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Understanding the impact of vegetation on surface roughness length for enhancing wind resource characterization in Iowa

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UNDERSTANDING THE IMPACT OF VEGETATION ON SURFACE ROUGHNESS LENGTH FOR ENHANCING WIND RESOURCE CHARACTERIZATION IN IOWA

An Abstract of a Thesis

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Master of Arts

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ABSTRACT

Wind energy development shows a rapid growth in the United States. This renewable energy source not only mitigates environmental concerns by reducing greenhouse gas emission, but also provides energy independence. Wind is clean and abundant, and is one of the most promising sources of alternative energy. Iowa is among the top wind energy producers in the nation, it is third by installed capacity and first in per capita production. In order to utilize wind resource potential most efficiently, accurate wind resource assessments are required. Changes in the aerodynamic characteristics of a site can have a major influence on the wind regime at the surface/air interface. Estimation of hub height wind speed and thus, available wind resources, may be influenced by the values chosen for zero-plane displacement and surface roughness length (Z_0). Aerodynamic roughness (Z_0) is a widely used parameter describing the effective roughness of a surface to fluid flow. This study was conducted to identify surface roughness coefficients for corn and soybeans and determine the effect of seasonal change of crops on Z_0. Ten minute average wind speed data together with wind direction, measured over a 35 day period above a corn and soybeans

field near Ames, IA, were used to determine Z_0 coefficients. Hub height wind speed was calculated using table values of surface roughness and Z_0 derived from observations. Obtained values of surface roughness and hub height wind speed were compared to each other using independent sample t-test. Significant difference was found between predefined Z_0 and Z_0 derived from wind profiling. This leads to discrepancy in resulting hub height wind speed calculated using measurement based Z_0 and traditional assumptions using table values of roughness. Also, a growing trend in seasonal surface roughness change was identified.

The results highlight the importance of improving aerodynamic roughness parameterization of vegetation. Research suggests that the use of enhanced Z_0 coefficients could improve wind resource characterization and would be beneficial for use in wind farm site suitability models.

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This Study by: Andrei V. Kushkin

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has been approved as meeting the thesis requirement for the Degree of Master of Arts in Geography

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CHAPTER 1

INTRODUCTION

Energy is presently considered one of the most valuable commodities in the economic progress and wealth generation of a country, being one of the main driving forces of industrial development (Carvalho, Rocha, & Santos, 2013). Considering the escalating costs and environmental impacts of the traditional fossil energy sources, supported by the growing global demand for energy production, renewable energy development has accelerated in the last decade to reduce the amount of fossil and nuclear fuel in energy production (American Wind Energy Association [AWEA], 2012b; Sousa, & Fernandes, 2012; U.S. Department of Energy [DOE], 2008). Among the several available renewable energy sources, wind-derived energy is the one that has witnessed greatest growth in the recent years (DOE, 2008; Carvalho et al., 2013). The use of wind energy provides positive impacts on the environment in terms of atmospheric emissions (greenhouse gas reduction), water consumption, effective land use and energy security (DOE, 2008). Wind is a clean, sustainable, ample and entirely renewable source of energy. In the state of Iowa source of wind is leading and the most promising source of alternative energy (AWEA, 2012a).

As rated by the National Renewable Energy Laboratory (NREL) resource assessment, Iowa takes 7th place in the nation for wind resource availability. (AWEA, 2012b).Iowa, with 27.1% of electricity provided by wind, is currently first in the percentage of electricity generated by wind energy and second in total production of wind energy in the United States (AWEA, 2012a). This amount of energy is enough to power 1.3 million average Iowan homes (AWEA, 2012a). As of August 2012, the state had an installed capacity of 4,524MW, a 20.2 percent increase from 2011(Halvatzis, & Keyser, 2013). Iowa ranked first in wind production capacity per square per sq. mile, third in wind power installed per capita and third in total wind capacity installed (AWEA, 2012b). Because of Iowa’s tremendous wind energy resources, the state will continue to be a leader in the development of wind energy technology and the expansion of production capacity (AWEA, 2012a, 2012b). Numerous conditions drive wind energy development in Iowa. Iowa has excellent wind resources, supportive state and energy market policies, robust transportation infrastructure, and a trained workforce (Halvatzis, & Keyser, 2013). These characteristics make Iowa an optimal study site to explore new methods of wind resource estimation and modeling turbine suitability.

The principle of wind turbine power generation is basically converting the kinetic energy of wind first into rotational kinetic energy of the turbine and then to electrical energy (Wind Turbine Power Calculations). Wind power is calculated based on the Newtonian kinetic energy law and equals to:

$$0.5A\rho V^3$$

where A is swept area of the blades, ρ is air density and V is wind velocity (Kalmikov, & Dykes, 2011). This formula shows that wind speed is the key parameter of wind power calculation. Thus, when planning a wind farm, it is important to know the exact wind speed to be able to calculate energy output of each wind turbine, and the whole wind farm economic viability. Wind speed varies with height and with the shape and roughness of the terrain. Surface roughness is usually determined by landcover or vegetation type. Local topography and other variability in the local terrain exert a major influence on wind speed (Geoscience Australia, 2010; Blumberg, & Greeley, 1993). Local scale meteorological studies are very important to understand and model the interaction of wind and the Earth’s surface (Raupach, 1992; Wolfe, & Nickling, 1996). Variation of wind speed with elevation is a crucial issue as it directly impacts the power available at different wind turbine hub heights (Gualtieri, & Secci, 2011). Unfortunately, wind measurements are usually made at a height lower than the turbine hub height and near-surface wind speed measurements are often used as a basis for wind power resource assessments (Hahmann et al., 2011; Hahmann, Vincent, Badger, & Mark, 2013). This is usually done by extrapolating surface (10 m) wind speed to the hub height by using the well-known logarithmic law (De Bruin, & Moore, 1985; Dong, Gao, & Fryrear, 2001; Kou-Fang Lo, 1995; The National Center for Atmospheric Research [NCAR], n.d.). In fact, wind speed proved to increase with height, but the degree of increase is highly affected by atmospheric stability, wind speed and surface roughness length (Gualtieri, & Secci, 2011). The aerodynamic roughness length (Z_0) is a key parameter affecting mass and energy flows (Raupach, 1992). The quantitative role of surface roughness depending on vegetation is the subject of ongoing research.

Detailed assessment of wind energy resources for potential wind farm location requires integration of high quality wind velocity measurements with a microscale modeling of wind flow, which incorporates effects of topography and terrain roughness (Badger, Kelly, & Jørgensen, 2010; Clerc, Anderson, Stuart, & Habenicht, 2012; Junge, & Westerhellweg, 2011; Promsen, Masiri, & Janjai, 2012). An important factor of surface roughness is seasonal changes in vegetation. According to existing surface roughness coefficients for different land cover types, Z_0 substantially changes during a year. Especially it concerns crops such as corn, for which surface roughness changes from bare earth (Z_0=0.005 m) to dense vegetation cover (Z_0=0.25 m) following an annual cycle (World Meteorological Organization [WMO], 2008). Existing tables of surface roughness coefficients provide Z_0 values for very generic landcover types and don’t, include seasonal variability of this important coefficient (Baldocchi, 2012; Hammond, Chapman, & Thornes, 2011; WMO, 2008).

Conducted research results in a number of benefits. First of all, it provides more accurate surface roughness values. These data will be published and might be used by meteorologists or other researchers who might need it. Such data will be very useful, especially when there are not so many available data of this type. Coefficients for the most common vegetation types such as corn and soybeans will help to improve wind resource characterization and wind farm siting in Iowa. It is worth to mention, that these empirically derived coefficients will be available for different time periods or, in other words for different grow stages of vegetation. This time variability is an important factor and is a subject of studies as it was said above, which makes it a valuable outcome of this research. Data on temporal variability of surface roughness might be used not only for wind resource estimation in particular, but for various meteorological studies in general.

Incorporating enhanced Z_0 values along with high resolution landcover and elevation data into a wind resource prediction model will show, whether there is a benefit of using calculated Z_0 instead of just table coefficients. It is expected that, the use of surface roughness derived from field measurements will result in more precise hub height wind speed assessment.

The results of this study might be used for better and accurate atmosphere modeling. This will be beneficial to micrometeorological studies and will lead to more optimal use of wind resources and development of wind energetics in Iowa.

1.1 Research Goal and Objectives

The goal of this research is to develop an enhanced-quality roughness input variables for local and regional wind resource characterization in Iowa. Improving multiscale modeling capabilities for wind energy characterization in Iowa will help optimal wind farm siting and more effective use of available wind resources. The research will address the following questions:

1. What is the effect of vegetation on surface roughness?
2. What are the trends and mean surface roughness values for corn and soybeans?
3. What is the effect of wind turbines on Z_0?
4. What is the difference between hub height wind speed estimated using predefined surface roughness and using values derived from field measurements?

According to the research questions, objectives of this study are:

1. Develop enhanced-quality surface roughness coefficients for corn and soybeans.
2. Identify changes in surface roughness caused by vegetation growth.
3. Identify the effect of wind turbines on surface roughness.
4. Estimate hub height wind speed using derived from field measurements and predefined surface roughness coefficients.

Using mentioned research questions, this study will test several hypotheses. First hypothesis says that Z_0 should have a growing trend respectively to corn growth and then settle around the same value when corn reaches its max size, and Z_0 value for full sized corn should be close to table values.

Second hypothesis is that Z_0 for soy beans has less seasonal changes and overall smaller values than Z_0 for corn.

Third hypothesis is that wind farm has a significant influence on wind flow, which leads to strong disturbance in Z_0 values for respective wind sector. Also, wake from a single turbine effects Z_0 values, leading to higher fluctuations and overall higher Z_0.

Fourth hypothesis is that there is a difference in hub height wind speed calculated using table and measured values of Z_0.

1.2 Thesis Structure

Chapter 2 of this thesis provides a literature review, describing significance of wind energy in the United States and the state of Iowa. This chapter defines wind resource estimation models, their accuracy and contributing factors. Also, the importance of microscale modeling for the optimal wind resource characterization and the problem of the accurate surface roughness measurement or estimation are outlined. Chapter 3 gives a thorough description of the data used in this research, along with environmental characteristics of the study area. In this chapter there is also a description of applied calculation and analysis methodologies. Chapter 4 presents the results. Chapter 5 provides discussion and explanation of the results. It also discusses limitations and overall conclusions of the research.

CHAPTER 2

LITERATURE REVIEW

2.1 Importance of Wind Energy

People have been harnessing the wind's energy for hundreds of years. From old Holland to farms in the United States, windmills have been used for pumping water or grinding grain. Today, the windmill's modern equivalent - a wind turbine - uses wind's energy to generate electricity. The rise of energy prices, supply uncertainties, environmental concerns and nuclear energy problems are driving many countries worldwide to look for other alternatives to the conventional fossil energy reserves (AWEA, 2012a; BP Statistical Review of World Energy, 2013; DOE, 2008; Früh, 2013). Emission-free wind power is one of those green renewable energy sources that are already working to reduce greenhouse gasses. Consequently, renewable energy systems have been extensively developed during the last two decades. Among renewable energy sources, wind energy has been the fastest growing resource, expanding at a rate of 27% over the past five years. (Abbes, & Belhadj, 2012) Wind energy, accounted for more than half of renewable power generation growth (BP

Statistical Review of World Energy, 2013). In addition to the strong development of increasingly large wind farms there is a substantial interest in smaller turbines, partly motivated by individual interests and partly by government's aims to reduce their carbon emissions through both centralized and distributed generation (Früh, 2013; Millward-Hopkins, Tomlin, Mab, Ingham, & Pourkashanian, 2013). That is why accurate wind resource assessment is very important (Promsen et al., 2012).

As Figure 1 shows, United States is one of the world's leaders of power consumption. The use of wind to generate electricity is a way to provide clean and relatively cheap energy to customers. The U.S. Department of Energy provides 50-meter height, wind resource map (Figure 2), which displays that there is plenty of wind resource available. Although power consumption in the United States is high and only about 2.5 percent of it is generated by wind, it is predicted by many research, that the United States has the potential to generate 20% of its electricity from wind by 2030 (DOE, 2008). Before installing a new wind turbine or a wind farm, it is necessary to know, if the wind resource in that location is adequate. States, utilities, and wind energy developers use utility-scale wind resource maps to locate and quantify the wind resource, identifying potentially windy sites within a fairly large region and determining a potential site's economic and technical viability. Wind resource or wind speed maps like Figure 2 or Figure 3, help to determine whether an area of interest should be further explored or not. The average wind speeds indicated on Figure 3 are model-derived estimates that may not represent the true wind resource at any given location. Small terrain features, vegetation, buildings, and atmospheric effects like precipitation or convection may cause the wind speed to depart from the map estimates (Hahmann et al., 2013; Patil, 2005). Expert advice or detailed wind resource assessments should be sought when estimating energy production potential (DOE, 2008).

