

GIS approach to estimate windbreak crop yield effects in Kansas-Nebraska

by

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Abstract

Windbreaks were originally promoted across the Great Plains region of the U.S to reduce wind erosion in general. A review paper published nearly 30 years ago showed yield increases for a variety of crops associated with windbreaks. However, with the widespread use of no-till systems in all farming and advanced crop genetics, the question is “Do windbreaks still provide a yield benefit?” This study compared multiple years of data from protected and unprotected fields across Kansas and few sites in Nebraska looking at relative crop yield differences of five crops: soybeans, wheat, corn, sorghum and sunflowers. Georeferenced data already existed, generated by automated combine yield monitors, and stored on farmer's computers. There were three sets of data collected for each field. The first level is general field level information, using aerial photography and on-site observations to measure the characteristics of the windbreak (length, height and density). The second was from the yield monitor; this data was analyzed with ArcGIS 10.3.1 to visualize windbreak interaction with crop yield. 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. The third data-layer is climate data that was factored into yield analysis to compare wet, normal and dry growing seasons through a Chi-Square 2x2 test analysis. Optical density of windbreaks from leaf-on/off ground-based photos was assessed using SigmaScan Pro 5.0 software as possibly an important factor influencing the windbreak effect. Finally, the 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 soybeans (81 crop/years) had the most positive response to windbreak effect with a yield increase 46% of the time, with a 16% average yield increase. Sorghum (31 crop/years) had the highest average yield increase with 25%. Narrow windbreaks

(1 to 2 tree rows with an average of 52 ft. width) and those on the north edge of fields resulted in yield increases which compensated for the footprint of the windbreak more often than wider windbreaks on the south edges of fields. Significant yield increases were less than the decreases in the protected area. There was no evidence to show the windbreak effect on yield had any association with critical month precipitation for any crop or orientation group. According to the results obtained, modern hybrids and varieties are possibly less responsive to yield increases due to windbreak effect than older crop varieties. Future studies should collect more data from fields with different windbreak widths distributed more widely across the region to confirm these results. Overall, this project updated our knowledge of windbreak/crop yield interactions and may possibly influence their future role as a conservation practice in the Great Plains.

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Dedication

To my beloved Claudia Castaneda for supporting and making me smile every day, you are my motivation. For my aunt Nancy who raised me along with my grandmother Clemencia who is my angel, always protecting me from above. To my sister Sabine whom I admire for her human quality, intelligence and constancy in life. To my dad, Eusevio who always encouraged me to learn English and supports me in everything. Last but not least to the most important person in my life, my mom Liliana, my role model not only professionally but also in a personal level, teaching me all her values and to never give up. This success is yours.

Chapter 1 - Introduction

Windbreaks were widely promoted and established across the Great Plains region of the U.S. to reduce wind erosion, following the 1930s Dust Bowl that damaged the U.S. and Canadian agricultural prairies. Field windbreaks/shelterbelts are considered to be part of a sustainable agricultural system consisting of single or multiple lines of trees and shrubs planted along the edge of agriculture lands mainly to reduce the wind erosion and provide protection to the crop fields (Brandle et al., 2004).

This chapter will focus on understanding how windbreaks work and their effects and benefits in crop fields. It will also review the main environmental reason for widespread windbreak promotion and establishment in the Great Plains-United States. Lastly, it will discuss general features of shelterbelts, their function when protecting crops by summarizing their main effects and benefits through a review of worldwide studies that show an overall crop yield increase due to windbreaks.

Dust Bowl and Windbreaks in the Great Plains

During 10 years (1930- 1940) the Great Plains were effected by one of the most critical environmental issues the United States has ever addressed. The Dust Bowl, caused by drought and soil erosion (Hansen & Libecap, 2004). Warm Atlantic sea surface temperatures along with the natural phenoma called “La Nina” and low soil moisture were the reasons for the 1930’s drought (Cook et al., 2009). During this decade (1930- 1940), extreme high temperatures and lack of precipitation eradicated most of the crop field vegetation coverage leading to severe drought conditions and vulnerability for soil erosion due to high-speed winds (Schubert et al., 2004).

The Dust Bowl caused severe agricultural and economic losses, farmers and rural resident migration, and biodiversity degradation caused by the widespread dust storms all over the region (Cook et al., 2009). According to Hornbeck (2012) this environmental phenoma resulted in the loss of more than 75 percent of topsoil in many crop fields and even uncultivated areas. Therefore, this was the main reason that lead the U.S Congress to propose and finance the Prairie States Forestry Project. This project was funded to promote windbreak/shelterbelt establishment by the U.S Forest Service throughout the Great Plains in order to reduce wind erosion and protect the Plain lands (Droze, 1977). From Texas to Canada, by 1942, in a 100-mile wide zone, a total of 250 million trees in total were planted in 18,600 miles of 30,000 windbreaks (Droze, 1977; Croker, 1991). Most were 10 to 12 rows and over 100 feet wide.



Figure 1.1 Prairie States Forestry Project planting crew 1936-1937 (USDA-NRCS, 2017).



Figure 1.2 First tree (Austrian Pine) planted as part of the Prairie States Forestry project in Willow, Oklahoma. 1935 (Taken by Howard Carleton Jr. 5/1/1940) (Southern Group of State Foresters, 2014).

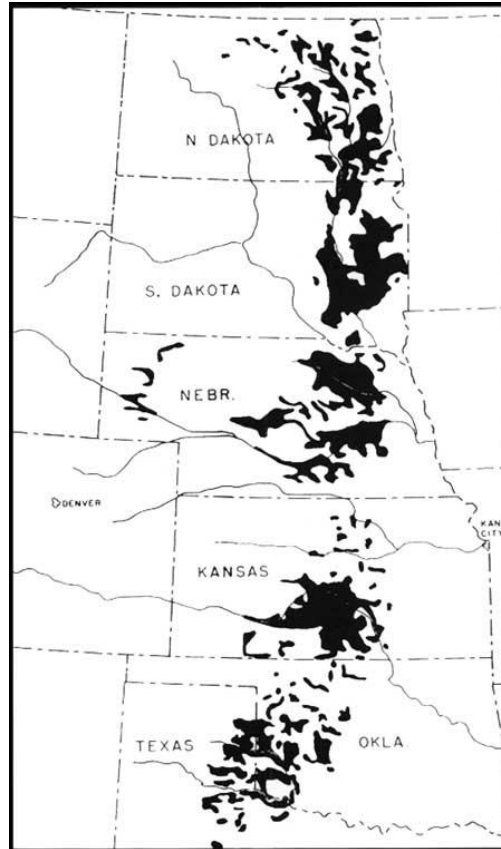


Figure 1.3 Areas of windbreak establishment as part of the Prairie States Forestry Project, 1930's (USDA Forest Service, 2008).

In the 1960s and 1970s many of the windbreaks planted in response to the Dust Bowl were removed to install large center-pivot irrigation systems. Later, the perceived value of field windbreaks was minimized due to the adoption of minimum and no-till practices which reduced vulnerability to wind erosion. Years later because of environmental concerns, conservation programs have encouraged the planting of modern windbreaks consisting of just two or three rows that offer most of the benefits of a wider windbreak, while reducing costs in maintenance, removal and establishment (Helmert & Brandle, 2005).

In Kansas, the last windbreak assessment was conducted by the Great Plains Initiative in 2008 and 2009. Moser et al., (2008) using GIS across multi-county regions, reported an estimate

of 289,577 windbreaks with a length of 43,436 miles' protecting 1.2 million acres of land.

Ghimire (2014) estimated that 44% of Kansas windbreaks are declining in condition, from good-fair to poor conditions. In this research, most of the windbreaks (83%) were located in Kansas, and the trend of condition declining was confirmed for most of the study windbreaks.

After 40 years of windbreak establishment to reduce soil erosion, windbreaks were also responsible for the improvement of crop yields and the quality of the harvest itself in protected fields, this was due to factors like the reduction of wind erosion, better microclimate conditions and the increase in soil moisture (Kort, 1988).

Design and Establishment of Windbreaks

In general terms, windbreaks modify the microclimate to protect crops, properties, roads and livestock. It depends on the primary purpose of the vegetative barriers to designate them as a living snow fence, a field or crop windbreak, or farmstead livestock shelterbelt (Schoeneberger, 2009).

Windbreak design, establishment and management requires the knowledge of good agroforestry practices. Pre-and post-planting techniques are necessary in order to successfully establish the windbreak. The first and main parameter to consider before planting is orientation. Windbreaks are most effective when they are located perpendicular to the prevailing wind direction (Tamang et al., 2015). Besides cultivation after the final harvest, the windbreak establishment phase for crop fields requires minimum site preparation which differs from the more intensive methods in grasslands like using herbicides in the windbreak zone (Mize et al., 2008). During the planting phase the key is to employ proper planting techniques. It is important

to select and manage quality plants appropriate to the type of soil and resistant to environmental conditions of the area in order to ensure success in windbreak establishment (Boehner, 1996).

Various species of trees can be planted in windbreaks; however, using all deciduous trees is not recommended for year-round protection. Deciduous trees are less effective during the winter season due to leaf loss, even when planted in multiple rows (Beetz, 2002; Gonzales, 2015). Also, optimal field crop yield increases are achieved when narrow windbreaks have dense to medium porosity, consisting of fast-growing and non-competitive trees species (Kort, 1988).

In general, within the rows, spacing between trees varies from 7-16 ft. and 3-7 ft. for shrub species although this varies according design. For faster barrier formation, closer spaces reduce the time for canopy closure but this practice reduces the life span of the windbreaks, unless periodic thinning is performed. Wider spacing requires more time for barrier formation but increases the life span of the shelterbelt (Mize et al., 2008). According to Helmers and Brandle, (2005) optimal spacing between multiple windbreaks was approximately 13 times the height of the windbreak (386 feet), assuming a tree height of 20 feet in 40 years and a conservative growth rate.

The maintenance phase or post-planting care involves practices like weed control, irrigation, protection from wildlife and livestock, monitoring for insects and disease problems, and replanting if necessary, in order to maintain the vigor and health and the overall performance of vegetative barriers (Boehner, 1996).

In order to provide maximum crop protection and improve yields Stoeckeler (1962) recommended field windbreaks should consist of one or two rows and occupy <5% of the total land area. Several tall, long-lived species with deep root systems and similar growth should be planted. Windbreak density should be 40 to 60 percent, especially at the time of crop planting

when soil is exposed and when deciduous trees are without foliage (Brandle and Hodges, 2000). According to Bates (1944) the maximum width that windbreaks should occupy is twice their mature height.

Windbreak Effects and Benefits

The principal effects of windbreaks are directly related to modifying air flow, particularly wind speed reduction, resulting in changing the field environment, and microclimate changes (Kort, 1988). These effects provide agricultural, environmental and economic benefits. As an agricultural benefit, windbreaks have a variable effect on the increase of crop yield depending on growing season conditions. Examples of environmental effects are carbon sequestration by trees and wildlife benefits for hunting or pollinators. Reduction of wind erosion addressed one of the most critical environmental problems in the Great Plains: soil loss. As mentioned before, wildlife increases are considered an environmental positive effect, but also the enhancement of wildlife has negative effects particularly on crop costs because of crop and windbreak damage. Aesthetics and improvement of air quality while reducing odor emissions are valuable contributions (Batish et al., 2007) for windbreaks that serve as vegetative barriers associated with confined animal operations, like poultry or hog houses.

Reduction of wind damage

Shape, external and internal structure of windbreaks influence effects. The effectiveness of windbreaks depends on factors like species of tree, shape, height, length, width, orientation, canopy density and porosity, which is the most common parameter of internal structure, defined as the amount of open space, density defined as the inverse of porosity, therefore the amount of solid material (Tamang et al., 2015). Two primary factors that determine windbreak

effectiveness in reduction of wind speed are the windbreak height and porosity (Koh et al., 2014).

When air flow approaches the windbreak, some wind passes through the barrier, some wind moves around the barrier, but most of it goes up and over the shelterbelt. Therefore, a reduction of the wind velocity occurs in the windward side, to a side lesser extent than the reduction on the downwind or leeward side. (Heisler & Dewalle, 1988; Brandle and Hodges, 2000; Straight & Brandle, 2007). Windbreak height determines the horizontal length of the sheltered area (Koh et al., 2014). According to Heisler & Dewalle (1988) upwind and downwind effects are usually assumed to be proportional to windbreak height, noted as H in formulas and models. Reductions of wind speed have been recorded 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. On the leeward side the peak protected zone extends 10 to 20 H and to a lesser extent 30 H downwind. Most benefits occur within 10 H on the leeward zone or between 0-3 H on the windward side (Baldwin, 1988; Cleugh et al., 2002 ; Helmers & Brandle, 2005; Figure 1.4).

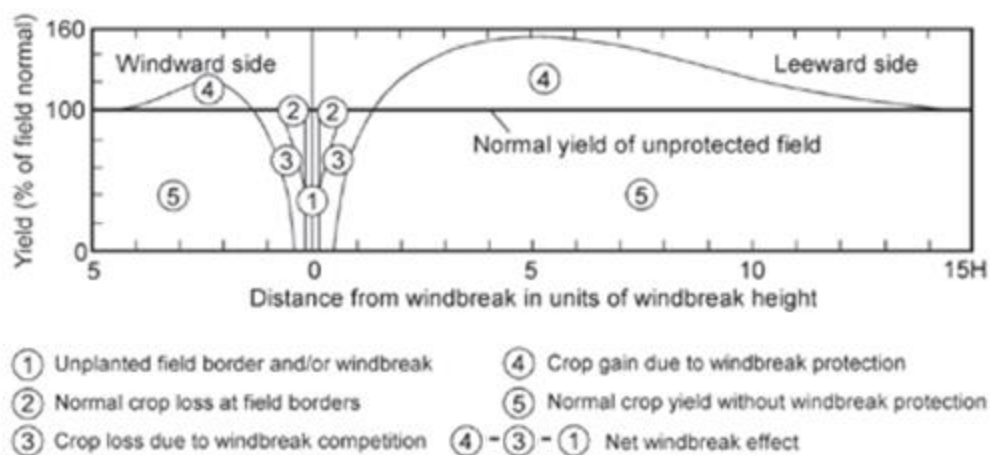


Figure 1.4 Crop yield response for a field windbreak in the Great Plains (Brandle et al., 2000).

Windbreaks reduce wind damage to crops from the moment of seeding during the critical period through germination and establishment (seed removed from the soil due to sandblasting) until post-harvest when plants are left in the field to dry (Kort, 1988). Windbreaks also reduce crop lodging due to wind damage (Cleugh, 1998). Lodging is the damage of crops (tearing, flattening or striping) due to rain and high speed winds. The most important benefit of wind protection may be the improvement in quality of the product in order to obtain a larger-bigger size fruit, with a healthy characteristic color, not bruised, with a good shape in vegetable gardens, orchards, vineyards and specialty crops such as soybeans (*Glycine max (L.) Merr.*) sugar beets (*Beta vulgaris L.*), tobacco (*Nicotiana sp.*) pimentos (*Capsicum annuum L.*) (Baldwin, 1988).

