD readings by taking measurements of leaflets on the uppermost part of the plant.

Leaf Temperature

Infrared temperature (IRT) readings were also taken to gauge leaf temperature differences between treatments (Apogee Infrared Radiometer Model MI-210, Logan, Utah, USA). Previous research has determined that dusted leaves can have higher leaf temperatures than non-dusted leaves (Eller 1977; Hirano et al. 1995; Sharifi et al. 1997; Zia-Khan et al. 2015) and may influence leaf photosynthetic rates (Eller 1997). Leaf temperature was measured at the same growth stages of V4, R1, R3, and R6 and taken the same day as chlorophyll readings. Leaf temperature readings were measured before SPAD readings were taken to ensure leaves were not disturbed. To determine leaf temperature, a leaflet from three separate plants in a treatment area were selected from the uppermost fully expanded trifoliate. Furthermore, leaflets were facing approximately the same direction as the sun and were unshaded from other leaflets. After leaf selection the infrared radiometer was held approximately 5.08-7.62 cm away from the leaf surface so the field of view contained only the selected leaf surface. The infrared radiometer was held in that position until a constant temperature reading was obtained for the selected leaflet.

Prior to reading leaf temperatures, atmospheric temperature readings were recorded in each cardinal direction and directly above the plots. Atmospheric readings occurred right before leaf temperatures were taken, half way through leaf temperature readings, and at the end to account for ambient air temperature and changes over the sampling period. Atmospheric temperature readings were then used to correct leaf temperature data for leaf emissivity before data analysis using a leaf emissivity coefficient (ε) of 0.96 (ECIRS, n.d.):

$$\mathrm{T_{target}} = \sqrt[4]{\frac{\mathrm{T_{sensor}}^4 - (1-\varepsilon)\times \mathrm{T_{background}}^4}{\varepsilon}} \qquad \text{Eq. 1}$$

where T_{target} is the leaf temperature corrected for leaf emissivity in Kelvin (K), T_{sensor} is leaf temperature measured by the infrared radiometer (K), and $T_{background}$ is the temperature of the sky measured by the infrared radiometer (K) (Apogee Instruments, Inc. 2016).

Yield and Seed Composition

Soybeans were harvested 7 to 14 d after full maturity was reached and each treatment area was hand harvested. All plants in a treatment area were hand clipped at ground level and placed into a polypropylene bag, each replicate and treatment were collected individually. In order to obtain pod number per plot and to minimize pod breakage and seed loss, plants were not dried. Seeds were transported back to a lab at NDSU and were hand threshed. Data on number of pods and seeds per plot were accounted for along with seed weight, moisture content, and yield adjusted to 13% moisture content were determined for each treatment and replicate. The threshed seeds were then sent to the Northern Crops Institute (NCI) Laboratory (Fargo, North Dakota) to be analyzed for the seed composition components listed in Table 2.2.

Table 2.2

Soybean seed composition parameters that were determined from harvested seeds.

Parameter	Parameter cont'd	Parameter cont'd
Alanine	Leucine	Raffinose
Arginine	Linoleic acid	Serine
Ash	Linolenic acid	Stachyose
Aspartic acid	Lysine	Stearic acid
Available lysine	Methionine	Sucrose
Cysteine	Moisture content	Taurine
Fiber	Neutral Detergent Fiber	Threonine
Glutamic acid	Oil	Tryptophan
Glycine	Oleic acid	Tyrosine
Histidine	Ornithine	Valine
Hydroxylysine	Palmitic acid	
Hydroxyproline	Phenylalanine	
Isoleucine	Proline	
Lanthionine	Protein	

Statistical Analysis

The data analyses for this paper was generated using SAS® software, Version 9.4 of the SAS System for Windows (Copyright © 2015 SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA). Leaf dust quantification data collected via a randomized design were analyzed using ANOVA in SAS software via PROC-GLM (SAS 9.4 2015). Pair-wise comparison of means were adjusted using the Tukey correction. Before analysis, individual leaf dust amounts per leaf area were calculated and percent deviation from target rate of application was determined. All data collected between the two growing seasons were evaluated separately and then analyzed for differences among treatments within each year (2015 and 2016). Weather data from the nearest NDAWN weather station was recorded to help interpret results within an environmental context.

Individual leaf data collected from IRT and SPAD readings were averaged per treatment within each replication and then averaged at the treatment level across vegetative stages. A repeated measures randomized complete block design was used to determine differences of IRT and SPAD readings within and over vegetative stages. The repeated measure was the different vegetative stages. A mixed procedure (PROC-MIXED) analysis of variance (ANOVA) was used with a restricted maximum likelihood (REML) method (SAS 9.4 2015). Pair-wise comparisons used the Tukey correction.

Yield data was collected via a randomized complete block design and was analyzed as ANOVA in SAS software using the general linear model procedure (PROC-GLM) (SAS 9.4 2015). Selected yield factors included the following for both years: pods/plot, seeds/pod, yield at 13% moisture content, and seed weight. The Tukey correction was used to adjust *p*-values for pair-wise comparisons.

Seed composition data utilized a randomized complete block design and underwent a permutational multivariate analysis of variance (PERMANOVA) analysis with treatments as a fixed effect factor implemented in PC-ORD Version 6 software (McCune and Mefford 2011). Prior to analysis, percent seed composition variables were transformed with arcsine method and a few seed composition variables were discarded due to machine non-calibration for the selected variable. A Euclidean Similarity index was used in the PERMANOVA analysis. Nonmetric Multidimensional Scaling (NMS) was utilized via PC-ORD (McCune and Mefford 2011) to graphically represent seed composition data for both years (2015, 2016). To quantify the pairwise interrelationship of seed composition data, points were given spatial distribution using the Euclidean Similarity index. Arrangement of the data was revealed by running PC-ORD with 500 iterations of the seed composition data for each year, where 2015 data was reduced to three axis from six and 2016 to one axis from six, both with an instability criterion of 0.00000. Dimensions and model selection were founded on (1) a significant Monte Carlo test of $p < 0.05$, (2) a model with a final stress <20, (3) an instability <0.0001, and (4) a discontinuation of additional axes if stress was not reduced by a minimum of 5 points. Factors with a correlation coefficient (r) greater than 0.4 or less than -0.4 with the NMS axes were considered to be interpretable. Factor analysis of a priori seed composition variables was also conducted as ANOVA through SAS software with PROC-GLM (SAS 9.4 2015) and pair-wise comparisons adjusted using the Tukey method. Selected a priori seed components for factor analysis are provided in Table 2.3.

Table 2.3

Selected a priori seed components for factor analysis in 2015 and 2016.

Parameter	Parameter cont'd	Parameter cont'd
Alanine	Leucine	Protein
Arginine	Linoleic acid	Raffinose
Aspartic acid	Linolenic acid	Serine
Available lysine	Lysine	Stachyose
Cysteine	Methionine	Stearic acid
Glutamic acid	Moisture content	Sucrose
Glycine	Oil	Taurine
Histidine	Oleic acid	Threonine
Hydroxylysine	Ornithine	Tryptophan
Hydroxyproline	Palmitic acid	Tyrosine
Isoleucine	Phenylalanine	Valine
Lanthionine	Proline	

Results and Discussion

Dust Characterization

The dust used for this study was 72.8% sand (2.0 mm to 0.05 mm), 20.9% silt (0.05 mm to 0.002 mm), and 6.3% clay (<0.002 mm) (Table 2.4). Other chemical parameters can be found in Table 2.5. Of the parameters determined the dust material did not have properties that would be limiting to plant growth.

Table 2.4

Mechanical analysis of dust composition based on United States Department of Agriculture classification of size fractions (Gee 2002).

Percent Sand	**Percent Silt**	**Percent Clay**	**Soil Texture**
72.8	20.9	6.3	SANDY LOAM

Table 2.5

Chemical parameter amounts found in experimental dust.

Parameter (units)	**Amount**
Ammonium-nitrogen (mg/kg)	5.80
Calcium (mg/kg)	4620
Calcium carbonate equivalent (%)	16
Cation exchange capacity (mmolc/kg)	13.7
Chloride (g/m^2)	27.45
Copper (mg/kg)	1.62
Electrical conductivity (dS/m)	0.43
Iron (mg/kg)	6.2
Magnesium (mg/kg)	242
Manganese (mg/kg)	2.9
Nitrate-nitrogen (g/m^2)	0.56
Organic matter (%)	0.40
pH	7.70
Phosphorus (mg/kg)	2
Potassium (mg/kg)	52
Sodium (mg/kg)	22.4
Sulfate-sulfur (g/m^2)	1.79
Zinc (mg/kg)	0.75

Leaf Dust Quantification

From the leaf dust quantification study in 2016, average dust masses per leaf area and average deviation from the target rate of application were not significantly different among treatments (Table 2.6). However, the deviation increased as target rate increased (Table 2.6).

Visual observations indicated that as the dust rate increased the leaves were less green (Figure 2.4).

Table 2.6

Leaf dust quantification target rate of application per treatment and average dust amount per leaf area for each rate of application. Average deviation of dust amount per leaf area from target rate of application is also given.

Treatment (g/m^2/day)	**Dust Amount Applied (g/m^2)**	**Target Rate of Application (mg/cm^2)**	**Average Dust Amount/Leaf Area (mg/cm^2)**	**Average Deviation from Target Rate (mg/cm^2)**
4	15.8	2.80	1.49	-1.24
20	78.8	14.0	5.60	-7.89
40	158	28.0	11.0	-10.3
80	315	56.0	39.2	-17.1

Dust accumulation on leaf surfaces were found to be influenced by leaf size and shape, surface texture, level of pubescence, leaf orientation, and petiole length (Younis et al. 2013). Large deviations from target rate of application among treatments could be from leaf surface orientation along with petiole length. Leaf angle could have hindered the ability of dust to adhere to leaf surfaces and larger dust amounts could have been unable to be retained by leaves due to long petioles and the nature of dust application. Therefore, as applied, dust amount was a larger deviation from the target rate was expected. Furthermore, weekly dust applications are more aligned with pulse events than how actual road dust is deposited. Road dust deposition may have a higher frequency than pulse events and vary in intensity depending on fine particle content of road, soil moisture content, vehicle weight, and vehicle speed (Gillies et al. 2005).