Wind energy is especially important in the state of Iowa, where 27.1% of energy is provided by wind (AWEA, 2012a). Due to the state and local policy, advantageous geographical location and well developed infrastructure, Iowa’s installed wind capacity has been growing steadily during last decade and will keep growing in future (AWEA, 2012a; Russell, 2014). According to NREL, 75% of Iowa is suitable for harvesting wind energy, but in order to keep decreasing the cost of wind power per kilowatt hour, wind turbines should be erected at the most optimal locations. Avoiding the high resolution modeling nearly always creates biased underestimate if the wind resource in the order of 20 -80% onshore (Badger et al., 2010). Additional meteorological observations and microscale wind resource modeling will not only help to site turbines in an optimal way, but may also reveal additional wind resources.

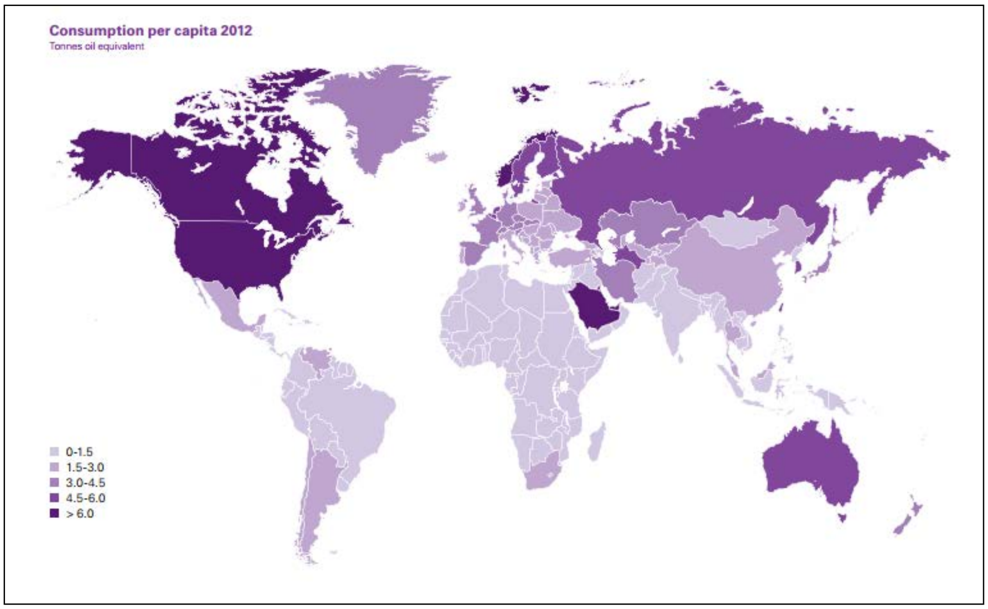

Figure 1: BP Statistical Review of World Energy June 2013

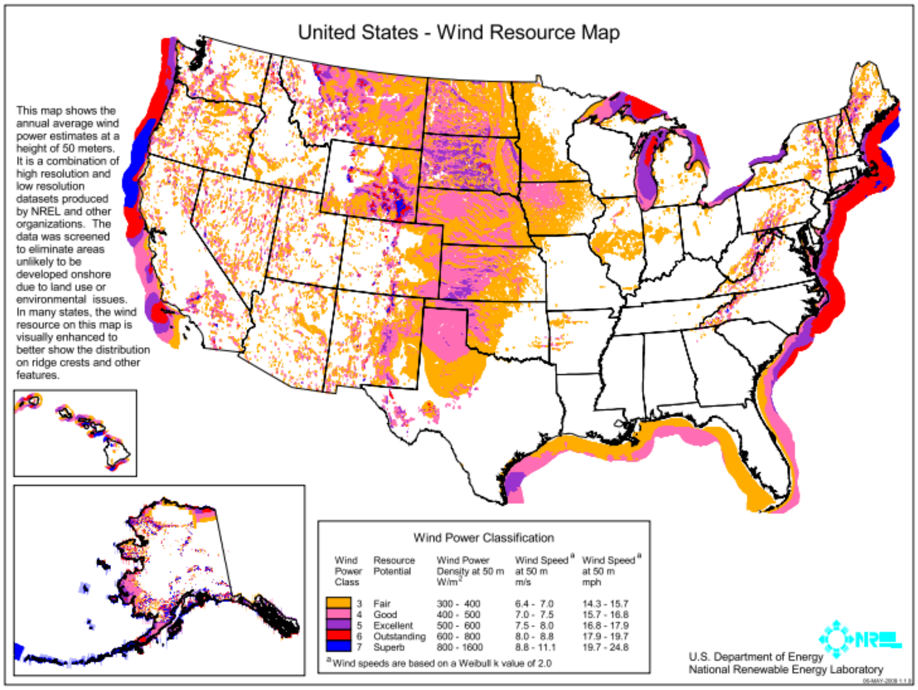

Figure 2: United States wind resources

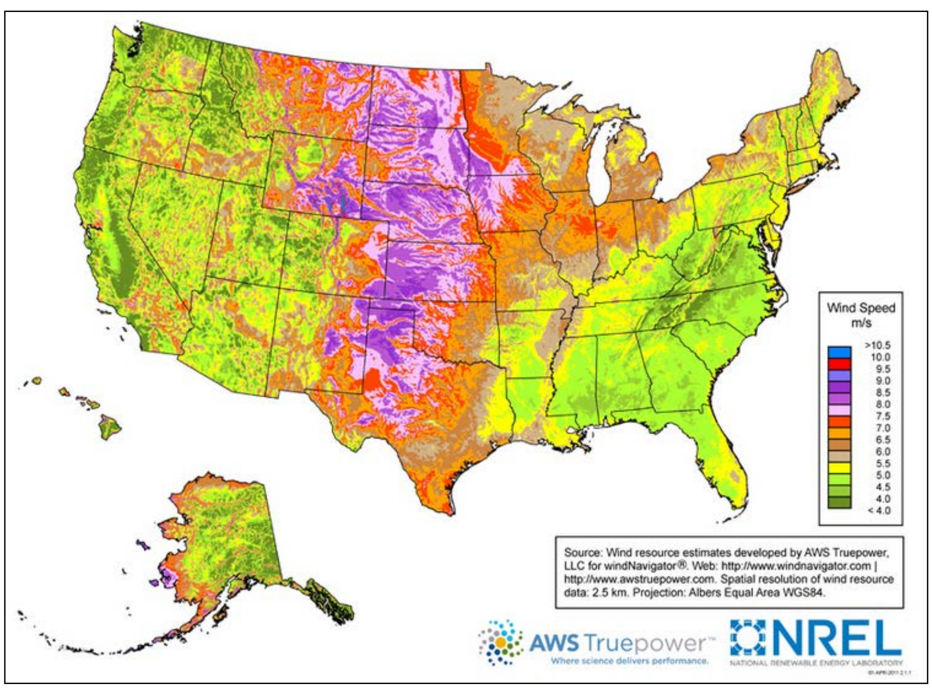

Figure 3: Wind speed at 80 meters high

2.2 Wind Resource Estimation Models

An estimate of energy yield uncertainty is essential information for assessing the financial risk of a potential wind farm. The uncertainty associated with the wind flow model can make up a significant part of the overall energy yield uncertainty. The main question to answer is how the surrounding topography will perturb the wind. The effects of topography are generally broken down into orography (e.g. wind flow over hills), roughness (e.g. landcover and lakes) and obstacles (e.g. buildings; Clerc et al., 2012).

As Lange and Højstrup (2001) say, the wind resource prediction model “WAsP” is the standard method for wind resource predictions on land. It has been validated extensively for land conditions. Lange and Højstrup (2001) describe how this model may be used in the process of predicting the wind resource at a site from wind measurements. First, regional wind climatology is calculated from a measured time series of wind speed and direction, i.e., wind speed distributions for 12 directional sectors for the geostrophic wind are calculated. It is then assumed that the geostrophic wind climate is representative also for the predicted site. The

WAsP models are then used to predict the wind resource for the prediction site (Lange, & Højstrup, 2001).

For designing a wind turbine, it is of high importance to accurately predict the imposed aerodynamic forces and moments on the structure (Esfahanian et al., 2013; Fingersh, Hand, & Laxson, 2006). These forces are used in aeroelastic simulation and structural design and also in predicting the power curve of the wind turbine. One of the most common ways for predicting these forces is simulating the whole flow field around the turbine by computational fluid dynamics (CFD) model (Esfahanian et al., 2013).

The physical aspects of any fluid flow (such as wind flow) are governed by three fundamental physical principles (Wendt, 2009):

- Mass is conserved
- Newton's second law (force equals mass times acceleration)
- Energy is conserved

These fundamental principles can be expressed in terms of equations, which for fluid flow take the form of unsteady Navier-Stokes equations (Cattin, Schaffner, & Kunz, 2006; Promsen et al., 2012). CFD is the science of determining a numerical solution to these equations whilst advancing the solution through space or time to obtain a numerical description of the complete flow field of interest (Cattin et al., 2006). In order to compute a numerical solution, the situation is discretized: Space is split into numerous small elements (boxes) for which the flow is determined for small time steps (Promsen et al., 2012). In wind energy applications this procedure is repeated until a steady-state flow is found for certain boundary conditions. In contrast to diagnostic models, e.g. to WAsP, which calculates wind statistics by parameterizing the influence of topography, roughness and obstacles, CFD modeling computes the three dimensional wind flow field (Cattin et al., 2006).

Linear models tend to perform well for terrain slopes lower than about 25% and have the advantage of short execution times (Probst, & Cárdenas, 2010). Today's wind energy industry demands software that delivers more accurate simulations. Studies prove that CFD captures terrain effects on wind conditions more realistically than one dimensional column models using log-law (or power law) scaling relationships.

In Table 1 methods comprising of the acceptable global standards for wind resource analysis and prediction are categorized.

Table 1: *The traditional wind assessment process complemented with advanced approaches (Anjum, 2014)*

Task	Traditional Approach	Tools	Advanced Approach
Site Prospecting	Cartographic survey + onsite evaluation	Political and physical maps. European Wind Atlas. Met office statistics of nearby stations	Regional wind atlas produced with a mesoscale model. Integration of other feasibility parameters in GIS database
Measurement Campaign	Onsite reference mast as close as possible to the hub height and several additional shorter masts (in large sites)	40-80 m tall masts, equipped with cups and vanes	Velocity profile and Turbulence characterization using dedicated instruments
Long-term Extrapolation	Correlation with nearby historical observations	Measure-Correlate-Predict (MCP) methods	Onsite virtual met mast with historical and homogeneous wind time series
Microscale horizontal extrapolation	Linear model, near-neutral conditions	Wind Atlas Methodology (WAsP)	Non-linear model, different stabilities, built-in forest model
Microscale vertical extrapolation	Define most likely wind shear based on lower measurements and experience	Linear model, near-neutral and/or Experience	Profile calibration based on remote sensing and CFD modelling
Wind Farm Design	Analytical wake modeling	Wind farm design tools based on WAsP	Built-in wake effects CFD model
IEC Classification (Vref)	Vref from limited (1-3 years) measurement periods	Extreme Value Analysis Methods IEC 61400-1	Onsite virtual met mast with historical homogeneous wind speed time series

2.3 Microscale Modeling

An intimate knowledge of a site’s wind resource is essential for many aspects of wind energy development. For site finding, resource assessment, wind flow modeling, turbine micrositing and wind farm energy yield optimization and power curve verification, wind-induced load measurements and for insurance purposes, high-quality wind measurement data is necessary (Lang, & McKeogh, 2011). However, in many parts of the world, there is only poor or even no wind data available (Promsen et al., 2012). Therefore, in the past few years, several methods of wind resource assessment have been developed and applied ranging from ground-based measurement network to numerical modeling (Lang, & McKeogh, 2011; Lehmann, 2010; Wong, Webster, & Vosper, 2012). Additionally, the resolution scales of the maps have been taken into account ranging from synoptic scale (horizontal resolution of greater than 2,000 km) mesoscale (horizontal extents are between 2 km – 2,000 km) and microscale (horizontal resolution of smaller than 2 km; Promsen et al., 2012). Various wind research apply microscale modeling for estimation of wind resources (Badger et al., 2010; Promsen et al., 2012; Wong et al., 2012). As Badger et al., (2010) says, neglecting the high resolution modeling leads to underestimate of the wind resource. Microscale wind maps reveal wind distribution more accurate, allow more effective wind turbine siting and provide a support for appropriate choose of wind turbine type.

Surface roughness plays an important role in all mentioned wind resource assessment technics (Anjum, 2014; Cattin et al., 2006). The energy available in the wind has cubic relationship with wind speed and surface roughness is one of the crucial parameters for vertical extrapolation of wind profile (Anjum, 2014; De Bruin, & Moore, 1985; Kou-Fang Lo, 1995).

