Influence of windbreaks on crop yields in the Great Plains

by

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Abstract

After the Dust Bowl in the 1930s, windbreaks become a more prominent way to reduce wind erosion. Windbreaks are single or multiple lines of trees and shrubs planted along the edge of agricultural lands. There are many other benefits from windbreaks, such as modifying airflow, wind speed reduction, and microclimate changes. Windbreak effectiveness in reducing wind speeds depends on the windbreak's height and porosity. Very few recent studies have evaluated the crop yield benefits of windbreaks. The main objective of this study was to build database and evaluate the effect windbreaks have on modern crop yields. With the specific objectives to identify crops that show improved yield due to windbreaks, quantify whether the yield increase is enough to compensate for the footprint of the windbreak and characterize the impact of crop yield with the windbreak width. Yield data were obtained from protected and unprotected fields across several counties in Kansas and Nebraska over several crop years. Windbreak influences on crop yield were estimated using farmers' pre-existing georeferenced data, generated by automated combine yield monitors, with ArcGIS 10.7.1 software. Multiple means comparisons (protected versus unprotected) through two sample t-tests were conducted to determine if the yield in protected areas of fields was significantly different from the yield in unprotected areas. Yield loss was estimated from the windbreak footprint to see if yield increases are enough to compensate for the area taken out of crop production. Results showed that wheat had the most positive response to the windbreak effect with a yield increase 63% of the time, with a 13% average yield increase. Soybean had the highest average yield increase with 21%. Yield increase from north and south windbreaks compensated for the windbreak footprint more often than east and west windbreaks. Windbreak width and crop yields showed variable trends across different crops. However, windbreaks provided inconsistent, mostly positive yield benefits across a

variety of crops. Future studies in different counties and states for more crop field/years with different soil types and rainfall amounts, and intensities with different windbreak widths are recommended. More data collection is recommended for sorghum to overcome the issues due to a smaller number of crop field/years. This research would deepen our understanding of the relationship between windbreaks and crop yield and affect their future role as a conservation practice in the Great Plains.

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Dedication

Dedicated to my loving family…

Chapter 1 - Introduction

One of the most severe environmental disasters in North America in the twentieth century was the Dust Bowl which occurred in the 1930s. During this period, severe drought and damaging wind erosion hit the Great Plains. Strong winds blew away an average of 480 tons of topsoil per acre, degrading soil productivity, harming human and animal health, and damaging air quality (Hansen and Libecap, 2004). During this decade, high temperatures and lack of precipitation eradicated most crop field vegetation coverage and led severe drought conditions and soil erosion vulnerability due to high-speed winds (Schubert et al., 2004). After the Dust Bowl windbreaks were introduced and established with federal funding across United States (U.S.) to reduce wind erosion. Windbreaks are part of sustainable agricultural systems. According to Brandle et al., (2004) field windbreaks are single or multiple lines of trees and shrubs planted along the edge of agriculture lands mainly to reduce wind erosion and provide protection to crop fields.

This review of literature focuses on general features of windbreaks and the establishment and management of windbreaks in the field. It describes their function and summarizes their main effects and benefits on crop yields. It also reviews the main environmental and economic aspects of windbreaks. Additionally, it describes how geographic information systems (GIS) can be used to estimate the effects of windbreaks on crop yields.

Establishment of windbreaks

The Prairie States Forestry Project was started in 1942 to address the environmental catastrophe brought on by the Dust Bowl in the 1930s, at which point windbreaks became a common practice to reduce wind erosion. This project was funded to promote windbreak/shelterbelt establishment by the U.S Forest Service in order to reduce wind erosion and protect the lands in the Great Plains (Droze, 1977). A total of 250 million trees were planted in 18,600 miles of 30,000 windbreaks (Droze, 1977; Croker, 1991). The areas of shelterbelt planting in the Great Plains region, 1935-1942 is given in Figure 1.1. In the early1970s many of the windbreaks were removed to install large center-pivot irrigation systems for agricultural crop production but due to environmental concerns, conservation programs have continued to encourage the planting of new windbreaks (Brandle et al., 2004).

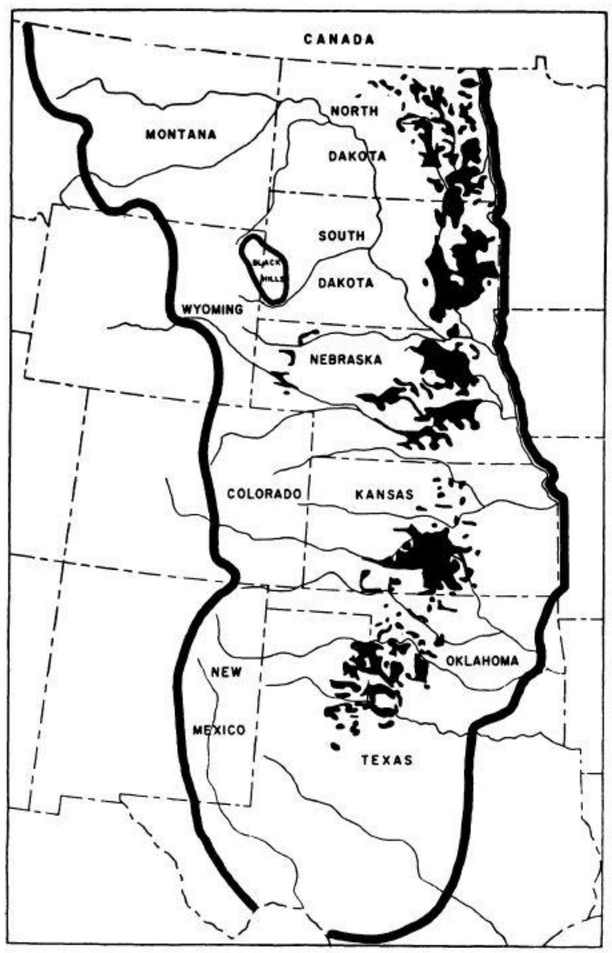


Figure 1.1 The areas of shelterbelt planting in Great Plains region, 1935-1942 (Schmaltz, 1980).

Windbreaks are mainly established on agricultural lands. The successful establishment of a windbreak begins with site preparation and requires knowledge of agroforestry practices. It is important to select and manage good quality plants appropriate to the type of soil and resistant to pests and environmental conditions (Mize et al., 2008). Although various tree species can be planted in windbreaks, planting only deciduous trees is not recommended for year-round protection. According to Gonzales et al., (2018) deciduous trees are less effective during the winter season due to leaf loss, even planted in multiple rows. According to Kort (1988) careful species selection for the windbreaks depends on soil-site conditions. Additionally, designing the windbreak to reduce its width maximizes crop yield benefits. When narrow windbreaks have dense to medium porosity, consisting of fast-growing and non-competitive trees species, optimal crop yield increases are achieved (Kort, 1988). Several tall, long-lived species with deep root systems and similar growth should be planted in the windbreak. After planting tree and shrub seedlings, weed control for several years is an important management practice. Weed control reduces competition for nutrients, moisture, and light for the seedlings.

Effectiveness of a windbreak

The effectiveness of a windbreak is determined partially by its external structure, which is characterized by height, length, orientation, continuity, width, and cross-sectional shape (Brandle et al., 2004). The main factors that determine the windbreak's effectiveness in reduction of wind speed are the windbreak height and porosity (Koh et al., 2004). The windbreak is an obstacle placed on the land that changes and reduces wind speed and flow patterns, both upwind of the barrier and downwind of the barrier. Windbreak height (H) determines the extent of wind protection. The ideal distance from the windbreak is expressed as a function of H and is measured from the center of the outer row of the windbreak along a line parallel to the direction of the wind (Brandle et al., 2004). Some wind speed reduction can be as far as 50 H to the leeward zone and reductions of about 20% may extend to about 25 H from the windbreak. The protected zone on the windward side is in the range of 2 to 5 H. Spacing between trees within the row depends on plant species, purpose of the windbreak, and site conditions. In general, spacings of 2–5 m for most tree species and 1–2 m for most shrub species is typical. Closer spacings reduce the time to reach canopy closure but may shorten the overall life span of the windbreak unless timely thinning is conducted. Wider spacings requires more time to form an effective barrier but can extend the life span of the shelterbelt.

Windbreaks which have an average porosity of 35%–40%, can be considered most effective (Skidmore and Hagen,1971). As the wind flows through open portions of a windbreak, less wind passes through a denser windbreak. Therefore, on the leeward side of a denser windbreak, low pressure develops, which creates turbulence and reduces protection downwind. In the moderately dense windbreaks, the amount of air passing through the windbreak increases. It moderates the low pressure and turbulence and extends the length of the downwind protected area (Figure 1.2).