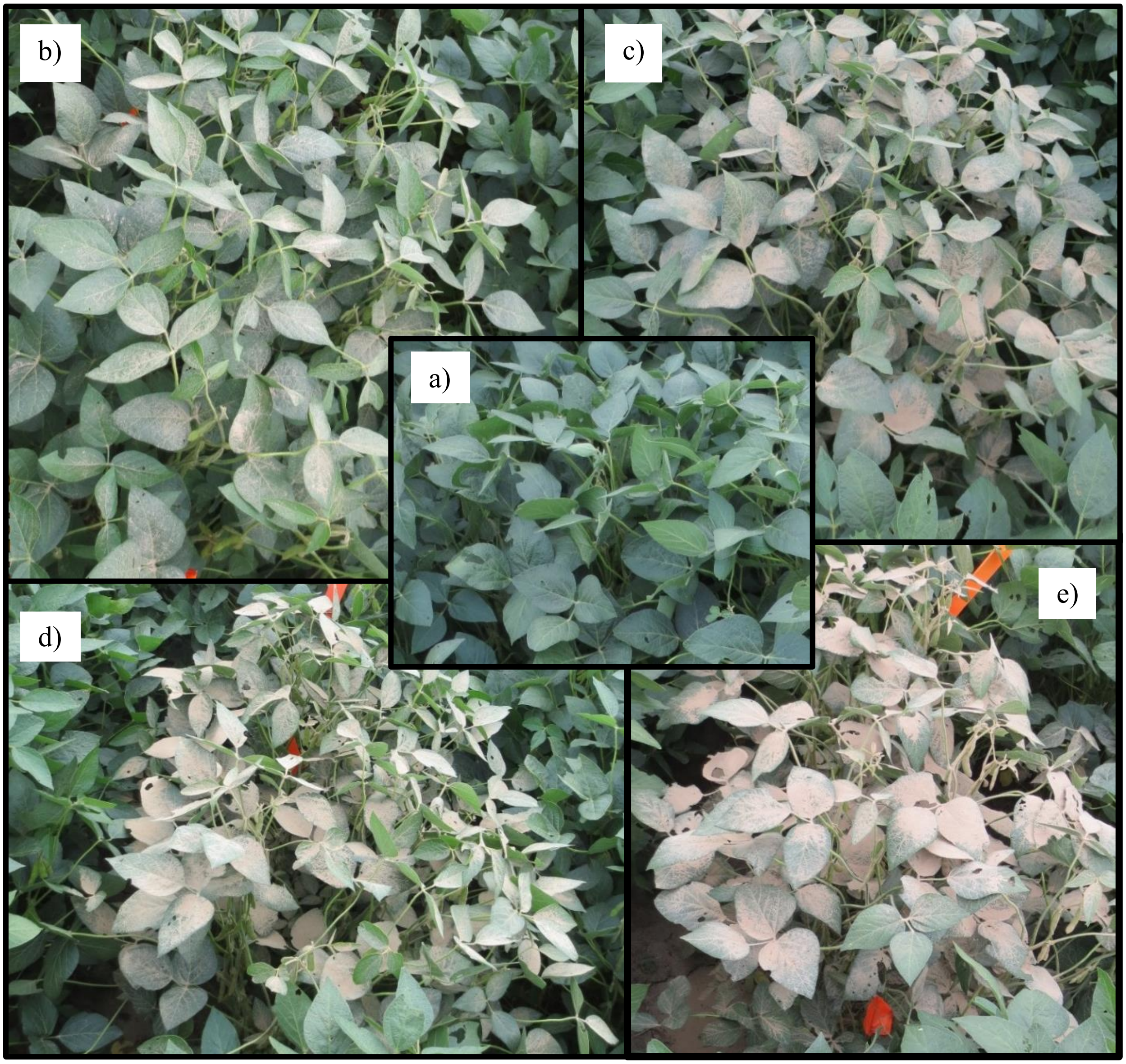

Figure 2.4. Soybean treatment areas after weekly dust application: a) 0 g/m^2; b) 15.8 g/m^2; c) 78.8 g/m^2; d) 158 g/m^2; e) 315 g/m^2.

Even then, deposition of road dust on vegetation depends on wind speed, vegetation characteristics, plant distance from dust source, and dust particle size (Farmer 1993; Everett 1980; Tamm and Troedsson 1955; Rao 1971). Headlands, along with gravel roads, create dust and edge effects; however, this study didn't account for these random edge effects. This study examined pulse dust effects on soybean production and seed quality. Results of the study provide a knowledge base for future research on dust effects on soybean production and seed quality.

Chlorophyll Content

No significant differences were seen in chlorophyll content of treatments within the 2015 growing season ($p > 0.05$), and no trends existed. The average chlorophyll contents were lowest for 0 g/m^2, increased at the 15.8 g/m^2, decreased at the 78.8 g/m^2, but increased at the 158 g/m^2 (Table 2.7). In 2016, given that the statistical repeated measures model accounted for the different growth stages, the test of the main treatment effects for chlorophyll content were found to be significantly different ($p < 0.05$) (Table 2.8). The highest amount of chlorophyll content belonged to the 2×158 g/m^2, with 315 g/m^2 having the second highest chlorophyll content (Table 2.8). In 2016, chlorophyll content at the 15.8 g/m^2 treatment was significantly different from the chlorophyll content of 315 g/m^2 ($p < 0.05$) and the 2×158 g/m^2 treatment ($p < 0.05$) (Table 2.8). Chlorophyll content of treatments within each growth stage, were not significantly different for 2015 or 2016 ($p > 0.05$). Chlorophyll content among growth stages in 2015 and 2016 were significantly different ($p > 0.05$) except for V4 and R3 in 2016. Interactions between stages and treatments were not significant ($p > 0.05$).

Leaf chlorophyll content is expected to be different at different growth stages as leaf composition and color are functions of leaf age (Gupta and Woolley 1971). In young leaves the rate of chlorophyll synthesis starts out rapid and then as leaf cells age chlorophyll development gradually slows down until a constant value of chlorophyll has been achieved (Gupta and Woolley 1971). A study on a number of genotypes for wheat by Hamblin et al. (2014), found averages of SPAD measurements of chlorophyll content consistent over time, when time differences in plant measurements were accounted for with a mixed linear model approach. Wheat is similar to soybean as it has been recommended that both could use SPAD readings to determine chlorophyll content, in relation to nitrogen deficiency (Hamblin et al. 2014; Fritschi and Ray 2007).

Table 2.7

Average chlorophyll content in SPAD units at each growth stage measured for the 2015 growing season.

Treatment (g/m^2)	**Measured Growth Stages**				**Overall Average**
	V4	**R1**	**R3**	**R6**	
0	30.8 (3.68)	33.1 (2.38)	34.1 (1.59)	38.3 (2.36)	34.1
15.8	31.3 (3.37)	33.3 (1.51)	35.2 (2.51)	38.4 (2.10)	34.5
78.8	31.2 (2.74)	32.8 (2.75)	34.3 (1.96)	39.0 (1.46)	34.3
158	31.6 (4.11)	33.7 (2.36)	35.6 (1.31)	39.7 (1.30)	35.2
Average	31.2^a	33.2^b	34.8^c	38.8^d	

Note. Small letters denote significance across row. Different letters in superscript denote significance at $p < 0.05$. Overall average is the average chlorophyll content across all the measured growth stages. Standard deviations are presented in parentheses.

Table 2.8

Average chlorophyll content in SPAD units at each growth stage measured for the 2016 growing season.

Treatment (g/m^2)	**Measured Growth Stages**				**Overall Average**
	V4	**R1**	**R3**	**R6**	
0	34.0 (0.78)	30.3 (1.30)	31.9 (2.11)	42.0 (1.03)	34.6^{AB}
15.8	32.0 (2.09)	30.1 (1.27)	33.7 (1.46)	41.0 (1.10)	34.2^{A}
78.8	33.6 (1.52)	31.9 (1.02)	32.2 (2.26)	41.5 (1.81)	34.8^{AB}
158	33.0 (3.36)	31.2 (0.87)	33.3 (1.84)	41.8 (1.18)	34.8^{AB}
315	34.9 (2.10)	32.0 (1.02)	33.1 (1.61)	41.9 (1.21)	35.5^{B}
2×158	34.7 (1.92)	32.3 (0.98)	33.9 (1.38)	41.4 (1.58)	35.6^{B}
Average	33.7^a	31.3^b	33.0^a	41.6^c	

Note. Small letters denote significance across row. Capital letters denote significance down column. Different letters in superscript denote significance at $p < 0.05$. Overall average is the average chlorophyll content across all the measured growth stages. Standard deviations are presented in parentheses.

Overall this study only found a significant difference in chlorophyll content in 2016 between the dust treatment of 15.8 g/m^2 and 315 g/m^2, as well as, 15.8 g/m^2 and 2×158 g/m^2 (Table 2.8). However, no significant differences were seen between dusted treatments and the zero dust treatment. The 15.8 g/m^2 had an average chlorophyll content just below that of the zero dust treatment and significant differences from the 315, and 2×158 g/m^2 treatments may be due to the visual observation of chlorosis in the field at the V4 growth stage measurement of chlorophyll readings. Chlorosis in the field affected the 15.8 g/m^2 treatment in replicate one and two, and affected 78.8, and 158 g/m^2 in replicate one. Chlorosis was no longer visible at later growth stages (i.e. R1, R3, and R6) for chlorophyll readings.

Reductions in chlorophyll content by dust has been detected to be significantly different in dusted crops such as grape (Leghari et al. 2014), and wheat and garden pea (Jwan Khidhr Rahman 2015). In the study by Leghari et al. (2014), grape plants were exposed to road side dust containing a mixture of harmful metals. Furthermore, Jwan Khidhr Rahman (2015) reported the dust applied to wheat and garden pea contained a total concentration of 66 mg/kg of K, 400 mg/kg Na, 500 mg/kg Ca, 1.5 mg/kg N, 400 mg/kg Mg, 35 mg/kg Zn, an EC of 0.49 dS/m and a pH of 7.90. The experimental dust in this study contained a similar pH, EC, and K, however, it lacked concentrations of Na, Zn, and Mg, but had a greater amount of Ca. Therefore, a possible reason for the lack of significant differences in chlorophyll content in soybean caused by dust, maybe due to the applied dust not containing harmful elements or high enough amounts of harmful elements at the applied rates. Additionally, the weekly applied amounts of dust to soybeans could have received enough wind and rainfall to be removed from leaf surfaces between applications.

Removal of particulate matter (PM) by wind and rainfall have been found to affect dust accumulation amounts on leaves (Wang et al. 2015). In a study by Przybysz et al. (2014), 30 to 41% of PM washed off with 20 mm of simulated rainfall, of which contained about 38% very coarse (100 to 10 µm), 30% coarse (10 to 2.5 µm), and 25% fine (2.5 to 0.2 µm) fractions.