Crop yield increase

Many studies worldwide have shown an overall crop yield increase due to windbreaks in the protected zone. However most of the main U.S. studies (Bates, 1944; Stoeckeler, 1962; Brandle et al., 1984) have used small plots or trials protected by windbreaks as research areas to record data. Bates (1944) reported that windbreaks reduce lodging due to wind and that corn showed no yield loss due to windbreak competition. Stoeckeler (1962) found that a shelterbelt should occupy less than <5% of the total land area in order to enhance crop yield increases. Also he mentioned that greater crop yield increases are found in North and South Dakota than Kansas and Nebraska due to higher snowfalls. Brandle et al. (1984) reported in Nebraska a 15% of yield increases for winter wheat analyzing 6 years of data. An analysis of yield increases were summarized on a worldwide study in 1986 at the First International Windbreak Conference and indicated significant yield increases for winter wheat (23%), soybeans (15%) and corn (12%) (Kort, 1988).

Nearly all published reports from the 1950s have shown that there are no yield reductions caused by the windbreaks, except in the zone immediately adjacent to the barrier, and these reductions are more than compensated for the yield increased from the long downwind area protected zone (Figure 1.5). According to Stoeckeler (1962), yield reductions are present from 0.5 H to 1.5 H. Crop yield reductions close to the vegetative barriers result from a combination of above-and below-ground competition between shelterbelts and crops (Brenner et al., 1993).

Competition between tree and crop roots for soil moisture and shading is likely the primary cause for yield reductions adjacent to windbreaks. Other reasons for crop yield reductions include allelopathy, increased temperatures and nutrient leaching after heavy snow accumulation (Kort, 1988; Andrue, 2007). Greb and Black (1961) reported that moisture content of the area is a key factor that affects the competition between crops and windbreaks. Regional differences they mentioned were in the Western part of the Great Plains, where moisture competition between crops and windbreaks was more severe than in the eastern part and in the south was less than in the north. This might be because rainfall and snowfall differs from region to region; south and east are wetter than northern and western part of the Great Plains (Kunkel et al., 2013).

Crop type is another factor to consider in the effect of a windbreak on a crop field and their competition with shelterbelts. In one study, corn showed no apparent yield loss, alfalfa showed a small loss while wheat and oats showed larger losses in the zone close to the barrier (Bates, 1944).

Intensive agroforestry techniques like root pruning can reduce the windbreak competition with crops (Kort, 1988). A study in Oklahoma eliminated yield reductions by cutting roots of a black locust and Siberian elm windbreak in the top of 60 cm of soil at 0.5 H (Stoeckeler, 1962).

According to Hou et al., (2003) root-pruning increased soybeans yields in their study conducted in Nebraska in 1998. They compared root-pruned plots with non-pruned, finding that soil water content in the root-pruned plots was significantly higher than the non-pruned plots. It is important to consider the cost/benefit relation. According to Brandle et al., (2000) economic viability of root pruning depends on many factors like how large yield decreases were due to windbreak root competition, equipment and operation costs, how fertile is the land and how often maintenance practices will need to be conducted. Root pruning may cost more than the benefit, since powerful tractors use a lot of fuel to root plow (Barden, personal communication, 2017), while Lyles et al., (1984) reported economic returns from root pruning in a wheat field windbreak study. Careful species selection depending on the conditions of the site and designing windbreak to reduce its width, maximizes the crop yield benefits due to windbreaks (Kort, 1988).

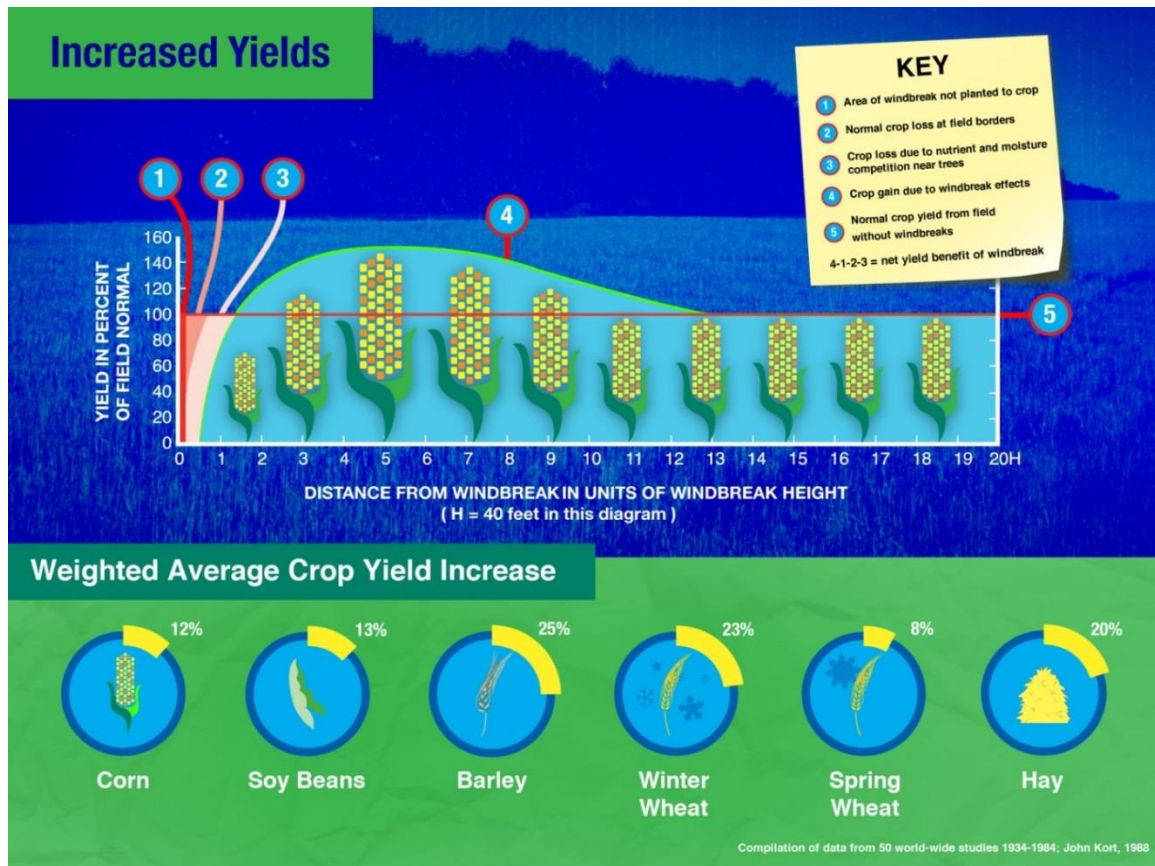


Figure 1.5 Compilation of data from 50 worldwide studies showing increased yields due to windbreak effects (Kort, 1988).

Kort's data compilation (Figure 1.5) shows that the net yield benefit of windbreaks are obtained when subtracting 4-1-2-3. We consider that #2 (normal crop loss at field borders) doesn't need to be subtracted because it occurs with or without windbreak. This research agrees more with Brandle et al., (2000) Figure 1.4, which subtracts 4-1-3 in order to get the net windbreak effect.

There are plenty of studies that demonstrate the distance of the sheltered area by windbreaks. The protected zone extends to 30 H distance from the windbreak in the leeward side (downwind) and for a distance of 5 H in the windward side (up-wind) (Brandle et al., 2004). According to Baldwin (1988) most of the yield increase due to windbreaks occur within 10 H in the downwind zone, or within 0-3 h in the windward side. The world data compilation done by

(Kort, 1988; Figure 1.5) showed yield increases from 0.5 H – 13 H on the leeward side of the field. Sudmeyer and Scott (2002) reported that regardless of the season, crops in the downwind protected zone from 3 to 20 times the windbreak height have demonstrated an increase yield of 16-30% comparing it to the unprotected area from 30 times the height of the windbreak and beyond. It has generally been confirmed that maximum yield gains are usually found between 3 and 10 H in the quiet zone, which is the zone immediately behind the windbreak (Cleugh, 1998). Some yield benefits of windbreak protection can begin as early as year 7, but the most yield benefit occurs when windbreak is mature (at 40- 70 plus years of age; Helmers & Brandle, 2005). Climate is an important variable that affects crop yield increases, depending on geographic location and relative precipitation (dry, wet and normal). Studies have shown that in drier regions of the Great Plains, low yields due to shelterbelt competition were more evident than in higher rainfall areas. (Kort, 1988) which agrees with (Greb and Black, 1961) assertions.

Other important reasons that explain crop yield increases in the protected zone are reduction in leaf abrasion, stripping and tearing of vegetable crops, and microclimate change (Cleugh, 1998) due windbreak effect.

Microclimate change

Windbreak's main purpose is to reduce wind speed close to the ground, which results in achieving the modification of the surrounding air flow, soil and plant environments (Cleugh, 1998). It was reported that nitrogen uptake by crops, increases in the leeward protected zone (Shah and Kalra, 1970). Windbreaks change the microclimate conditions, therefore temperature and evapotranspiration rate have a positive influence over plants, leading to better growth and yield of crops. Heat and water vapor are altered due to the modified turbulent airflow behind a

windbreak. Therefore, in the protected zone during the day, higher soil temperature, air temperature and humidity is expected. The increase or decrease of evaporation rates depends on weather, soil conditions and plant water status (Cleugh, 1998).

In Nebraska it was shown that microclimate modification due to windbreaks produced crop yield increases. Higher temperatures in the sheltered zone caused corn to have better responses to high density windbreaks than low density shelterbelts (Stoeckeler, 1962). There is a reduction in evapotranspiration of bare soil and transpiration from crops in the protected zone due to wind speed reduction of vegetative barriers. Therefore, plants behind the windbreaks suffered less moisture stress (Cleugh, 2002) and improved growth due to less mid-day wilting and stomatal closure resulting in cessation of the photosynthetic activity (Andrue, 2007).

Other effects and benefits

Beyond the two main effects of windbreaks, reduction of wind damage and enhancement of the microclimate to favor crop growth and protection of livestock (Koh et al., 2014), there are other impacts of windbreaks on the environment worldwide.

Economics

Establishment, maintenance and removal of shelterbelts involve costs. The first years of windbreak establishment provides a low economic return, but studies show the economic net return is positive over the life of the windbreak (Sudmeyer and Flugge 2006). Stoeckeler (1965) and Brandle et al (1992) reported that after an average of 15 to 18 years, windbreaks paid for themselves and increased net yields of grains and cereals, compensating for the costs of land occupation and crop shelterbelt competition. The total crop field % was the most universally agreed recommendation between several studies. Shelterbelts should occupy 5% of the total crop field (Kort, 1988; Brandle et al., 1992). In the Great Plains and other parts of the United States

studies have demonstrated annual increases of 15% or even more for wheat (*Triticum aestivum* L.) (Brandle et al., 1992) 7.6 % corn (*Zea mays* L.) and soybeans 9.2% (*Glycine max* L.) (Stoeckeler, 1962; Helmers & Brandle, 2005).

In field windbreaks, the area of protected crop field multiplied by the crop yield increase from windbreak protection should be more than the yield forfeited by the land occupied by the windbreak (the footprint). Also, yield increases in the protected zone should be more than yield losses due to windbreak and crop competition in the zone immediately adjacent to the windbreak in order to get an increased return from the agroforestry system. Overall, yield increase due to the windbreak effect should compensate for the costs of establishment and maintenance of the windbreak, and for the footprint of the windbreak (Brandle et al., 2000). Recent studies have developed models and economic analysis to evaluate the economic returns of field windbreaks. One of these studies concluded that the economic return depends on the rate of growth of the windbreak and the life expectancy (Grala and Colletti, 2003). Therefore, windbreaks that grow faster and live longer provide more economic benefits.

Environmental

Additional windbreak benefits are related to the reduction of negative impacts of agricultural practices and improvement of environment conditions. Including improvement of wildlife habitat, landscape aesthetics, improvement of air quality and other ecosystem services like water quality, carbon sequestration and nutrient cycling (Andrue, 2007).

Economic evaluation of other benefits that could provide economic returns include reduced wind erosion, enhanced wildlife habitat and aesthetics, which vary due to the area of study, soil type and climate, however values mentioned are difficult to quantify (Kort, 1988; Brandle et al., 1992). According to Cook and Cable (1990) the contingent valuation method

(CVM) has been used to determine the economic value of the environmental benefits mentioned above. They estimated a minimum net economic value of \$21.5 million per year for hunting in windbreaks as a recreational resource in Kansas.

Trees and shrubs enhance wildlife habitat providing home and resources like food, shelter and protection. Windbreaks serve as travel corridors for animals, which permit safe movement across agricultural fields to connect natural areas (Batish et al., 2007; Mize et al., 2008) while increasing biological diversity which allows natural predators to control crop pests and favor pollinators. Windbreaks can also reduce pesticide drift onto non-target areas and surface water bodies like rivers or ponds (Cleugh, 1998; Andrue, 2007). Windbreaks prevent 97% of the eroded wind-blown top soil from entering into the rivers and streams (Lovell and Sullivan, 2006).

It has been demonstrated that windbreaks can sequester large amounts of carbon in reduced land (5 %), and reduced dioxide emissions to prevent global warming (Ruark et al., 2003). Windbreaks also serve as barriers to reduce odor emissions from livestock activities. Lin et al., (2006) found that dense windbreaks consisting of coniferous trees that are perpendicular to the wind and are close to the source are the most effective for mitigating livestock odors.

Windbreaks are useful for snow management, too. In winter, a windbreak with a density of 25 to 35 % traps snow and evenly disperses it over a large part of the field (Brandle et al., 2004). Differences in snowfall due to geographic location results in northern regions exhibiting higher yield increases than in central regions of the Great Plains. This was concluded since snow melt increases soil moisture and reduces wind erosion which were the main reasons for lower yields (Stoekeler, 1962; Kort, 1988). Therefore, higher snowfall in places like North and South

Dakota were responsible for more crop yield increases than in Kansas and Nebraska (Stoekeler, 1962) .

Summary

Despite earlier worldwide studies showing an overall crop yield increase due to windbreaks, these results are not widely recognized. Obvious yield reductions immediately adjacent to windbreaks are the reason many farmers overlook overall yield increases in the protected crop area behind shelterbelts. There is also a perception that windbreaks are not needed any more due to soil conservation tillage practices and the difficulty of maneuvering ever-larger equipment that has induced the farmers to remove their shelterbelts. There are also very few recent studies evaluating crop yield benefits of windbreaks.

Significant global population growth by 2050 where increases in food and grain demand are a potential scenario where lack of cropland is going to be an issue to meet the population needs (Tilman et al., 2002). Newly available geo-referenced monitoring data, research that was never applied and new crop genetics are all good reasons to conduct this study.