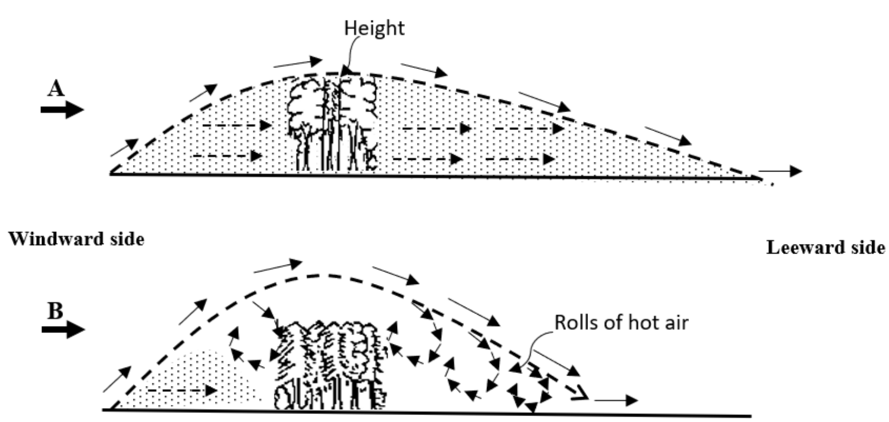


Figure 1.2 Wind flow through and over a moderately penetrable (A) and dense (B) windbreak (Adapted from Roose, 1996).

Benefits of windbreaks

Altering the field's environment and microclimate

Windbreaks are useful for altering the microclimate to protect crops, properties, roads, and livestock. Depending on the primary purpose of the vegetative barriers, they can be designated as a living snow fence, a field or crop windbreak, a farmstead, or livestock shelterbelt. Windbreaks are also important in modifying air flow, mainly in the reduction of wind speed, resulting in changing the field's environment and microclimate (Kort,1988). Airflow patterns change the heating, evaporation, transpiration, and microclimate in the areas upwind and downwind of a windbreak (Cleugh, 1998). These modified conditions are more favorable for reducing soil erosion and increasing plant protection, also may increase crop production.

Windbreaks reduce wind speed close to the ground, which results in modification of the surrounding air flow, soil, and plant environments (Cleugh, 1998). Due to changes in microclimate conditions, temperature and evapotranspiration rates change and they positively influence plants, which may result in better growth and higher yields. In 1962, Stoeckeler reported that higher temperatures in the sheltered zone caused corn to have better responses to high density windbreaks than low density windbreaks.

Reduce wind erosion

Windbreaks can minimize wind erosion and protect plants from wind damage, such as torn foliage. Windbreaks also reduce crop lodging due to wind damage (Cleugh, 1998). Windblown soil can damage plant tissues through abrasion as well as carry inoculum for bacterial and fungal diseases (Hodges and Brandle, 1996). Damaged tissues may be entry points for pathogens, and it can reduce the potential yield. A reduction in plant tissue damage is important for the improved productivity of many sheltered vegetable crops (Cleugh,1998).

Economic benefits

Windbreaks also produce other economic benefits as well. They protect crop fields by reducing wind erosion, improving crop water use, and increasing crop yields (Kort, 1988). They protect livestock from harsh winter conditions. Windbreaks also reduce cold stress on animals due to reduced wind velocity, thereby reducing feed energy requirements and resulting in better animal health and reduced input costs as well. On open grassland, windbreaks are especially valuable during the calving season when protection from late winter and early spring storms is critical. Kansas cattle producers indicate, that on average calving success increases by 2 percent if cows are protected by a windbreak (Quam et al., 1994). Around farm buildings they protect living and working areas, making outside work less stressful. Increasing the presence of wildlife is considered an environmental positive effect, but also enhancement of wildlife may have negative effects, particularly on crop costs because of crop and windbreak damage (Osorio et al., 2019).

Other benefits

Improving the environment is another benefit of using windbreaks. This includes improvement of wildlife habitat (as previously discussed), landscape aesthetics, improvement of air quality and other ecosystem services such as water quality, carbon sequestration, and nutrient cycling. Trees and shrubs in the windbreaks provide wildlife habitat, food, shelter, and protection. They also serve as travel corridors for animals (Mize et al., 2008). Windbreaks can also reduce pesticide drift onto non-target areas and surface water bodies like rivers or ponds

(Cleugh, 1998). According to Lovell and Sullivan (2006) windbreaks can prevent 97% of eroded wind-blown topsoil from entering rivers and streams.

Management of windbreaks

Windbreak establishment, maintenance and removal involve costs. The maintenance of the windbreaks involves practices like thinning, pruning, weed control, irrigation, protection from wildlife and livestock, monitoring for insects and disease problems, and replanting if necessary. Good windbreak design, suitable species selection and careful maintenance practices leads to enhance the crop yield (Kort, 1988).

Yield increases in the protected zone should be more than yield losses due to windbreak and crop competition to offset the cost of investing in windbreaks. Even when the first years of windbreak establishment provides a low economic return, the net return may be positive over the life of the windbreak (Sudmeyer and Flugge, 2006). After an average of 15 to 18 years, windbreaks pay for themselves and increase net crop yields, compensating for costs of land occupation and crop competition (Brandle et al., 1992). To evaluate the economic returns of field windbreaks economic analyses have been performed in recent studies. One of these studies showed that the economic return depends on the rate of growth of the windbreak and its life expectancy (Grala and Colletti, 2003).

Windbreaks and crop yield

Windbreaks are useful for improving crop yields. Most previous research indicates that yield increases due to windbreaks occur within 10 H in the downwind zone, or within 0–3 H in the windward side. Since the windbreak footprint consumes some amount cropland, to obtain the maximum advantage limiting the shelterbelt land occupation to < 5 % of the total land area is recommended (Stoeckeler,1962). The relationship between windbreaks and crop response is complex and dynamic, subject to continual change as a result of changes in mesoclimate, windbreak efficiency, and growth and development of the protected crop (Rognerud and Varum, 1974). Crop yield response for an idealized field windbreak is given in Figure 1.3.

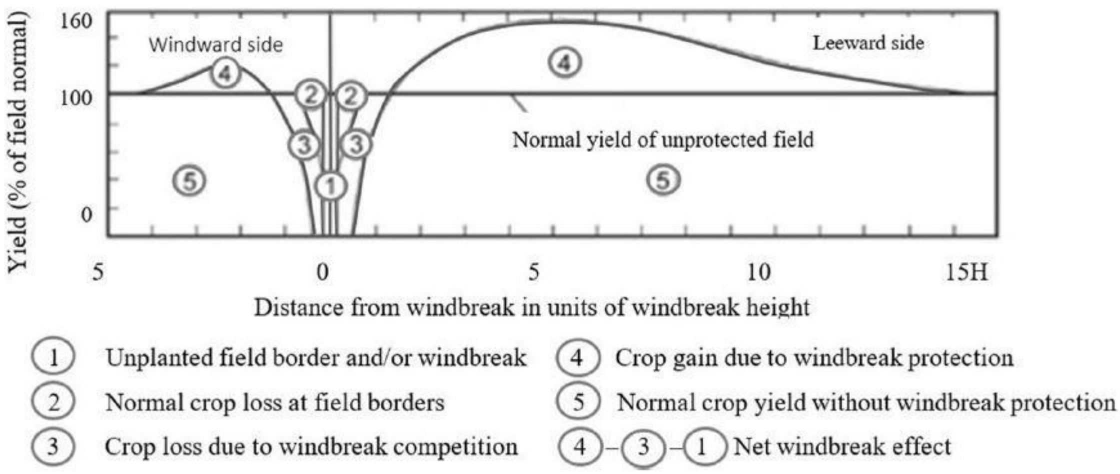


Figure 1.3 Crop yield response for a field windbreak. Modified from Read (1964) and Helmers and Brandle (2005).

Yield reductions can be present from 0.5 H to 1.5 H; this occurs as a result of below-ground competition between shelterbelts and crops (Stoeckeler, 1962). Competition from the windbreak can reduce crop yield in areas immediately adjacent to the windbreak. Trees compete for soil moisture and nutrients with crops growing within their root zone. This competition may lead to excessive nutrient leaching due to snow's heavy accumulations and the resulting snowmelt. These problems may be overcome by root pruning of the windbreak which can reduce the competition of trees with crops for resources (Kort, 1988).

According to Kort (1988) yield increases in a worldwide study summarized through 1986 indicate significant increases for winter wheat (*Triticum aestivum*) 23%, soybeans (*Glycine max*)

15%, corn (*Zea mays*) 12%. recent study conducted across Kansas and Nebraska using GIS reported windbreaks improved yields of soybeans and wheat (Osorio et al., 2019). Soybeans presented the most positive response to the effects of windbreaks showing a yield increase 46% of the time, with a 16% average yield increase. Winter wheat showed a yield increase 30% of the time, with a 10% average yield increase. North side and narrow windbreaks compensated for the footprint of the windbreak 71% of the time, while south side and wider windbreaks only compensated for the windbreak footprint 38% of the time (Osorio et al., 2019).

Use of Geographic Information System (GIS) to measure windbreak crop yield effect

Crop yield data can be analyzed using the geographic information system (GIS). Geographic Information System is a framework for gathering, managing, integrating, and analyzing many data types. This incorporates geographical features with tabular data to map, analyze, and assess real-world problems. Geographic information systems can be used to reveal data insights, such as patterns, relationships, and situations that help users make smart decisions. Geographic information systems can also serve geostatistics by aiding geo-registration of data, facilitating spatial exploratory data analysis, providing a spatial context for interpolation and conditional simulation, and offering easy to use and effective tools for data visualization (Burrough, 2001).