2.4 Existing Research

Interaction between Earth surface and atmosphere have always been studied very active. There are different directions of studies which include investigations of surface roughness or aerodynamic roughness length. Some of them study urban air flow (Millward-Hopkins et al., 2013; Nicholas, & Lewis Jr., 1980) or impacts of vegetation and terrain (Baldocchi, Verma, & Rosenberg, 1983; Moore, & Bailey, 2004), or pollutants transfer, or aeolian erosion

(Dong et al., 2001). Other researches try to develop methods for surface roughness estimation from various remotely sensed data (Brown, Hugenholtz, & Barchyn, 2013; Borak, Jasinski, & Crago, 2005; Hammond et al., 2011; Saatchi, & Rodriguez, 1999) or in wind tunnel modeling (Dong et al., 2001; Xian, Tao, Qingwei, & Weimin, 2002). There are studies which implement different models for wind resource estimation (Abbes, & Belhadj, 2012; Clerc et al., 2012; Probst, & Cárdenas, 2010; Promsen et al., 2012) or investigate their quality and accuracy (Cattin et al., 2006; Esfahanian et al., 2013; Lange, & Højstrup, 2001). But there are a few studies concerning impacts of roughness length input data on microscale modeling of wind resources (Badger et al., 2010; Wong et al., 2012). There is also little known about temporal variability of surface roughness or surface roughness sampling (usually look-up tables are being used; Borak et al., 2005).

A lot of progress has been made in atmospheric boundary layer modeling and Earth surface parameterization. Different mathematical models for wind resource estimation and wind flow simulation have been developed (WAsP, CFD). There are also various methods for obtaining wind speed (cup and sonic anemometers, SoDARs and LiDARs) and surface characteristics like roughness or displacement high (calculation from direct wind measurements, estimation from remote sensed data and estimation from measurements of surface elements; Brown, & Hugenholtz, 2013; WMO, 2008). These models and methods have been tested and validated onshore and offshore, on simple and complex terrain, homogeneous and heterogeneous vegetation (Carvalho et al., 2013; Cattin et al., 2006). Other than measurement methods, look-up tables for surface roughness were created and updated (Wieringa, Davenport, Grimmond, & Oke, 2001). Many local studies of wind interactions with surface and wind resources have been conducted worldwide. They applied different methods, but the result uncertainty still exists and no ideal combination of field measurement methods and computer models is known (Hammond et al., 2011).

2.5 Surface Roughness as Key Parameter for Wind Resource Estimation

Nicholas and Lewis (1980) define roughness length as the height above the surface at which the horizontal component of the wind speed approaches zero, measured logarithmically downward from the gradient wind level where the free flowing winds are an energy source free of surface influences. Roughness length is thus some fraction of the thickness of the obstructed surface boundary layer in the lower troposphere (Nicholas, & Lewis, 1980). In other words, roughness length is a measure of the aerodynamic roughness of a surface affecting the height at which the neutral wind profile near to the ground extrapolates to zero (Oke, 1987). In fact, Z_0 lies within the roughness sub-layer where wind speed deviates from the log law. It represents the bulk effects of roughness elements in the surface layer and very approximately has value around 0.1 times height of the roughness element (Bretherton, 2013). Traditionally a parameter of roughness length Z_0 is used as the primary measure of the aerodynamic roughness of a surface, but Z_0 is notoriously difficult to estimate (Hammond et al., 2011). The surface roughness length over land depends on the characteristics of the surface cover. A subjective way of determining Z_0 is by a visual survey of the terrain around the wind station with the help of the table of landcovers (WMO, 2008). A detailed review of roughness data from boundary-layer experiments conducted in the 1970s and 1980s was undertaken by Wieringa (1993), who found that the 1960 Davenport classification of effective terrain roughness (Davenport, 1960) most reliably described the effective roughness of realistic landscape types. The original Davenport classification has since been updated at both ends of the classification scale (Wieringa et al., 2001), providing arguably the best field-validated roughness classification to date (Table 2).

Table 2: *Davenport classification of effective terrain roughness* (Wieringa et al., 2001)

Z_0 (m)	Landscape Description
1. 0.0002 “Sea”	Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2. 0.005 “Smooth”	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, marsh and snow-covered or fallow open country.
3. 0.03 “Open”	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without wind breaks, heather, moor and tundra, runway area of airports. Ice with ridges across-wind.

Table continues

Z_0 (m)	Landscape Description
4. 0.10 *"Roughly Open"*	Cultivated or natural area with low crops or plant covers, or moderately open country with occasional obstacles (e.g. low hedges, isolated low buildings or trees) at relative horizontal distances of at least 20 obstacle heights.
5. 0.25 "Rough"	Cultivated or natural area with high crops or crops of varying height, and scattered obstacles at relative distances of 12 to 15 obstacle heights for porous objects (e.g. shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g. buildings).
6. 0.5 "Very Rough"	Intensively cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low densely-planted major vegetation like bush land, orchards, young forest. Also, area moderately covered by low buildings with interspaces of 3 to 7 building heights and no high trees.
7. 1.0 "Skimming"	Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacle heights; e.g. mature regular forests, densely built-up area without much building height variation.
8. ≥ 2.0 "Chaotic"	City centers with mixture of low-rise and high-rise buildings, or large forests of irregular height with many clearings

Surface roughness changes according to the geometry, spacing and arrangement of roughness elements on the Earth’s surface (Garratt, 1992; Lettau, 1969). Empirical research has established, that in homogeneous terrain with closely-spaced roughness elements (i.e. where a skimming wind-flow regime is induced), Z_0 is proportional to the roughness element height (Brown, & Hugenholtz, 2011). The length Z_0 is related, but not equal to the height of the surface elements and is also a function of the shape and density of the elements (Hammond et al., 2011).

Aerodynamic roughness height is a key parameter affecting mass and energy flows near the Earth’s surface (Raupach, 1992; Wolfe, & Nickling, 1996). Changes in the aerodynamic characteristics of a site can have a major influence on the wind regime at the surface/air interface (Hammond et al., 2011). Wind speeds can vary considerably across a wind farm site if the terrain is complex (hilly) or if there are changes in roughness (the height of vegetation or buildings; Ministry of New and Renewable Energy [MNRE], Government of India, n.d.). The vertical distribution of wind speed is a function of both surface roughness and the stability of the atmosphere (Nicholas, & Lewis, 1980).

Local wind maps are based on the predicted modification of the regional wind flow pattern by the local atmospheric boundary layer, which in turn depends on both topographic and roughness features and the measured wind rose obtained from measurement towers within the boundaries of the planned development site (Probst, & Cárdenas, 2010). Given the significant rise of the utilization of wind energy the accurate assessment of the wind potential is becoming increasingly important (Halvatzis, & Keyser, 2013). Direct applications of wind assessment techniques include the creation of wind maps on a local scale (typically 5-20 km plot) and the estimation of vertical wind speed variations, prospecting on a regional scale (>100 km) and estimation of the long-term wind resource at a given site (Probst, & Cárdenas, 2010). Uncertainty in the effective surface roughness is an important factor in the uncertainty of wind model output for wind energy applications (Moore, & Bailey, 2004). Z_0 helps to characterize the intensity of turbulence and the efficiency of turbulent exchanges of heat, moisture and momentum between the land surface and the atmosphere (Borak et al., 2005).

2.6 Surface Roughness Calculation and Measurements

Both field experimental and theoretical approaches have been developed for estimating roughness. Analysis of field-based measurements of wind profiles under neutral stability conditions is a typical method if a specific location is of interest (Driese, & Reiners, 1997; Peña, Gryning, & Hasager, 2010; Toriumi, 2003). Most published values of Z_0 are derived in this manner (Borak et al., 2005).

Atmospheric stability has to do with how air density varies with height above the ground. Vertical profiles of potential temperature can be used to classify the atmosphere as statically unstable, neutral, or stable as shown in Figure 4 (Wenzel, Bleeg, Tilman, & Marco, 2013). Unstable conditions are often associated with the daytime: the sun warms the ground, which in turn warms the air near the ground, resulting in air that is generally lighter than the air aloft. This creates an unstable cycle where warmer, lighter air from near the ground rises while cooler, heavier air from above descends. Conversely, stable conditions are often associated with night-time: when the sun sets, the ground cools, cooling the air near the ground. This creates a stable situation where the warmer, lighter air aloft tends to stay aloft while colder, heavier air near the ground tends to stay near the ground. Neutral conditions typically occur briefly around sunrise or sunset. It is important to take atmosphere stability into account when calculating surface roughness, because different stability leads to different behavior of a wind flow, as shown on Figure 5.

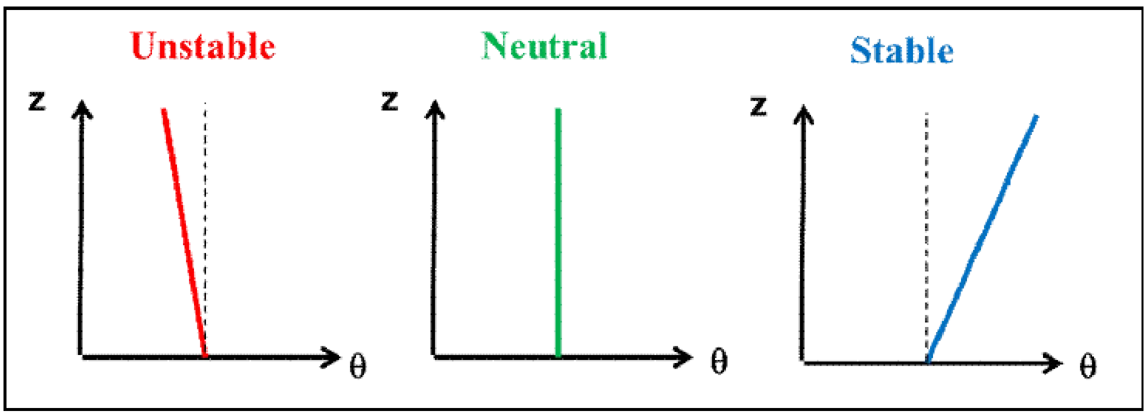

Figure 4: Potential temperature profile for different atmospheric conditions (Wenzel et al., 2013)

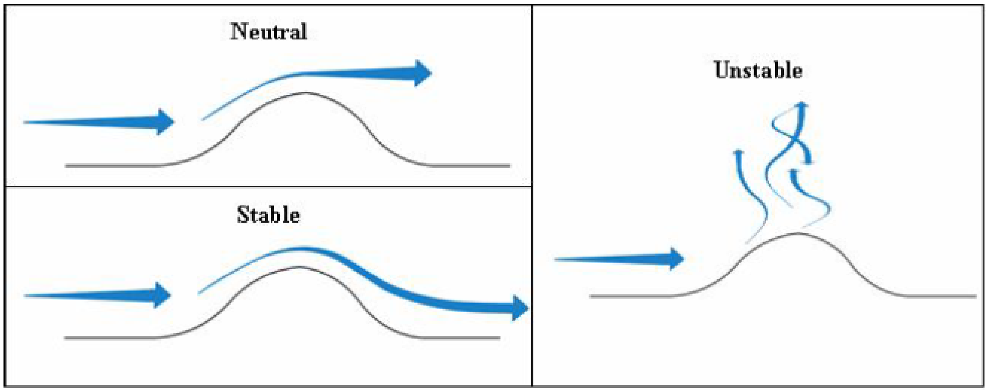

Figure 5: Wind flow over terrain under different atmospheric conditions (Wenzel et al., 2013)

Although roughness length is determined from wind speeds at various heights, it is caused by the roughness elements. In other words, the aerodynamic roughness length is determined for a particular surface. Lettau (1969) said: it is not difficult to estimate fairly accurately, without detailed numerical analysis, the aerodynamic roughness parameter Z_0 at a new micro-meteorological site, after an anemometer mast has been installed and the first wind-profile data plot on semi-logarithmic graphs can be inspected. Surface roughness length is defined on the basis of a logarithmic profile shown on Figure 4. Given the logarithmic relationship, Z_0 can be obtained by measuring the wind speed at two or more heights. Once this roughness length is determined for a certain surface, it does not change with wind speed, stability or stress (Saatchi, & Rodriguez, 1999). However, it can change if the structure and density of surface roughness elements change, for example because of land cover change, deforestation, soil erosion, etc.

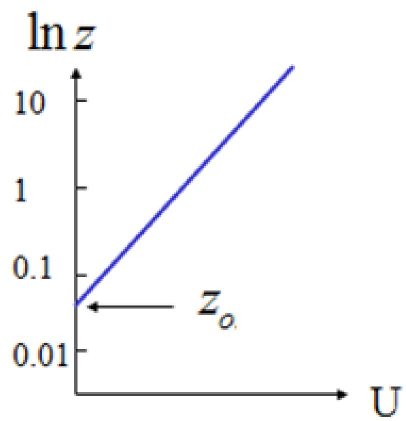

Figure 6: Z_0 on logarithmic profile

Generally, measurements of the speed of the horizontal winds at two or more different heights above the ground within the unobstructed surface boundary layer are extrapolated to yield the roughness length (Nicholas, & Lewis, 1980). Nowadays a series of measurement techniques is available for on-site wind resource measurement ranging from point measurements performed at different heights using cup anemometers or ultrasonic sensors to profiling techniques like SODAR or LIDAR (Probst, & Cárdenas, 2010). The majority of measurement campaigns for commercial wind farms rely on cup anemometry (Kristensen, 1999) and occasionally on ultrasonic sensors (Pedersen et al., 2003; Wyngaard, 1981), where the latter is often preferred in research applications. Remote-sensing techniques like SODAR or LIDAR (Cuerva, & Sanz-Andrés, 2000; Wilczak, Oncley, & Stage, 2001) are increasingly explored as a complementary approach, particularly in large wind farm projects, where the profiling device can be conveniently relocated within the project area for an exploration of the wind resource at different sites, following an initial calibration period where the profiler is operated in conjunction with a conventional tower-based measurement system (Probst, & Cárdenas, 2010).