Area of study

The area of study consisted of 29 crop fields in total, with 23 non-irrigated fields and 6 irrigated fields. The fields were located in the north central part of Kansas in the following counties: Mitchell (1), Ottawa (2), Dickinson (10), Clay (3) and in south central Kansas: Stafford (1), Edwards (2), Rice (3). Also in two counties of Nebraska: Red Willow (6) and Knox (1) two farmers were willing to share combine yield monitor data from their fields. For this study, fields were selected under the following criteria: long enough fields (length more than 30 times the height of the windbreak) or pairs of fields one with windbreak and the other without windbreak

in order to compare the yield in the protected and un-protected zone (30 H + or fields without windbreaks adjacent to a protected field). Fields selected had windbreaks with good structural features: Height, orientation, length, width, uniformity and continuity (Brandle et al., 2000).

Objectives

Food and water scarcity along with the lack of crop land predicted in 30 years due to world population growth (Tilman et al., 2002) suggests farmers must make important decisions for sustainable agriculture practices, for example, a future return to dryland farming and better management of natural resources to adjust to climate change conditions (Rosegrant and Cline, 2003). In order to find solutions to the problems stated above, windbreaks could play an important future role as an agroforestry conservation practice in the Great Plains. Therefore, the increase of productivity in crop yields due to windbreak effects demonstrated in earlier research, needs to be updated with new georeferenced monitoring data generated by farmer's combines and coupled with the advanced crop genetics currently being planted.

This study was done in order to substantiate the effect windbreaks/shelterbelts have on modern crop yields with the following two main goals:

1. Determine if windbreaks provide yield benefits across a variety of crops.
2. Update our knowledge of windbreak/crop yield interaction in different crops and seasons.

Specific objectives will answer the following questions:

- Do windbreaks improve yields of modern varieties. And of which crops?
- Is the yield increase enough to compensate for the footprint of the windbreak?
- Does the windbreak effect on crop yield change during dry, normal and wet seasons?

- Is there any association between the windbreak optical density and the crop yield increase?

Chapter 2 - Methods

This chapter will review the study methods applied in this project which compared multiple years of data from protected and unprotected fields across Kansas and Nebraska, looking at relative crop yield differences. Three sets of data were collected: general information about the windbreak fields (on the ground data collection and aerial photos), crop yield monitor data and climate data.

Data analysis was done using Geographic Information Systems software ArcGIS 10.3.1 (Esri, 1995-2016), where the monitor yield data were cleaned, projected and extracted. Furthermore, data was evaluated and analyzed for statistical comparisons between protected and unprotected fields and relations of the crop yield data with the climate data with the Statistical Analysis System SAS 9.3 (SAS Institute, Inc.) with the collaboration of the Statistical Consulting Laboratory at Kansas State University. Optical density of windbreaks was determined using SigmaScan Pro software from ground-based photos.

Study promotion

The first step was to identify farmers and landowners that might be willing to share yield monitor data from crop fields with similar rotations, both with and without windbreak protection.

This study was part of a larger Great Plains crop yield research project that has been promoted in the past 4 years by K-State Research and Extension, Natural Resources Conservation Service (NRCS), and County Conservation District personnel through state conferences and magazine articles. K-State Research and Extension also mailed a total of 406 letters to landowners in Kansas with windbreaks in good condition already identified in a previous study (Ghimire, 2014) with the collaboration of the Kansas Forest Service. Two

hundred eight letters were mailed to the Smoky Hill area (Russell, Logan, Ellis counties) and 198 letters mailed to Coronado Crossings area (Clark, Meade, Gray, Hodgeman). The letters contained general information about the study (Appendix A) requesting the landowner's collaboration in the study and crop yield monitor data. A data collection form to provide general features of the field and the windbreak were requested (Appendix B). No cooperating farmers came forward from the letters.

Most of the cooperators were obtained through presentations at KARTA (Kansas Agricultural Research & Technology Association) annual meetings, with a few referrals from the NRCS offices and an article published in the *Furrow* John Deere magazine called "A Break for Higher Yields" (Reichenberger, 2015). Study challenges were to access the data and securing cooperation of producers. Several farmers expressed reluctance to share personal yield data with government agencies. It took several visits (3 years in a row) to the KARTA annual meeting to gain the trust of several cooperators.

Data collection

Field windbreak general information

In earlier studies, the main methods used to assess windbreak effects were: field measurements, wind tunnel tests and computational fluid dynamics (Lin et al., 2006). In this study we collected field measurements including on-the-ground landowner data, which consisted of field location, date, landowner name, crops grown, agricultural practices and windbreak general measurements (tree species, average height, length, width and optical density) which were collected through field visits in 2015-2016 winter and summer seasons. Data was recorded in a field data sheet (Appendix B).

Height and width of trees were measured using terrestrial laser scanning (TLS) with a laser rangefinder as accomplished by (Moskal and Zheng, 2011). Srinivasan et al., (2015) demonstrated that terrestrial laser scanning is an effective tool to measure tree level height, crown width and stem diameter.

Ground based photos were taken in order to determine optical density following the guidelines provided by Kenney (1987). Photos were taken in summer and winter seasons 2015-2016 for a subset of the windbreaks to assess optical density in both leaf-on/off conditions. Digital photos were processed using SigmaScan image analysis software to determine optical density which is related to functional density of the windbreak.

Tree measurements and photos were taken at different points along the windbreak. The number of measurements and photos depended on the shelterbelt length. In shorter windbreaks (100-300 yards' length) 3 to 4 measurement locations were assessed, in longer windbreaks (400 + yards' length) 5 to 7 measurement locations were recorded.

Windbreak field locations were identified in aerial photographs. Aerial photographs were obtained from the Kansas Data Access and Support Center, the website Kansasgis.org called DASC and from the FSA National Agriculture Imagery program (NAIP).

Crop yield data

The key to this study is that crop yield data already exists with farmers that have crop yield monitors installed on their equipment and have stored the information on their computer for years. According to Tilman et al., (2002) crop yield monitors are electronic devices that incorporate data from a yield sensor designed to measure crop yield in the field while harvesting. Arslan and Colvin (2002), mentioned that commercial yield monitors are based in a variety of measurement methods like flow (mass and volume), impact, infrared or gamma ray sensors. The

most common is the mass flow sensor which can determine total grain harvested by measuring harvested grain mass flow, moisture content is recorded by a moisture sensor, and ground speed by a ground speed sensor (Tilman et al., 2002). Also, in most cases, crop yield monitors are coupled with a Differential Global Positioning System (DGPS) to record crop yield data for virtually every point in a field relating the grain flow to yield with location (Nowatzki, 2007). Summaries are downloaded via the storage devices to the farmer's computer and opened in spreadsheets for further data analysis and record keeping.

Generally, computer software associated with crop yield monitors has a data export function to extract data for each field. Yield data was exported as a point shapefile which is a format with four file extensions: shp., dbf., shx., prj. In most cases this monitor data was collected on a portable hard drive from the landowner's computer during the field visits or flash drives were mailed directly to the authors.

A total of 414 crop/years were collected in nine counties in two states, Kansas: Mitchell (16 crop/years), Stafford (2 crop/years), Edwards (32 crop/years), Ottawa (26 crop/years), Rice (38 crop/years), Dickinson (111 crop/years), Clay (152 crop/years); and Nebraska: Red Willow (33 crop/years) and Knox (4 crop/years) from nine farmers of five crops: soybeans (*Glycine max*), wheat (*Triticum*), corn (*Zea Mays*), sorghum (*Sorghum bicolor*), and sunflowers (*Helianthus*). The two largest data sources from Dickinson and Clay counties were recruited from the KARTA annual meeting in 2016. These two ownerships provided data from 13 fields, 263 crop/years, equivalent to the 64% of the total data.

After cleaning, selecting and sorting the data (process explained in the GIS data analysis in Appendix C) along with the selection of fields where the windbreak condition was "good" according to literature guidelines (Bates, 1944) with long enough fields (length more than 30

times the height of the windbreak) or adjacent unprotected fields planted with the same crop for comparisons of the yield. Thus protected and un-protected zone (30 H + or fields without windbreaks close enough a protected field could be validly compared) similar to what Sudmeyer and Scott (2002) reported that crops in the downwind protected zone from 3 to 20 times the windbreak height have demonstrated an increase yield comparing it to the unprotected area from 30 times the height of the windbreak and beyond.

After cleaning, sorting and selecting data to compare, a total of 230 crop/years were available for data analysis. Mitchell (16 crop/years), Stafford (2 crop/years), Edwards (14 crop/years), Ottawa (8 crop/years), Rice (15 crop/years), Dickinson (93 crop/years), Clay (48 crop/years) and Nebraska: Red Willow (30 crop/years) and Knox (4 crop/years). Total analyzed crop/years by crops were: Soybeans (81 crop/years), wheat (62 crop/years), corn (50 crop/years), sorghum (31 crop/years), sunflowers (6 crop/years). The rest of the data could not be used for this study because the fields were not long enough to have protected and un-protected zones, unpaired small fields (just with protected or un-protected areas), windbreaks were not uniform or not in good condition (many gaps). There were a few yield monitor data sets that had a lot of errors and zeros in the files which made them unusable, this is explained in more detail in the ArcGIS data analysis section.

Crop yield monitor data information along with location data is essential to analyze the effects of field windbreaks on crop yield through the creation of grain yield maps (data projection) and data extraction. This was done using ArcGIS 10.3.1, this process is further explained in the data analysis section. It is important to mention that combine crop yield monitor data has never been used before in a windbreak study of this scale.

Climate data

The third set of data collected was climate data, factored into yield analysis. Information from weather stations close enough to the fields of study were obtained with the help of the survey climatologist (Knapp, personal communication, 2016) in the agronomy department at Kansas State University hosted on the ACIS (Applied Climate Information System) (Lawrimore et al., 2011).

According to Kort (1988) efficacy of the windbreak effect is related to stage of crop development and weather year to year. Daily precipitation and normal averages were obtained for critical months of stage development for the five crops for every year. Critical month information was obtained with help from the Crop Production Team at Kansas State University (Ciampitti, personal communication, 2017). To obtain corn climate data, the month of July was selected since flowering is the most critical stage of the crop. For soybeans, sorghum and sunflowers, the month of September was selected and for wheat the month when water is most critical is April. In order to classify the years as wet, dry and normal growing seasons thresholds were set on standard deviation units. For example, in a crop/year where the average critical month precipitation was 2.5 inches with a standard deviation of 0.19 inches. Then, if the critical crop month was 0.19 inches above average was considered a wet crop/year, a month that was 0.19 inches below average was considered as a dry crop/year for that crop. A total of 78 wet, 80 dry and 5 normal years were assessed in the study. For the irrigated crop field/years precipitation was not considered. This information was important to gather since precipitation is an important variable for crop development when analyzing the windbreak effect on crops and water competition. It has been demonstrated that in areas where trees and crops are planted together, both are more likely to extract water from the same locations in the soil profile (Smith, 1995).

This would affect more the crop yield reductions in the zone immediately closer to the barrier. Other studies concluded that the shade effect from shelterbelts affects the crop yield only when water is not a limitation (wet seasons) since water stress in any agricultural system is an issue (Nuberg, 1998). There is a disagreement between studies that indicate greater windbreak effects are found in wet seasons, others conclude that dry seasons benefit more from windbreaks. (Kort, 1988). Therefore, this study follows Kort's (1988) recommendation to study windbreak effects over a number of years and crops in order to reduce the variability year to year when documenting the overall benefits of windbreaks on crop yields in the Great Plains.

Data analysis

ArcGIS 10.3.1© (Redlands, CA) was used to clean, project and extract monitor yield data. Statistical comparisons between protected and unprotected fields and relations of crop yield data with climate data were done using Statistical Analysis System SAS 9.3® (Cary, N.C.). The optical density of windbreaks was determined using SigmaScan Pro© software (San Jose, CA) from ground-based photos.

ArcGIS analysis

Crop yield data was collected on hard drives from the farmer's computers as a point shapefile which is a format with four file extensions: shp., dbf., shx., prj. Data and aerial photos were added in ArcGIS 10.3.1® (Esri, 1995-2016) which was a first step necessary to clean the crop yield data. This process was done by removing zeros and outlier values greater than ± 3 standard deviation units from the mean, (Figure 2.1) which originated because a number of yield monitor data errors can be associated with each data set (crop/year) generated within a field. These are errors that occur when the harvest equipment passes more than one time through

the same point of the field for turns and begins harvesting the next swath at the beginning of the previous cut. At the end of the line the combine header moves from down position during the completion of a pass to the up position, this lag can generate more errors in the data which mostly occurs at the edges of the field (Arslan and Colvin, 2002).

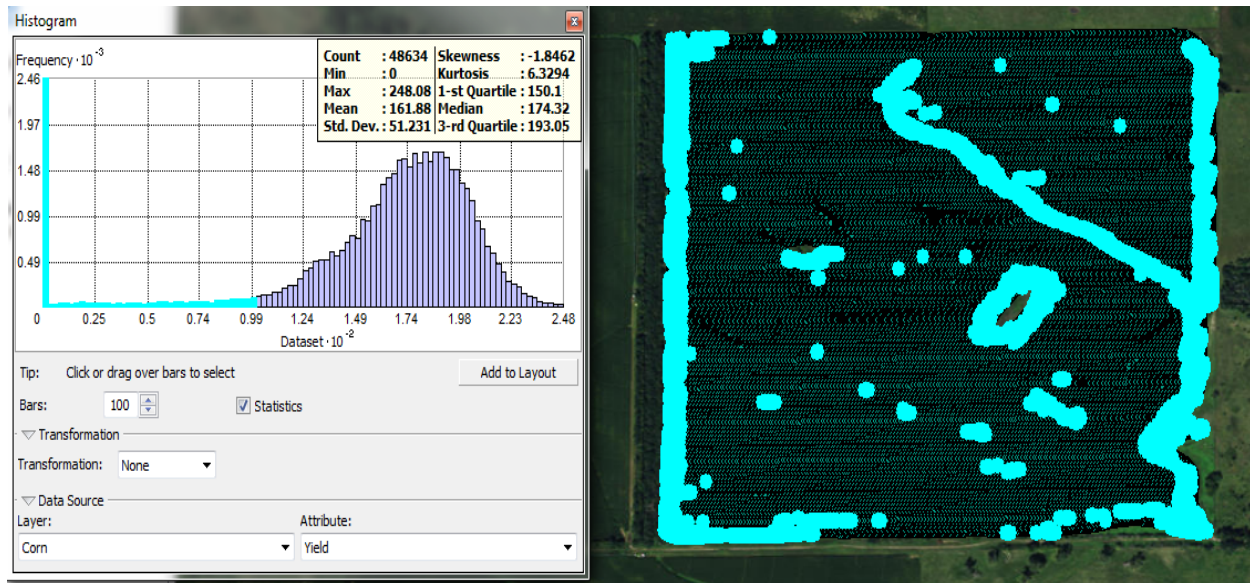


Figure 2.1 Cleaning yield data process of a study field in Mitchell County, Kansas.