Combine yield monitors are also very useful tools for collecting data for most field inputs and yields. Data from yield monitors are used to develop yield trends for decision making in site specific management. Normally these yield monitors measure yield data within ±.5% error, even for the low flow rates. Yield monitor measures yield more accurately if properly calibrated and operated at a constant combine ground speed (Arslan and Colvin, 2002b). Crop yield monitors incorporate data from a yield sensor designed to measure crop yield in the field while harvesting (Arslan and Colvin, 2002a). In most cases these crop yield monitors are coupled with a Differential Global Positioning System (DGPS). This allows crop yield data to be recorded for virtually every point in a field and relate the grain flow to yield with location. These data are downloaded from storage devices to the famer’s computer and opened in spreadsheets for further analysis as well as record keeping (Osorio et al., 2019). These data can be stored for long periods time and can be used to compare inputs and outputs over time. Better financial outcomes can be achieved by using these data and varying crop inputs to achieve higher yields, which is called precision agriculture. Sometimes there are errors in this data. Most of the time this occurs with different devices of combine harvester and improper calibration of yield meters (Arslan and Colvin, 2002a).

Summary

Of the many benefits to be obtained from maintaining windbreaks in the agricultural landscape, reduction of wind erosion and crop yield improvement are the major ones. Even though overall crop yield increase due to windbreaks has been shown in earlier studies, these results are not widely recognized. There are several factors that farmers consider before establishing windbreaks. One is obvious yield reduction immediately adjacent to windbreaks. Another factor is the difficulty of operating larger equipment due to the windbreaks. Additionally, there is a perception that windbreaks are not needed any more due to conservation tillage practices (Barden, personal communication, 2021). Farmers may tend to overlook the less obvious overall yield increases in the protected crop area and other benefits of having windbreaks.

Osorio et al., 2019 is a recent study evaluating crop yield benefits of windbreaks for soybean and wheat. The current study used the data of newly collected 309 crop field/years for soybean, corn, wheat, and sorghum across seven counties in two states (Kansas and Nebraska). With newly available geo-referenced yield monitoring data and the changing nature of crop species genetics, it is worthwhile to assess the crop yield benefits of windbreaks further. This research would deepen our understanding of the relationship between windbreaks and crop yield and affect their future role as a conservation practice in the Great Plains.

Objectives

Sustainable agricultural practices are essential to deal with food and water scarcity and the lack of cropland due to exponential human population growth (Kopittke et al., 2019). Windbreaks could play an important future role as agroforestry conservation practices in the Great Plains. According to previous research, an increase in crop yields due to the windbreak effect is documented and needs to be updated with the advanced crop varieties being planted. The insight of crop yield benefits of windbreaks revealed from this research will help farmers in decision-making about their windbreak establishment and management. Therefore, the main objective of this study was to build database and evaluate the effect windbreaks have on modern crop yields. The specific objectives were;

- To identify crops that show improved yield due to windbreaks
- To quantify whether the yield increase is enough to compensate for the footprint of the windbreak
- To characterize the impact of crop yield with the windbreak width

Chapter 2 - Methods

This chapter focuses on the materials and methods that have been used during this study. Crop yield data from protected and unprotected for 29 fields from 1999 to 2020 across Kansas and Nebraska were used. Field general information like field location, crops grown, windbreak length, height and width, and crop yield data were collected for each field. Geographic Information Systems software ArcGIS 10.7.1 was used to analysis data. Crop yield data was cleaned, projected, and extracted. The Statistical Analysis System SAS 9.4 (SAS Institute, Inc., Cary, NC) was used to analyze the data.

Study promotion

The study promotion was done to find the farmers who would be willing to share their crop yield data. Agricultural conferences, annual meetings, radio columns, and magazine articles were used to promote this study. Presentations at Kansas Agricultural Research & Technology Association (KARTA) annual meetings and the articles published in the Furrow John Deere magazine called "A Break for Higher Yields" (Reichenberger, 2015) and in The Forestry Source magazine called "Agroforestry Delivers Multiple Benefits for Great Plains States" (Watts, 2019) were mainly used to find the cooperators. Even with all these promotion channels, only seven farmers (3 from Nebraska and 4 from Kansas) were located that had the appropriate data and were willing to share it. These farmers had fields, with and without windbreaks, both with similar crop rotations for several crop years. Phone calls and emails were used to communicate with these farmers. Only one farmer shared data for both this study and Osorio et al., 2019 study. But in this study, recent data which was not used in Osorio et al., 2019 study was used.

Data collection

Field windbreak general information

Field visits were used to collect landowner and field information and windbreak information. Field location, date, landowner name, crops grown, agricultural practices and windbreak length, height and width data were collected. Terrestrial Laser Scanning (TLS) with a laser rangefinder was used to measure the height and width of windbreak trees. The number of measurements were dependent on the length of the windbreak. Three measurement locations were recorded for the shorter windbreaks which are less than 300 yards in length and six measurement locations for the longer windbreaks which are more than 300 yards in length.

Crop yield data

Crop yield data was collected from the crop yield monitors installed in the harvesting machines. These data were then transferred to the farmer's computers and relevant data were downloaded to a portable hard drive (WD My passport ultra, Western digital, San Jose, CA). There are data export functions to extract data for each field in the computer software associated with crop yield monitors. There are four different type of file extensions which export yield data for the shapefile. Those are shp., dbf., shx., and prj file types.

Data were collected from 300+ crop field/years from seven counties in two states: Kansas, and Nebraska. In Kansas Rawlins County, Clay County, Mitchell County and Osage County, and in Nebraska Red Willow County, Otoe County and Hitchcock County (Figure 2.1) for four different crops as soybeans (*Glycine max*), wheat (*Triticum*), corn (*Zea mays*), and sorghum (*Sorghum bicolor*).

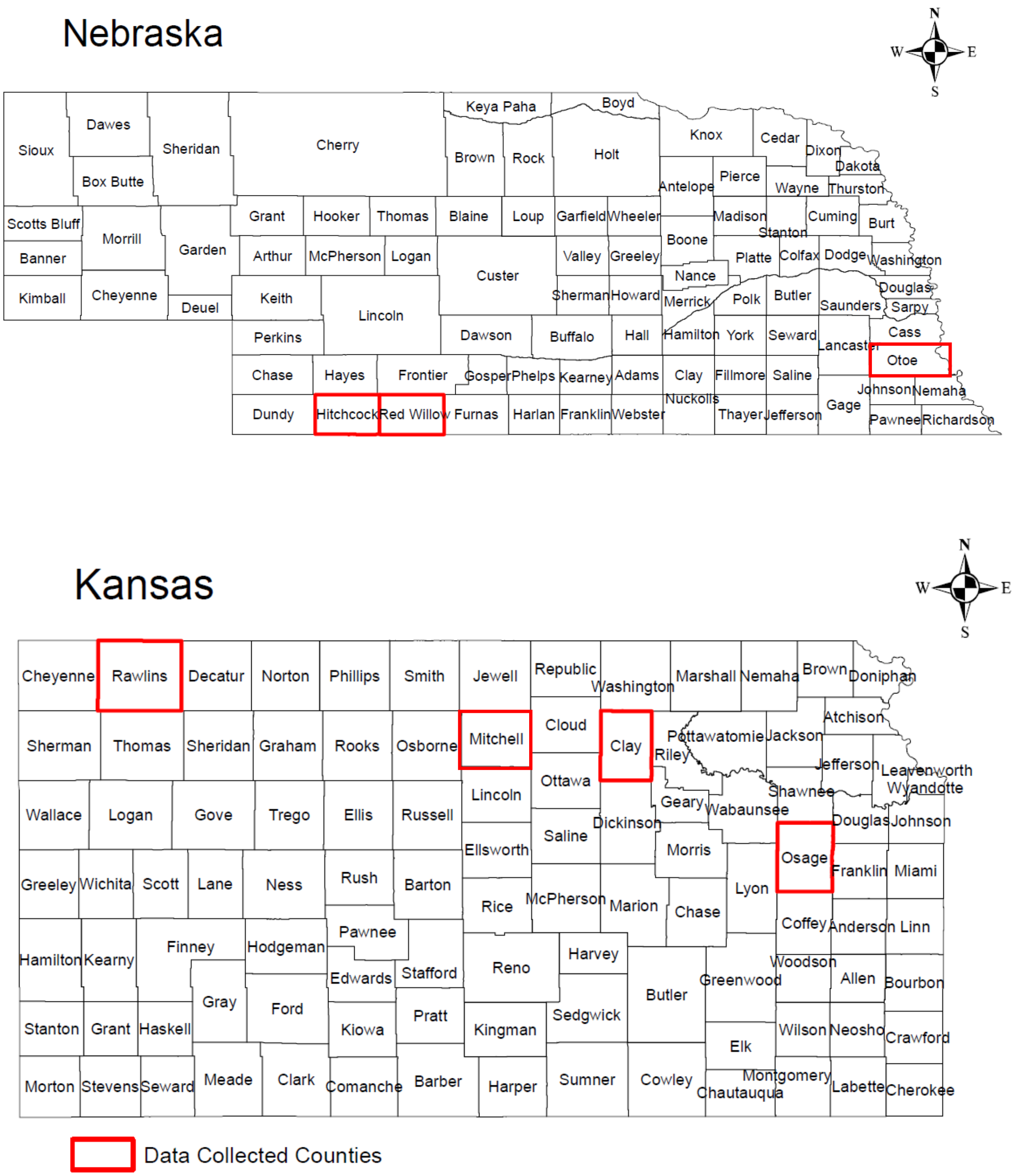


Figure 2.1 Data on windbreak and crop yields collected from seven counties in Nebraska and Kansas.