Furthermore, Freer-Smith et al. (2005) reported that accumulation of coarse (<10 µm), fine (<2.5 µm and >0.1 µm), and ultra-fine (< 0.1 µm) PM on poplar (*Populus deltoides*), field maple (*Acer campestre*), pine (*Pinus nigra*), cypress (*Cupressocyparis leylandii*), and whitebeam (*Sorbus intermedia*) were not significantly different before and after a two day rainfall event. The studies above examined trees near urban and rural sites that experienced dust deposition on a daily basis and could explain why significant amounts of dust remained on leaf surfaces after a rainfall event.

The particle size fraction that makes up the dust applied to soybeans could have hindered the capacity of dust to accumulate on leaves. The applied dust was determined to be 72.8% sand (2.0 mm to 0.05 mm), 20.9% silt (0.05 mm to 0.002 mm), and 6.3% clay (<0.002 mm). Standardization of the applied dust with a number 40 sieve removed coarse sand particles (2.0 mm to 0.4 mm) (Gee 2002). Particles sizes of 0.044 to 0.177 mm were found to be removed by 46% from leaf surfaces due to wind in 2.5 days and 90% lost in a week due to wind and rain (Armbrust 1986). For larger particles (0.088 to 0.77 mm), the maximum retention time was found to be 10 days (Armbrust 1986). Particle losses have also been found to be rapid in the first day of application (Armbrust 1986). Particle sizes of the applied dust fall largely in the size range for larger particles and were more easily removed than smaller particles of silt or clay.

Along with particle size, retention of dust on leaf surfaces was determined to be based on leaf surface characteristics (Chauhan et al. 2010). A positive correlation between total PM accumulation and leaf hair density, along with quantity of leaf waxes were found, but not for leaf surface roughness or leaf size (Sæbø et al. 2012). Soybean leaf hairs add around 10 percent surface area to leaf surfaces and are about one mm long and spaced one mm apart on leaf surfaces (Woolley 1964). However, the orientation of leaf hairs are not perpendicular to the leaf surface but slant toward the tip and sides. In young leaves the hairs are filled with water but become hydrophobic and air-filled or flattened as leaves age or if hairs are bent (Woolley 1964). Soybean leaves have rosette-like clusters of wax platelets on both adaxial and abaxial surfaces (Damato et al. 2017), but adaxial surfaces may not contain enough wax content to capture PM as was found in conifer needles (Sæbø et al. 2012). Furthermore, the orientation of soybean leaf hairs, leaf hair density, and leaf hair age may not be conducive in dust accumulation on leaf surfaces.

Leaf Temperature

Average leaf temperature of treatments for growing season 2015 are in Table 2.9 and the same data for 2016 are displayed in Table 2.10. Differences in leaf temperature occurred among treatments but were variable in both years, with treatment differences from ambient air temperatures ranging from 0.46 to 7.72 ˚C and from the zero dust treatment from -1.35 to 1.15 ˚C across growth stages. No significant differences were found in leaf temperatures of treatments within each growth stage for 2015 or 2016 ($p > 0.05$). Interactions between growth stages and treatments were not significant ($p > 0.05$).

Table 2.9

Average leaf temperature (˚C) of treatments in 2015 growing season.

Treatment (g/m^2)	**V4**	**R1**	**R3**	**R6**
0	25.6 (1.15)	28.7 (2.35)	24.8 (1.12)	28.2 (1.28)
15.8	25.8 (1.02)	28.7 (1.68)	24.7 (0.86)	28.3 (1.59)
78.8	25.9 (1.29)	29.3 (1.12)	24.6 (1.42)	27.7 (0.91)
158	25.8 (1.22)	29.4 (1.14)	25.2 (1.43)	28.6 (1.33)

Note. Standard deviations are presented in parentheses.

Table 2.10

Average leaf temperature (˚C) of treatments in 2016 growing season.

Treatment (g/m^2)	**V4**	**R1**	**R3**	**R6**
0	20.1 (1.05)	28.3 (0.87)	25.6 (2.06)	24.0 (0.79)
15.8	20.2 (1.30)	28.7 (0.72)	24.5 (3.26)	23.9 (0.73)
78.8	20.7 (1.36)	29.1 (0.90)	24.8 (3.04)	24.0 (0.69)
158	21.3 (1.66)	28.7 (1.34)	24.3 (3.20)	24.4 (0.60)
315	20.7 (1.56)	29.2 (1.76)	25.7 (2.42)	24.5 (0.81)
2×158	21.3 (1.31)	29.0 (1.04)	26.1 (2.83)	24.1 (0.70)

Note. Standard deviations are presented in parentheses.

Studies on dust impacts on crops has typically reported an increase in leaf temperature from dust. Increases in leaf temperature have been reported in cotton (*Gossypium hirsutum* L) (Zia-Khan et al. 2015), where dusted cotton leaves were found to have the highest increase in temperature of 4.1 ˚C when compared to leaves that were rinsed with water (Zia-Khan et al. 2015). In cucumber (*Cucumis sativus* L.) and kidney bean (*Phaseolus vulgaris* L.), Hirano et al. (1995) reported leaf temperature differences of dusted leaves from control leaves to be 3.7, 3.1, and 1.7˚C at air temperatures of 15, 25, and 40 ˚C, respectively. In comparison to this study, on days that leaf temperature readings were taken between 1000 and 1400, ambient air temperatures differed anywhere from 2 to 9˚C (NDAWN 2015; NDAWN 2016) and had more variation than leaf temperature differences of dusted leaves in comparison to non-dusted leaves. Over the course of the growing season ambient air temperatures ranged from -6 to 34 ˚C (NDAWN 2015; NDAWN 2016). Ambient air temperature fluctuations could have mitigated increases in leaf temperature between dust applications and before leaf temperature readings. Furthermore, a study on an evergreen shrub (*Viburnum tinus*), found that leaf temperature didn’t increase by dust due to a high air flow rate which kept the leaf temperature close to air temperature (Thompson et al. 1984). Leaf temperature measurements were taken irrespective of wind speed so the reduction in the boundary layer over the leaves due to wind may have normalized leaf temperatures across treatments.

Another possibility could be leaf temperatures of dusted soybean leaves could have returned to normal by the time leaf temperature readings were taken a week after dust application. Leaf temperature readings were done right before the weekly dust application and was at a point of maximum dust 'wear off'. Even though, soybean leaf hairs were found to reduce wind speed by 40%, 0.50 mm from the leaf surface, it is unknown what leaf hair affect would have on wind speeds of more than 100 cm/s (Woolley 1964). Furthermore, leaf hairs have been found to minimize water loss at the leaf surface, even when hairs were flattened or air-filled (Woolley 1964). Leaf hydraulic conductance of aged leaves on the plant may also prevent leaf temperature increases in the measured leaflets in the uppermost part of the plant. As leaves age a decline in leaf hydraulic conductance was found and enabled the hydraulic supply to be kept in balance with plant demand without limiting transpiration (Locke and Ort 2014). Therefore, by the time leaf temperature readings were taken any spikes in leaf temperature by dust may have been lost, as dust was removed before leaf temperature readings and leaf transpiration could have mitigated any temperature effect caused by dust.

Yield

Analysis of the yield data found no significant differences in treatment yields for either 2015 or 2016 ($p > 0.05$) (Table 2.11). Variation in yield characteristics was observed among treatments, but no significant differences were found ($p > 0.05$) in 2015 (Table 2.12) or in 2016 (Table 2.13). It has been shown that soybean seed yield has a significant positive relationship with number of seeds per pod, number of seeds per plant, and number of pods per plant, with the strongest relationship with number of seeds per pod (Ali et al. 2013). In both years, number of seeds per pod was accounted for; however, number of seeds per plant and number of pods per plant were only determined in 2016.

Table 2.11

Yield of treatments were adjusted to 13% moisture content and are presented in g/m^2 and bu/ac (adjusted to 13% water content) for growing season 2015 and 2016.

Treatment (g/m^2)	**2015**		**2016**	
	g/m^2	**bu/ac**	**g/m^2**	**bu/ac**
0	288 (46.7)	42.8 (6.95)	334 (50.3)	49.6 (7.47)
15.8	286 (37.1)	42.5 (5.51)	379 (45.9)	56.3 (6.82)
78.8	291 (66.9)	43.3 (9.94)	378 (46.7)	56.3 (6.95)
158	276 (74.3)	41.1 (11.1)	335 (31.7)	49.9 (4.71)
2×158	-	-	320 (36.1)	47.6 (5.36)
315	-	-	359 (77.8)	53.3 (11.6)

Note. Standard deviations are provided in parentheses following averages.

Table 2.12

Yield characteristics per treatment for 2015 growing season.

Treatment (g/m^2)	**# pods/plot**	**# seeds/pod**	**# seeds/plot**	**Seed weight (g)**	**Seed weight (mg)/seed**	**Seed weight (mg)/pod**
0	529 (72.2)	2.47 (0.07)	1305 (186)	203 (33.2)	155 (6.04)	383 (17.20)
15.8	551 (51.7)	2.42 (0.06)	1335 (129)	202 (26.0)	151 (7.85)	366 (21.64)
78.8	556 (113)	2.41 (0.07)	1335 (253)	206 (47.1)	153 (9.32)	369 (24.15)
158	542 (149)	2.43 (0.10)	1311 (340)	196 (52.8)	149 (6.68)	363 (28.14)

Note. Standard deviations are provided in parentheses following averages.

Table 2.13

Yield characteristics per treatment for the 2016 growing season.

Treatment (g/m²)	**# pods/ plot**	**# seeds/ pod**	**# seeds/plot**	**Seed weight (g)**	**Seed weight (mg)/seed**	**Seed weight (mg)/pod**	**# seeds/ plant**	**# pods/ plant**
0	580 (81.4)	2.61 (0.24)	1517 (268.6)	235 (35.5)	156 (10.1)	406 (16.4)	73.9 (9.18)	28.4 (4.06)
15.8	652 (71.0)	2.47 (0.10)	1606 (166.6)	267 (32.5)	166 (7.05)	410 (21.7)	72.9 (16.8)	29.7 (7.51)
78.8	642 (65.0)	2.57 (0.17)	1652 (242.9)	267 (33.7)	162 (9.22)	415 (14.6)	81.9 (12.8)	32.2 (6.22)
158	601 (37.4)	2.43 (0.11)	1455 (94.54)	236 (22.5)	162 (6.71)	393 (19.9)	76.4 (10.8)	31.5 (3.99)
2×158	591 (73.0)	2.41 (0.14)	1416 (136.3)	226 (25.5)	159 (4.56)	383 (22.6)	70.7 (10.1)	29.4 (4.38)
315	611 (95.1)	2.53 (0.18)	1554 (305.0)	253 (55.7)	162 (5.65)	411 (39.3)	73.4 (10.5)	29.1 (4.29)

Note. Standard deviations are provided in parentheses following averages.