Once the yield data was cleaned (removed the zeros and the outlier values greater than ± 3 standard deviation from the mean due to monitor errors) 230 out of 414 crop/years collected, were included in the analysis. Inaccurate monitor yield data is usually due to lack of calibration, improper installation, operation and inspection of the yield monitors. Some calibration methods include: the use of weigh wagons in the field, transferring a considerable amount of the harvest to a truck and weighing it at a grain elevator or commercial scale, calibrating in different areas of the field, calibrating for each different crop, avoiding edges or irregular parts of the field, turning off monitor when harvesting at end of the rows or corners (Arslan and Colvin, 2002; Nowatzki,

2007). It is important to mention that yield monitors were not calibrated during the study period, thus only relative differences were compared.

After the data was cleaned, selection of data to analyze per field was done through the select features option (Figure 2.2). Creation of strips or bands along the study field was the next step. This was achieved using the fishnet tool where the strip width was equal to the windbreak's average height measured in the field. Afterwards, a spatial join was run in order to join the bands with the yield data points calculating an average of all the yield points that fall in each band (Figure 2.3). Creation of a choropleth map was done using the layer properties. Finally, the data was extracted from ArcGIS to an Excel spreadsheet by an export function. A more detailed ArcGIS step by step process is explained in Appendix C.

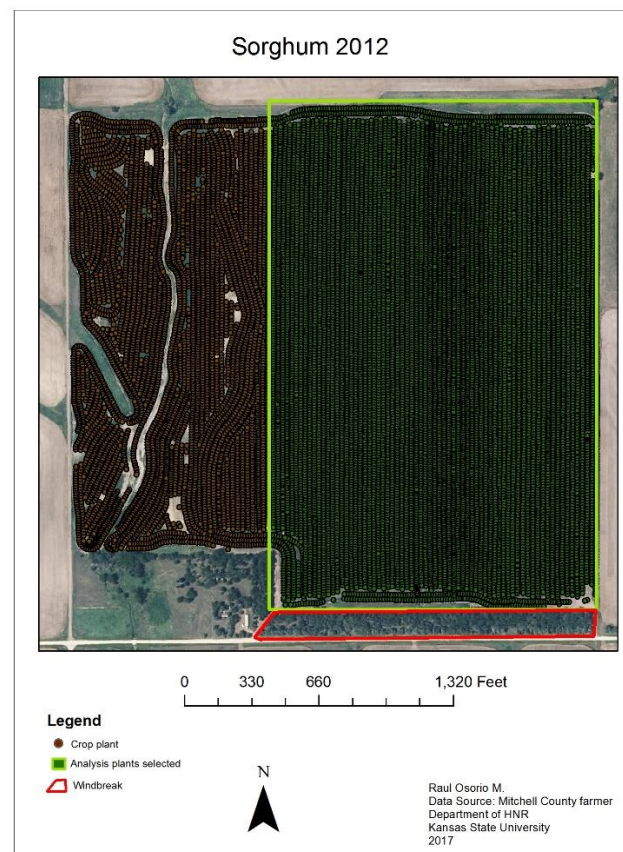


Figure 2.2 Selection of analysis points for a sorghum study field in Mitchell County, Kansas

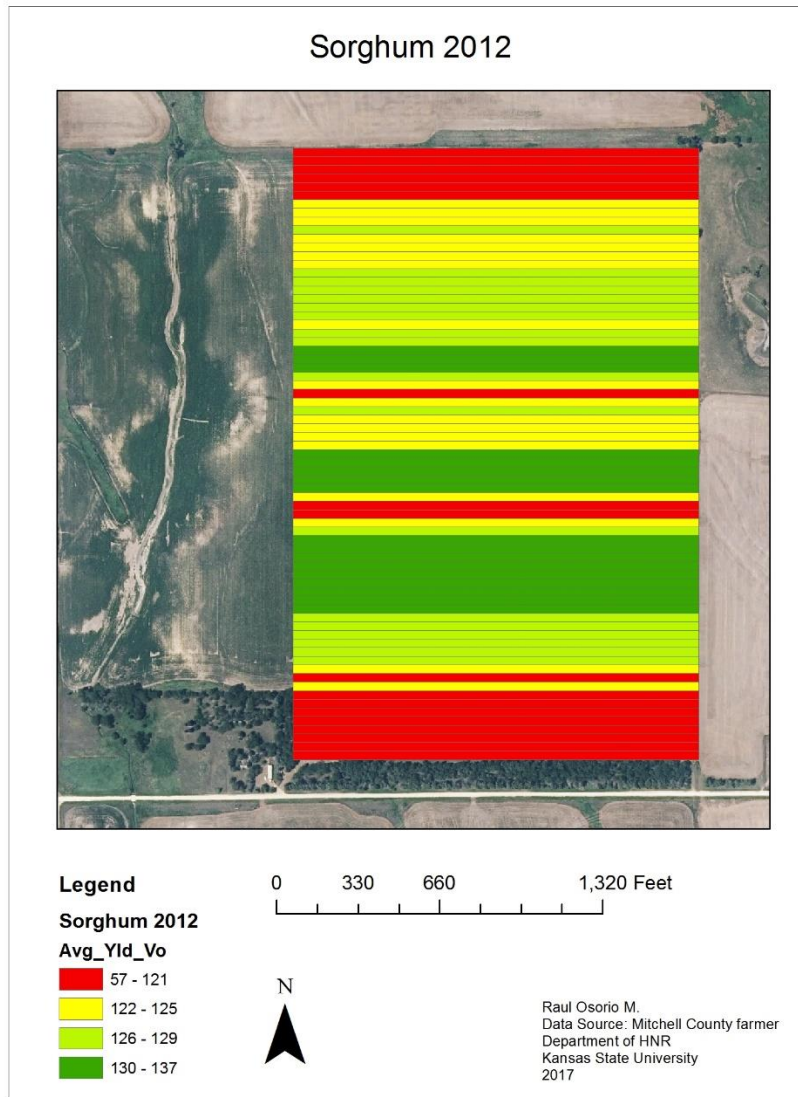


Figure 2.3 Sorghum choropleth crop yield map in Mitchell County, Kansas 2012.

Statistical analysis

Once the crop yield data was exported from ArcGIS to an Excel spreadsheet, a data set in tabulate format was built with the field name, the year, the season and the crop yield data in bushels per acre. Afterwards the data was analyzed using two-sample t-tests to compare group means between protected and un-protected fields defined by unique combination of field name, year and season with PROC TTEST in SAS 9.3 (SAS Institute, Inc.). Prior to the t-test for

means, a hypothesis test of equal population variances was conducted, based on which the decision of which t-test to use was drawn. If the variance was unequal then Satterthwaite test was applied, if there was equal variance a Pooled test was used. There is evidence that the yield in protected field is different from yield in no-protected fields if $p\text{-value} < 0.05$.

Next, a Chi-square test or Fisher's exact test for 2x2 contingency tables was conducted to test the association between two precipitation conditions (i.e. dry and wet) and two yield advantages (i.e. protected field had more yield or un-protected had more yield) among significantly different pairs from the results of t-tests. Precipitation considered was the precipitation received during critical months of crop development.

Optical density analysis

On the field visits, an average of three to six ground-based photos of the windbreak were taken for both leaf-on and leaf-off conditions. Photos were taken one tree height away from the shelterbelts in multiple locations along its length. In each location two photos were taken, also we marked the trees with brightly colored flagging in order to measure and record data from the same location along the windbreak in summer and winter seasons. Kenney (1987) recommend photos be taken during calm, non-windy conditions (to minimize foliage movement) and an overcast day in order to avoid reflection, one tree height away from the windbreak. These guidelines were not fully followed. Particularly recording the data during calm conditions in not too brightly days, because field visits were scheduled when farmers were willing to receive us and when there was availability of time to travel, not considering weather conditions (a clear or cloudy day), since fields were far away from campus. The closest was 2 hours driving (Clay County, Kansas) and the farthest field that we visited was about 5 hours away (Red Willow, Nebraska) from Manhattan, Kansas. Therefore, this could somehow affect the estimation of more

precise optical density percentages as too much brightness would increase reflection from tree elements (Zhu, 2008).

Image analysis software used was SigmaScan Pro 5.0 (Systat Software, 2017) in order to determine the density percentage of each windbreak. To begin with, each photo was cropped from top (average windbreak height) and bottom (to avoid ground clutter) in order to avoid errors due to background and to be more accurate with the height measurement respectively. Once the picture was open in SigmaScan Pro, a threshold was set in order to separate the sky background from the trees and leaves foreground (pixels in red color) as shown in the figure 2.4.

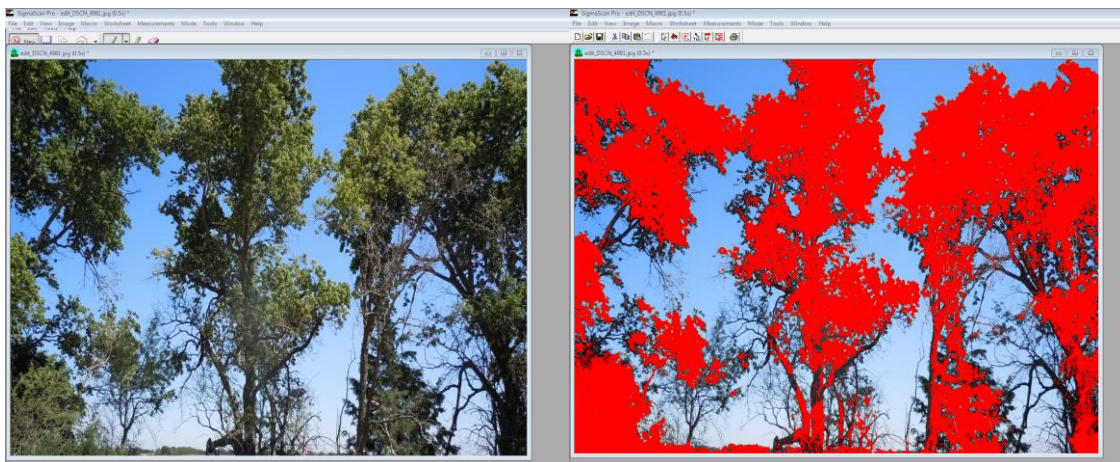


Figure 2.4 Optical density assessment of a windbreak in Clay County, Kansas using SigmaScan Pro software.

Then each picture was re-sized to half of its original size since the software runs better and faster with smaller-size pictures. Finally, the cover analysis was performed and windbreak density percentage was the output in an Excel spreadsheet.

Chapter 3 - Results and Discussion

Windbreak characteristics by county

Most of the study windbreaks (83%) were located in Kansas. Ghimire (2014) estimated that 44% of Kansas windbreaks are declining in condition. This trend was most likely confirmed in most of the data collection field visits (>60%). Many windbreaks were declining from good to fair or even poor conditions; many of them need renovation and good maintenance practices.

Windbreak general measurements were collected as part of the field general information of the study. Tree species, average height, width and photos in leaf off/on season of the windbreaks were recorded through field visits using the tools and procedures mentioned in the methodology section. Table 3.1 shows the summary of the windbreak configuration by county, the average number of rows, average width, and the most common primary, secondary, tertiary and volunteer tree species (spp) among all fields of each county where a study windbreak was assessed. A detailed description of the windbreak configuration by field is found in (Appendix D).

Table 3.1 Summary of windbreak characteristics by county.

County	# of fields	# of rows	width ft.	Primary spp	Secondary spp	Tertiary spp	Volunteer spp
Mitchell	1	3	113	E. redcedar	Honeylocust	Osage-orange	Hackberry
Stafford	1	4	134	E. redcedar			
Edwards	3	4	74	E. redcedar	Siberian elm	Honeylocust	Mulberry
Ottawa	1	4	110	Green ash	E. redcedar	Osage-orange	Hackberry
Rice	3	3	96	Mulberry	Siberian elm	E. redcedar	
Dickinson	10	2	59	Osage-orange	Hackberry	Green ash	Hackberry
Clay	3	1	45	Osage-orange	Hackberry	E. redcedar	Hackberry
Red Willow	6	3	44	E. redcedar	Pine		
Knox	1	4	130	E. redcedar	Osage-orange		

Tree species found in the study windbreaks like Eastern redcedar (*Juniperus virginiana* L.), Green ash (*Fraxinus pennsylvanica* Marsh.), Hackberry (*Celtis occidentalis* L.) and Osage-orange (*Maclura pomifera* Nutt.) are suitable for silty and clay soils, Siberian elm (*Ulmus pumila* L.) and Hackberry for silty-clay and sandy soils and Honeylocust (*Gleditsia triacanthos* L.) develops better in sandy soils (Josiah and Wilson, 1996). Silty and clay soil types were commonly found in the study fields in Kansas and Nebraska (Soil Survey Staff, NRCS, USDA, 2017).

In counties with more data collected Dickinson (111 crop/years), Clay (152 crop/years), the windbreak primary and secondary species were Osage-orange and Hackberry which are deciduous trees that thrive under poor conditions. However, Beetz (2002) does not recommended deciduous trees for year round protection because of leaf loss in the winter season that results in a less dense and effective windbreak. Also windbreak width in those largest counties of data collected was narrower with 1 or 2 rows than others. According to Stoeckeler (1962) and Kort (1988) this is good to increase total crop yields since wide windbreaks remove land from production, therefore it is preferred to have narrower windbreaks that occupy <5% of the total land area.

Two counties collaborated with moderate amounts of data: Edwards (32 crop/years) and Red Willow (33 crop/years) had evergreen trees, specifically Eastern redcedar as the main windbreak specie, while Edwards county had secondary Siberian elm which is a deciduous short-lived species and tertiary Honeylocust. Rice county (38 crop/years) had as the primary species Mulberry (*Morus rubra* L.) and the secondary specie Siberian elm. Siberian elm has been reported by Lyles et al. (1984) to reduce wheat yields and use more water than other species in Kansas. Also Frank (1982) stated Siberian elm as a competitive species with adjacent crops,

more than Green ash and Hackberry. Windbreak width from these counties were average with 3 to 4 rows.

Wider windbreaks in the study belong to Mitchell (16 crop/years), Stafford (2 crop/years), Ottawa (26 crop/years) and Knox (4 crop/years) counties where Eastern redcedar was the primary species with the exception of Ottawa county where the main windbreak species was Green ash, a moderately-lived deciduous species. Wide windbreaks consisting of conifer species like Eastern redcedar provide dense shade, producing little understory vegetation (Mize et al., 2008). Cedars can also lose density at older ages (40+ years) therefore, lose effectiveness in crop protection, because of thinning of the foliage due environmental factors like heavy snowfalls and shading (Josiah and Wilson, 1996). Green ash has been reported to be less competitive with crops immediately close to the barrier in the Northern Great Plains than Siberian elm. Green ash drops its leaves earlier due to drought stress which makes it active for a shorter time in the year, thus reduces its use of soil water (Frank, 1982).