More challenging is the problem of estimating a Z_0 value strictly based on a visual site survey and exclusively using metric measurements to describe the characteristic roughness elements (Lettau, 1969). Many efforts have been given to describe the relationship between the roughness length and the condition of the surface (Xian et al., 2002). Progress in estimating the surface roughness of spaced crops by the use of empirically determined regression equations has stimulated investigation of the relation between aerodynamic roughness and the geometry of the surface elements (Nicholas, & Lewis, 1980). A common goal in this area of research has been to develop better parameterizations of Z_0, especially across landscapes where surface conditions are poorly represented by existing look-up tables. Two types of approaches have been used since remote sensing was introduced as a technique to estimate Z_0 (Brown, & Hugenholtz, 2011). The first approach involves empirical relations linking in situ measurements of Z_0 from wind profiles to airborne- and spaceborne-derived measures of roughness. The second approach is predicated on developing an estimate of Z_0 by combining physical models of the vegetation canopy with theoretical models of the boundary layer (Brown, & Hugenholtz, 2011).

Thus, considerable effort has been made to develop methods that estimate Z_0 accurately across the landscape. In the absence of wind measurements a common approach is to use empirically- formulated look-up tables that provide estimates of Z_0 for different surface classes (Brown, &

Hugenholtz, 2011; Garratt, 1992; Oke, 1987). However, the look-up table approach has been criticized for being overly simplistic and inflexible with respect to temporal and within class variability (Borak et al., 2005). These look-up approaches ignore the inherent temporal and spatial variability of land cover and the concomitant effects on momentum transfer (Borak et al., 2005).

2.7 Summary

Accurate wind resource assessment relies on high quality data. The most important input parameter for wind modeling is wind speed. Vertical wind speed distribution is highly dependent on topography and surface characteristics. It is usually calculated based on a log-law using surface roughness coefficient for each specific land cover type. Surface roughness can be taken from a look up table or derived from field wind observations. Atmosphere stability should be taken into account in isolating neutrally stratified flow conditions for proper calculations of surface roughness, as it significantly changes the characteristics of wind flow.

As demonstrated in this chapter, there is only limited research addressing temporal variability of surface roughness length and its influence on microscale wind resources modeling. There are only a few field studies of local roughness length as well. On one hand different ways to estimate this parameter without direct measurements are available, but on the other hand, literature indicates that sometimes these methods demonstrate significant discrepancy with measured values. This makes field observations, probably, the most reliable method for getting accurate surface roughness length values. As far as there are not many local studies of surface roughness for various landcovers, any additional field observations will help to identify more accurate values of Z_0 for local landcovers. Furthermore, to perform microscale modeling of wind speed and wind resources, denser micrometeorological observations need to be done.

It is known that surface roughness changes during the seasons and incorporating this into wind resource estimation model will probably take a positive effect on model outcomes.

CHAPTER 3

METHODOLOGY

3.1 Environmental Characteristics of Iowa

Iowa is a state in the Midwestern United States. Iowa is bordered by the Mississippi River on the east and the Missouri River and the Big Sioux River on the west. Iowa is bordered by Wisconsin and Illinois to the east, Missouri to the south, Nebraska and South Dakota to the west, and Minnesota to the north (Figure 7). The state of Iowa covers 55,857.1 square miles and has a population of 3,090,416 people (State Data Center of Iowa, 2013). The topography of Iowa was generally shaped by glaciers which were moving down from the north during the last ice age (Fitzpatrick, 2007; Freedman, 2010). Iowa can be divided into eight landform regions based on glaciation, soils, topography, and river drainage (Prior, 1991). Figure 8 illustrates, that due to the glacial history, Iowa consists of flat plains and rolling hills (Freedman, 2010; Prior, 1991). The mean elevation is 340 meters, the highest point in the state is 509 meters above sea level and the lowest point is 146 meters above sea level (Russell, 2014). North central is the flattest part of the state, while southern and western Iowa consist mostly of rolling to hilly land.

Figure 7: Location of Iowa

Figure 8: Topography of Iowa, with counties and major streams

The various landform regions provide rich soils that make Iowa a fertile and agricultural base (Fitzpatrick, 2007; Russell, 2014). Iowa's natural vegetation is tall grass prairie and savanna in upland areas, with dense forest and wetlands in flood plains and protected river valleys, and pothole wetlands in northern prairie areas (Prior, 1991). However, widespread use of irrigation farming and large-scale farm machinery in the 20th century, coupled with a shift toward a more mass agricultural production, transformed Iowa’s landscape from diverse prairie plants into the large-scale monoculture farming that are common today (Freedman, 2010). Most of Iowa is used for agriculture. The land cover map of the state is shown on Figure 9. Crops cover 60% of the state, grasslands (mostly pasture and hay with some prairie and wetland) cover 30%, and forests cover 7%, while urban areas and water cover another 1% each (Gallant, Sadinski, Roth, & Rewa, 2011).

Because of its latitude and interior continental location, Iowa has a seasonal climate. Winters are cold, with January temperatures averaging about 15 °F (−10 °C) (Iowa, 2014; National Climatic Data Center [NCDC], 2006a). Iowa summers are known for heat and humidity. In July the average temperature is in the mid-80s F (about 30 °C) but rarely reaches 100 °F (38 °C) (Iowa, 2014; NCDC, 2006a). Precipitation averages around 34 inches per year for the State, ranging from 26 inches in the extreme northwest to as much as 38 inches in the southeast. However, annual totals vary widely from year to year and locality to locality (NCDC, 2006a). Annual distribution of temperature and precipitation is illustrated on Figure 10.

Iowa has experienced severe flooding as a result of rapid snow melt and heavy summer rainstorms. Floods are most frequent in June which has the highest average rainfall of any month (NCDC, 2006a). Mid-March through early April is another favored time for flood occurrence when snowmelt, combined with rain and frozen soils, can produce significant flooding on the major rivers (NCDC, 2006a). Iowa averages about 50 days of thunderstorm activity per year (National Oceanic and Atmospheric Administration [NOAA], 2010). Tornadoes are common during the spring and summer months, with an average of 37 tornadoes in a single year (NCDC, 2006b).

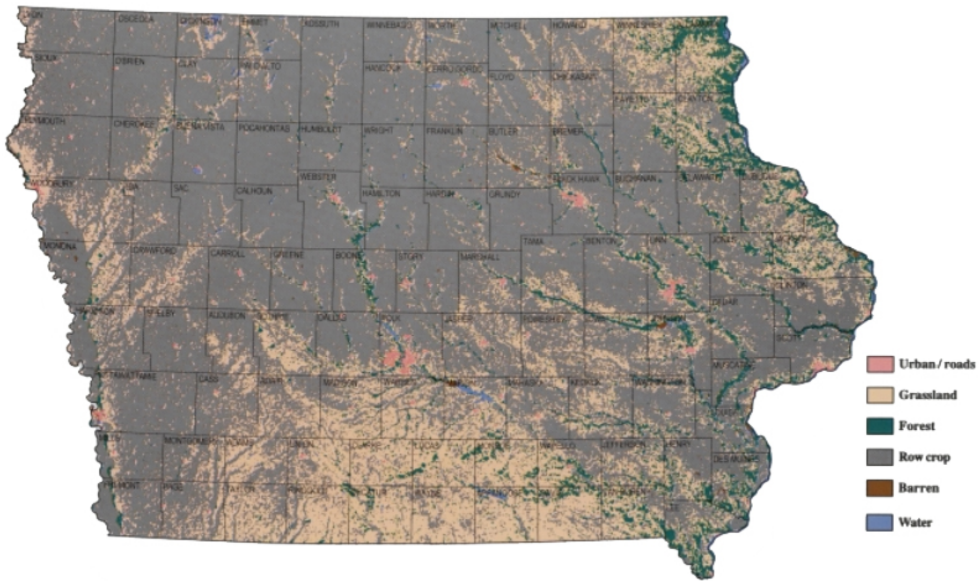

Figure 9: Land Cover Map of Iowa (State Library of Iowa, 2007)

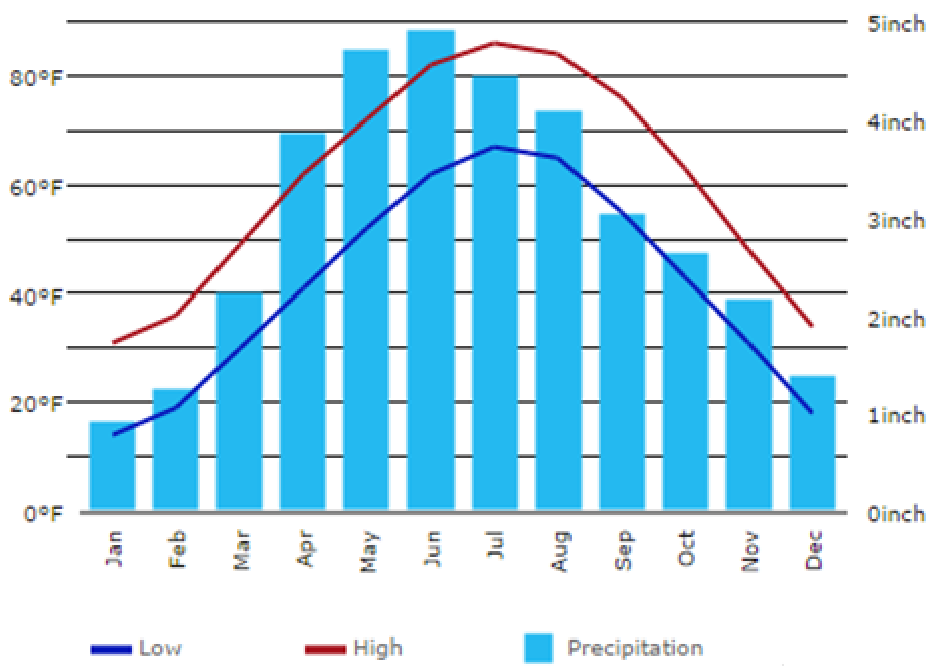

Figure 10: Iowa climograph (US Climate Data, 2014)

3.2 Iowa Wind Resources Characteristics

The climatology of wind in the Upper Midwest exhibits significant seasonal variability (EnerNex Corporation and WindLogics Inc., 2004). The essential meteorology driving the wind resource is largely controlled by the position and strength of the upper-level polar jet stream and disturbances (jet streaks) within the jet stream (EnerNex Corporation and WindLogics Inc., 2004; Russell, 2014). Jet streams are relatively strong winds concentrated as narrow currents at altitudes of 6 to 9 miles (9 to 14 kilometers) above sea level (American Meteorological Society [AMS], 2012; Barry, & Chorley, 2003). As Figure 11 shows, the jet stream in the winter season is farther south and stronger than in the summer (AMS, 2012). In the transition seasons of spring and fall, the average jet stream position generally lies between these locations (EnerNex Corporation and WindLogics Inc., 2004). The main factor controlling both the jet stream position and speed is the magnitude and location of the tropospheric meridional temperature gradient (AMS, 2012; Barry, & Chorley, 2003). Because of higher north-south temperature contrast in the winter than in summer, jet stream winds are faster in winter (AMS, 2012).

Since jet streams display a gigantic wavy pattern around the globe, Figure 12 indicates a mean ridge axis over western and eastern North America, but at any particular time (day, week, or even several week period), the jet stream orientation and strength could be very different from that indicated in Figure 12 (EnerNex Corporation and WindLogics Inc., 2004).

Figure 11: Mean winter and summer positions of the upper-tropospheric jet stream. Line width is indicative of jet stream wind speed

There is significant seasonal weather variability at the Upper Midwest. Due to this variation and the position of the jet stream wind speeds are often very high in this region (EnerNex Corporation & WindLogics Inc., 2004).

Iowa’s seasonal wind is stronger in the winter and early spring and weaker in the summer (EnerNex Corporation & WindLogics Inc., 2004). Typically, wind resource at hub height increases in the nocturnal hours and decreases during daylight hours (EnerNex Corporation and WindLogics Inc., 2004). Wind speed near the surface (e.g., 10 m) shows the reversed trend with maximum occurring during the afternoon and the minimum during the nighttime hours.