No study to date has specifically looked at the impacts of dust on soybeans or its yield as a result of dusts being present on leaves. Dust impacts on crop production have been observed in cotton (Zia-Khan et al. 2015), grape (Leghari et al. 2014), and in wheat and garden pea (Jwan Khidhr Rahman 2015); however, only Zia-Khan et al. (2015) looked at yield specifically. Zia-Khan et al. (2015) found that dust decreased cotton yield by 28%; while Leghari et al. (2014) determined a negative correlation between growth rate and dust amount but didn’t investigate yield. Dust has also been shown to impact wheat and garden pea through decreases in plant height, leaf area, and in wheat spike length and pea pod length (Jwan Khidhr Rahman 2015). Among different soybean varieties tested under semi-arid condition, a significant positive relationship has been determined for soybean seed yield and plant population, plant height, plant biomass, and leaves per plant (Ali et al. 2013). Therefore, a similar photosynthetic response could have been seen in soybeans, with the appearance of new leaves, along with the removal of dust by rain and wind between dust applications, any hindrances by dust to plant metabolic processes could have been mitigated, thereby, preventing reductions in soybean yield.

Effects of car exhaust dust on an evergreen shrub (*Viburnum tinus*) were observed with 5 to 10 g/m^2 of dust per leaf (Thompson et al. 1984). However in the same study, leaves of shrubs in central reserves of motorways were only found to have a maximum dust load of 2 g/m^2 and car exhaust dust was determined to have a minimal effect on plant photosynthesis (Thompson et al. 1984). In comparison to soybeans, it is likely that in our study, the average dust amount found per leaf area per treatment were too small to have hindered any physiological processes. On the other hand, dust loads of 1.0 to 1.5 g/cm^2 from an urban road were found to increase leaf temperature in aspen (*Populus tremula*) (Fluckiger et al. 1979) and urban road dusts at 0.0039 to 0.0077 g/cm^2 declined leaf area, chlorophyll concentration, photosynthetic rate, and water-use efficiency in four tree species (*Anthocephalus cadamba*, *Mangifera indica*, *Syzygium cumini*, and *Tectona grandis*) along the roadside (Chaturvedi et al. 2013). Even so, Chaturvedi et al. (2013) determined that *Tectona grandis* and *Mangifera indica* had greater declines in the aforementioned traits and were; therefore, more sensitive to higher dust loads than *Syzygium cumini* and *Anthocephalus cadamba*. Plant response to dust contamination level is variable between species and is apparent at higher dust loads. For soybeans, the lack of significant differences in yield could mean that it may take a more frequent application of dust for dust to accumulate and cause negative effects on soybean yield and yield characteristics.

Seed Composition

The NMS analysis of the seed composition data set for the 2015 growing season produced a final solution in 59 iterations, as three dimensional that accounted for 97.2% of the variation in the data, at a final stress of 6.15, and a final instability of 0.00000 (Figure 2.5). Strong positive correlations with axis 1 included linoleic acid (0.886), and linolenic acid (0.609). A strong negative correlation with axis 1 occurred with oleic acid (-0.981), while weak negative correlations included: glycine (-0.441), methionine (-0.488), stearic acid (-0.516), and tryptophan (-0.412). For axis 2, a strong positive correlation involved the following: alanine (0.850), arginine (0.886), aspartic acid (0.898), available lysine (0.833), glutamic acid (0.897), glycine (0.720), histidine (0.830), isoleucine (0.853), leucine (0.870), lysine (0.892), phenylalanine (0.823), proline (0.801), protein (0.874), serine (0.881), threonine (0.892), tyrosine (0.835), and valine (0.821). Weak positive correlations with axis 2 were cysteine (0.440), and linolenic acid (0.548). A strong negative correlation with axis 2 included oil (-0.655) and weak negative correlations involved hydroxylysine (-0.586), and raffinose (-0.434).

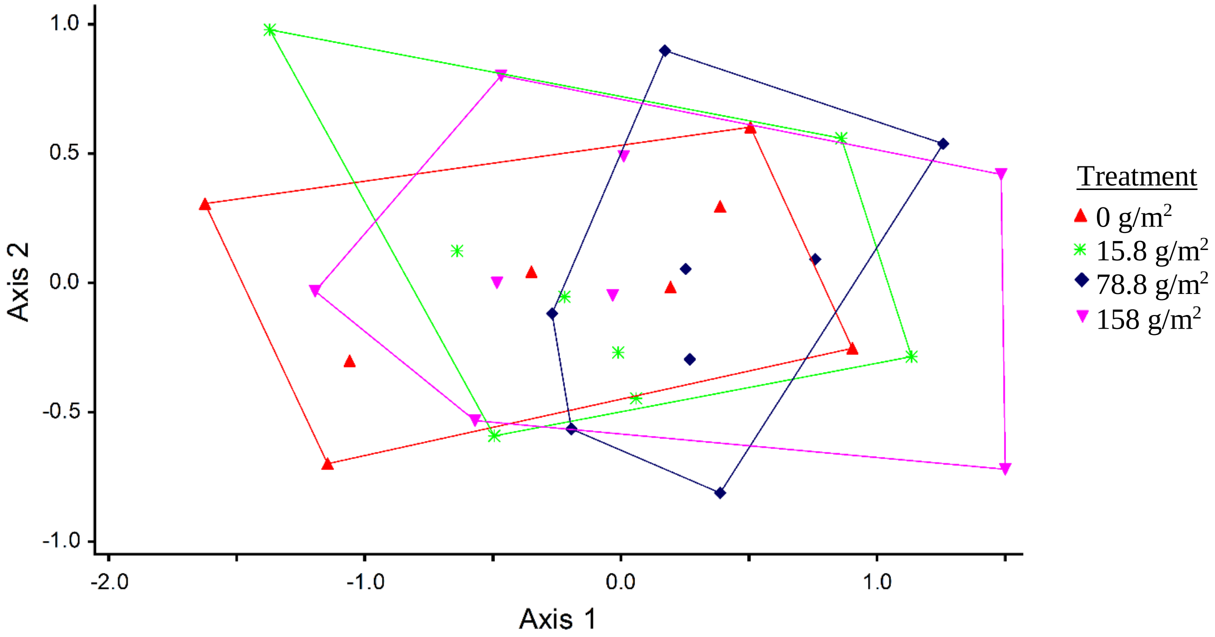

Figure 2.5. 2015 growing season Nonmetric Multidimensional Scaling (NMS) ordination of soybean seed composition data for each treatment of 0, 15.8, 78.8, and 158 g/m^2. Points in ordination space represent a replication of a treatment.

The NMS analysis of seed composition data for the 2016 growing season produced a one dimensional final solution in 62 iterations that explained 98.0% of the variation in the data, with a final stress of 7.23, and a final instability of 0.00000 (Figure 2.6). A strong positive correlation (*r*) with axis 1 occurred with linoleic acid (0.988) and a weak positive correlation with moisture percentage (0.420). Strong negative correlations with axis 1 included linolenic acid (-0.795), and oleic acid (-0.992), and a weak negative correlation with neutral detergent fiber based on percent dry matter (-0.477), and palmitic acid (-0.429). Differences observed in ordination of seed composition data may result from genetics in the use of two different varieties and from ecological variations between the two growing seasons (Anwar et al. 2016; Bellaloui et al. 2015). PERMANOVA of seed composition amongst treatments were not significantly different for 2015 or 2016 ($p > 0.05$). Factor analysis of a priori seed components found no significant differences in either year for selected seed components ($p > 0.05$) (Table 2.3).

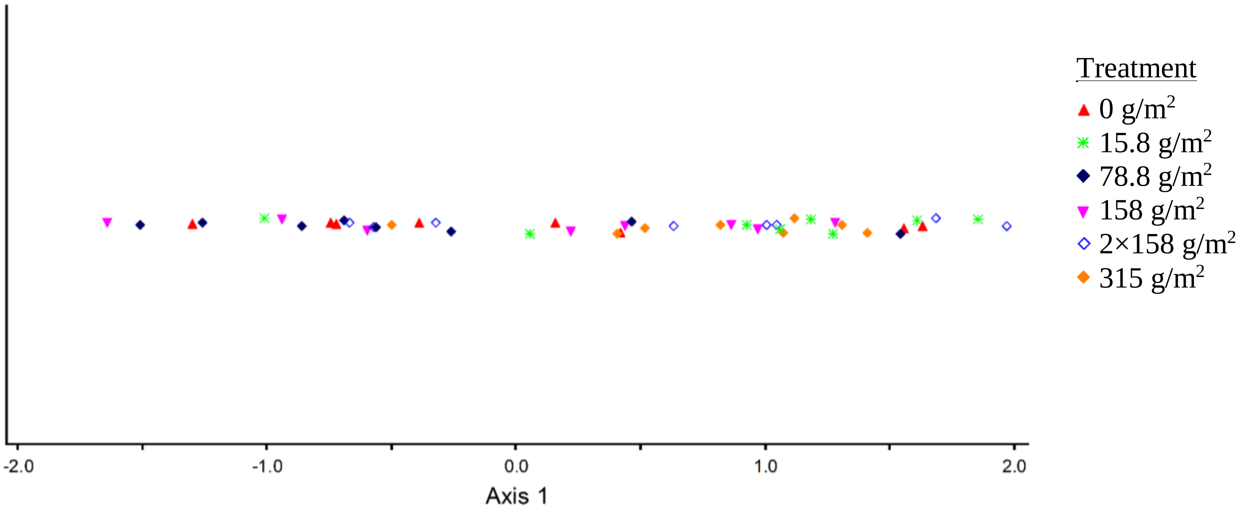

Figure 2.6. 2016 growing season Nonmetric Multidimensional Scaling (NMS) ordination of soybean seed composition data for each treatment of 0, 15.8, 78.8, 158, 2×158, and 315 g/m^2. Points in ordination space represent a replication of a treatment.

Seed composition factors that have been effected by road dust include wheat, garden pea, and field mustard (Chauhan et al. 2010; Jwan Khidhr Rahman 2015). In the study by Jwan Khidhr Rahman (2015), total carbohydrate and water content decreased in wheat as proline content increased; whereas, in the garden pea total carbohydrate content decreased as water content and proline content increased. The decrease in total carbohydrate content in both wheat and garden pea were due to dust containing harmful metals which reduced the amount of food available to the plants. Furthermore, the proline content rise in both crops was found to be a defense mechanism towards environmental stress (Jwan Khidhr Rahman 2015). Chauhan et al. (2010) established a similar response in wheat and mustard; however, the response triggered a decline in ascorbic acid and carotenoids. The ascorbic acid was utilized by the plant to combat oxidative stress while the carotenoids protected chlorophyll-protein complexes against photo-oxidative stress (i.e. activation of oxygen) due to high exposure to ultraviolet irradiation (Chauhan et al. 2010). In both studies, dust deposited on plants contained chemical elements and may have prompted a defensive metabolic plant response. Furthermore, photo-oxidative stress is known to damage pigments, proteins, and lipids in the thylakoid membrane, which decreases photosynthetic efficiency (Szabó et al. 2005). In this study, no significant defense responses were observed in soybean seed composition and could be from the experimental dust not containing elements that are harmful to plant processes.