Data analysis

ArcGIS analysis

ArcGIS 10.7.1 (ESRI, Redlands, CA) was used to clean, project and extract crop yield data. First the crop yield data were cleaned. Initially the crop yield data and aerial photos were added in ArcGIS 10.7.1. Then zeros and outlier values greater than ± 3standard deviation units were removed from the mean (Figure 2.2). These zero values are generated when the harvesting machine passes more than one time through the same point of the field. They are indicated in blue color dots in the Figure 2.2.

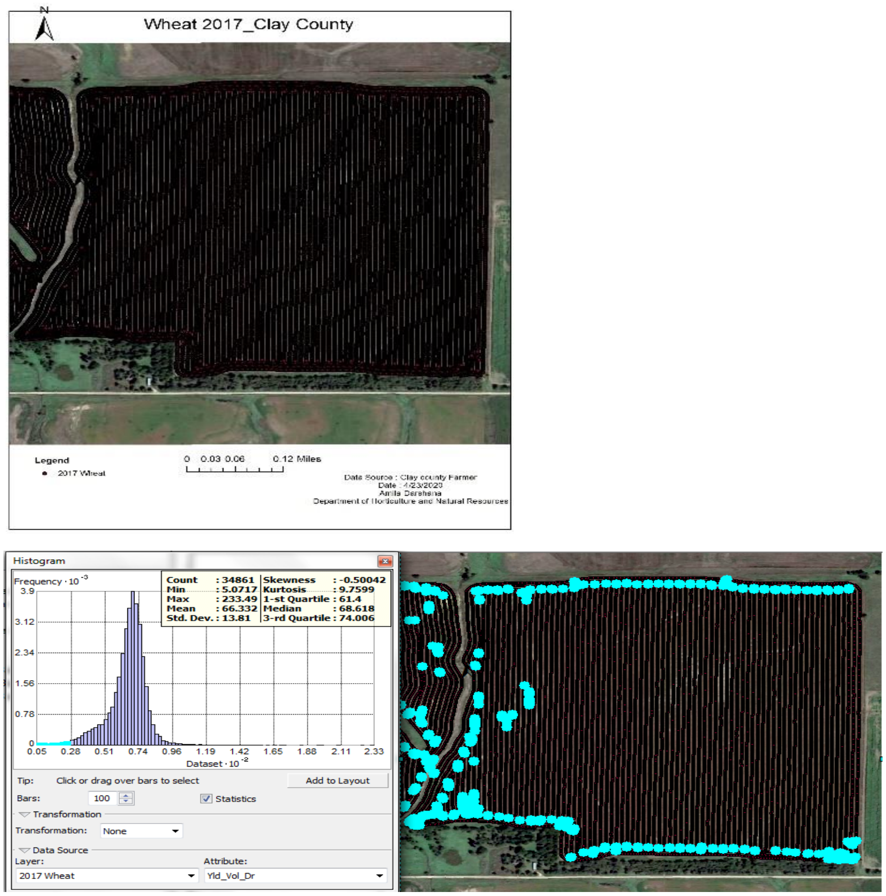


Figure 2.2 Process of cleaning yield data in a study field in Clay County, Kansas.

After the cleaning, field selection was done (Figure 2.3). The selected fields had a length of more than 30 times the height (H) of the windbreak or there were adjacent unprotected fields planted with the same crop for comparisons of the yield. A total of 309 crop field/years were available for data analysis after these steps. Some data was rejected, due to not having enough length for the protected and unprotected zones, having non uniform windbreaks or having poor condition in windbreaks with gaps.

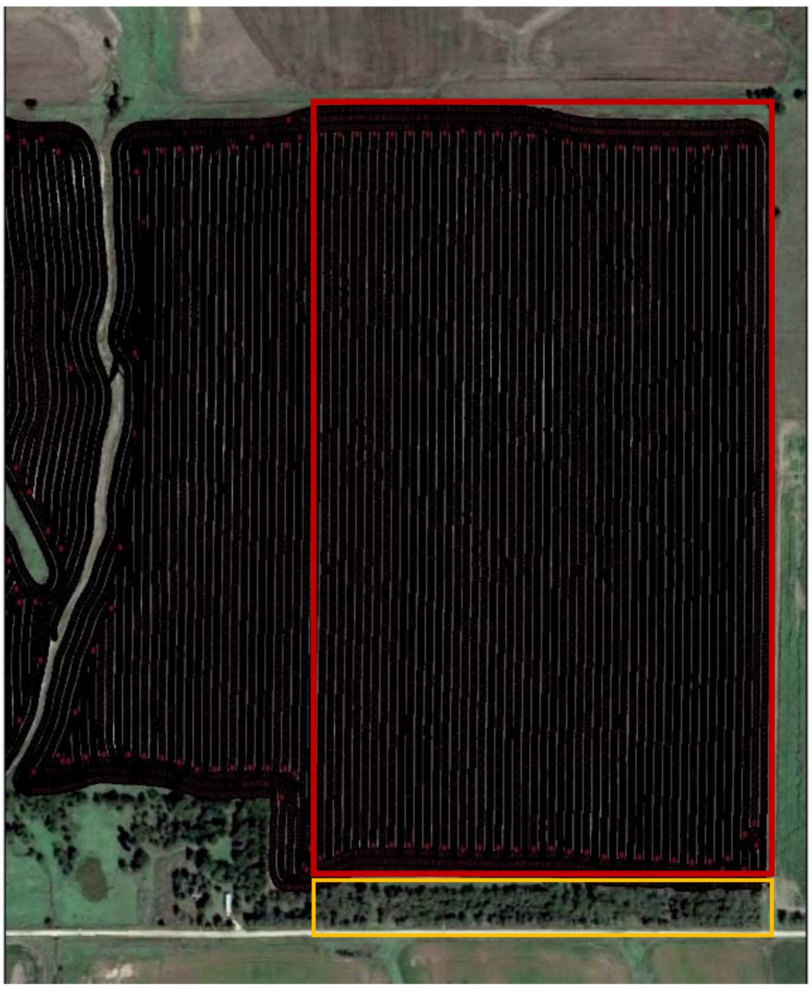


Figure 2.3 Field selection for a study field in Clay County, Kansas.

Next step was to create strips along the study field. The Fishnet tool in ArcGIS 10.7.1 (ESRI, Redlands, CA) was used to create the strips. The width of the strip was equal to the average height of the windbreak measured in that field. Then a spatial join was run to join the strip with the yield data points calculating an average of all the yield points that fall in each strip. Then a choropleth map was created (Figure 2.4).

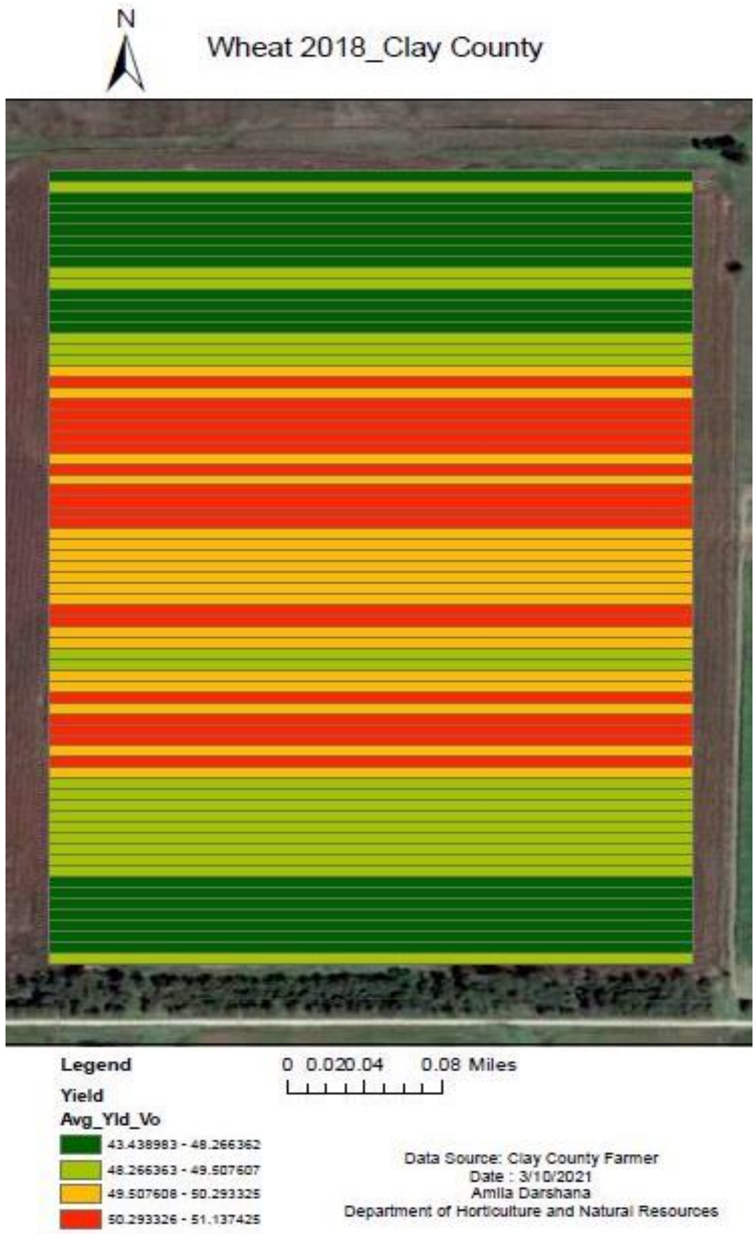


Figure 2.4 Choropleth crop yield map in Clay County, Kansas.