The distribution of wind speed in Iowa provided by the Iowa Energy Center is shown on Figure 12. The north central and the northwest parts of the state have the highest wind speed about 7.0 - 8.0 m/s on average. In opposite, the southeastern part of Iowa has the lowest wind speed of 6.0-6.5 m/s. Between the high and low wind speed areas, there is a transition belt, stretched from southwest to northeast with 6.5 - 7.0 m/s winds. Advantageous geographical location in combination with other environmental factors makes Iowa one of the richest states in wind resource potential (Figure 13).

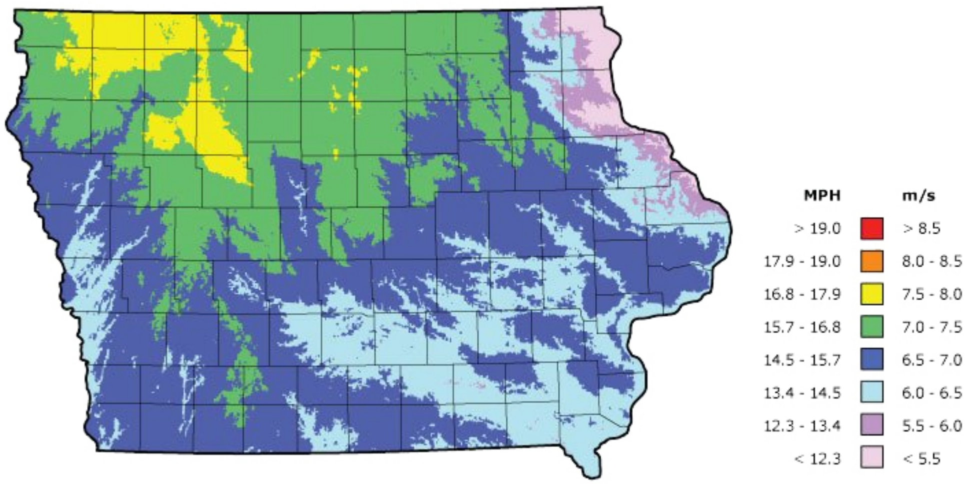

Figure 12: Estimated annual average wind speed at 50 meters (Iowa Energy Center, 2012)

Figure 13: Annual average wind resource potential at 50 meters (National Renewable Energy Laboratory [NREL], 2012)

3.3 Study Area

The study area for this research was located on the southwest end of a 200-turbine wind farm in central Iowa. The hub height of wind turbines within study area is 80 m and rotor diameter is 77 m. The relief of the study site is generally flat, with some variations in slope from 0^0 to 2^0, mostly south and southwest aspect as displayed on Figure 14. The study site and surrounding landcover is a patchwork of mostly corn and soybeans. At the start of data acquisition (early July), the crop height was about 1.5 m, and by the second to third week of July the canopy reached its maximum height near 2.8 m (Rajewski et al., 2013).

Several wind turbines rise within the study area. They form a line of six turbines, and there are no other turbines to the directly to the south. Aerial photo and a 3D model of the study site are shown on Figure 15. Mast number 1 shown in blue considered as reference, because it is located south to wind turbine row and due to prevailing winds experiences less impact of surrounding turbines. Mast 2 shown in red was used for comparison additional calculations control.

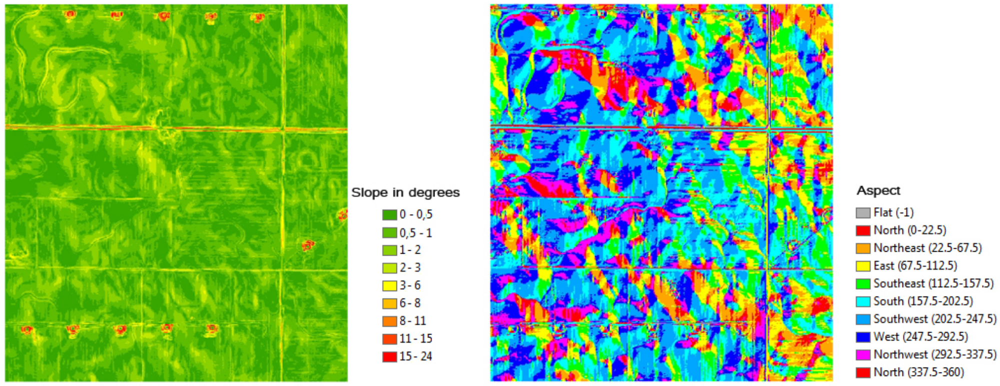

Figure 14: Slopes (left) and aspect (right) of the study site. Produced, using LiDAR data by Iowa DNR.

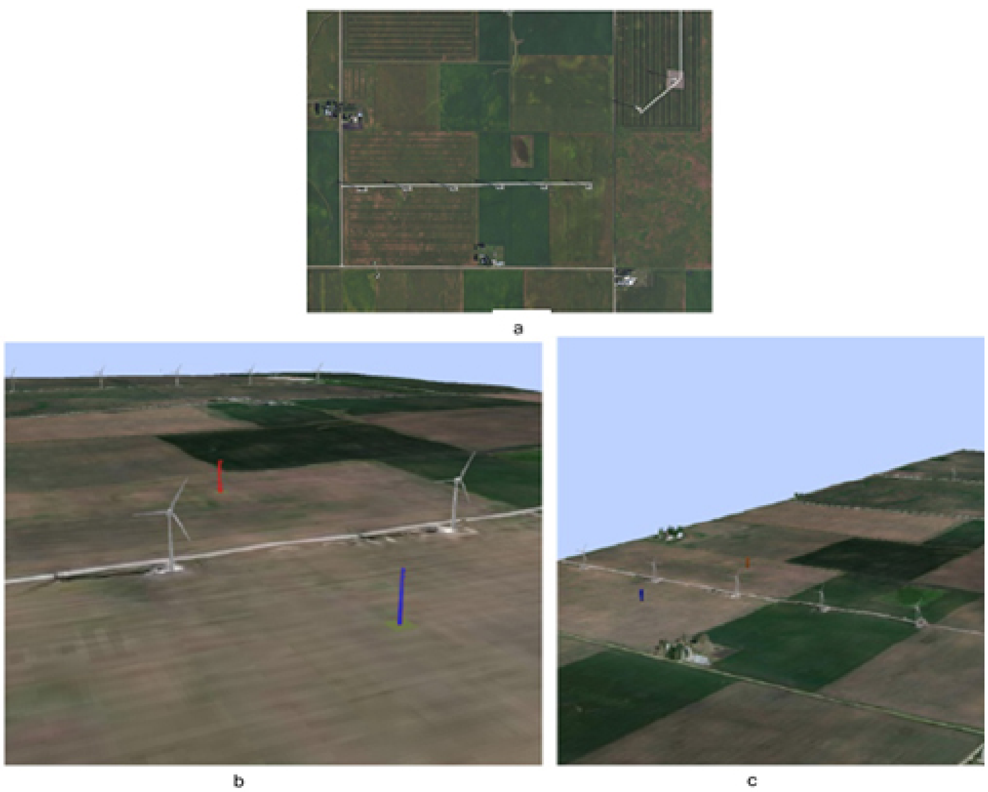

Figure 15: Study site on aerial image (a), 3D model of a study site with wind measurement stations (b, c)

3.4 Data Description

Two micrometeorology field data sets from the 2011 and 2012 Crop Wind Energy Experiment (CWEX) were used in this research. They were tables containing 10 min average wind measurements, plus additional coefficients such as friction velocity and Monin-Obukhov length for corn and soybeans.

For this report, data was used from two surface flux stations. Each measurement mast was equipped with cup and sonic anemometers, temperature and relative humidity probes. Wind direction data were obtained from the sonic anemometers. Cup anemometers were installed at the height of 3m and 9m, while sonic anemometers were only at 4,5m height. Initial data tables contained not only direct measurements from sensors (wind speed, wind direction, time), but also friction velocity, Monin-Obukhov length and stability category calculated from the wind and temperature data. Temporal resolution of data is 10 minutes for the time period from 07/01/2011 to 08/16/2011 and from 07/05/2012 to 09/07/2012 for CWEX-11 CWEX-12 data respectively.

Some additional data were also used in this study. It was LiDAR and landcover data, provided by Iowa Department of Natural Resources (GIS Library, 2012). LiDAR data were obtained as LAS files using web service by GeoInformatics Training Research Education and Extension (GeoTREE) Center. These data were used to produce 1 meter resolution digital elevation model of the study site. Table 3 represents all data used in this research. Data can be divided into two categories. First is micrometeorological data, used for surface roughness and hub height wind speed calculations. Second category is additional data (elevation and aerial imagery), used for general study site description.

Table 3: *Data Description and Source*

Data	Description	Source
LiDAR	Raw LAS file	Iowa DRN GIS Library
Aerial image	High resolution image of study site	Google
CWEX-11	Spreadsheet with 10 minute average meteo data	Iowa State University
CWEX-12	Spreadsheet with 10 minute average meteo data	Iowa State University

3.5 Data Processing

As far as there are two different types of data (spatial and non-spatial) used in this research, two separate processing procedures were applied. First procedure included table data preprocessing, filtering, running calculations and results export and analysis. Second procedure contained geoprocessing of spatial data and wind resource modeling.

Preprocessing

The goal of this step was preparing initial table data for automated calculations. One table, representing CWEX-2011 data contained about 65 hundred records and 28 columns. The table of CWEX-12 data had around 9 thousand records and 27 columns. For this study, only some of the presented columns were necessary. A subset of each table with only columns needed for calculations was created. In order to make processing of such amount of data more efficient, a decision was made to import tables into a database and manage them using SQL queries.

PostgreSQL - a powerful, open source object-relational database system was chosen for storing and processing meteo data. As it is stated on the official web site, “PostgreSQL has more than 15 years of active development and a proven architecture that has earned it a strong reputation for reliability, data integrity, and correctness.” Even though only basic functionality of such database management system was used in this research, having data organized and stored in a database will be useful for further studies, sharing or publishing.

To import Excel spreadsheet into a database, it has to be first converted to a CSV (comma separated values) file. Once the file is converted to a CSV it can be uploaded in a database. In order to be able to do this, there must be an existing database with a table already created. Moreover, this existing table must have the same structure as the one being imported. Therefore, initial Excel spreadsheet was modified, and all unnecessary columns were eliminated. Remaining parameters were: timestamp, diurnal flag, wind speed for each mast and each sensor, wind direction, wake direction, friction velocity and Monin-Obukhov length. The table of the same structure was created in a database and populated with all 13 thousand records. Similarly, Excel spreadsheet for CWEX-12 data was imported to the same database.

The next step of preprocessing was editing the data types for each column of the tables. It was necessary for optimal computer memory usage and ability to do mathematical operations. Three main data types were used: string type for all text values, auto increment integer type for id's and floating point number type of different precision for the rest of the columns. At the last step of preprocessing additional columns essential for further calculations were created.

Surface Roughness Calculation

Calculation of surface roughness from field micrometeorological observations is a common, but not a trivial task. Literature indicates that most of the formulas for Z_0 are based on the well-known logarithmic law (De Bruin, & Moore, 1985; Driese, & Reiners, 1997; Kou-Fang Lo, 1995; McInnes, Heilman, & Gesch, 1991; Nakai et al., 2008):

$$u_z = \frac{u_*}{k} \ln \frac{z-d}{z_0} \quad (1),$$

Where u_z is horizontal wind speed at height z, u_* is friction velocity, k is Von Karman's constant, d is the zero plane displacement (or displacement height) and z_0 is roughness length. Friction velocity is a scale of the turbulence, Von Karman's constant is a scaling factor of the logarithmic law of mean wind profile in the atmospheric boundary layer and displacement height is the level at which the mean drag on the surface appears to act (Acevedo et al., 2009; Jackson, 1981; Zhang, Ma, & Cao, 2008). Formula 1 was used for hub height wind speed estimation, and as a base for surface roughness calculation. De Bruin and Moore (1985) say, that this formulation should be used only for $z > z^*$ where the height z^* represents lower limit of the inertial sublayer and has an order of magnitude by $z^* \sim d+20z_0$. Otherwise equation of logarithmic law is not valid (De Bruin, & Moore, 1985). According to Table 2, surface roughness for CWEX-11 data (measured over corn) should be from 0.2m to 0.25m. Displacement height can be estimated to be 0.65 of the corn height, which gives us 1.8m (Kustas, Choudhury, Kunkel, & Gay, 1989). Thus, the high estimate of z^* is 6.3m. In this research data from sensors at 3m, 4.5m and 9m were available. This means that data from 2 of 3 available anemometers were under effect of roughness sublayer. The choice was made to use 4.5m and 9m, upper two heights anemometers even though they are not of the same type (9m is cup anemometer and 4.5m is sonic anemometer). The use of these 2 sensors should give the most reliable results (Nakai et al., 2008).