In general, tree species selection for field windbreak design must be done considering many factors like soil type, environmental conditions and intended use of the windbreak. Single- or two-row windbreaks may be enough for crop field protection to enhance yields. Multi-row windbreaks are recommended for purposes like wildlife, woody production and commercial non-timber products (fruits and nuts; Brandle et al., 2004). Most windbreaks in this study were composed of a diversity of tree species in the windbreak itself which is good for the benefits that a windbreak provides and its health (Josiah and Wilson, 1996). Also, using a combination of species in windbreaks has become more common in the last 60 years (Schroeder, 1988).

Do windbreaks improve yields of modern hybrids?

After the yield monitor data was projected in maps, analyzed and extracted from ArcGIS, statistical analysis was run using statistical software SAS (SAS Institute, Inc. Cary N.C.) through two-sample t-tests comparing group means between protected and un-protected fields divided by windbreak location. It is important to mention that most of the study fields were long, with more than 80 H length in units of windbreak height. In those fields, the unprotected control area was considered starting at 30 H downwind, and this zone was more than two times larger than the area of the windbreak protected area (20 H) in this study.

Results showed that 156 out of 230 crop/years were significantly different ($P < 0.05$), which means that for 156 crop/years the yield in protected area was different from yield in the unprotected area. Based on the analysis, 48 out of 156 crop field/years showed significant yield increases, showing that the average yield in the protected area was greater than in the unprotected area. The rest of the significantly different crop field/years (108) showed significant yield decreases, showing that the average yield in the protected area was less than the average yield in the unprotected area. According to Greb and Black (1961) in drier regions of the Great Plains, competitive yield decreases were more predominant due to moisture competition.

Figure 3.1 shows the yield increase and decrease frequency percentage by crop from 156 significantly different crop field /years and the average size of the fields in acres respectively.

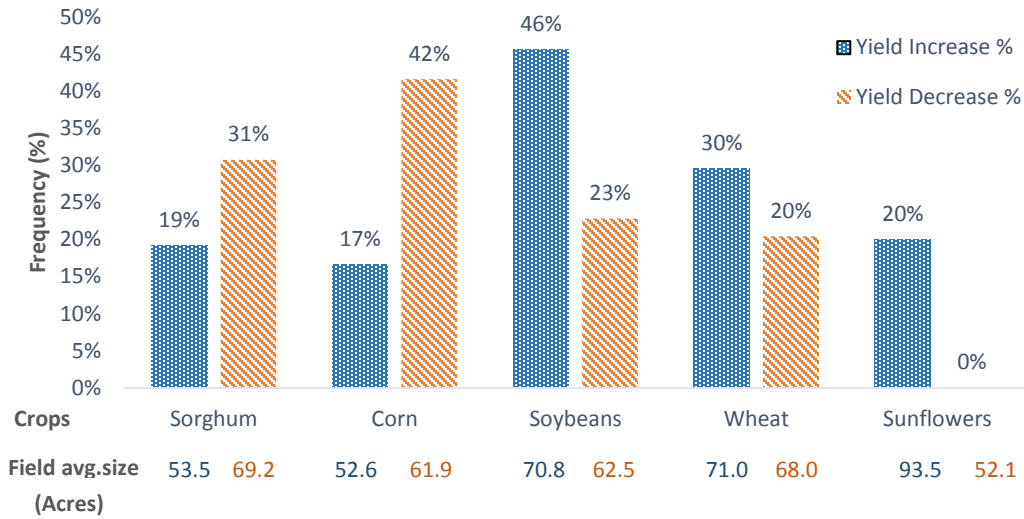


Figure 3.1 Significant differences in frequency (%) by crop for both yield increase and decrease due to windbreak effect. Field average size (acres) is shown for each category.

Soybeans were the most responsive crop to windbreak effect with a 46% yield increase frequency followed by wheat with a 30% increase frequency due to windbreak effect. According to compilation of data from 50-worldwide studies from 1934-1984 reported by Kort (1988), wheat was also reported as one of the highly responsive crops to windbreak protection followed by soybeans. Sorghum and corn had a less positive response with a 19% and 17% yield increase frequency, respectively. Kort (1988) also reported corn to be less responsive to the windbreak effect, which agrees with the findings in this study. However, caution should be used with Kort’s grain sorghum and corn data as his analysis is only based on older varieties, perhaps newer hybrids will behave differently than older varieties.

The two most responsive crops with significant differences had a larger data set with soybeans at 57 crop/years and wheat at 44 crop years than the less positive response crops, sorghum and corn with just 26 and 24 crop/years respectively, as shown in table 3.2.

Table 3.2 Significant differences by crop for both yield increase and decreases due to windbreak effect and the number of crop field/years analyzed.

Crop	Yield Increase %	Yield Decrease %	Crop field/Years
Sorghum	19	31	26
Corn	17	42	24
Soybeans	46	23	57
Wheat	30	20	44
Sunflowers	20	0	5
Total			156

According to USDA-NASS (2017) average production of soybeans in Central Kansas is very high. In 2016, Dickinson county was leading it with 102,550 acres harvested with an average yield of 47.7 bu. A^{-1} . Ranked fourth is Rice county with 44,900 acres harvested with an average yield of 43.3 bu. A^{-1} . In the study, five soybeans fields out of nine with significant differences were located in Dickinson county and one field in Rice County. In North Central Kansas, Clay county is leading the soybeans production. In 2016 soybean production was 97,900 acres harvested with an average yield of 48.9 bu. A^{-1} , and there were two soybeans study fields with significant differences. Therefore, soybeans had a bigger sample size than other crops since most of the data was collected from the leading soybean production counties in Kansas where the yield increase was enhanced by the windbreak effect.

Kansas is known as the “Wheat State” due to being the leading wheat producing state in the country. In 2016 Central Kansas was the leading region with 1,305,500 acres harvested with an average of 55.4 bu. A^{-1} (USDA-NASS, 2017). Therefore, as expected, wheat sample size was the second largest data set collected after soybeans.

Irrigated fields were analyzed, too. A total of 30 crop field/years were collected with 17 crop field/years showing significant differences, with five showing a significant crop yield increase and 12 showing significantly different crop yield decreases. Again, this is too small a sample size to draw firm conclusions from. Central pivot irrigation study fields were the larger ones with over 150 H average length of the field. Therefore, the unprotected zone was much larger than the protected area in this fields.

Which crops show yield increase due to the windbreak effect?

The average crop yield increase percentage due to windbreak effect for each crop/year that were significantly different was calculated by the following formula:

$$\frac{\textit{Average mean difference increase}}{\textit{Average yield in the unprotected area}} * 100$$

Where the average mean difference increase value was obtained from the SAS output and average yield in the unprotected area was calculated by the following formula:

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

Figure 3.2 shows the average crop yield increase percentage due to the windbreak effect by crop for 48 crop/years that had significantly increased yields and the average size of the protected area (1-20 H) in acres. Summer crops like sorghum (25%), corn (22%) and soybeans (16%) had greater yield increases than winter crop wheat (10%) due to the windbreak effect. Kort (1988) also reported less yield increase in winter wheat (23%) out of 131 crop/years and spring wheat (8%) out of 190 crop/years, many authors in his worldwide summary reported that sheltered wheat yield decreases due to many reasons, such as: Brandle et al., (1984) reported that windbreaks, overall, enhanced fungal diseases in winter wheat, and yields were reduced by wheat scab. Bates (1944) mentioned that wheat showed higher yield decreases due to windbreak competition.

Stoeckeler (1962) reported that dense to medium porous windbreaks maximize total crop yields. Most study field windbreaks were primarily composed of deciduous trees and few

evergreen trees. Therefore, the windbreak's optical density was denser with less porosity in summer than in the winter season, in that way sorghum, corn and soybeans were protected by a denser windbreak during the growing season than wheat. Beetz (2002) and Gonzales (2015) agreed that using all deciduous trees in windbreaks are not recommended for year round protection, even if planted in multiple rows since they are less effective during winter season due to leaf loss.

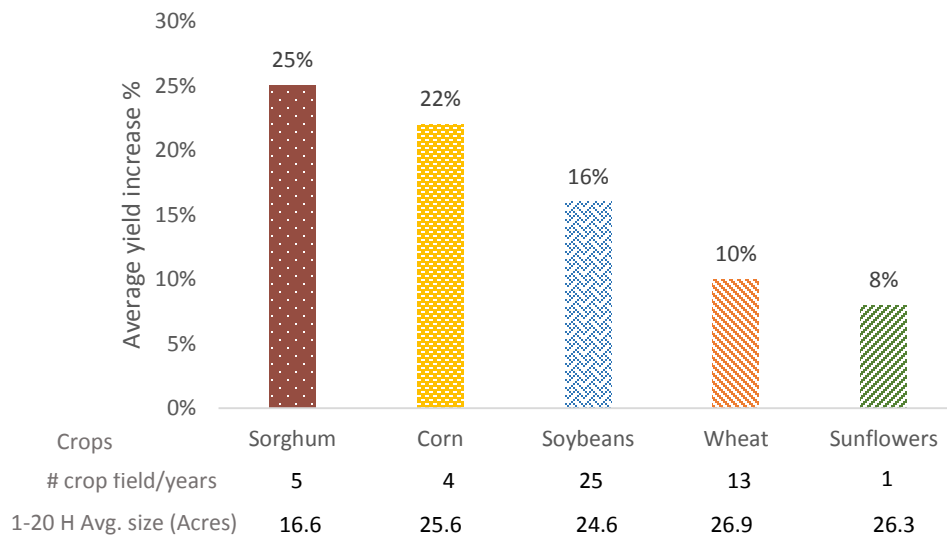


Figure 3.2 Mean yield increase and protected area (1-20 H) average size (acres) for crop/years with significant positive windbreak effects.

Significant positive windbreak effects on yield were seen across fields, counties and both states. In Kansas, counties and crop/years that showed significant differences in yield increase were: Stafford (one/one field, one/2 crop/year), Mitchell (one/one field, two/16 crop/years), Ottawa (one/two fields, three/8 crop/years), Rice (one/2 fields, five/13 crop/years), Clay (two/three fields, 17/48 crop/years), Dickinson (six/eight fields, 18/93 crop/years). In Nebraska: Knox (one/one field, one/4 crop/year), Red Willow (one/2 fields, one/11 crop/year). According to Stoeckeler (1962) climate is a factor and the geographic location varies the crop response to

the windbreak effect. In places where there are major snowfalls like in North and South Dakota, yield increase is greater than places like Kansas and Nebraska.

Grand mean of protected vs unprotected yields

An overall mean of yield in protected and unprotected zones by crop was calculated, ignoring the significant increases or decreases obtained in the statistical analysis by including all the data collected in order to have a broader and general idea of the study crops response to windbreak effect. Table 3.3 shows the results of the grand mean.

Table 3.3 Grand mean of the yield in the protected and unprotected zones by crop.

Study Crops	Protected (bu. A⁻¹)	Unprotected (bu. A⁻¹)
Soybean	37.26	36.43
Sunflowers	30.35	28.46
Corn	109.04	109.3
Wheat	45.66	47.45
Sorghum	101.79	106.57

Results showed small yield differences between protected and unprotected areas confirming what we found in the statistical analysis that less than the 2/3 of the data (156/230 crop field/years) had significant yield differences. Table 3.3 shows that soybean and sunflowers had more average yield in protected than in unprotected zones. Soybean rooting system is deeper than cereals, therefore, soybean roots do not share the same rooting zones of close trees like cereal crops do. According to Greb and Black (1961) and George (1971) this could be a factor of less yield reduction for soybean due windbreak competition, and any yield decreases could be related to nutrients leaching in greater snowfall regions. It is hard to draw conclusions from sunflowers, since it was the crop with less data collected, 6 crop field/years in total and all from one field. Corn had the same overall average yield in the protected and unprotected zone, while wheat and sorghum showed less yield in the protected than in the unprotected area. Bates (1911)

reported in his study that corn due windbreak competition showed no visible yield loss but wheat showed larger losses while Stoeckeler (1965) classified wheat and corn as a low-response crops to windbreak effect. Another fact that the grand mean also agreed with the statistical analysis results is that the significantly different yield increases were less (48 crop field/years) than yield decreases (108 crop/field years). Average yield differences for crops that showed more yield in the unprotected than in the protected zones (wheat 1.79 bu. A^{-1} and sorghum 4.78 bu. A^{-1}) is bigger than the yield difference for the crops that had more yield in the protected than the unprotected area (soybean 0.83 bu. A^{-1} and sunflowers 2.39 bu. A^{-1}). Calculated yields are less than NASS (National Agricultural Statistic Service) averages, which could be due to uncalibrated yield monitors or underestimated yield.

Overall, geographic location is an important factor that influences windbreak benefits to crop yields. Greb and Black (1961), Stoeckeler (1962) and Kort (1988) agreed that windbreak competitive yield decreases are more pronounced in dryer regions of the Great Plains than in wetter regions. The precipitation pattern in the Great Plains goes from much drier lands in the west to wetter ones in the east (Kunkel et al., 2013). Most of the study fields were located in dryer regions which could be a reason for few significantly different yield increases in this study. Stoeckeler (1962) mentioned that according to snowfall differences, greater yield increases due to windbreak protection were found in the northern Great Plains states than in Kansas and Nebraska.

Probably another reason that led to having few differences in yield increases due to windbreak effect is that most of the study windbreaks were not in the best condition due lack of maintenance practices and design. Kort (1988) concluded that 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. Nowadays, windbreaks practices (planting or maintenance) in Kansas have decreased due to many reasons such as farmers adopting no-till systems as a conservation practice in order to avoid soil erosion. It is important to mention that all fields in the study were no-till fields. Also farmers are removing their windbreaks in order to install large irrigation systems or for a better maneuvering of ever-large equipment (Barden, personal communication, 2017).

Is the yield increase enough to compensate for the footprint of the windbreak?

Considering the 48 crop/years that demonstrated significantly different yield increases due to the windbreak effect, several equations were calculated in order to assess if the yield increase is enough to compensate for the land taken out of production (the footprint of the windbreak). In order to answer this question, 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. The yield increase due to windbreak effect and the yield within the footprint was calculated with the following formulas. Figure 3.3 graphically explains what the formulas calculated. There is a calculation example for sorghum 2011 in Clay county in appendix E.