Finally, the data was extracted from ArcGIS to an Excel spreadsheet. It was considered as up to 20H of the windbreak as protected and beyond 30H as unprotected, when extracting the data (Figure 2.5). The yield data for 21 – 29H was ignored.

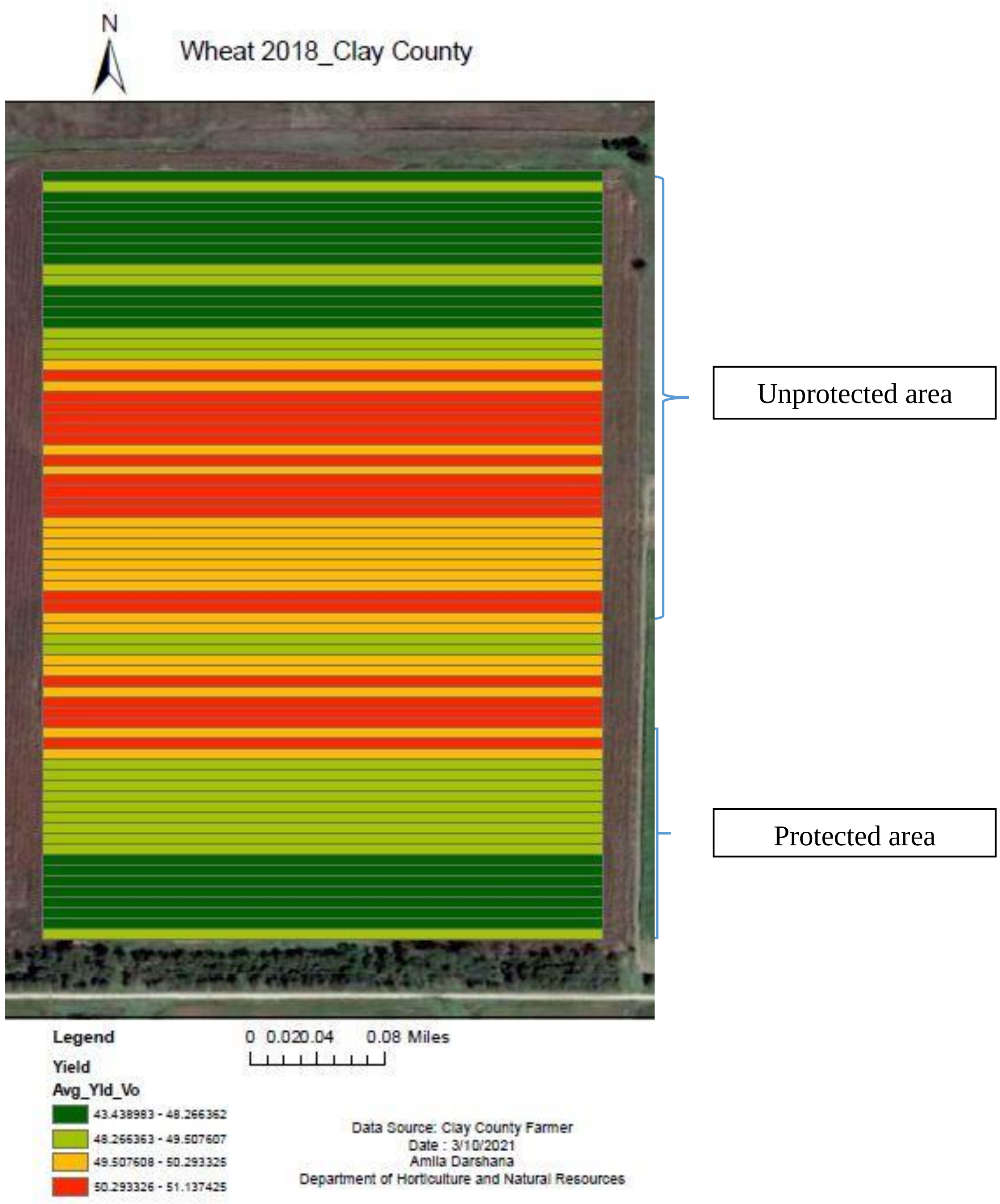


Figure 2.5 Protected and unprotected areas from the windbreak in a study field in Clay County, Kansas.

Statistical analysis

Statistical Analysis System SAS® 9.4 (SAS Institute, Inc., Cary, NC) was used to make comparisons in crop yields between protected and unprotected fields. Two-sample t-test was done to compare group means between protected and unprotected fields using PROC TTEST in SAS 9.4. A hypothesis test of equal population variances was conducted before t-test. If there was equal variance a Pooled test was used and if the variance was unequal, then Satterthwaite test was used. If the $p\text{-value} < 0.05$ there is evidence that the yield in the protected field is statistically different from the yield in unprotected fields.

Windbreak footprint compensation

Crop field/years that demonstrated significantly different yield increases due to the windbreak effect, were selected. Several equations were used to assess if the yield increase is enough to compensate for the land taken out of production (the footprint of the windbreak). The yield increase due to windbreak effect was compared with the projected yield lost within the footprint of the windbreak. The projected lost yield was calculated from the unprotected area field edges, equivalent to the width of the windbreak. This average yield was then multiplied by the area of windbreak footprint. Then the yield increase due to windbreak effect and the yield within the footprint was calculated.

Chapter 3 - Results and Discussion

Windbreak characteristics by county

In this study, general windbreak information such as tree species, the average number of rows, average height, and width was collected. Table 3.1 shows the summary of the windbreak characteristics in all fields of each county where a study windbreak was assessed. Among the studied fields, most windbreak fields were in Kansas. Except for the Clay and Rawlins counties all others had some fields where the riparian or woodland areas act as windbreaks.

Table 3.1 Summary of windbreak characteristics by county.

County	Average number of rows	Number of Fields	Primary species
Clay County, KS	2	9	Osage-orange (*Maclura pomifera* Nutt.), Hackberry (*Celtis occidentalis* L.), Eastern redcedar (*Juniperus virginiana* L.), American elm (*Ulmus americana* L.), Mulberry (*Morus rubra* L.)
Rawlins County, KS	2	3	Eastern redcedar (*Juniperus virginiana* L.), Rocky mountain juniper (*Juniperus scopulorum* Sarg.), Autumn olive (*Elaeagnus umbellata* Thunb), Hackberry (*Celtis occidentalis* L.), Siberian elm (*Ulmus pumila* L.)
Mitchell County, KS	2	2	Eastern redcedar (*Juniperus virginiana* L.), Osage-orange (*Maclura pomifera* Nutt.), Hackberry (*Celtis occidentalis* L.)

Red Willow County, NE	2	1	Hackberry (*Celtis occidentalis* L.), Green ash (*Fraxinus pennsylvanica* Marsh.), Eastern redcedar (*Juniperus virginiana* L.)
Osage County, KS	3	12	Hackberry (*Celtis occidentalis* L.), American elm (*Ulmus americana* L.), Green ash (*Fraxinus pennsylvanica* Marsh.)
Otoe County, NE	2	1	Hackberry (*Celtis occidentalis* L.), American elm (*Ulmus americana* L.), Eastern redcedar (*Juniperus virginiana* L.)
Hitchcock County, NE	3	1	Eastern redcedar (*Juniperus virginiana* L.), Siberian elm (*Ulmus pumila* L.), Hackberry (*Celtis occidentalis* L.)