However it is considered that log law well describes vertical wind speed distribution for neutral and near-neutral conditions, it must be modified in order to be used for non-neutral conditions (Kou-Fang Lo, 1995):

$$u_z = \frac{u_*}{k}\left(\ln\frac{z-d}{z_0} - \psi_m\left(\frac{z}{L}\right)\right) \quad (2),$$

where $\psi_m\left(\frac{z}{L}\right)$ is the integrated diabatic influence function for momentum. In other words, it is a correction coefficient for stability. Based on (1) and (2) it is possible to derive Z_0 formulas for neutral (3) and non-neutral (4) conditions (NCAR, n.d.):

$$z_0 = \frac{(z_2 - z_1)}{\left[exp\left(\frac{ku_2}{u_*}\right) - exp\left(\frac{ku_1}{u_*}\right)\right]} \quad (3),$$

$$z_0 = \frac{(z_2 - z_1)}{\left[exp\left(\frac{ku_2}{u_*} - \psi_m\left(\frac{z}{L}\right)\right) - exp\left(\frac{ku_1}{u_*} - \psi_m\left(\frac{z}{L}\right)\right)\right]} \quad (4)$$

Calculation of $\psi_m\left(\frac{z}{L}\right)$ depends on stability category. The formulation for stable conditions is different from the one for unstable conditions. For stable conditions (McInnes et al., 1991):

$$\psi_m\left(\frac{z}{L}\right) = 4.7\frac{z}{L} \quad (5),$$

and for unstable conditions (McInnes et al., 1991):

$$\psi_m\left(\frac{z}{L}\right) = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}(x) + \frac{\pi}{2} \quad (6),$$

$$x = \left(1 - \left(15\frac{z}{L}\right)\right)^{0.25} \quad (7)$$

For better control of calculation and elimination of possible human errors, surface roughness was calculated using formulas (4) to (7) one by one, without combining them into one formula. However, atmospheric stability categories had to be determined before performing Z_0 calculation. Different research apply different approach to stability classification (Gryning, Peña, & Hasager, 2008; Sucevic, & Djurisic, 2012). Classification based on the value of Monin-Obukhov length, which is the height at which contributions to the turbulent kinetic energy from buoyancy and shear stress are comparable (The Meteorological Resource Center [MRC], 2012), by Gryning et al., (2008), was used in this study (Table 4). It was chosen because it is used in other research (Hahmann et al., 2011, 2013) there are more stability categories than in other classifications, which seems to be more suitable for this research, where atmosphere stability plays a significant role. Stability categories were assigned to each record using values of Monin-Obukhov length, which were already available in initial dataset. Classification by Gryning (Table 4) has a gap and values from -50 to 10 are not assigned to any category. This acts as additional data quality filtering.

In application of conditions described above, a series of SQL queries were created. First, queries solving equations (5), (6), (7) for stable and unstable conditions respectively were applied. Then was applied the main query, solving equations (3) and (4) for corresponding stability classes. The last step was to calculate wind speed at the hub height (80 m) using both table and derived surface roughness values. To do this, another SQL query solving equations (1) and (2) was applied.

Table 4: *Stability classes according to Obukhov length (Gryning et al., 2008)*

Obukhov length (m)	Atmospheric stability class
$10 \le L \le 50$	Very stable
$50 \le L \le 200$	Stable
$200 \le L \le 500$	Near stable/neutral
$\|L\| \ge 500$	Neutral
$-500 \le L \le -200$	Near unstable/neutral
$-200 \le L \le -100$	Unstable
$-100 \le L \le -50$	Very unstable

All calculations were the same for CWEX-11 and for CWEX-12 data sets. When surface roughness and wind speed were calculated, the outcome data quality was thoroughly inspected and it turned out that additional filtering is required.

Filtering

According to literature, there are several criteria for data quality evaluation in terms of surface roughness calculation. In order to keep only the most reliable results of calculations, data filtering was performed.

First, a low wind speed filter was applied. Zero or very low wind speeds for one or both heights used in Z_0 calculation lead to meaningless or unreliable values of surface roughness. In order to eliminate this effect, records with wind speed less than 2 ms^{-1} were filtered out (Peña et al., 2010).

Another data quality factor related to wind speed is its vertical distribution. If wind speed decreases with height, calculated surface roughness tends to be unrealistically large or show erroneous values (Anjum, 2014; Jaramillo, & Borja, 2004). Therefore, all cases when wind speed shown by anemometer at 9m height was less than the one shown by 4.5m anemometer were filtered.

It is noticed, that for a larger difference between wind speed measurement height and planned turbine height, effects of atmospheric stability have larger impact on estimated hub height wind speed (Sucevic, & Djurisic, 2012). Formulation for surface roughness for neutral conditions has fewer variables than for non-neutral, which leaves less possibility to an error. It is also more common for similar research to use only neutral conditions data for surface roughness calculation (Nakai et al., 2008; Patil, 2005; Sucevic, & Djurisic, 2012; Tian et al., 2011).

Thence, a subset of data, containing only records for neutral atmosphere conditions was created for further analysis and interpretation. Neutral condition filtering was based on stability categories, which were determined using values of Monin-Obukhov length, as described in previous section. Only cases matching $|L| \geq 500$ interval were used.

Preliminary examination of filtered data indicated, that there is still a number of negative or unrealistically large values of Z_0. The vast majority of these records referred to north-west, north and north-east wind directions. Some of the unrealistic values were also noticed at east and south-east wind directions. In order to eliminate the effect of wakes from surrounding turbines, directional filter was applied to the datasets. Excluding the northern sector from calculations helped to significantly reduce the amount of meaningless values of surface roughness. In addition to directional filter, the negative value filter was applied to expel some few negative outliers from the datasets.

After applying all filters, remaining data were exported from the database to a CSV file, which was then converted to an Excel document for further processing.

Aside from this data set, two additional tables were created by grouping all data by day and calculating daily average and median values of roughness length and wind speed at the hub height.

Thus, at this point of research, 4 new data sets for each CWEX observation year were created and exported from a database:

1 surface roughness and wind speed at hub height with data quality filtering
2 surface roughness and wind speed at hub height with data quality filtering daily average
3 surface roughness and wind speed at hub height with data quality filtering daily median
4 surface roughness calculated for neutral and non-neutral conditions, with no wind speed filtering

Data Analysis

Data analysis started with applying descriptive statistics to calculated surface roughness and wind speed values. Univariate analysis involves describing the distribution of each variable, including its central tendency (mean and median) and dispersion (the range and measures of spread, such as variance). Variance measures how far a set of numbers is spread out.

In order to identify the tendencies in the data, trend estimation was applied. Trend estimation is a statistical technique to aid interpretation of data. By relating the measurements to the times at which they occurred, valid statements about tendencies in the data can be made. When a series of measurements of a process are treated as a time series, it is possible to construct a model which can then be used to describe the behavior of the observed data. In this case, it is useful to determine whether calculated surface roughness values exhibit an increasing trend which is statistically distinguished from random behavior.

An accurate comparison of calculated Z_0 was required for answering stated research questions. T-test - a statistical examination of two population means was applied. This statistical technique indicates whether or not the difference between two group's averages most likely reflects an actual difference in the population from which the groups were sampled. An independent sample t-test was implemented to examine ten pairs of values. First, Z_0 values for each measuring point of CWEX-11 (over corn) data were tested. Then, the same procedure was applied to CWEX-12 (over soybeans) data. After surface roughness values, wind speeds at hub height were compared. There were two pairs of wind speed values (calculated using table values of Z_0 and Z_0 derived from measurements) within each year of observations, which leads to eight separate t-tests. Table 5 illustrates all performed comparison. In addition to mentioned statistical analysis, bivariate correlation was conducted to check whether surface roughness depends on wind speed or not.

Table 5: *Conducted t-tests*

		Corn					Soybeans				
		Z_0_1	W_1	W_2	W_1t	W_2t	Z_0_1	W_1	W_2	W_1t	W_2t
Corn	Z_0_2										
	W_1t										
	W_2t										
	W_1										
	W_2										
Soybeans	Z_0_2										
	W_1t										
	W_2t										
	W_1										
	W_2										

3.6 Study Flowchart

In order to outline the workflow and the methodologies used in this study, a flowchart is shown on Figure 16. At first, the most suitable approach for surface roughness length calculation and data quality factors are identified from the extensive literature review. Then data processing based on identified factors is implemented. This includes data preprocessing, filtering and calculation of Z_0 and hub height wind speed. The outcomes of first stage of processing for corn and soybeans are then used in further analysis. During this step, calculated surface roughness coefficients as well as hub height wind speed are analyzed using statistical methods. Descriptive statistics and independent sample t-test are implemented. Next, final results of the study are presented. Discussion of obtained results and making conclusions is the next step of this research. At the end, limitations of the study are described and possible further directions are outlined.

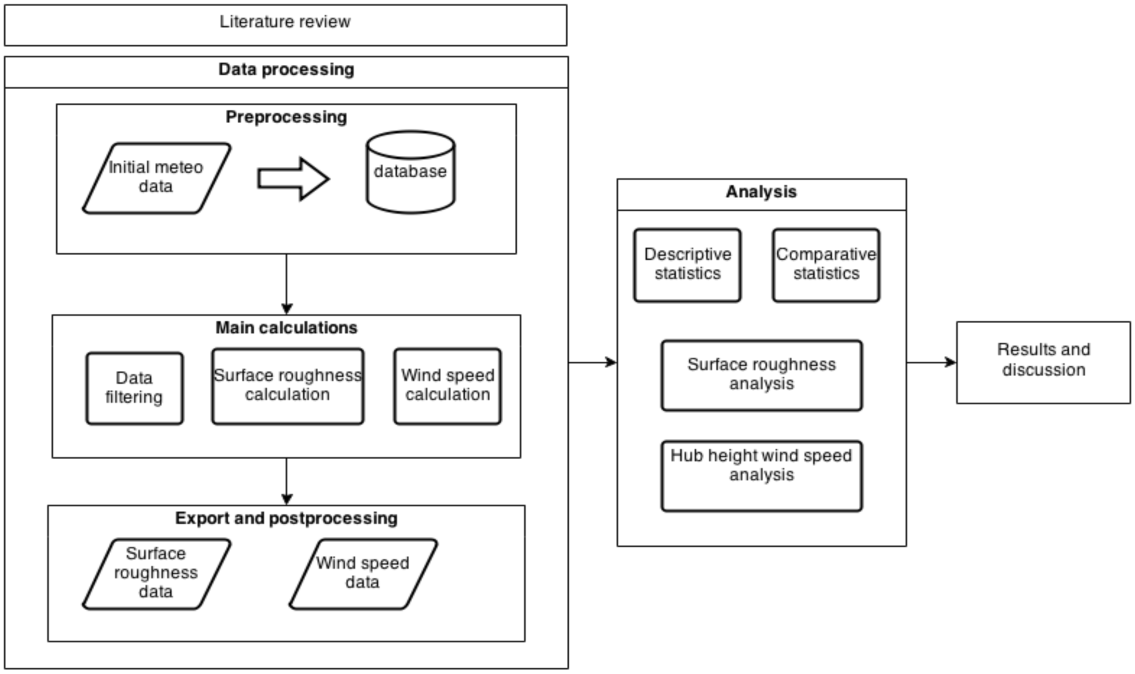

Figure 16: Study Flowchart

CHAPTER 4

RESULTS

The results of this research can be divided into two groups: calculated values of surface roughness and hub height wind speed, and results of statistical analysis.

4.1 Surface Roughness and Wind Speed for Corn

There are several resulting tables with data calculated based on initial CWEX-11 data set. First table consists of the least filtered data and contains about 8 thousand records. Table 6 shows a small sample of unfiltered surface roughness table.

Table 6: *Sample of unfiltered data for corn*

			Mast 1				Mast 2			
Date	Wake	Stability	Wind speed 4.5m	Wind speed 9m	Roughness	Wind direction	Wind speed 4.5m	Wind speed 9m	Roughness	Wind direction
02.07.2011 0:05	B23G	nsn	4.87	6.39	0.018	174.1	5.32	6.53	0.045	178.8
02.07.2011 0:15	B23G	s	5.01	6.46	0.015	175.4	5.47	6.93	0.008	181.8
02.07.2011 0:25	B23G	nsn	4.99	6.54	0.027	175.9	5.81	7.31	0.025	180.5
02.07.2011 0:35	B23G	s	4.64	6.18	0.020	176.2	5.53	6.89	0.025	179.3
02.07.2011 0:45	B23G	s	4.96	6.40	0.010	175.5	5.87	7.41	0.030	179.5
02.07.2011 0:55	B23G	s	4.53	6.06	0.024	176.4	5.23	6.62	0.011	178.8
02.07.2011 1:05	B23G	s	4.84	6.43	0.029	179.4	5.70	7.25	0.016	181.3
02.07.2011 1:15	B23G	s	4.86	6.48	0.014	178.9	5.60	7.08	0.014	181.7
02.07.2011 1:25	B23G	s	4.73	6.41	0.013	177.6	5.96	7.50	0.019	180.9
02.07.2011 1:35	B23G	s	4.98	6.59	0.022	173.9	5.69	7.16	0.033	177.5
02.07.2011 1:45	B23G	s	5.11	6.95	0.009	174.1	5.92	7.59	0.027	177.6
02.07.2011 1:55	B23G	nsn	5.54	7.57	0.029	176.9	6.30	7.97	0.018	180
02.07.2011 2:05	B23G	s	5.22	7.10	0.013	175.8	5.93	7.55	0.023	178.8
02.07.2011 2:15	B23G	s	4.57	6.13	0.034	178.6	5.11	6.54	0.024	182
02.07.2011 2:25	B23G	s	4.41	5.88	0.012	179.7	5.30	6.69	0.024	182.5
02.07.2011 2:35	B23G	s	4.71	6.23	0.016	183.2	5.54	6.94	0.011	184.1
02.07.2011 2:45	B23G	s	4.53	5.98	0.018	184.9	4.97	6.43	0.028	185.5
02.07.2011 2:55	B23G	s	4.32	5.79	0.019	182.8	4.87	6.09	0.023	185.5

Due to the great amount of unrealistically large and negative roughness values, this table does not have hub height wind speed calculated. Nevertheless, this table not only helps to identify factors impacting data quality, but also gives general view of surface roughness values distribution. A plot of Z_0 time change based on this table is presented on Figure 17. According to the plot, the vast majority of Z_0 values are concentrated in 0 to 0.5 interval, although there is a number of outliers far beyond the range illustrated on the plot. Red line on the plot shows linear trend of the data set.