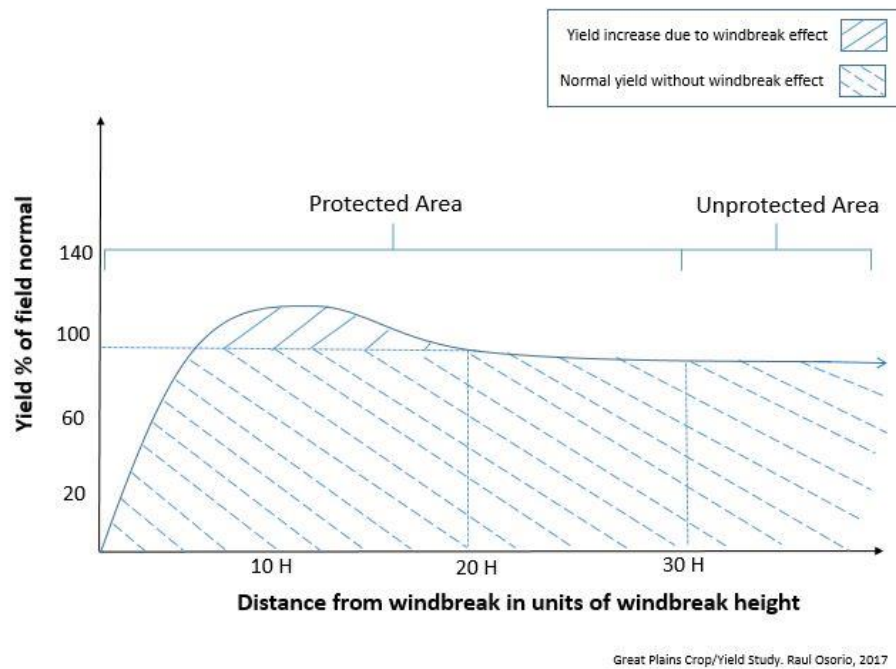


Figure 3.3 Yield increase due to windbreak effect vs normal yield without windbreak effect.

Yield increase (bu)

Total yield protected area – Total yield of an equal area of unprotected field

Where:

Total yield protected area (bu) (1H-20 H)

$$\text{protected area (ac.)} * \text{avg. yield protected area (bu. A}^{-1}\text{)}$$

Total yield unprotected area (bu) if there was no windbreak

$$(\text{avg. yield protected area (bu. A}^{-1}\text{)} - \text{avg. yield Mean difference (bu. A}^{-1}\text{)}) * \text{protected area (ac.)}$$

*The avg. yield mean difference was obtained from the SAS analysis. Appendix F shows an example of the SAS analysis output.

The footprint of the windbreak in acres was calculated with the following formula:

$$\frac{\text{length (ft)} * \text{width (ft)}}{43,560 \text{ft}^2}$$

Lost yield within the footprint of the windbreak was calculated with the following formula:

$$\text{Avg. yield at the unprotected field edges (bu. A}^{-1}\text{)} * \text{windbreak footprint area (ac.)}$$

Where:

(Width of unprotected field edges = windbreak width)

Avg. Yield at the field edge: obtained in ArcGIS (Step by step process in Appendix C).

Results of calculations showed a total of 29 out of 48 (60%) crop/years that showed a significant yield increase also compensated for lost yield in the windbreak footprint. For irrigated fields the yield increase compensated for the footprint of the windbreak for just one out of five crop/years.

Figure 3.4 shows that there is a yield compensation 77% of the time for north windbreaks and Figure 3.5 shows that there is a yield compensation 46% of the time for south windbreaks.

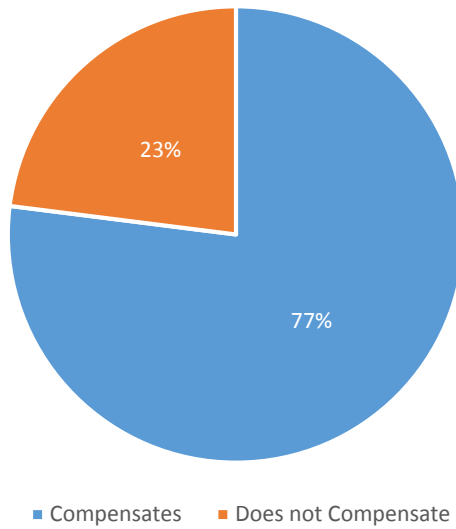


Figure 3.4 North windbreak compensation due to windbreak effect.

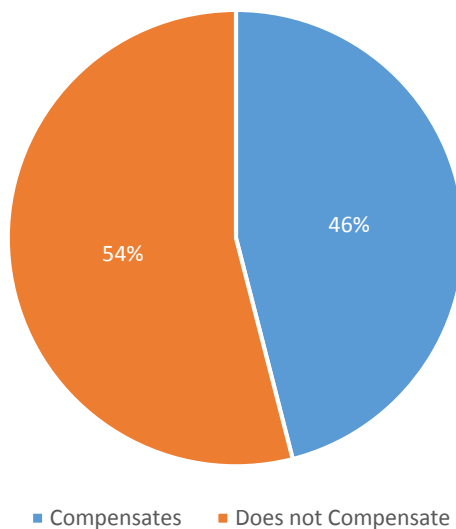


Figure 3.5 South windbreak compensation due to windbreak effect.

The variable windbreak width and effect due to location may be confounded by the fact that north windbreaks average width was 37 ft., while south windbreaks had an average width of 80 ft. Therefore, as Kort (1988), Josiah and Wilson (1996) and Brandle et al., (2004) mentioned narrow windbreaks (one or two rows) are better than wider windbreaks when considering total yield and whether the yield increase compensates for the footprint of the windbreak. The wide

shelterbelts take more land out of production. As mentioned earlier Stoeckeler (1962) recommended that field windbreaks should occupy <5% of the land area for the yield to compensate for the footprint of the windbreak and to provide maximum crop protection.

Does the effect change during normal, wet and dry seasons?

In general, most seasons of data collected were either wet (78) or dry (80) since there is a trend of high variability in precipitation from year to year for the last 121 years, particularly in the central part of Kansas (Lin et al., 2017), very few average (5) precipitation months were found.

The analysis was done for crop/years that showed a significantly different yield increase (48 in total), figure 3.6 show that 26 out showed increase in dry years, 21 in wet years and one in a normal year. Some authors (Frank and Willis, 1978; Brandle et al., 1984) that Kort (1988) based his worldwide summary on and Campi et al., (2009) agreed that windbreak benefits are greatest during dry years, whereas only a few authors like Grace (1988) state that the benefits are better in wet years.

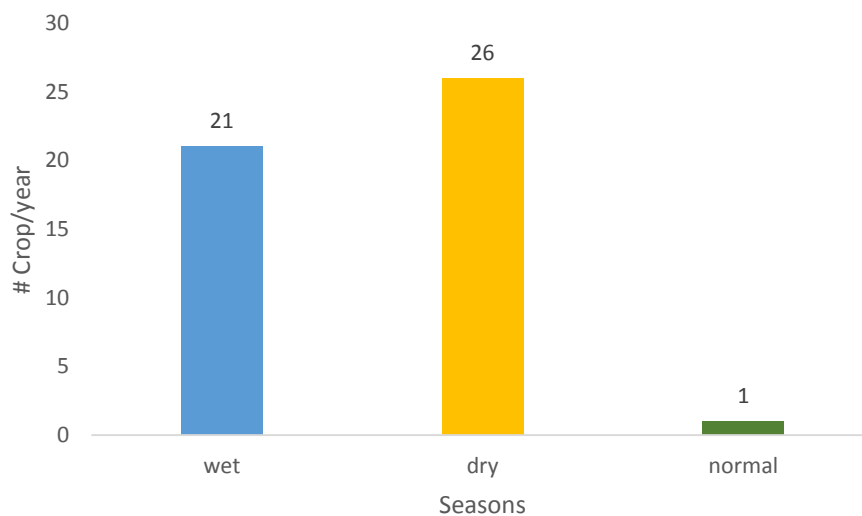


Figure 3.6 Number of significant different crop/year seasons.

In order to find any association between critical rainfall classifications (dry and wet) and the two categories of significant yield differences (protected field has more yield and unprotected has more yield) a Chi-square analysis or Fisher's exact test was conducted. If protected-unprotected > 0 = positive windbreak effect, then the yield status was "protected area has more yield". Otherwise "unprotected area has more yield". A 2 (seasons) x 2 (yield status) contingency table was formed which consisted of 4 total combinations, each combination was filled with the count number of significant comparisons. The chi-square test was conducted using the contingency table. For each crop, windbreak orientation groups were categorized as "North" for windbreaks oriented on the North-West, North-East, North-West-East and North side of the field. "South" combined windbreaks on the South, East-South and West side of the fields.

Overall results were that there is no evidence to show that the yield status is associated with critical month rainfall, for any crop or orientation group at the 95% confidence level. Most of the multiple year studies conducted involving windbreak effects on crop/yield have shown high variability year to year either increasing or decreasing yields. Therefore, as Kort (1988) states, it is important to conduct studies that gather quality data from as many crop/years as possible, in order to reduce the annual variability of windbreak effects on crop yields.

Windbreak optical density association with crop yield increase

Optical density was determined from leaf-on and leaf-off photos taken of the windbreak, with a Nikon Coolpix S6000 with 14.2 megapixels camera, using a photo analysis software (SigmaScan Pro 5.0) that gave as an output a coverage percentage. Table 3.4 shows the average optical density percentage of the fields where significant increases in yield were found.

Table 3.4 Optical windbreak density percentages for both leaf on/off condition with a significant yield increase.

Field	Windbreak location	Leaf off %	Leaf on %
Clay (Gardner)	North	25	58
Clay (Stagner)	North	28	74
Dickinson (Stoskopf South)	North	16	62
Dickinson (L-Patch)	South	25	88
Dickinson (Kuntz)	South	15	61
Dickinson (Stoskopf West. East field)	East-South	30	73

Besides the fields mentioned above there were eight more fields with a significant difference in yield increase but photos of just one season, either leaf-off or leaf-on season were taken, respectively. In order to get a simple linear regression formula to predict the missing values, a linear regression model was performed in SAS 9.3 using the repeated optical density measures that were averaged in table 3.3. The SAS output fit plot of the simple linear regression is shown in figure 3.7.

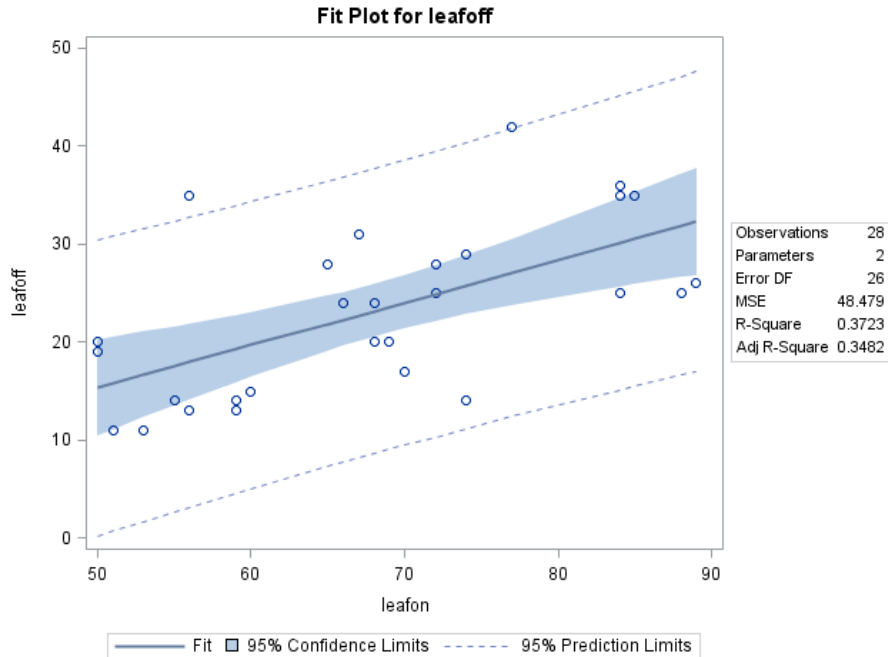


Figure 3.7 Optical density leaf-off vs leaf-on fit plot of fields with a significant different yield increase (SAS Institute, Inc.).

The model provided an R-Square of just 0.37 thus there is only a moderate relationship between the quantitative variables leaf-off and leaf-on at a 95% confidence level. Therefore, a linear regression formula derived from the model was not useful to predict the missing values of the other fields.

Also a linear regression model with prediction was performed in SAS 9.3 using the values of all fields with a significant yield increase showed in table 3.5. The result still did not provide a strong prediction of the missing values with an R-Square of 0.30 at a 95% confidence level.

Table 3.5 Optical density percentages for some leaf on/off fields with a significant yield increase.

Field	Windbreak location	Leaf off %	Leaf on %
Dickinson (Stoskopf North.East field)	North-West	.	70
Dickinson (Stoskopf North.West field)	North-West-East	.	72
Mitchell (Beloit)	South	59	.
Rice-Sterling (Key South)	South	48	.
Stafford	South	.	.
Red willow-Mcook (Grafs NE DRY)	South	.	76
Ottawa (West half)	South	17	.
Rice-Sterling (Key North)	South	.	50
Knox	West	69	.

The association between seasonal windbreak optical density and crop yield increase was examined for the following crops: wheat, corn, soybean, sorghum. A linear regression model was performed in SAS 9.3 using the leaf-on optical density percentage for summer crops and the leaf-off optical density percentage for winter crops, respectively. Table 3.6 shows the r-square values by crop and the number of significantly different crop/years assessed.

Table 3.6 Simple linear regression results (optical density % vs crop yield increase %) by crop and number of crop years analyzed.

Crop	R-Square	Crop/years
Wheat	0.0002	9
Sorghum	0.6781	4
Corn	0.6643	4
Soybeans	0.4464	21
Total		38

A total of 38 significantly different crop/years was analyzed out of 48. Ten fields were not considered in the analysis due to lack of data (either leaf-off or leaf-on photos and percentages missing). Summer crops showed a stronger association between windbreak optical density and crop yield increase with a higher r-square at a 95% confidence level than the winter

crops (wheat). This may be due to most of the study field windbreaks containing primarily deciduous trees and very few of evergreens. Therefore, windbreaks were denser in summer than in the winter season, which agrees with previous reports that sorghum, corn and soybeans had higher yield increases than winter wheat.