Eastern redcedar (*Juniperus virginiana* L.) was observed in most of the windbreaks in this study. The height of the redcedar was often about 30 to 35 feet, and the branches may spread 12 to 15 feet (Kansas Forest Service, 2018). Eastern redcedar makes excellent windbreaks and living snow fences due to its dense, compact, long-lived foliage and low branches. In multiple-row windbreaks, Eastern redcedar serves as the evergreen component. Redcedar is also useful as a single-row windbreak due to its density (Kansas Forest Service, 2018). Hackberry (*Celtis occidentalis* L.) was also observed in all counties. Hackberry is a good choice for windbreaks due to its ability to tolerate drought conditions. Hackberry is used in both single and multiple row field windbreaks. In multiple-row windbreaks, this can be used as an interior row and can also be used to prevent overtopping by faster, more vigorous trees in multiple windbreaks (USDA- NRCS National Plant Data, 2020). Rocky Mountain juniper (*Juniperus scopulorum*

Sarg.) is also a suitable evergreen tree species for windbreak which is used for both single and multiple row windbreaks in the western part of the region. Rocky Mountain juniper is generally planted in place of Eastern redcedar. Autumn Olive (*Elaeagnus umbellata* Thunb) was found only in one windbreak in Nebraska and is not very common in windbreaks. According to USDA NRCS National Plant Data (2020) Siberian elm is used as a windbreak tree species to protect livestock, enhance crop production, and control soil erosion. American Elm (*Ulmus americana* L.) is another drought tolerant species which is a tall tree species and frequently used as farmstead and field windbreaks and riparian plantings. Throughout Eastern Kansas, Mulberry (*Morus rubra* L.) is used as an excellent windbreak species and can be used in both single and multiple row windbreaks. In multiple row windbreaks, this is a good middle or outer row species. Green ash (*Fraxinus pennsylvanica* Marsh.) is a moderately sized tree species and versatile in windbreaks which are used in both single and multiple row windbreaks. In multiple row windbreaks, green ash was planted as the interior or outside row. However, ash is no longer recommended species due to the widespread mortality caused by the invasive, non-native emerald ash borer (*Agrilus planipennis* Fairmaire). The larvae of emerald ash borer feed on the phloem tissue and affect the flow of nutrients between the tree's roots and canopy. Canopy thinning, branch dieback, and eventually tree death are caused due to this damage (USDA Forest Service, 2013).

In the study fields across Kansas and Nebraska, silty and clay soil types were commonly found (Soil Survey Staff, NRCS, USDA, 2017). For silty and clay soils, Eastern redcedar, Green ash, Hackberry, and Osage-orange (*Maclura pomifera* Nutt.) are more suitable. For silty-clay and sandy soils, Siberian elm (*Ulmus pumila* L.) and Hackberry are better choices as windbreaks, and in sandy soils, Honeylocust (*Gleditsia triacanthos* L.) develops better (Josiah and Wilson, 1996).

The farms in Osage County, KS, had the widest windbreaks in the study, which were actually native riparian woodlots. Deciduous species like Hackberry, Green ash, and American elm were the main windbreak species in those windbreaks. Conifer species like Eastern redcedar provide dense shade, producing little understory vegetation in wider windbreaks (Mize et al., 2008). In the Northern Great Plains, Green ash has been reported to be less competitive with crops immediately adjacent to the windbreak than Siberian elm (Frank, 1982). Due to drought stress, green ash drops its leaves and makes it active for a shorter time in the year, thus reducing soil water use (Frank, 1982).

Soil type, environmental conditions, and intended use of the windbreak are factors that should be considered when selecting the tree species for field windbreak design. For the crop protection to enhance yield, single or two row windbreaks may be effective. Multiple row windbreaks are used for wildlife, woody production, and commercial non-timber products (Brandle et al., 2004). In this study, diverse tree species were observed in field windbreaks. The diverse windbreak is good for the benefits and its health (Josiah and Wilson, 1996).

Windbreaks and crop yields

Projected maps of the yield monitor data were extracted and analyzed using ArcGIS software. Then the statistical analysis was done using SAS version 9.4 (SAS Institute, Inc. Cary N.C.). In protected and unprotected fields that were divided by windbreak location, group means yield data were compared using two-sample t-tests. Windbreak height is H, most of the study fields were long, with more than 70 H in length. In this study, the protected area was considered up to 20 H downwind, and the unprotected control area was considered starting at 30 H downwind. The unprotected zone was more than two times larger than the area of the windbreak protected area. Some fields were not considered as their length were not enough to designate the protected and unprotected areas.

The results showed that out of 309 crop field/years, 181 were significantly different at $p<0.05$ significance level. In those 181 crop field/years, the yield in protected area was different from yield in the unprotected area. Out of the 181 crop field/years, 102 crop field/years showed significant yield increases, where the average yield in the protected area was greater than the average yield in the unprotected area. The remainder, 79 crop field/years showed significant yield decreases, where the average yield in the protected area was less than the average yield in the unprotected area. Figure 3.1 shows the yield increase and decrease frequency percentage by crop from 181 significantly different crop field/years.

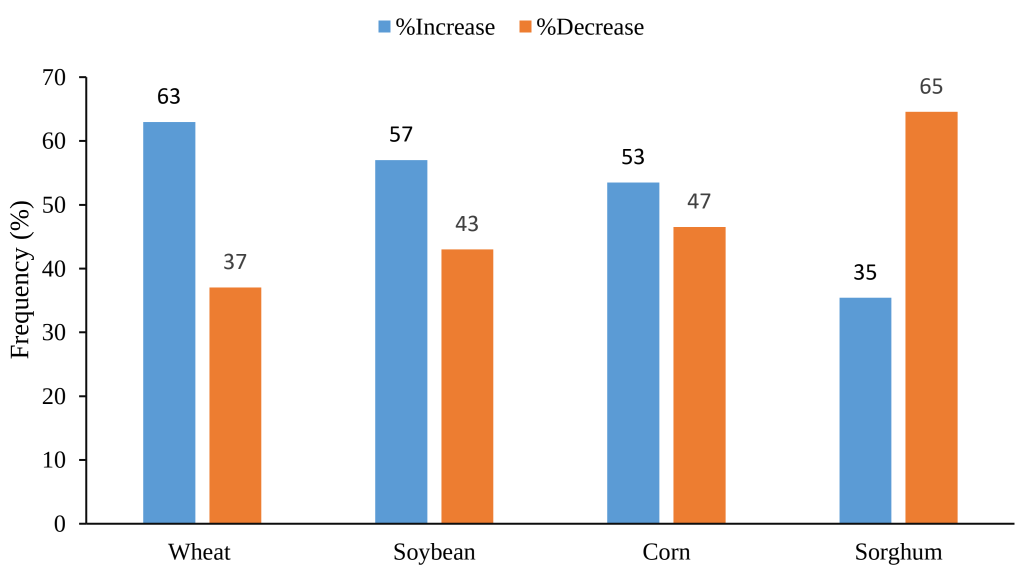


Figure 3.1 Significant differences in frequency percentage by crop for both yield increase and decrease due to windbreak effect with number of crop years for each crop.

When considering the crop years that showed a significant difference in crop yield due to windbreaks, wheat was the most responsive crop with a 63% yield increase frequency, followed by soybean, corn, and sorghum with a 57%, 53%, and 35% increase frequency respectively. According to Kort (1988) wheat was reported as one of the highly responsive crops to windbreak protection, followed by soybeans in a compilation of data from 50 worldwide studies from 1934-1984. Soybeans were the most responsive crop to windbreak effect with a 46% yield increase frequency followed by wheat with a 30% yield increase frequency due to windbreak effect in a study conducted by Osorio et al., (2019). In this study, there was a large data set with a total of 80 crop field/years for wheat, 109 crop field/years for soybeans, and 105 crop field/years for corn, which were the most responsive crops with significant differences for the windbreak effect. The less positive response crop, sorghum had only 15 crop field/years. All the used data (309 crop field/years) for this study are newly collected data that have never been used for any other windbreak crop yield study.

Kansas is the number one wheat producing state in the U.S. and is known as the "Wheat State". The total production of wheat in 2020 was 562,500,000 BU and the total acres harvested is 12,500,000, while the average yield is 44 bu/ac (USDA-NASS, 2020). According to USDA-NASS (2020) the average production of wheat in Central Kansas is the highest. In 2020, Rawlings County had 4,163,000 bu of wheat harvest in 101,300 acres harvested with an average yield of 41.1 bu/ac. Clay County had 2,099,000 bu of wheat harvest in 41,400 acres harvested with an average yield of 50.7 bu/ac. Osage county had 252,000 bu of harvest in 4690 acres harvested with an average yield of 53.7 bu/ac. In Kansas, 2019 soybean production was 8,980,000 acres harvested with an average yield of 42.2 bu/ac. Soybeans had a bigger sample size than other crops, and yield increase was followed by wheat due to the windbreak effect.