Conclusion

This study examined impacts of dust on soybean production and seed quality. Production, as determined by chlorophyll content, leaf temperature, and yield were not significantly different among treatments and seed quality via seed composition of treatments, were not significantly different among treatments. The minimal effect that dust had on physiology and yield fills a knowledge gap in how increased deposition of road dust may affect soybean production and quality. Previous studies have reported increased leaf temperature, altered photosynthetic rate, and decreased yield or yield components. However, even at the highest dust amounts this study found no significant differences in those factors which in part could be attributed to the inert nature of the dust, in that no biologically harmful elements were found at the rates applied.

Further studies should determine the constituents and potential harmful agents found in road dust and determine if those constituents impact soybean production and seed quality; as the inert dust showed no impact on yield or seed components even with high application rates. In addition, dust was shown to be removed from leaves after a duration of time. Due to constraints this study was only able to apply dust one or two times per week, thus understanding the daily loads of dust to the plants should be investigated. Also, further investigations into soybean leaf temperature immediately following dust application may better quantify the impacts that dusts have on soybeans.

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APPENDIX A. WEATHER VARIABLES FOR THE 2015 GROWING SEASON

Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
5/18	18.9	1.78	4.1	0.4	2.29	-29.38	126.80	
19	9.90	0.00	13.7	-0.3	6.71	-24.95	678.86	
20	8.14	0.00	22.6	0.7	11.64	-20.58	650.05	
21	8.78	0.00	21.6	5.8	13.70	-18.52	678.67	
22	7.34	0.00	25.4	3.9	14.66	-17.56	663.24	
23	10.1	0.00	24.0	7.1	15.57	-17.21	641.86	
24	9.42	0.00	22.2	8.5	15.37	-17.41	309.98	
25	5.25	7.62	19.5	10.4	14.93	-17.85	234.33	
26	8.30	0.00	26.8	8.4	17.59	-15.74	546.95	
27	10.1	0.25	28.0	12.4	20.22	-13.11	605.76	
28	18.2	11.18	29.8	15.4	22.61	-10.72	366.32	
29	15.5	0.25	17.2	5.3	11.22	-22.67	394.00	
30	11.2	0.00	15.2	0.9	8.03	-25.86	710.87	
31	10.2	0.00	17.5	4.8	11.14	-22.75	398.07	
6/1	15.0	0.00	24.0	10.8	17.37	-17.08	387.30	
2	11.8	0.00	27.8	14.7	21.22	-13.23	314.63	
3	9.90	0.00	20.9	12.3	16.63	-17.81	158.41	
4	11.2	0.00	24.3	12.2	18.23	-16.78	522.57	
5	9.90	0.00	25.5	13.2	19.37	-15.63	457.70	
6	12.9	10.16	23.8	14.0	18.90	-16.11	280.61	
7	12.3	0.00	29.8	13.6	21.69	-13.87	665.09	
8	12.0	0.25	31.2	12.8	22.01	-13.55	632.78	
9	14.7	0.00	33.2	13.1	23.15	-12.41	578.88	
10	6.70	0.00	23.9	13.7	18.77	-16.79	442.55	
11	6.86	0.00	27.8	15.4	21.60	-14.51	658.51	
12	11.0	0.00	29.0	11.9	20.46	-15.65	705.56	
13	11.7	0.00	29.6	14.2	21.94	-14.18	628.32	
14	9.10	40.41	21.5	13.8	17.67	-18.45	382.28	
15	9.26	0.00	20.5	10.3	15.41	-21.26	557.53	
16	6.86	7.37	15.6	7.0	11.29	-25.38	170.29	
17	5.09	0.00	21.3	10.8	16.07	-20.60	385.43	
18	9.58	0.25	20.4	10.5	15.44	-21.23	612.32	ALL
19	12.5	1.27	29.2	12.6	20.89	-16.34	596.10	
20	9.10	1.78	26.7	14.0	20.37	-16.86	467.25	
21	15.8	13.97	30.1	11.7	20.88	-16.34	662.33	

Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
22	13.7	3.81	23.0	13.6	18.28	-18.95	499.49	
23	7.66	0.00	28.2	11.6	19.89	-17.89	645.34	ALL
24	12.8	1.78	28.6	14.8	21.66	-16.12	491.49	
25	5.74	0.25	27.1	12.2	19.66	-18.12	613.15	
26	11.5	0.00	29.4	15.6	22.51	-15.27	656.82	
27	11.3	28.47	28.9	15.0	21.93	-15.85	439.68	
28	8.46	0.00	27.6	15.4	21.49	-16.29	632.00	
29	6.54	0.00	24.4	16.6	20.50	-17.83	309.71	
30	4.45	0.00	23.5	13.6	18.51	-19.82	311.44	ALL
7/1	6.54	0.00	24.8	15.3	20.02	-18.31	509.73	
2	7.66	0.00	25.9	13.1	19.52	-18.81	533.42	
3	4.77	0.00	28.5	15.8	22.17	-16.17	508.46	
4	9.42	0.00	29.5	14.5	22.04	-16.29	557.73	
5	9.58	0.00	28.5	18.4	23.45	-14.88	397.38	
6	10.9	0.00	20.1	8.2	14.14	-24.75	540.32	ALL
7	7.34	0.00	23.1	6.4	14.73	-24.16	711.49	
8	7.66	6.10	21.7	12.0	16.86	-22.03	368.41	
9	5.42	0.00	28.0	10.3	19.11	-19.78	663.19	
10	7.18	0.00	30.5	12.2	21.37	-17.52	657.39	
11	9.42	0.00	29.3	19.2	24.27	-14.62	539.09	
12	13.6	3.05	31.8	18.6	25.18	-13.71	531.89	
13	6.54	2.79	28.1	18.0	23.05	-15.84	495.97	
14	5.42	0.00	30.8	18.1	24.41	-14.48	613.15	
15	13.4	2.79	30.8	18.1	24.46	-14.43	350.20	
16	10.1	1.27	27.1	18.4	22.75	-16.69	359.96	
17	18.2	35.08	29.1	14.9	22.01	-17.44	571.48	ALL
18	12.9	0.25	23.3	14.8	19.02	-20.43	564.28	
19	9.26	0.00	29.1	13.9	21.53	-17.91	686.64	
20	7.66	0.00	24.0	13.5	18.71	-20.73	685.38	
21	4.13	0.00	27.4	12.0	19.72	-19.73	570.38	
22	7.66	12.19	29.2	18.0	23.60	-15.85	632.23	ALL
23	12.1	10.67	29.9	17.8	23.84	-15.60	624.68	
24	7.66	4.57	27.9	17.6	22.76	-16.69	559.33	
25	8.62	0.00	29.2	14.7	21.98	-17.47	423.06	
26	6.22	0.00	30.1	15.5	22.80	-16.65	656.95	
27	8.62	0.00	30.4	17.4	23.94	-15.50	604.67	
28	15.4	9.65	24.9	18.2	21.54	-17.91	611.05	

Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
29	13.9	0.00	26.9	16.4	21.63	-17.81	600.34	
30	11.3	0.00	27.6	13.7	20.66	-18.78	621.60	
31	7.66	0.00	27.5	12.1	19.78	-19.66	660.07	ALL
8/1	6.06	0.00	29.4	11.6	20.50	-18.94	605.69	
2	9.26	0.00	25.1	11.8	18.44	-21.01	598.88	
3	8.62	0.00	25.4	9.6	17.48	-21.96	668.68	
4	6.22	0.00	26.5	8.9	17.71	-21.73	646.70	ALL
5	7.18	0.00	26.7	10.1	18.37	-21.08	456.14	
6	6.06	0.00	24.2	17.0	20.58	-18.86	235.45	
7	12.0	12.47	29.2	12.9	21.03	-17.86	574.06	
8	5.25	2.03	28.1	15.6	21.85	-17.04	537.56	
9	6.06	0.00	26.4	15.0	20.71	-18.18	495.41	
10	5.25	0.00	27.9	12.9	20.40	-18.49	615.90	ALL
11	5.90	0.00	29.7	11.4	20.52	-18.37	609.49	
12	10.5	0.00	32.3	13.2	22.77	-16.12	563.17	
13	6.70	0.00	31.1	18.4	24.72	-14.17	327.74	
14	5.25	0.00	33.5	16.9	25.19	-13.15	555.99	
15	10.5	1.78	33.6	21.3	27.43	-10.91	563.63	
16	10.2	0.51	23.1	12.5	17.80	-20.54	212.63	
17	4.77	0.00	24.0	10.0	17.02	-21.32	485.44	
18	8.30	11.68	18.0	10.1	14.03	-24.30	108.12	
19	9.10	0.76	21.6	8.3	14.97	-22.81	408.00	
20	5.90	0.00	24.3	5.6	14.92	-22.85	591.29	ALL
21	7.98	0.00	27.5	13.1	20.32	-17.46	424.00	
22	16.0	4.57	23.8	10.8	17.28	-20.50	122.52	
23	18.1	2.54	20.8	10.9	15.85	-21.38	502.88	
24	9.58	0.00	21.5	7.6	14.55	-22.67	583.57	
25	6.06	0.00	22.7	5.6	14.19	-23.03	566.35	
26	6.38	0.00	24.6	6.3	15.47	-21.75	504.02	ALL
27	5.58	0.00	25.6	10.5	18.07	-18.60	388.23	
28	8.78	0.00	27.3	15.1	21.20	-15.47	456.32	
29	7.66	0.00	28.4	15.6	21.99	-14.68	369.83	
30	9.42	0.00	29.8	16.2	23.00	-13.12	455.20	
31	7.98	0.00	28.2	13.2	20.70	-15.41	341.95	
9/1	5.90	0.00	31.6	11.2	21.39	-14.72	512.31	
2	8.46	0.00	31.8	18.1	24.94	-10.62	504.36	ALL
3	11.0	0.00	33.4	20.8	27.13	-8.43	436.58	

Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
4	9.58	1.52	28.0	20.2	24.09	-10.91	185.34	
5	5.74	7.62	25.8	17.7	21.74	-13.26	152.55	
6	10.1	0.25	26.2	10.6	18.40	-16.61	257.49	
7	5.74	0.00	22.1	7.1	14.63	-19.82	246.14	
8	9.90	0.00	24.0	7.6	15.78	-18.67	509.06	
9	6.06	0.00	24.0	7.3	15.64	-18.25	332.16	
10	7.98	0.00	19.0	5.0	11.99	-21.90	407.54	
11	7.66	0.00	20.4	5.1	12.74	-21.15	471.53	ALL
12	10.1	0.00	25.1	3.1	14.14	-19.19	459.93	
13	10.7	0.00	30.8	9.7	20.24	-13.09	478.47	
14	8.30	0.00	26.5	10.0	18.24	-14.54	404.30	
15	13.6	0.00	29.1	18.2	23.68	-9.10	348.20	
16	7.50	0.00	25.9	13.9	19.92	-12.30	358.16	
17	11.8	0.00	21.5	6.4	13.95	-18.28	293.35	
18	5.90	0.76	16.1	3.2	9.63	-22.60	140.45	
19	10.9	0.00	25.8	5.0	15.35	-16.31	428.17	
20	8.78	0.00	26.3	7.7	17.00	-14.67	442.05	
21	10.2	0.00	33.3	9.6	21.45	-9.67	439.77	ALL
22	8.46	0.00	19.4	6.4	12.90	-18.21	297.18	
23	9.10	11.68	14.8	9.6	12.21	-18.90	71.57	
24	4.61	0.00	21.9	12.6	17.23	-13.33	143.46	
25	7.50	0.00	27.0	11.6	19.30	-11.26	316.83	
26	13.9	0.00	28.8	14.0	21.39	-8.61	401.10	
27	9.58	0.00	27.1	12.4	19.74	-10.27	303.91	
28	10.1	0.00	21.5	4.9	13.15	-16.29	356.31	
29	6.86	0.00	21.1	0.0	10.58	-18.87	403.45	
30	12.6	0.00	22.2	7.3	14.73	-14.71	324.36	HARVEST
10/1	12.9	0.00	19.4	8.3	13.85	-15.04	214.44	

APPENDIX B. WEATHER VARIABLES FOR THE 2016 GROWING SEASON

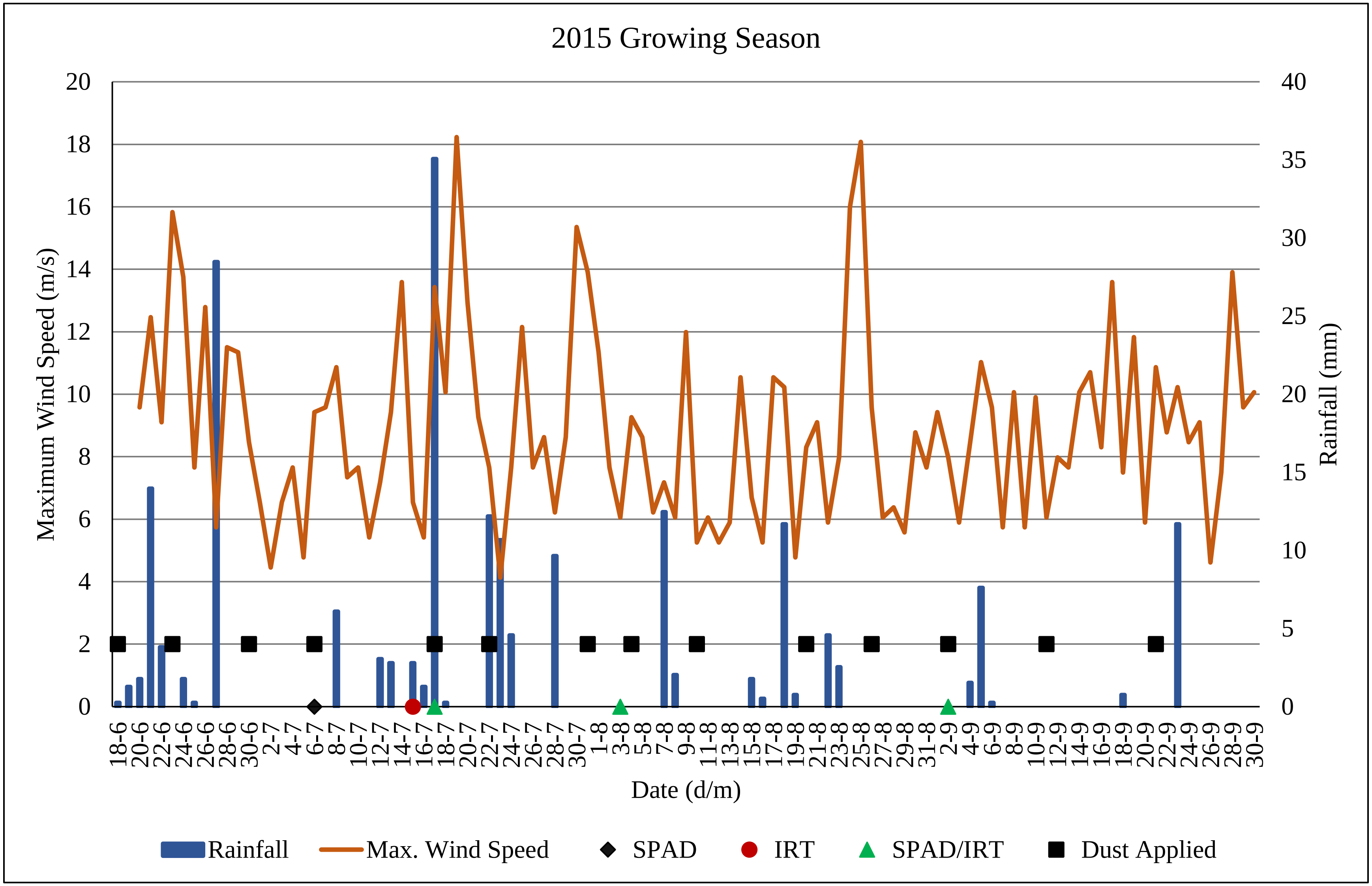
Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
5/18	11.1	0.00	24.3	1.5	12.90	-18.77	664.44	
19	13.7	0.00	27.9	9.9	18.90	-12.77	603.22	
20	12.9	0.00	24.0	12.0	17.97	-14.26	328.56	
21	14.0	0.00	28.8	6.9	17.87	-14.35	685.10	
22	17.0	2.79	28.4	10.2	19.28	-12.95	355.64	
23	9.04	6.86	28.1	16.4	22.24	-10.54	688.37	
24	12.2	0.00	27.7	13.9	20.77	-12.01	662.27	
25	11.2	24.66	20.0	13.8	16.91	-15.87	229.80	
26	11.3	10.92	23.6	10.9	17.26	-16.08	537.57	
27	7.94	6.35	22.3	11.9	17.08	-16.25	288.41	
28	9.14	0.00	21.5	14.4	17.99	-15.35	409.10	
29	11.9	0.00	25.5	12.3	18.87	-15.02	492.01	
30	16.6	25.93	30.6	10.8	20.71	-13.18	520.60	
31	13.2	3.30	20.2	10.8	15.54	-18.35	512.74	
6/1	13.3	0.00	17.0	9.7	13.31	-21.13	417.20	
2	6.47	0.00	25.1	6.9	16.00	-18.45	613.85	
3	11.9	9.65	22.7	15.1	18.90	-15.54	322.33	
4	11.9	0.00	23.0	13.6	18.30	-16.70	450.12	
5	13.5	0.00	27.2	12.9	20.02	-14.99	621.93	
6	20.8	2.54	20.8	11.8	16.27	-18.73	472.64	
7	7.14	0.00	21.9	8.1	15.00	-20.56	673.39	
8	7.61	0.00	28.2	9.5	18.85	-16.71	643.93	
9	9.34	0.00	31.7	13.7	22.67	-12.89	649.69	
10	16.1	4.06	31.8	18.4	25.13	-10.43	630.45	
11	11.2	0.00	25.3	17.1	21.21	-14.91	541.84	
12	11.4	0.51	29.5	17.3	23.44	-12.68	397.96	
13	9.04	0.00	27.9	12.9	20.39	-15.72	670.82	
14	10.9	10.92	20.7	15.8	18.23	-17.89	170.64	
15	9.14	0.25	24.6	15.8	20.20	-16.47	373.32	
16	12.2	0.00	27.9	11.9	19.90	-16.77	632.54	
17	8.94	1.02	29.4	20.4	24.93	-11.74	534.99	
18	7.77	5.08	25.8	17.0	21.43	-15.24	371.00	
19	11.4	0.00	31.1	18.6	24.85	-12.37	596.56	
20	10.9	0.00	24.5	13.6	19.04	-18.18	710.15	
21	7.11	0.00	28.0	10.7	19.35	-17.87	661.80	

Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
22	12.1	3.56	24.5	13.4	18.92	-18.31	489.04	
23	6.14	0.00	26.4	13.2	19.78	-18.00	709.56	ALL
24	12.9	0.00	29.4	13.9	21.66	-16.12	603.63	
25	12.9	0.00	28.7	15.6	22.14	-15.64	553.59	
26	13.9	0.00	26.5	15.6	21.00	-16.78	639.98	
27	9.01	0.00	21.7	10.5	16.06	-21.72	589.81	2×158
28	4.74	0.00	26.0	7.6	16.83	-20.95	718.80	
29	8.74	0.00	28.7	9.6	19.14	-19.19	669.28	
30	11.0	0.00	19.2	12.5	15.86	-22.48	581.18	
7/1	6.21	0.00	23.7	5.7	14.67	-23.67	690.18	ALL
2	5.74	0.00	26.2	14.1	20.18	-18.15	435.73	
3	10.7	0.00	27.1	12.9	20.00	-18.33	676.71	
4	12.9	5.59	30.8	16.2	23.50	-14.84	607.05	
5	11.6	0.00	26.5	14.7	20.60	-17.74	437.23	2×158
6	5.34	0.25	27.3	13.4	20.33	-18.56	500.39	
7	9.04	2.79	25.4	16.1	20.77	-18.12	396.82	
8	6.84	0.00	26.2	14.6	20.41	-18.48	595.90	
9	17.0	17.81	27.5	11.9	19.71	-19.18	490.11	ALL
10	19.5	10.16	27.9	16.9	22.43	-16.46	525.69	
11	17.5	38.38	23.4	15.0	19.19	-19.70	147.41	
12	13.6	0.25	26.6	14.3	20.44	-18.45	633.92	
13	13.3	0.76	23.4	15.8	19.59	-19.30	314.41	2×158
14	9.27	2.79	17.5	13.9	15.65	-23.24	202.82	
15	3.94	0.00	25.0	11.5	18.24	-20.65	645.29	ALL
16	8.17	0.00	24.7	12.1	18.36	-21.09	450.43	
17	9.14	0.00	26.6	15.0	20.79	-18.66	623.51	
18	3.60	0.00	29.3	12.3	20.81	-18.63	628.87	2×158
19	11.8	0.00	30.2	17.2	23.70	-15.75	581.81	
20	18.6	5.08	31.0	19.9	25.42	-14.03	381.41	
21	5.24	0.25	32.5	18.7	25.60	-13.84	582.73	
22	5.77	0.00	32.0	17.3	24.64	-14.81	528.64	ALL
23	9.64	0.00	29.1	18.4	23.75	-15.69	337.32	
24	10.2	0.00	27.7	14.4	21.05	-18.40	619.46	
25	7.67	0.00	32.1	13.6	22.86	-16.59	644.33	2×158
26	8.44	3.56	29.5	18.1	23.78	-15.67	390.58	
27	9.07	0.25	25.3	16.8	21.05	-18.39	602.52	
28	7.14	0.00	26.7	14.7	20.70	-18.75	601.22	ALL