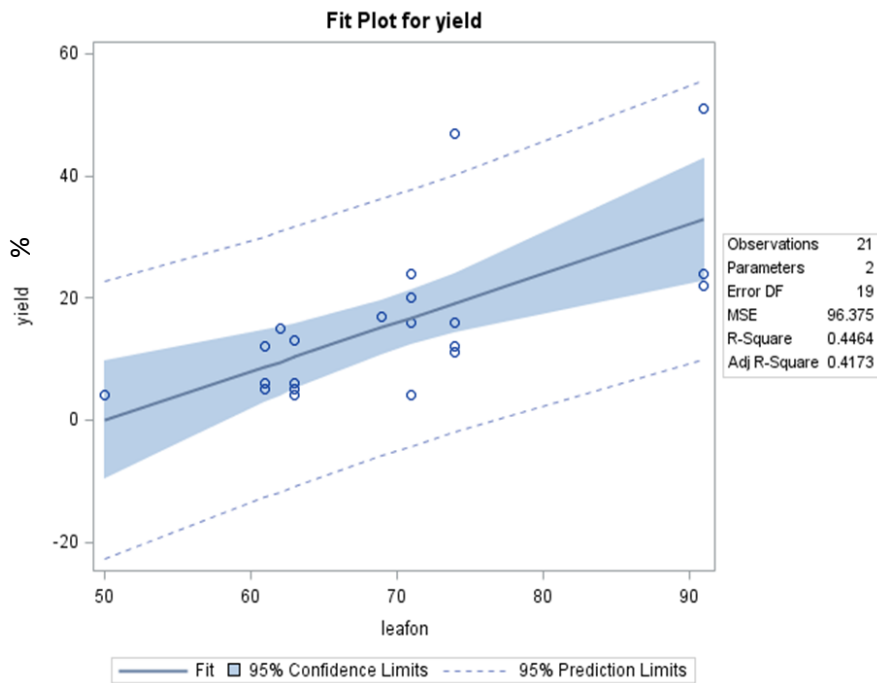


Figure 3.8 Soybean yield percentage vs windbreak leaf-on percentage fit plot of fields with a significant yield increase (SAS Institute, Inc.).

Soybean was the crop with the largest sample size but with only a moderate r-square that showed evidence of the association between variables. Figure 3.8 shows the fit plot for soybean yield vs windbreak leaf on optical density.

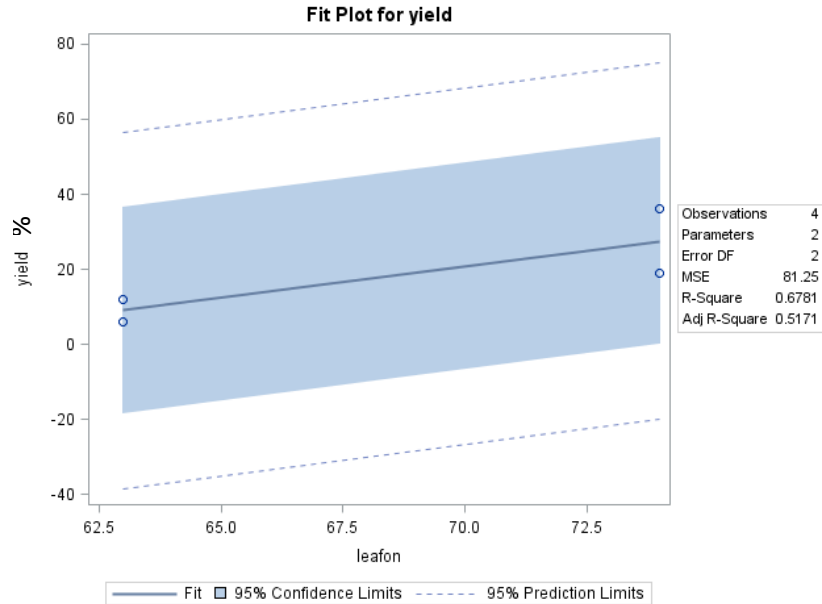


Figure 3.9 Sorghum yield percentage vs windbreak leaf-on percentage fit plot of fields with a significant yield increase (SAS Institute, Inc.).

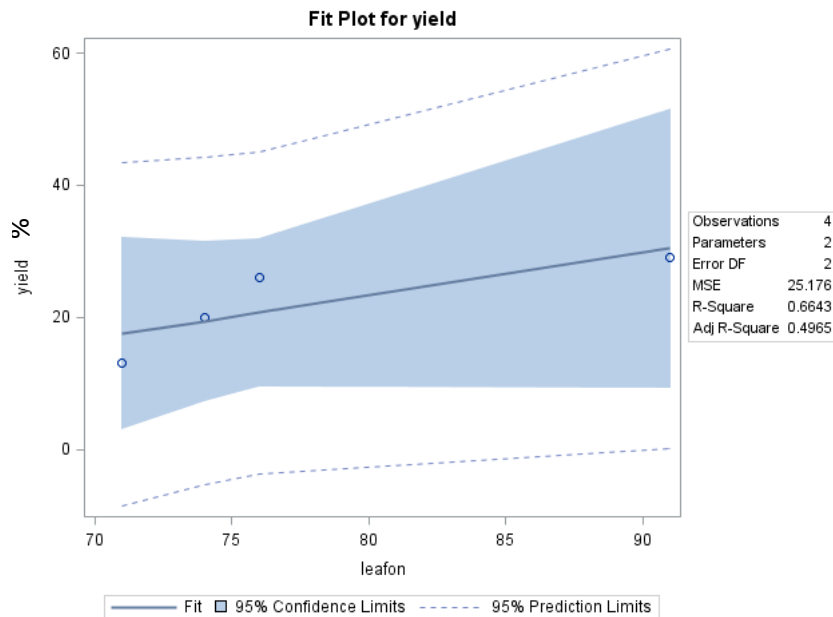


Figure 3.10 Corn yield percentage vs windbreak leaf-on percentage fit plot of fields with a significant yield increase (SAS Institute, Inc.).

Sorghum (Figure 3.9) and corn (Figure 3.10) had a much smaller sample size, but resulted in a higher r-square values, however, a correlation based on just four points can be misleading. Stoeckeler (1962) reported that dense windbreaks increase corn yields more than low density

ones due to higher temperatures in the protected area result of the microclimate modification from the barrier.

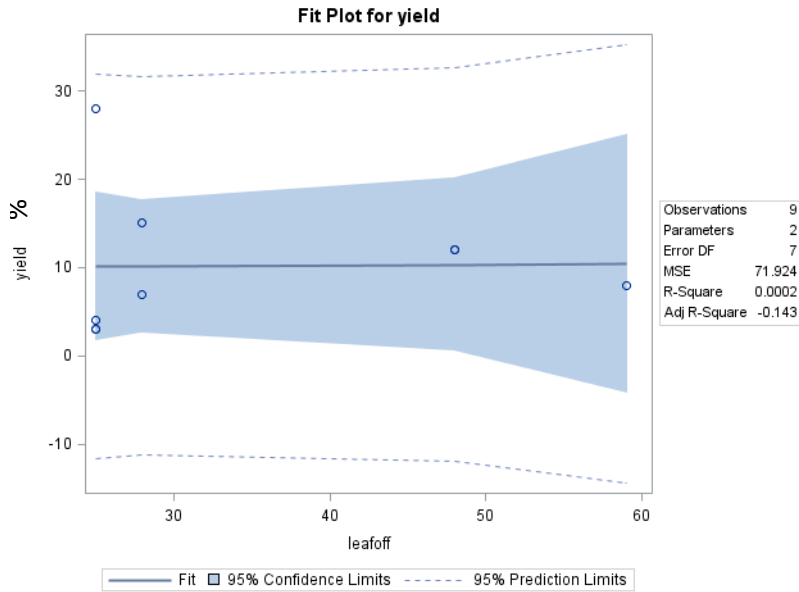


Figure 3.11 Wheat yield percentage vs windbreak leaf-on percentage fit plot of fields with a significant yield increase (SAS Institute,Inc.).

Winter crop (wheat) results for 9 crop/years showed the lowest r-square value (0.0002) founding not association between the two variables at a 95% confidence level (Figure 3.11).

Chapter 4 - Conclusions and Recommendations

The Kansas-Nebraska windbreak crop/yield study had as its purpose to address two main objectives and several specific goals. The study faced limitations and challenges that were learned and overcome through the process.

According to the main study goal and the first specific objective: determine if windbreaks improve yields of modern varieties, and of which crops? Windbreaks provided inconsistent yield benefits across a variety of crops, improving yields for the following: Soybeans had the most positive response to windbreak effect showing a yield increase 46% of the time, with a 16% of average yield increase; followed by wheat with a 30% of the time, with a 10% average yield increase; Sorghum and corn had a less positive response with a 19% and 17% yield increase, respectively, and negative effects on yield were more common than positive. Despite this fact, the average yield increase was higher, sorghum had 25% average yield increase and corn a 22% average yield increase. The overall grand means of protected and unprotected yields by crop showed small differences between both areas. Soybean (37.3 bu. A^{-1}) and sunflowers (30.3 bu. A^{-1}) had more average yield in the protected than in the unprotected zone with 36.4 bu. A^{-1} and 28.5 bu. A^{-1} , respectively. Corn had the same overall average yield in the protected and unprotected zone with 109 bu. A^{-1} , while wheat (45.7 bu. A^{-1}) and sorghum (101.8 bu. A^{-1}) showed less yield in the protected than in the unprotected area with 47.4 bu. A^{-1} and 106.6 bu. A^{-1} , respectively. According to these results we conclude that modern hybrids are possibly less responsive to yield increases than older crop varieties due windbreak effects.

In order to address the second main study goal, to update our knowledge of windbreak crop/yield interaction, the following specific objectives were addressed. The second specific objective consisted in determining if yield increase is enough to compensate for the footprint of

the windbreak. Yield increase from north and narrow windbreaks compensated for the footprint of the windbreak more often than south and wider windbreaks. The purpose of the third specific objective was to address if the windbreak effect changed during dry, normal and wet seasons. Overall, it was found that there was no evidence to show that windbreak yield response was associated with precipitation, for any crop or orientation group. Also there was not strong evidence to show an association between the windbreak optical density and the yield increases in this study.

For future studies it is recommended further data collection with different windbreak widths in different counties and states in order to broaden the tillage regime, soil types, windbreaks and climate represented.

Overall, the main limitations were related to the data collection and analysis. Most of the data was collected from a few producers in Kansas (>60% of data collected was from two farmers in the North Central part of the state) and two landowners in Nebraska. All data was from no-till fields, where the crop-soil moisture relations may be different from tilled fields. Many of the past windbreak effect studies were done in conventionally tilled fields, this could be a reason for the inconsistent yield effects that were observed compared to earlier studies. About 2/3 of the yield monitor data collected was usable once it went through the cleaning process. The 1/3 non-usable data, showed errors likely generated due to lack of calibration of the equipment, highly variable field conditions (drainages crossing through the fields) or variable windbreak conditions. A major study achievement was to collect and analyze four times more (69 crop/years) soybean yield data than reported by Kort (1988) (17 crop/years) in his data compilation of 50 worldwide studies relating windbreak benefits to field and forage crops.

It was difficult to find farmers willing to collaborate in the study. Most landowner contacts came about through presentations at the Kansas Agricultural Research & Technology Association conference (KARTA), which is made up for farmers who use the latest technology and have a history of working with Kansas State University. More data may be collected if we can involve more local trusted personnel with farming backgrounds to have direct contact and persistent outreach with landowners.

Data analysis challenges were found from the very beginning when downloading the data from the farmer's computer. The data export process varies from system to system, and it took time to figure out how to proceed.

Only about 15% of the fields had the ideal adjacent protected and non-protected fields for comparison. The rest of the fields had to use as unprotected control areas 30 H downwind. Developing and applying a method of analysis based on the average height of the windbreak (H) along the entire field using ArcGIS was a time consuming process that had many challenges and pitfalls, especially when trying to include as much as possible of the data. Perhaps the development of a method which included every single point of crop yield instead of doing an average H width band would yield more precise estimates.

Collecting more of the combine crop yield monitoring data, this pilot project might be the start of important findings in the future. This would deepen our understanding of the interaction between windbreaks and crop yield and perhaps effect their future role as a conservation practice in the Great Plains.

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Appendix A - Sample letter requesting monitor yield data



College of Agriculture
Department of Horticulture
and Natural Resources.

mm/day/2016

(landowner's address)

Dear XXXX:

Since the Dustbowl, windbreaks have been providing important conservation and wildlife benefits to western Kansas. A recent assessment of windbreaks in Hodgeman County found the majority to be in fair or poor condition, but **windbreaks on your farm** were rated in good condition and protecting crop fields. This assessment was conducted using remote sensing data by the Kansas Forest Service, KSU, in cooperation with Coronado Crossing RC & D. A detailed report entitled *Assessing Windbreak Condition in Coronado Crossing RC & D* is on the web (<http://www.kansasforests.org/pubs/rural/index.shtm>).

The good windbreaks on your property make you a prime candidate to participate in a new research project I am conducting, to document the effect that windbreaks have on crop yields. If you harvest your crops with a combine that collects GPS referenced yield data, we are asking you to share that data with us. We are interested in data both from fields with windbreaks, and fields without windbreaks. A windbreak can even be just a single row of Hedge trees. We will maintain confidentiality of all your information.

If you wish to participate, or would just like to learn more about this study, please feel free to call (785) 532-1444 or email me at cbarden@ksu.edu. We will send you out a packet of information about the study, a flash drive to submit the data files, and a postage paid envelope to return the forms and data to KSU. Thank you very much for considering this request.

Sincerely,

Charles Barden, KSU Forestry Professor

Cc XXX, Hodgeman County Conservation District Manager

XXX, Hodgeman County Extension Agent

Appendix B - Study description and data collection form



Kansas Windbreak/Crop Yields Study

Purpose of the Study

Windbreaks/shelterbelts were established throughout the Great Plains following the Dust Bowl to reduce wind erosion. Most research studies show an overall crop yield increase associated with windbreaks. These yield increases were summarized on a world-wide basis in 1986 at the First International Windbreak Conference and indicated significant yield increases for winter wheat (23%), soybeans (15%) and corn (12%).* Economic analysis indicates that windbreaks also “pay for themselves” within 10 to 15 years and provide additional income over their remaining life, even when factoring in the loss of land from production that the windbreak occupies. However, this research is not widely recognized and obvious yield reductions immediately adjacent to windbreaks cause many people to overlook the overall subtle yield increases in the larger crop area protected by windbreaks.

Why now?



Time-worn research that was never applied, new monitoring data and new crop genetics are all reasons to conduct this study. Additionally, significant global population growth in the next 30 years will increase demands for grain dramatically and experts acknowledge there will not be enough cropland to meet these needs. Therefore increased crop yields must come through increased productivity and the role windbreaks can offer in the Global Food Initiative (<http://www.k-state.edu/globalfood/>) should not be overlooked. Kansas still has an estimated 25 million acres of cultivated cropland with wind erosion issues. Periodic dust storms responsible for vehicle accidents and fatalities are directly related to a changing climate and cultivated soil subject to prolonged drought. Reductions in water tables suggests a future return to dryland farming. All of these factors point to the need to substantiate the effect windbreaks and shelterbelts have on crop yields.

How will this study be done?

This project is part of a larger Great Plains Crop Yield Study which will compare multiple years of data from fields across the region with and without windbreaks. Because we are looking for relative crop yield changes and not absolute numbers, this approach will minimize the variables of rainfall, fertility, crop rotation, and farming methods. The key to this study is that the data already exists with farmers because many have crop yield monitors installed on their equipment. When combined with GPS, monitors can provide crop yield data for virtually every point in a field. Yield data will be compared from protected and unprotected areas. The fact that many farmers maintain this data over several years will also mitigate the variables that weather, location and different cropping systems might have on the overall results.