The following formula was used to calculate the average crop yield increase percentage due to windbreak effect for each crop/year that were significantly different.

$$\frac{\text{Average mean difference increase}}{\text{Average yield in the unprotected area}} \times 100$$

Where the average mean difference increase value was obtained from the SAS output and following formula was used to calculate the average yield in the unprotected area.

$$\text{Average yield in the protected area} - \text{Average mean difference increase}$$

The average crop yield increase percentage due to the crop's windbreak effect is given in Figure 3.2. It is for the 102 crop field/years that had significantly increased yields due to the windbreak effect. Summer crops like soybean (21%) and corn (18%) had greater yield increases due to the windbreak effect. Osorio et al., (2019) also reported that soybeans (16%) had a greater yield increases than the winter crop wheat (10%) due to the windbreak effect. Most study field windbreaks were primarily composed of deciduous trees and a few evergreen trees. The windbreak is denser with less porosity in summer than in the winter season. According to Stoeckeler (1962) dense to medium porous windbreaks maximize total crop yields. Therefore, during the summer, soybean and corn were protected by a denser windbreak than wheat. Gonzales et al., (2018) reported that using all deciduous trees in windbreaks is not recommended for year-round protection, even if planted in multiple rows, since they are less effective during the winter season due to leaf loss. According to George (1971) the rooting system of soybean (compared to cereals) does not share the same rooting zones of nearby trees resulting in less yield reduction due to windbreak competition. Winter wheat (13%) showed less yield increase due to the windbreak effect. Sorghum had the lowest yield increase of 8% due to the windbreak effect but with the smallest sample size, 15 crop field/years. According to Kort (1988) winter wheat also showed less yield increase of 23% out of 131 crop field/years and spring wheat 8% out of 190 crop field/years. This could be due to several reasons. According to Brandle et al., (1984) windbreaks enhanced fungal diseases in winter wheat, and yields were reduced by wheat scab. Kort (1988) also reported that corn showed no visible yield loss due to windbreak, while wheat showed larger losses. Stoeckeler (1965) classified wheat and corn as low responsive crops to the windbreak effect. However, in this study, corn showed positive responses.

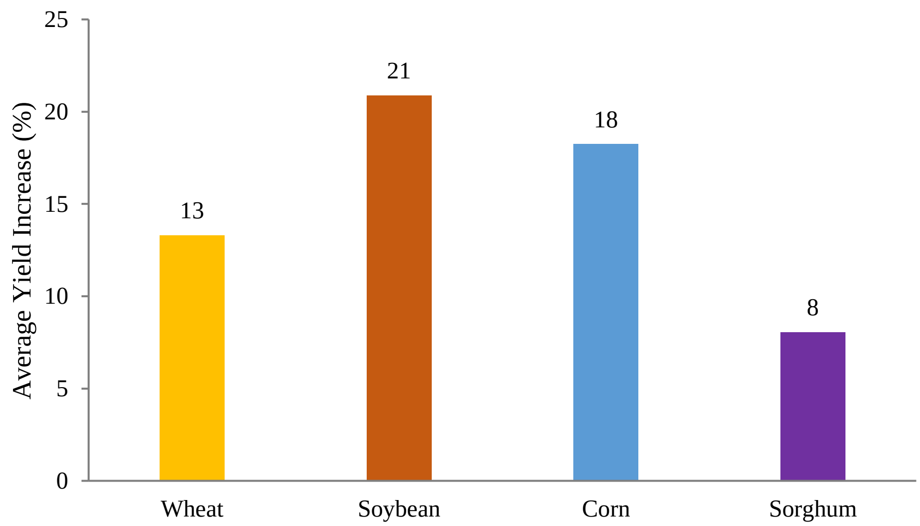


Figure 3.2 Mean average yield increase percentage in protected area for each crop with significant positive windbreak effects.

Possible factors to enhance crop yield increases are good windbreak design, suitable species selection, and careful maintenance practices like renovation, trimming, root-plowing, and weed control (Kort, 1988). There are not many windbreak practices in Kansas due to farmers adopting no-till systems as a conservation practice to avoid soil erosion.

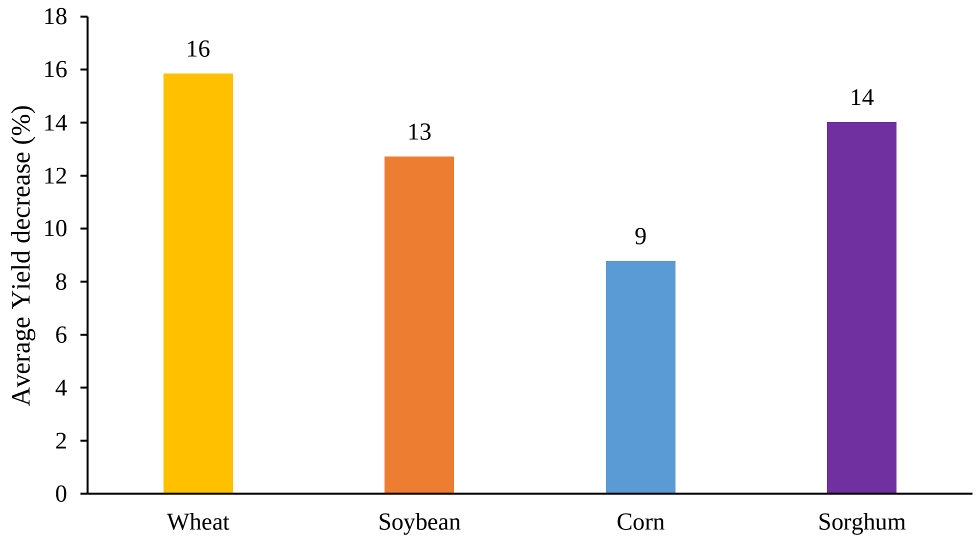


Figure 3.3 Mean average yield decrease percentage in protected area for each crop with windbreak effects.

The average crop yield decrease percentage due to the crop's windbreak effect is given in Figure 3.3. It is for the 79 crop field/years that had significantly decreased yields due to the windbreak effect. Wheat (16%) had the greatest yield decrease, followed by sorghum (14%) and soybean (13%). Windbreaks competition with crops for both above- and below-ground resources such as sunlight, water, and nutrients could be led to poor growth in the crops in the vicinity of a windbreak. According to Hou et al., (2003) soil water competition was the major reason for yield suppression at the windbreak/crop interface. Campi et al., (2009) reported that the competition between the crop and the windbreak caused a reduction in the wheat yield from the area directly sheltered by the windbreak. Rivest and Ve'zina (2015) reported in their study that the greatest corn yield variation was observed at the tree-crop interface, where substantial yield reductions occurred.

Geographic location is a factor that influences windbreak effects on crop yields. Windbreak competitive yield decreases are more pronounced in dryer regions of the Great Plains than in wetter regions (Stoeckeler, 1962 and Kort, 1988). According to snowfall differences, greater yield increases due to windbreak protection were found in the northern Great Plains states than in Kansas and Nebraska (Stoeckeler, 1962).

Yield increase to compensate for the footprint of the windbreak

The windbreak footprint is the area taken out of production due to the windbreak. The 81 crop field/years except for the woodland areas that demonstrated significantly different yield increases due to the windbreak effect were used to calculate the windbreak footprint. The footprint of the windbreak is compared with the yield increase due to the windbreak effect. The average projected yield loss was calculated from an area that is equivalent to the width of the windbreak in the unprotected area along the field edges. Then this average yield was multiplied by the windbreak area to get lost yield due to the footprint of the windbreak. The yield increase due to the windbreak effect is also calculated. It was then assessed to find if the yield increase is enough to compensate for the windbreak footprint.

Projected area = 1H-20 H

Unprotected area = >30H

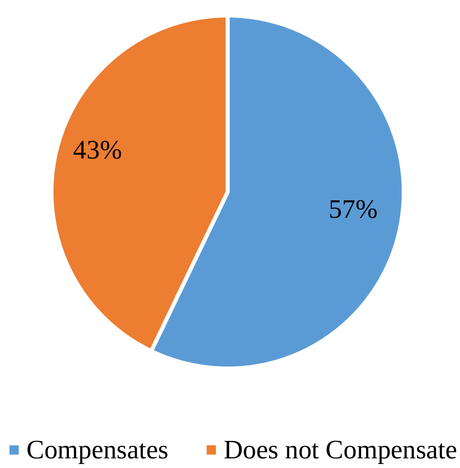
Yield increase due windbreak effect

$$\text{Total average yield in the protected area} - \text{Total average yield in the unprotected area} \\ = \text{Yield increase due windbreak effect}$$

Yield within the footprint of the windbreak

$$\text{Average yield of the unprotected field edges} \times \text{Windbreak area} = \text{Footprint of the windbreak}$$

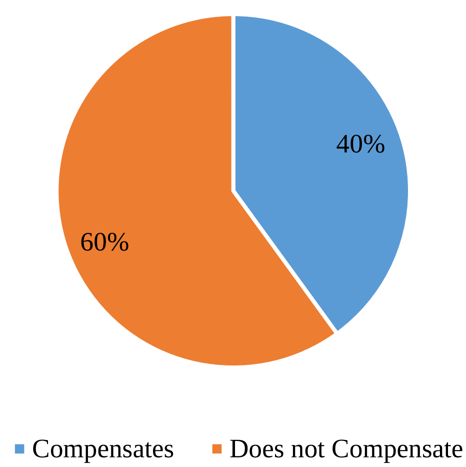
$$\text{Where the Windbreak area} = \text{Windbreak length} \times \text{Windbreak width}$$



n=38

Average width of the windbreak: 72ft

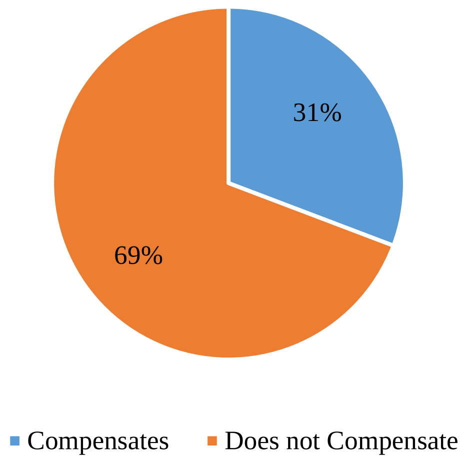
North windbreak compensation due to windbreak effect