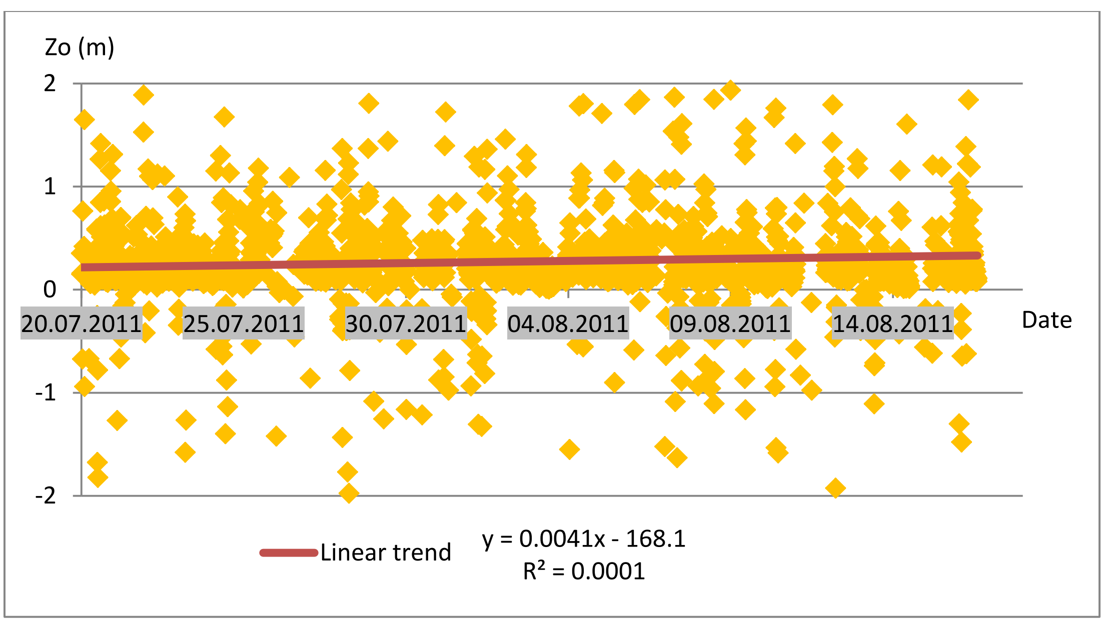

Figure 17: Distribution of unfiltered Z_0 values (corn)

The next table contains calculations of surface roughness and hub height wind speed only for neutral conditions of atmosphere and with data filtering applied. The number of records decreased from several thousands to just 200. Aside of Z_0 values, this second table also has wind speed at the hub height calculated for each wind measurement mast using both plain roughness value of 0.25 for corn (Table 2) and Z_0 calculated from field measurements. Table 7 shows a small sample of these data.

Table 7: *Sample of filtered, neutral conditions data for corn*

			Mast 1						Mast 2					
Date	Wake	Stability	Direction	Wind speed 4.5m	Wind speed 9m	Roughness	Hub height wind speed	Hub height wind speed(table Zo)	Direction	Wind speed 4.5m	Wind speed 9m	Roughness	Hub height wind speed	Hub height wind speed(table Zo)
02.07.2011 8:25	NA	n	308.7	4.81	5.82	0.080	8.68	4.33	310.2	4.18	5.45	0.093	8.43	4.31
02.07.2011 11:55	NA	n	337.2	2.50	3.84	0.027	5.77	2.50	340	2.23	3.61	0.034	6.94	3.09
02.07.2011 12:05	NA	n	340	2.53	4.28	0.009	6.13	2.32	346.9	2.18	3.68	0.021	6.45	2.70
02.07.2011 23:15	NA	n	13.9	2.16	3.15	0.043	4.83	2.22	17.7	2.09	2.76	0.089	4.65	2.36
06.07.2011 22:35	NA	n	25	2.11	2.78	0.101	4.36	2.26	25	2.42	3.24	0.042	5.29	2.42
07.07.2011 15:15	B3456h1	n	98.6	3.78	4.68	0.063	6.99	3.38	104.3	3.81	4.50	0.096	6.51	3.33
09.07.2011 23:15	B23G	n	179.5	3.86	5.45	0.088	8.63	4.38	180.9	4.75	6.29	0.040	10.78	4.90
09.07.2011 23:25	B23G	n	172.8	3.49	5.07	0.063	7.92	3.83	177.8	4.13	5.42	0.047	8.72	4.05
09.07.2011 23:35	B23G	n	172.2	3.61	5.17	0.075	8.14	4.04	177.9	4.27	5.75	0.042	9.69	4.44
09.07.2011 23:45	B23G	n	169.4	3.87	5.52	0.055	8.53	4.06	173.2	4.32	5.82	0.049	8.26	3.86

A plot of the filtered data set, shown on Figure 18, demonstrates much less scattering. Surface roughness values are located within 0 to 0.3 interval. Since the surface roughness data are more consistent, a polynomial trend was applied for more accurate reflection of Z_0 seasonal behavior. There is a distinct growing trend from the beginning of the experiment to about 20th of July, when trend line reaches the plateau. This date corresponds to the time when corn reaches its maximum height.

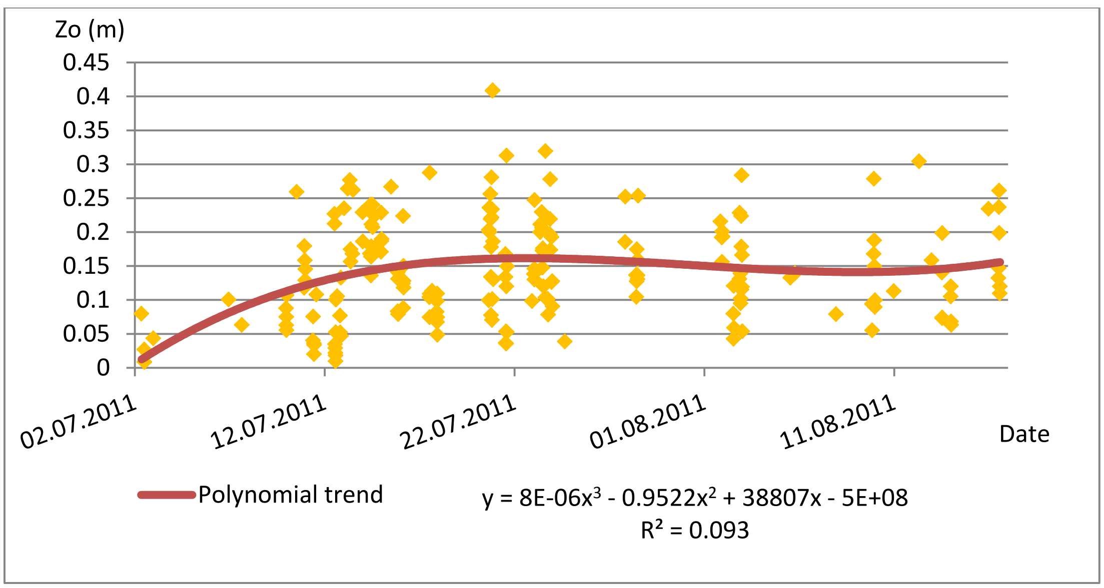

Figure 18: Distribution of filtered Z_0 values for neutral conditions (corn)

Seasonal change of calculated hub height wind speed (in meters per second) along with trend lines are illustrated on Figure 19. Green line represents wind speed calculated using measurement-derived surface roughness and grey line shows values calculated using table Z_0 coefficient.

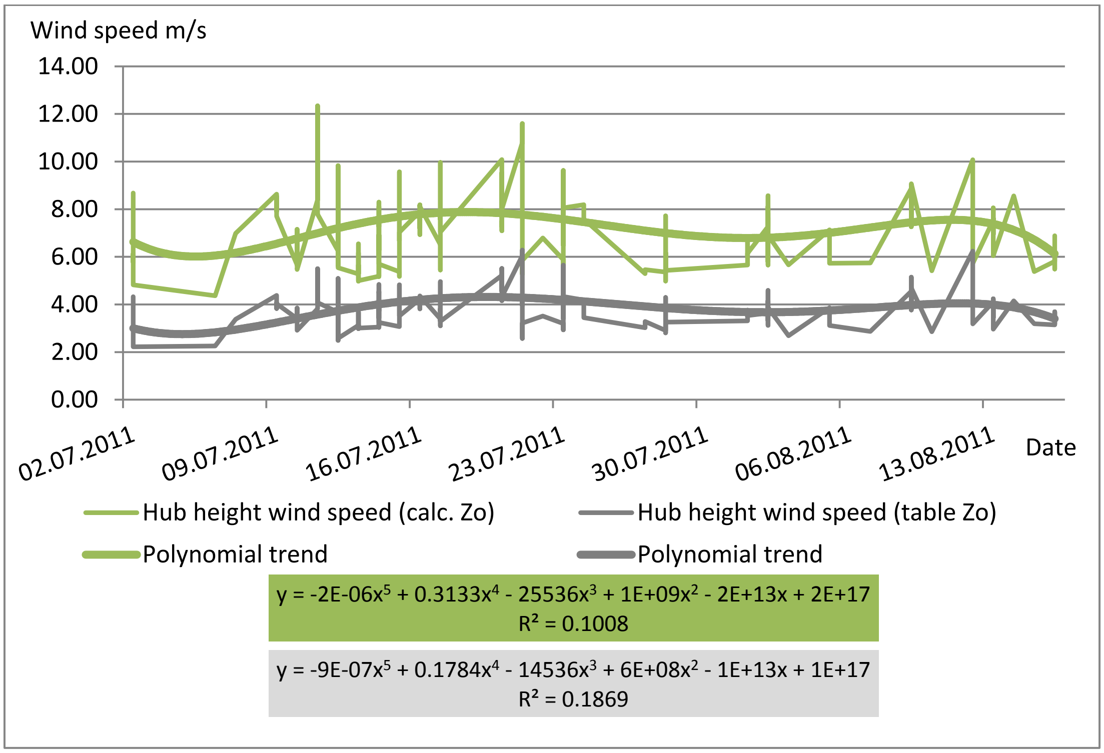

Figure 19: Distribution of calculated hub height wind speed (corn)

Among the results for corn, there are two more tables of surface roughness and hub height wind speed data. These data were produced by aggregating filtered data for neutral conditions by day. First table contains daily averages and second contains daily median values. Table with median data was created to check whether there are any outlier values in data and if so, reduce their impact on averaged values. Samples of these two aggregated tables are given in Table 8 and Table 9.