What are the general requirements for this study?	The first step is to identify farmers through local county K-State Research and Extension, NRCS and County Conservation District personnel that might be willing to share yield monitor data from crop fields with similar rotations, both with and without windbreak protection. Field locations will be identified on aerial photographs and permission obtained to make a few on-site observations and measurements such as windbreak height, density and width.
How will the data be handled?	<p>There will be two sets or kinds of data taken for each field: 1) General information including location, date, landowner name, aerial photo, crops grown, and windbreak length, height, width and condition. This information will be kept confidential with local county K-State Research and Extension, NRCS and County Conservation District personnel serving as liaison between farmers and the project manager.</p> <p>The second set of data will be from the yield monitor. Generally, the computer software associated with these instruments has a data export function to extract data for each field. The preferred file structure for this data is the "shapefile" format. Yield data exported as a shapefile will result in four separate files: <i>XXX.shp</i>, <i>XXX.dbf</i>, <i>XXX.shx</i>, and <i>XXX.prj</i> which will be collected on flash or thumb drives.</p>
How will the data be used?	This study will update our knowledge of windbreak/crop yield interaction and perhaps effect their future role as a conservation practice in the Great Plains. Results will be shared with all participants, farmers and conservationists through technical reports and journals, ag related publications, meetings and conferences. Because of confidentiality it will not be possible to compare yields between farmers.
Local Contacts Participating in the Study:	<p>Charles Barden K-State Research and Extension - Forestry 785-532-1444 cbarden@ksu.edu</p> <p>Ignacio Ciampitti K-State Research and Extension - Agronomy 785-532-6940 Ciampitti@ksu.edu</p> <p>Bob Atchison Kansas Forest Service, KSU 785-532-3310 atchison@ksu.edu</p>

* American Society of Agronomy, 2009; North American Agroforestry: An Integrated Science and Practice, 2nd edition, H.E. Garrett (ed.); Chapter 5, pages 85-87; <http://www.kansasforests.org/documents/rural/NAAgroforestry%20Chapter%205%20%28WB%20Yield%20Brandle%29.pdf>

Windbreak Yield Monitor Study

Date: _____

Landowner Name: _____ Phone: (opt.) _____

Landowner Email: _____

Local Field Office Staff Contact Name: _____

Local Field Office Contact Email: _____

Field Office Phone: _____ Address (opt.) _____

Site _____ Windbreak Data (one data sheet per windbreak or section of windbreak):

Location: (legal, or lat./long., GPS coordinates of windbreak ends or curves, or descriptive narrative)

Avg. Effective Height _____ Avg. Footprint Width (non-crop area) _____ Est. Length _____

Predominant growing season wind direction: _____

Identify species by row on the lines below (Assume row 1 to be north or west side.) If it is a native stand and not in rows, identify the species by percentage of stand. (Note: To work as a windbreak native stands should not be over an effective width of 100.')

Crop Field Data for Field(s) Protected by Windbreak:

Location: (legal, or lat./long., GPS coordinates of field corners, or descriptive narrative)

Notes:

Crop Field Data for Field(s) Not Protected by Windbreak:

(Beyond 35H from the windbreak in the same field or in a nearby field farmed by same producer.)

Location: (legal, or lat./long., or descriptive narrative)

Notes:

Complete sketch on page 2 (reverse side)

Sketch location of inventoried windbreak and juxtaposition to crop fields. (This could be an attached aerial photo with north arrow, windbreaks, and fields clearly marked.) Include information (aerial imagery would be best) about nonowned windbreaks that are within ¼ mile of the fields with yield data.



Appendix C - ArcGIS methodology

1. Open ArcMap.
2. Add the aerial photography of the field.
3. Add the crop field/year shapefile.

Perimeter of the field

4. Right click in the shapefile folder.
5. Select “New” < “Shapefile”.
6. In the new window, provide a name to the new shapefile i.e. Perimeter. In “select feature type” < “Polygon”. Add the appropriate site coordinates, for these fields:
GCS_WGS_1984. Click Ok and the new shapefile will be added in the table of contents.
7. Click in “Editor” < “Start editing”, select the shapefile perimeter.
8. Click in the “Create features” icon and select the shapefile perimeter. Then click in “Arrange templates by grouping and filtering” < “Filter by” < “Polygon” and start plotting the perimeter of the field based in the aerial photography of the area in the background, when done plotting, click “Editor” < “Stop editing”.

Monitor yield data cleaning

1. Click in the “Geostatistical Analysis” icon, select “Explore Data” < “Histogram”.
2. In the Histogram window, select the crop/year to clean in “Layer”. In “Attribute” select yield volume dry (the yield attribute name varies by each shapefile). In the “bars” option select 100 in order to have a better view of the data distribution.
3. In the “Frequency” window (where the data distribution is shown) select the outlier’s maximum and minimum values (all the zeros and errors) that are affecting the data normal distribution. Generally, these values are located within the field borders, originated due many reasons, particularly when the harvest equipment passes more than one time through the same point of the field for turns and begins harvesting the next swath at the beginning of the previous cut. At the end of the line the combine header moves from down position during the completion of a pass to the up position (Arslan and Colvin, 2002). Also when fertilizing, over rates are applied at the edge of the fields where the equipment passes more than one time.

4. Once these outliers and repeated values are selected. In order to clean and have a more normal distribution of the data. Click in “Editor” < “Start” editing and select the crop/year.
5. Right Click in the data frame, then select “Delete”.
6. Click “Stop editing”, select “Yes” in the save changes window. Keep selecting and deleting outlier values till in the histogram window the data distribution gets closer to a bell shape normal distribution and the Skewness and Kurtosis value as close as possible to 0 and 3, respectively.
7. Next, in order to delete the outlier values greater than ± 3 standard deviation from the mean, click in “Geostatistical analysis”, then select “Explore data” < “Normal QQplot”. Choose the respective layer (crop/year) and attribute (dry yield).
8. In the Dataset graph window, select these few outlier values greater than ± 3 standard deviation from the mean at a time. Click in “Start Editing”, then select the crop/year shapefile. Right click in the data frame and then select “Delete”. Click in “Stop Editing” and finally save changes.

Create a fishnet

1. Open the ArcToolbox. Click in “Data Management” tools < “Feature class” and double click in “Create Fishnet” a window will open.
2. In the Output feature class click in the folder button, a new window will open where the destination and the name of the fishnet needs to be specified. Once this was done, click Open.
3. In the Template Extent (Optional) window select the “field” Perimeter layer created in previous steps in order to get the coordinates and extensions of the new fishnet. Click open.
4. Leave in blank the cell size width and height spaces.
5. In north-south fields write 1 in the number of rows. In the number of columns, depending on the field length and the windbreak height, write the number of bands i.e. 36. In fields that go from west-east do the vice-versa.
6. Uncheck the “create label points (optional)” box and select polygon in the “geometry type (optional)” window. Click Ok. The fishnet will be projected and added to the table of contents.

Yield map analysis

1. Depending on the situation and the field shape, intersect the Fishnet with the perimeter layer, otherwise clip the crop/year shapefile points with the fishnet layer using the respective tools (Intersect or Clip) from the ArcToolbox.
2. Depending on the field, right click in the fishnet or in the intersect layer. Select “Joins and relates” < “Join”.
3. In the Join Data window select the option “Join data from another layer based on spatial location”. In “Choose the layer to join to this layer”, select the crop/year + fishnet Clip layer created in step 1.
4. In “you are joining: Points to polygons”. Check the first option which indicates that each polygon will be giving a summary of the numeric attributes of points to fall inside it, and count field showing how many points fall inside it.
5. In “how do you want the attributes to be summarized”, Check the “Average” check box.
6. Specify the destination folder where the join output will be saved. Click Ok. The join layer will be added to the table of contents.
7. Right click in the new Joined layer. Click properties < Symbology. In the show window select “Quantities” < “Graduated colors”. In “fields value”, choose the average yield volume dry, and select the classification method, number of classes and colors desired for the yield map. In this research the classification method used was quantile with four classes. Click Ok and the yield map showing the average yield per band will be created and projected.

Edge of the field

1. It is necessary to know the windbreak width value in order to proceed with the analysis. Using the ArcMap measure tool, from the field edges use the windbreak width measure i.e. 50ft to locate approximate points inside the field in order to create a new polygon that represents the non-protected edges of the field.
2. The polygon was created inside the non-protected field edges beyond 30 H downwind with the steps described in the “perimeter of the field” section.
3. Once the “edge” polygon was created, it was spatially joined with the crop/year points following the steps 2-6 in the yield map analysis section.

4. Finally, right click the new join layer in the table of contents and open the attributes table to get the average yield in $bu. A^{-1}$ at the non-protected edges of the field.

Appendix D - Windbreak characteristics by field

County/Field	# rows	Width (ft.)	Primary spp.	Secondary spp.	Tertiary spp.	Volunteer spp.
Mitchell	3	112.96	E. redcedar	Honeylocust	Osage-orange	Hackberry
Stafford	4	134	E. redcedar			
Edwards						
King	3	30	E. redcedar	Mulberry	Siberian Elm	
Home	3	30	HoneyLocust	Hackberry		E. redcedar
Lunt	5	114	E. redcedar	Siberian Elm	Honeylocust	Mulberry, Walnut
Collingsworth	4	82	Honeylocust	Siberian Elm	Osage-orange	
Collins	4	114	Osage-orange	Honeylocust	Hackberry	Mulberry, Kentucky Coffee
Ottawa	4	109.5	Green ash	E. redcedar	Osage-orange	Hackberry
Rice						
Key North	2	57	E. redcedar	Honeylocust	Siberian Elm	Mulberry
Key South	4	100	Mulberry	Siberian Elm	Kentucky Coffee	Green ash, E. redcedar
Fitz Patrick	3	89	Mulberry	Siberian Elm	E. redcedar	
Wuellneer	3	138	Siberian Elm	Honeylocust	Mulberry	
Dickinson						
Stoskopf West	3	70	Osage-orange	Hackberry		E. redcedar
Stoskopf South	2	36	Osage-orange			Hackberry
Stoskopf North 1	1	36	Osage-orange			
Stoskopf North 2	2	65	Hackberry			E. redcedar
Kuntz	1	44	Osage-orange			Hackberry
L-Patch	1	18	Osage-orange	Hackberry		
Goss 80	3	173	Hackberry	Elm	Green ash	Cottonwood, Walnut
East Fourty	1	30	Osage-orange			Hackberry (Seedlings)
Clay						
Gardner	1	38	Osage-orange			
Berggreen	2	48	Osage-orange	Hackberry		E. redcedar
Broses	1	31	Hackberry	Osage-orange	Honey Locust	Walnut, Bur Oak
Oberg	1	68	Osage-orange	Honeylocust	E. redcedar	Hackberry
Stagner	1	42	Osage-orange	E. redcedar		Hackberry
Red Willow						
Grafs TL East	3	64	E. redcedar			
Grafs NE dry	2	35	E. redcedar			
North of the house	3	42	E. redcedar	Pine		
Lockwood	2	35	E. redcedar			
Knox	4	130	E. redcedar	Osage-orange		

Appendix E - Calculation example of yield compensation and increase %

Sorghum 2011 in Clay county (Stagner field)

Protected area (1 H-20 H)

$$\text{Area (22.472 acres)} * \text{protected avg. yield} \left(124.174 \frac{\text{bu}}{\text{acre}}\right) = \text{Total yield (2790.438 bu)}$$

Unprotected average yield of an equal area from 1-20 H (if there was no windbreak)

$$\text{protected avg. yield} \left(124.174 \frac{\text{bu}}{\text{acre}}\right) - \text{Mean difference} \left(19.820 \frac{\text{bu}}{\text{acre}}\right) = \text{unprotected avg. } 104.354 \frac{\text{bu}}{\text{acre}}$$

Unprotected equal area (yield from 1-20 H if there was no windbreak)

$$\text{Area (22.472 acres)} * \text{Avg. yield unprotected} \left(104.354 \frac{\text{bu}}{\text{acre}}\right) = \text{Total yield (2345.043 bu)}$$

Total yield increase due windbreak effect

$$T. \text{ yield protected (2790.438 bu)} - T. \text{ yield unprotected (2345.043 bu)} = \text{Y. increase (445.395 bu)}$$

% Yield increase

$$\frac{\text{Mean yield difference} \left(19.820 \frac{\text{bu}}{\text{acre}}\right)}{\text{avg. unprotected yield} \left(104.354 \frac{\text{bu}}{\text{acre}}\right)} = 0.189 * 100 = \mathbf{19 \%}$$

Windbreak footprint area

$$\text{Windbreak length (1334.161 ft.)} * \text{Windbreak width (42 ft.)} = 56034.762 \text{ ft}^2$$

$$\frac{56034.762 \text{ ft}^2}{43560 \text{ ft}^2} = \text{w. footprint area (1.286 acres)}$$

Yield within footprint of the windbreak

$$\text{Avg. yield at the unprotected field edges} \left(98.660 \frac{\text{bu}}{\text{acre}}\right) * \text{w. footprint area} = \text{Footprint Y. 126.876 bu}$$

Conclusion: The yield increase due windbreak effect (445.395 bu) **compensates** the yield within the footprint of the windbreak (126.876 bu) with **318.519 bu more**.

Appendix F - T-test analysis, SAS output example

North Sorghum

Obs	Year	County_Field	fieldname	Variable	Method	Variances	tValue	Probt	Class	Mean	LowerCLMean	UpperCLMean	ProbF
1	2001	Clay	(Gardner)	Average_Yield	Satterthwaite	Unequal	-2.54	0.0133	Ctrl-Prot	-8.5990	-15.3544	-1.8435	0.0002
2	2002	Clay	(Gardner)	Average_Yield	Satterthwaite	Unequal	-5.37	<.0001	Ctrl-Prot	-7.1162	-9.7529	-4.4794	<.0001
3	2002	Clay	(Stagner)	Average_Yield	Satterthwaite	Unequal	-0.94	0.4152	Ctrl-Prot	-4.6143	-20.1157	10.8872	<.0001
4	2003	Clay	(Stagner)	Average_Yield	Pooled	Equal	-5.55	<.0001	Ctrl-Prot	-17.2367	-23.6611	-10.8124	0.1943
5	2011	Clay	(Stagner)	Average_Yield	Pooled	Equal	-2.82	0.0099	Ctrl-Prot	-19.8209	-34.3732	-5.2686	1.0000
6	2012	Dickinson	(Stoskopf)	Average_Yield	Pooled	Equal	2.82	0.0076	Ctrl-Prot	6.2740	1.7724	10.7756	0.3063
7	2013	Dickinson	(Stoskopf)	Average_Yield	Satterthwaite	Unequal	13.18	<.0001	Ctrl-Prot	13.7415	11.6546	15.8284	<.0001

Note: Observations (crop/years) within a red rectangle shows a significantly different yield increase. (Unprotected – Protected).