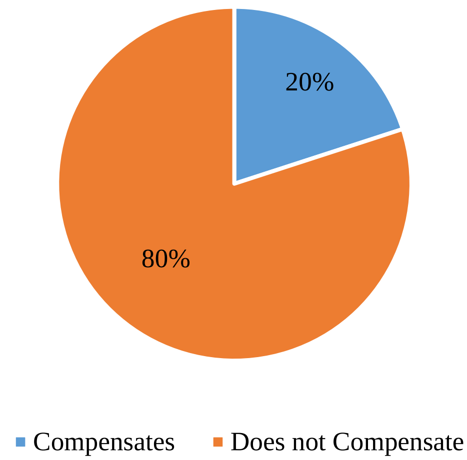


n=24

Average width of the windbreak: 67ft

South windbreak compensation due to windbreak effect





n=8

Average width of the windbreak: 59ft

East windbreak compensation due to windbreak effect

n=11

Average width of the windbreak: 58ft

West windbreak compensation due to windbreak effect

Figure 3.4 Yield compensation due to the windbreak effect related to the location of the windbreak. The blue color indicates windbreak compensation, and the orange color indicates non compensation due to the windbreak effect. n is the number of crop field/years in each location.

According to the results from the windbreak compensation due to the windbreak effect, the yield compensation is 57% of the time for north windbreaks, 40% of the time for south windbreaks, 31% of the time for east windbreaks, and 20% of the time for west windbreaks. North and south windbreaks showed higher windbreak compensation due to the windbreak effect. Osorio et al., 2019 also reported similar results that there is a yield compensation of 71% of the time for north windbreaks and yield compensation of 38% of the time for south windbreaks. The variable windbreak width and effect due to location could cause these differences. Narrow windbreaks with one or two rows are better than wider windbreaks when considering total yield and whether the yield increases compensate for the windbreak footprint (Brandle et al., 2004). According to Stoeckeler (1962) field windbreaks should occupy <5% of the land area for the yield to compensate for the windbreak footprint and provide maximum crop protection.

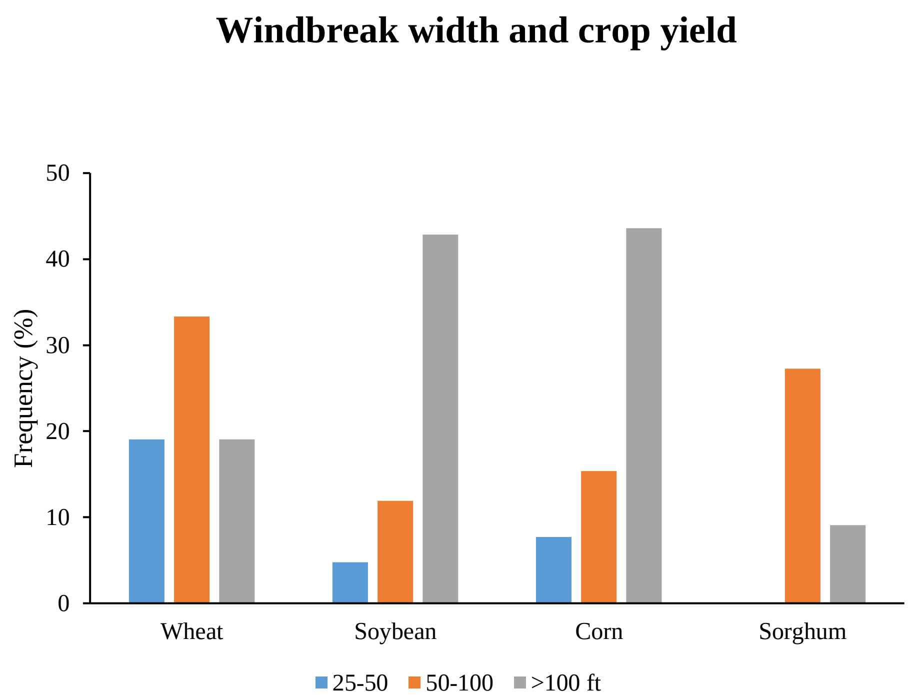


Figure 3.5 Average yield increase frequency percentage by crop with the windbreak width. Blue bars show the windbreak width range of 25-50ft, orange bars show the windbreak width range of 50-100ft, and ash bars show the windbreak width of more than 100ft.

Average yield increase was calculated based on the average mean difference increase over the average yield in the unprotected area. According to Figure 3.5, soybean and corn showed a similar trend in yield increase frequency percentage with the windbreak width. When the windbreak width was more than 100ft, soybean and corn showed highest yield increase frequency. Most of those fields had multiple row windbreaks or were a riparian woodland area. According to Skidmore and Hagen (1971) multiple row windbreaks create porosities much below 35 percent. This might provide better wind protection for the crops grown. When the windbreak width is 25 to 50 ft lowest yield increase frequency was observed for corn and soybean. The highest yield increase frequency for wheat and sorghum increase was observed when the windbreak width is between 50 to 100ft. As sorghum had a much smaller number of crop years, there is less confidence in these results.

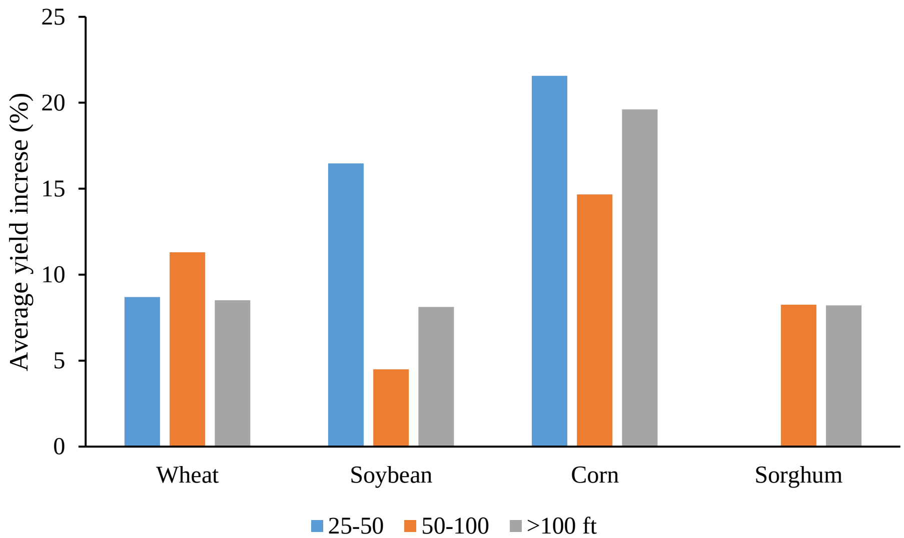


Figure 3.6 Average yield increase percentage by crop with the windbreak width. Blue bars show the windbreak width range of 25-50ft, orange bars show the windbreak width range of 50-100ft, and ash bars show the windbreak width of more than 100ft.

According to Figure 3.6, soybean and corn showed similar trend of average yield increase percentage with the windbreak width. When the windbreak width 25 to 50ft, soybean and corn showed highest average yield increase percentage, and when the windbreak width is 50 to 100 ft lowest average yield increase percentage. For wheat highest average yield increase percentage was observed when the windbreak width in between 50 to 100ft. For sorghum average yield increase percentage was similar with the windbreak width of 50 to 100ft and more than 100ft.

According to Yuasaivin and Tanaka (2009) the average wind velocity decreased in leeward side until the relative windbreak width was equal to 3H, and then the slightly increased as the width increased. Most windbreak heights were approximately 30 to 35ft. Therefore, when the windbreak width is higher than 100ft, the wind's protection is reduced. However, our results showed variable trends.

Chapter 4 - Conclusions and Recommendation

In this study, windbreaks provided inconsistent yield benefits across a variety of crops. Wheat had the most positive response with a yield increase of 63% of the time, with a 13% average yield increase; followed by soybean with a 57% of the time, with a 21% average yield increase; corn with a 53% of the time, with a 18% average yield increase, and lastly, sorghum with a 35% of the time, with 8% average yield increase. The highest yield increase frequency was shown for wheat and soybeans. The highest average yield increase % was shown for soybean and corn. The highest average yield decrease was shown for wheat and sorghum. However, windbreaks provided inconsistent, although mostly positive yield benefits across a variety of crops. Yield increase from North and South windbreaks compensated for the windbreak footprint more often than East and West windbreaks. Windbreak width and the crop yields showed variable trends across different crops.

Future studies in different counties and states for more crop field/years with different soil types and rainfall amounts, and intensities with different windbreak widths are recommended. More data collection is recommended for sorghum to overcome the issues due to a smaller number of crop field/years. Despite the apparent visual yield reduction adjacent to the windbreaks, improved yield often occurred in the protected area. Information from this research would help farmers decide whether to remove or renovate older windbreaks. This research would deepen our understanding of the relationship between windbreaks and crop yield and affect their future role as a conservation practice in the Great Plains.

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