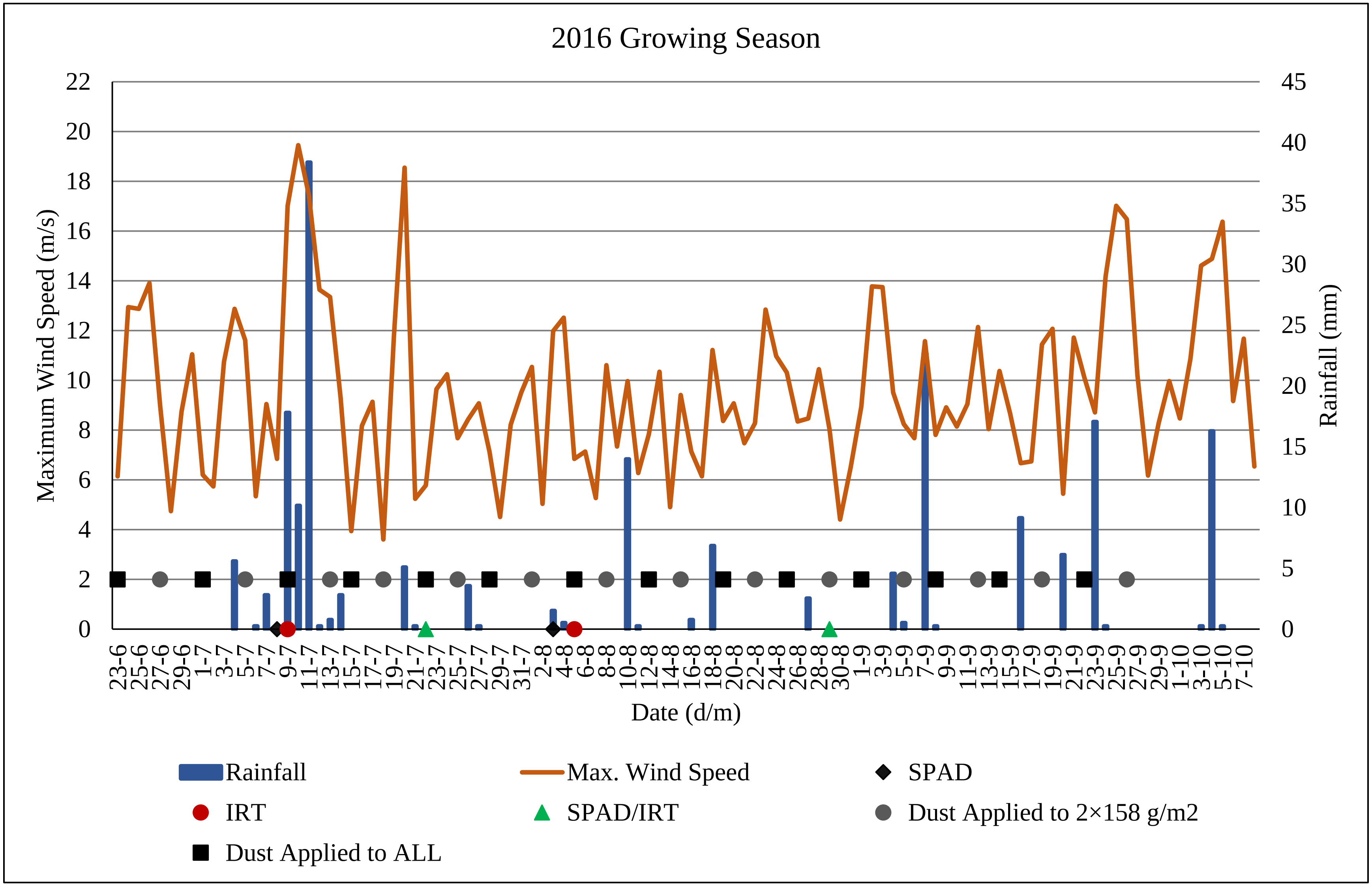
Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
29	4.50	0.00	27.5	12.5	19.96	-19.48	601.13	
30	8.21	0.00	27.7	16.1	21.87	-17.57	492.21	
31	9.51	0.00	29.7	15.5	22.61	-16.83	602.75	
8/1	10.5	0.00	30.4	21.0	25.70	-13.74	498.46	2×158
2	5.04	0.00	31.2	15.9	23.53	-15.91	633.08	
3	12.0	1.52	31.5	14.1	22.81	-16.64	545.93	
4	12.5	0.51	26.8	13.8	20.28	-19.16	555.42	
5	6.84	0.00	26.1	10.9	18.53	-20.92	555.25	ALL
6	7.14	0.00	28.1	10.9	19.49	-19.95	605.91	
7	5.27	0.00	29.2	13.4	21.28	-17.61	613.95	
8	10.6	0.00	28.6	13.1	20.86	-18.03	533.56	2×158
9	7.34	0.00	29.5	15.2	22.33	-16.56	582.28	
10	10.0	13.97	25.6	15.0	20.32	-18.57	251.41	
11	6.27	0.25	27.3	18.8	23.06	-15.83	381.03	
12	7.84	0.00	27.6	15.8	21.67	-17.22	543.13	ALL
13	10.3	0.00	27.6	12.4	19.99	-18.90	488.68	
14	4.91	0.00	28.4	11.2	19.80	-18.54	585.22	
15	9.41	0.00	26.2	14.7	20.47	-17.86	419.32	2×158
16	7.14	0.76	28.4	12.7	20.59	-17.74	382.55	
17	6.14	0.00	31.2	12.4	21.82	-16.52	573.57	
18	11.2	6.86	26.9	14.5	20.68	-17.66	275.72	
19	8.37	0.00	24.7	12.5	18.62	-19.16	511.95	ALL
20	9.07	0.00	21.5	9.9	15.70	-22.08	431.68	
21	7.47	0.00	26.5	6.2	16.35	-21.43	562.63	
22	8.27	0.00	29.4	12.0	20.67	-17.11	550.69	2×158
23	12.8	0.00	33.6	18.8	26.22	-11.00	501.82	
24	11.0	0.00	24.9	11.3	18.09	-19.14	478.89	
25	10.3	0.00	21.9	10.6	16.22	-21.01	267.01	ALL
26	8.34	0.00	25.5	6.3	15.92	-21.30	390.82	
27	8.47	2.54	25.1	14.9	19.99	-16.68	269.21	
28	10.4	0.00	31.4	14.1	22.72	-13.95	480.56	
29	8.04	0.00	28.0	12.0	20.04	-16.63	419.48	2×158
30	4.40	0.00	27.3	8.3	17.79	-18.32	525.67	
31	6.51	0.00	26.3	9.9	18.09	-18.03	509.73	
9/1	8.94	0.00	28.0	10.3	19.15	-16.96	481.45	ALL
2	13.8	0.00	26.8	14.0	20.44	-15.12	451.47	
3	13.7	0.00	29.7	17.0	23.33	-12.23	441.45	

Month /Day	Max. Wind Speed (m/s)	Rainfall (mm)	Maximum Air Temp. (˚C)	Minimum Air Temp. (˚C)	Avg. Air Temp. (˚C)	Departure from Normal Avg. Air Temp. (˚C)	Total Solar Radiation (MJ/m^2/day)	Dust Applied
4	9.51	4.57	25.6	16.0	20.81	-14.19	154.11	
5	8.24	0.51	18.6	14.1	16.38	-18.62	143.61	2×158
6	7.67	0.00	23.0	11.6	17.28	-17.72	390.83	
7	11.6	22.63	25.8	9.1	17.45	-17.00	276.48	
8	7.81	0.25	25.1	10.2	17.63	-16.82	447.95	ALL
9	8.91	0.00	21.9	9.7	15.81	-18.08	319.05	
10	8.14	0.00	22.7	9.3	15.96	-17.93	435.17	
11	9.04	0.00	29.4	9.7	19.53	-14.36	472.76	
12	12.1	0.00	19.8	9.3	14.57	-18.76	318.64	2×158
13	8.04	0.00	15.6	1.5	8.56	-24.77	338.21	
14	10.4	0.00	20.8	-0.2	10.34	-22.43	443.37	ALL
15	8.67	0.00	22.9	12.3	17.57	-15.21	158.76	
16	6.67	9.14	19.9	12.7	16.31	-15.91	154.79	
17	6.74	0.00	24.6	8.1	16.35	-15.87	460.82	
18	11.4	0.00	25.2	10.2	17.69	-14.54	196.59	2×158
19	12.1	0.00	25.6	8.3	16.92	-14.75	448.37	
20	5.44	6.10	20.8	7.0	13.89	-17.78	135.34	
21	11.7	0.00	23.0	8.8	15.91	-15.21	343.38	
22	10.1	0.00	19.5	9.0	14.25	-16.87	293.47	ALL
23	8.71	17.04	18.2	13.6	15.89	-15.23	85.53	
24	14.2	0.25	25.8	17.6	21.66	-8.90	184.48	
25	17.0	0.00	18.6	10.0	14.30	-16.26	171.55	
26	16.5	0.00	19.2	4.8	11.96	-18.04	426.37	2×158
27	10.2	0.00	18.7	3.5	11.09	-18.91	405.90	
28	6.17	0.00	17.7	3.8	10.78	-18.67	316.69	
29	8.27	0.00	19.8	3.0	11.40	-18.04	350.14	
30	10.0	0.00	22.2	5.2	13.73	-15.72	338.36	
10/1	8.47	0.00	23.3	7.9	15.60	-13.29	316.60	
2	10.9	0.00	26.1	12.7	19.40	-9.49	303.97	
3	14.6	0.25	26.0	13.3	19.64	-8.70	352.98	
4	14.9	16.28	18.9	13.1	16.03	-12.31	66.11	
5	16.4	0.25	13.1	4.7	8.89	-18.89	189.18	
6	9.17	0.00	10.8	0.7	5.74	-22.04	321.48	
7	11.7	0.00	6.3	-0.1	3.11	-24.11	145.07	
8	6.54	0.00	9.7	-0.8	4.43	-22.80	273.14	HARVEST

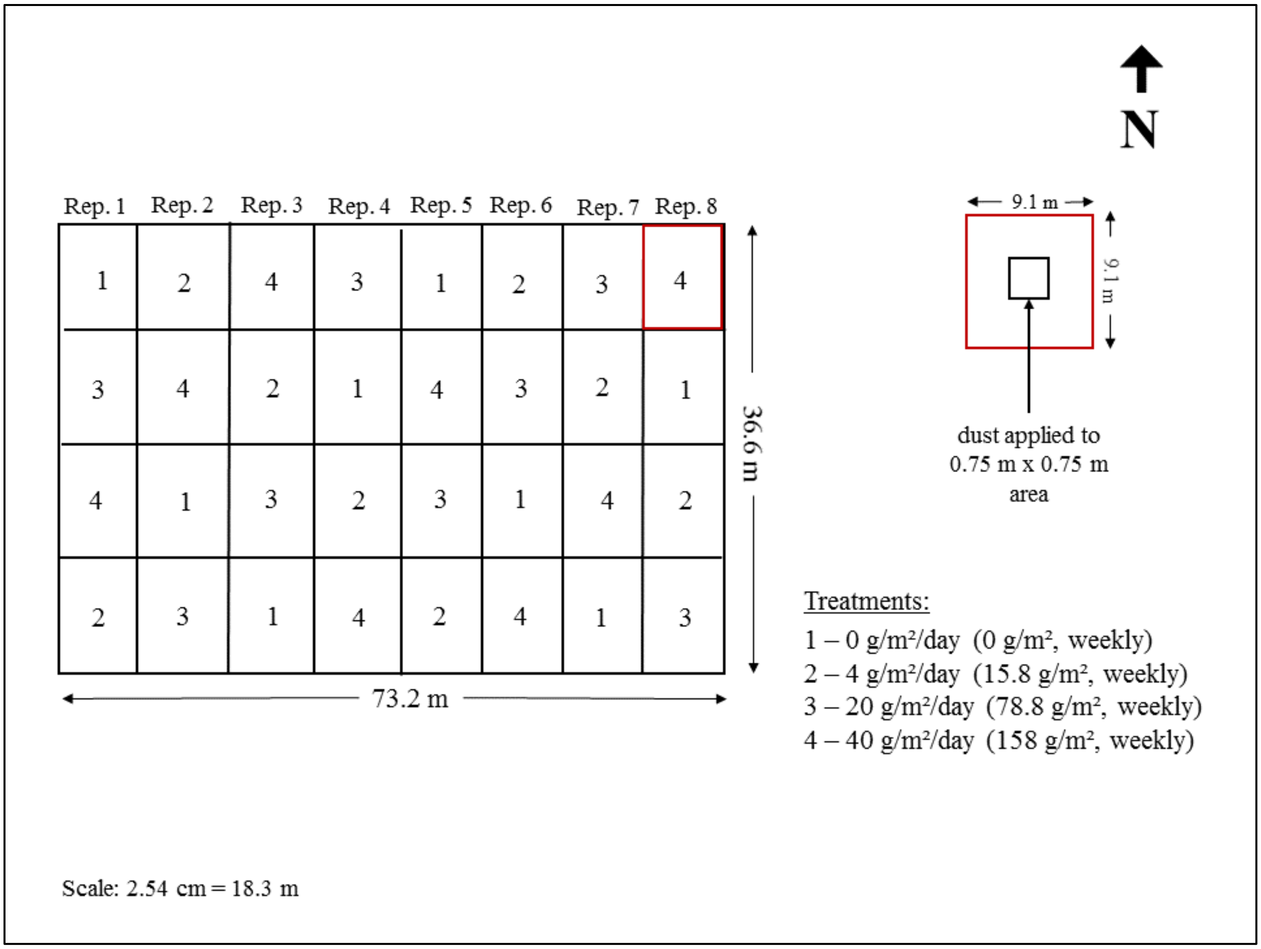
APPENDIX C. 2015 WEATHER VARIABLES AND DATES OF DUST APPLICATIONS AND IN SITU SOYBEAN MEASUREMENTS


2015 Growing Season
Maximum Wind Speed (m/s)
0
2
4
6
8
10
12
14
16
18
20
Rainfall (mm)
0
5
10
15
20
25
30
35
40
Date (d/m)
18-6
20-6
22-6
24-6
26-6
28-6
30-6
2-7
4-7
6-7
8-7
10-7
12-7
14-7
16-7
18-7
20-7
22-7
24-7
26-7
28-7
30-7
1-8
3-8
5-8
7-8
9-8
11-8
13-8
15-8
17-8
19-8
21-8
23-8
25-8
27-8
29-8
31-8
2-9
4-9
6-9
8-9
10-9
12-9
14-9
16-9
18-9
20-9
22-9
24-9
26-9
28-9
30-9
Rainfall
Max. Wind Speed
◆ SPAD
● IRT
▲ SPAD/IRT
■ Dust Applied

APPENDIX D. 2016 WEATHER VARIABLES AND DATES OF DUST APPLICATION AND IN SITU SOYBEAN MEASUREMENTS


2016 Growing Season
Maximum Wind Speed (m/s)
0
2
4
6
8
10
12
14
16
18
20
22
Rainfall (mm)
0
5
10
15
20
25
30
35
40
45
Date (d/m)
23-6
25-6
27-6
29-6
1-7
3-7
5-7
7-7
9-7
11-7
13-7
15-7
17-7
19-7
21-7
23-7
25-7
27-7
29-7
31-7
2-8
4-8
6-8
8-8
10-8
12-8
14-8
16-8
18-8
20-8
22-8
24-8
26-8
28-8
30-8
1-9
3-9
5-9
7-9
9-9
11-9
13-9
15-9
17-9
19-9
21-9
23-9
25-9
27-9
29-9
1-10
3-10
5-10
7-10
Rainfall
Max. Wind Speed
SPAD
IRT
SPAD/IRT
Dust Applied to 2×158 g/m2
Dust Applied to ALL

APPENDIX E. 2015 FIELD PLOT DESIGN

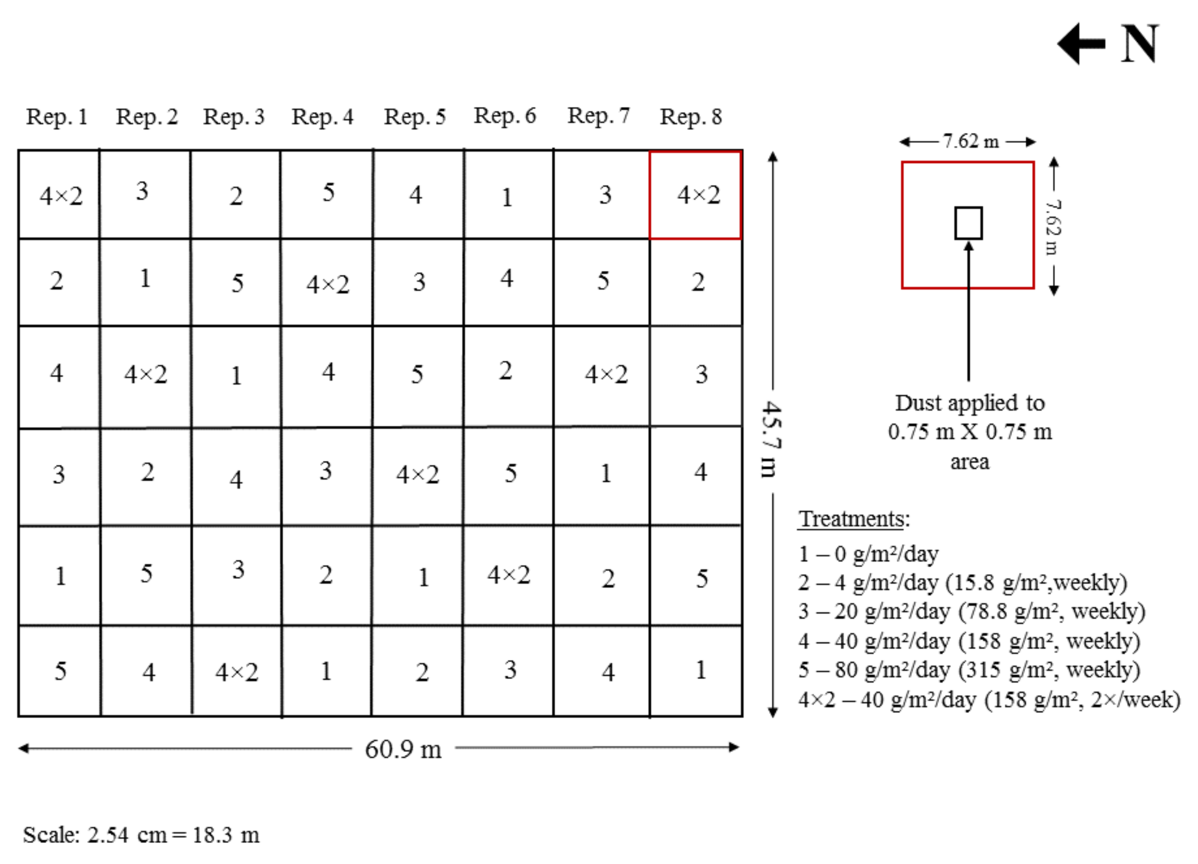


Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Rep. 7	Rep. 8
1	2	4	3	1	2	3	4
3	4	2	1	4	3	2	1
4	1	3	2	3	1	4	2
2	3	1	4	2	4	1	3

Treatments:

1 – 0 g/m²/day (0 g/m², weekly)
2 – 4 g/m²/day (15.8 g/m², weekly)
3 – 20 g/m²/day (78.8 g/m², weekly)
4 – 40 g/m²/day (158 g/m², weekly)

APPENDIX F. 2016 FIELD PLOT DESIGN



Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Rep. 7	Rep. 8
4×2	3	2	5	4	1	3	4×2
2	1	5	4×2	3	4	5	2
4	4×2	1	4	5	2	4×2	3
3	2	4	3	4×2	5	1	4
1	5	3	2	1	4×2	2	5
5	4	4×2	1	2	3	4	1

Treatments:

1 – 0 g/m^2/day
2 – 4 g/m^2/day (15.8 g/m^2,weekly)
3 – 20 g/m^2/day (78.8 g/m^2, weekly)
4 – 40 g/m^2/day (158 g/m^2, weekly)
5 – 80 g/m^2/day (315 g/m^2, weekly)
4×2 – 40 g/m^2/day (158 g/m^2, 2×/week)