Table 8: *Averaged data example (corn)*

	Mast 1					Mast 2				
		Wind speed					Wind speed			
Date	Roughness	4.5 m	9 m	hub height	hub height (table Zo)	Roughness	4.5 m	9 m	hub height	hub height (table Zo)
02.07.2011	0.04	3	4.27	6.35	2.84	0.06	2.67	3.88	6.62	3.12
06.07.2011	0.1	2.11	2.78	4.36	2.26	0.04	2.42	3.24	5.29	2.42
07.07.2011	0.06	3.78	4.68	6.99	3.38	0.1	3.81	4.5	6.51	3.33
09.07.2011	0.08	3.64	5.2	8.18	4.07	0.05	4.29	5.71	9.12	4.25
10.07.2011	0.16	2.7	3.77	6.18	3.41	0.16	3.06	4.03	6.41	3.43
11.07.2011	0.05	4.24	6.51	9.99	4.6	0.05	4.43	6.62	11.08	4.98
12.07.2011	0.08	2.86	4.48	7	3.38	0.08	2.94	4.46	7.73	3.68
13.07.2011	0.22	2.55	3.38	5.56	3.24	0.16	2.74	3.74	5.41	2.99
14.07.2011	0.2	3.19	4.21	6.86	3.93	0.18	3.25	4.27	7.36	4.12
15.07.2011	0.15	2.87	4.22	6.9	3.71	0.13	3.02	4.24	7.24	3.87
16.07.2011	0.14	3.47	4.8	7.75	4.19	0.06	3.24	5.67	8.47	3.98
17.07.2011	0.1	2.7	4.6	7.52	3.84	0.09	3.3	4.79	8.41	4.19

Table 9: *Median data example (corn)*

	Mast 1					Mast 2				
		Wind speed					Wind speed			
Date	Roughness	4.5 m	9 m	hub height	hub height (table Zo)	Roughness	4.5 m	9 m	hub height	hub height (table Zo)
02.07.2011	0.04	2.51	4.06	5.95	2.41	0.06	2.2	3.65	6.7	2.9
06.07.2011	0.1	2.11	2.78	4.36	2.26	0.04	2.42	3.24	5.29	2.42
07.07.2011	0.06	3.78	4.68	6.99	3.38	0.1	3.81	4.5	6.51	3.33
09.07.2011	0.07	3.61	5.17	8.14	4.04	0.05	4.27	5.75	8.72	4.05
10.07.2011	0.15	2.68	3.74	6.15	3.42	0.11	3.06	4.23	7.04	3.37
11.07.2011	0.04	4.27	6.31	9.89	4.67	0.04	4.14	5.95	10.11	4.8
12.07.2011	0.05	2.84	4.42	6.62	3.21	0.06	2.86	4.23	7.57	3.49
13.07.2011	0.24	2.48	3.23	5.29	3.12	0.16	2.96	3.87	5.58	2.93
14.07.2011	0.19	3.26	4.31	6.93	4.03	0.18	3.3	4.37	7.06	4.07
15.07.2011	0.14	2.74	4.22	6.85	3.56	0.12	2.96	4.29	7.57	3.86
16.07.2011	0.13	3.43	4.94	8.01	4.22	0.05	3.17	5.62	8.26	3.84
17.07.2011	0.08	2.77	4.48	7.27	3.75	0.08	3.18	4.79	8.68	4.36

4.2 Surface Roughness and Wind Speed for Soybeans

The structure of calculation results for observations over soybeans is similar to corn results, although values of surface roughness and hub height wind speed are different. Another difference was that resulting tables for soybeans have different number of data records. First, unfiltered data set with surface roughness has about three thousand records, while the same table for corn had almost four thousand. A sample of unfiltered soybeans data and a plot of Z_0 values with a linear trend line are shown on Table 10 and Figure 20 respectively.

Table 10: *Sample of unfiltered data for soybeans*

		Mast 1				Mast 2			
stability	date, time	direction (deg.)	wind speed 4,5m	wind speed 9m	roughness	direction (deg.)	wind speed 4,5m	wind speed 9m	roughness
vun	06.07.2012 14:15	212.9	2.429	2.652	0.22	210	3.111	3.3	0.05
vun	06.07.2012 14:35	221	2.202	2.307	0.39	209.9	2.778	2.897	0.14
vun	06.07.2012 20:15	188.4	2.977	3.499	0.14	194.1	3.621	3.949	0.09
vun	06.07.2012 20:55	235.7	2.591	2.797	0.21	228.2	3.081	3.502	0.15
un	06.07.2012 21:05	241.9	2.658	2.74	0.86	239.5	3.02	3.158	0.29
unn	06.07.2012 21:15	241.1	3.166	3.373	0.22	236	2.886	3.069	0.33
n	06.07.2012 21:25	243.8	3.501	3.637	0.22	236.7	3.519	3.842	0.09
n	06.07.2012 21:35	235.2	2.929	3.159	0.31	227.2	3.189	3.378	0.19
n	06.07.2012 21:45	239	2.855	2.977	0.16	229	2.805	2.968	0.04
s	06.07.2012 21:55	244.6	3.434	3.648	0.08	234.4	3.04	3.212	0.33
s	06.07.2012 22:55	254.5	2.121	2.148	0.62	247	2.211	2.38	0.13
s	06.07.2012 23:05	252.9	2.37	2.296	-0.08	248.1	2.403	2.547	0.07
vs	06.07.2012 23:15	251	2.072	2.09	0.69	241.4	2.415	2.655	0.09
vun	07.07.2012 21:25	16.2	4.376	5.51	0.01	22.9	3.873	4.784	0.06
un	07.07.2012 21:35	19	4.579	5.777	0.02	12.7	3.497	4.827	0.03
vun	07.07.2012 21:45	16.1	4.395	5.482	0.01	16.1	3.711	4.959	0.04
vun	07.07.2012 21:55	14.1	4.409	5.966	0.01	18.9	3.585	5.003	0.04
vun	07.07.2012 22:15	20.7	5.031	5.867	0.01	24.8	3.76	4.513	0.08

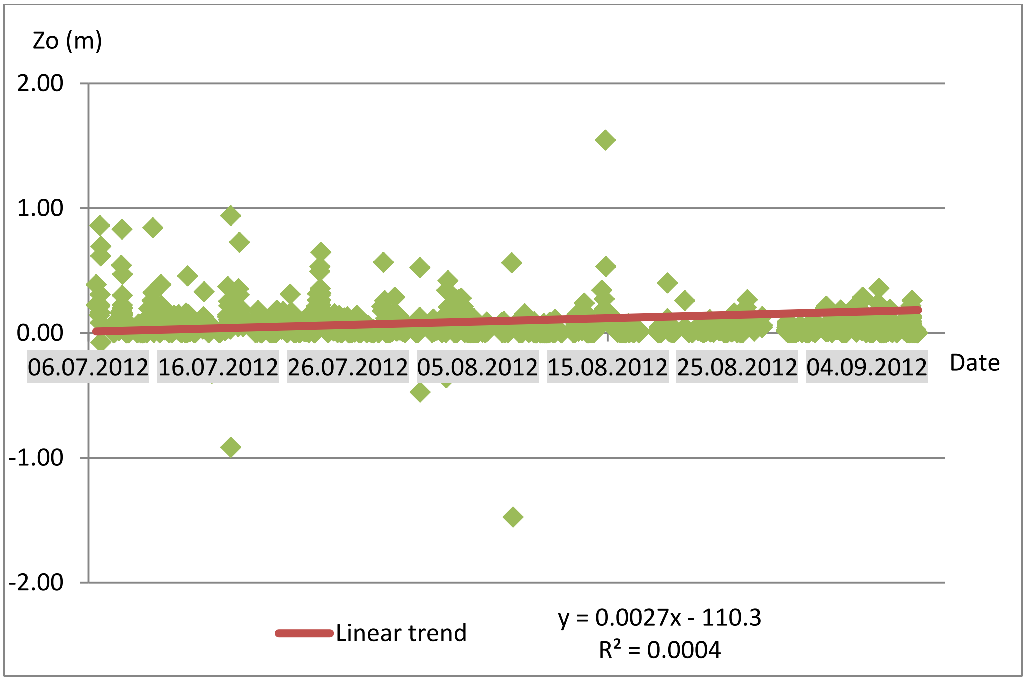

Figure 20: Distribution of unfiltered Z_0 values (soybeans)

Unfiltered values of surface roughness for both neutral and non-neutral conditions for soybeans demonstrate less scattering than for corn. Overall distribution tends to be within 0 m to 0.2 m interval. Linear trend, shown by red line, indicates a slight growing tendency. A sample of next data set, containing filtered calculations only for neutral conditions, is displayed in Table 11. The structure of this table is similar to the same dataset for corn, the number of records is also about the same as in corn table. Distribution of surface roughness values of soybeans (Figure 22) demonstrates that most of them are less than

0.06 m. On one hand, polynomial trend line (solid red line) reflects some growth of Z_0 at the beginning of measurements (early to late July) and then turns to a wavy pattern. On the other hand, linear trend is almost horizontal (red dot line), which indicates that there is a very small change in surface roughness during studied time period.

Table 11: *Sample of filtered, neutral conditions data for soybeans*

	Mast 1						Mast 2					
date, time	direction (deg.)	wind speed 4,5m	wind speed 9m	roughness	Hub height wind speed	Hub height wind speed(table Zo)	direction (deg.)	wind speed 4,5m	wind speed 9m	roughness	Hub height wind speed	Hub height wind speed(table Zo)
07.07.2012 23:35	10.9	3.68	5.39	0.00	7.12	4.19	10.7	3.45	5.13	0.00	9.30	5.65
07.07.2012 23:45	14.4	3.91	5.39	0.00	7.12	4.27	17.1	3.18	4.13	0.01	6.90	5.02
07.07.2012 23:55	20.4	4.04	4.61	0.01	6.16	4.48	20.6	3.23	3.92	0.01	7.61	5.91
08.07.2012 23:45	17.43	3.48	4.29	0.01	5.99	4.56	14.2	2.56	3.50	0.05	4.49	4.03
12.07.2012 13:05	127.6	2.80	3.33	0.04	4.80	4.29	131.4	3.31	3.74	0.11	3.82	3.88
13.07.2012 16:25	158.4	3.22	3.87	0.04	5.59	4.98	154.3	3.28	3.79	0.07	4.98	4.76
13.07.2012 17:15	166.7	3.38	4.13	0.02	5.87	4.81	172.1	3.57	4.12	0.04	5.06	4.50
13.07.2012 17:25	171.2	3.91	4.71	0.01	6.46	4.75	173.9	3.77	4.56	0.01	6.12	4.64
13.07.2012 17:35	166.6	3.61	4.30	0.01	5.90	4.40	171.9	4.23	4.97	0.00	8.23	5.34
13.07.2012 18:55	178.9	3.64	4.57	0.01	6.39	4.81	180	3.99	4.74	0.01	7.11	5.18
13.07.2012 19:45	171.8	2.61	3.15	0.01	4.35	3.29	175.5	2.97	3.50	0.00	5.75	3.91
22.07.2012 14:25	159.1	2.18	2.54	0.04	3.60	3.12	167	2.59	2.95	0.02	3.89	3.07
22.07.2012 15:55	196.9	4.63	5.85	0.05	8.69	7.85	195.3	5.10	6.22	0.03	9.37	8.09
22.07.2012 20:35	216	4.58	5.49	0.09	8.18	8.01	211.4	4.68	5.51	0.21	6.43	7.20
22.07.2012 20:45	216.5	4.54	5.59	0.04	8.17	7.28	219.1	4.37	5.18	0.15	6.12	6.54

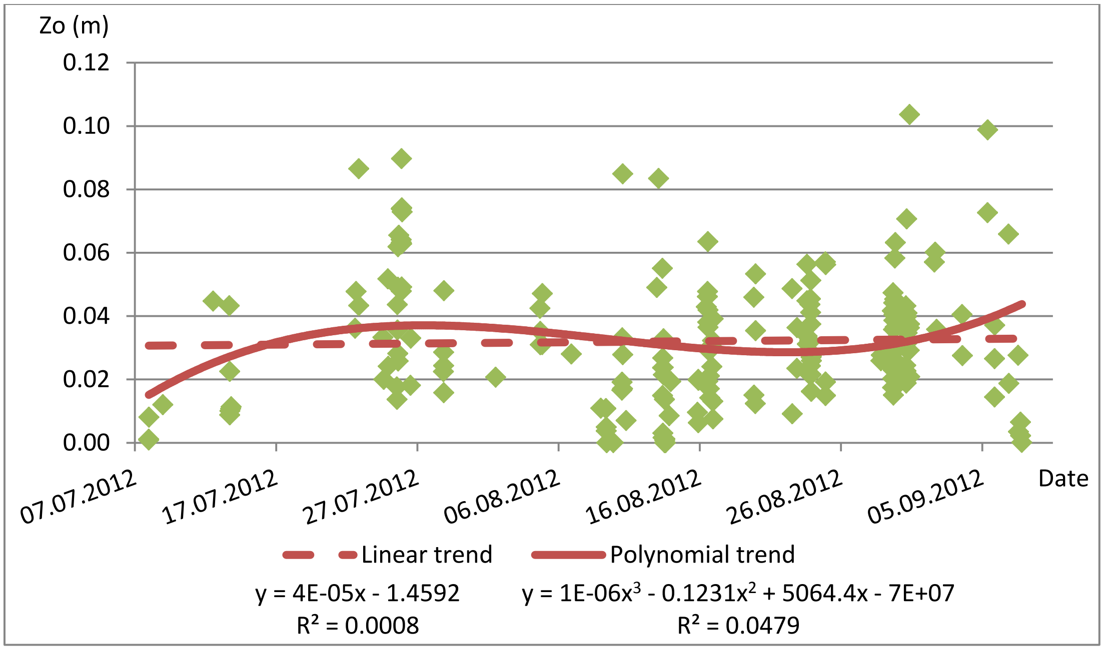

Figure 21: Distribution of filtered Z_0 values for neutral conditions (soybeans)

Hub height wind speed calculated for soybeans using table (grey line) and calculated (green line) surface roughness values is illustrated on Figure 22. To clarify overall difference between two wind speeds, there are also trend lines on the graph. It is clear from the figure that the use of calculated Z_0 values instead of table ones, results in higher estimated hub height wind speed.

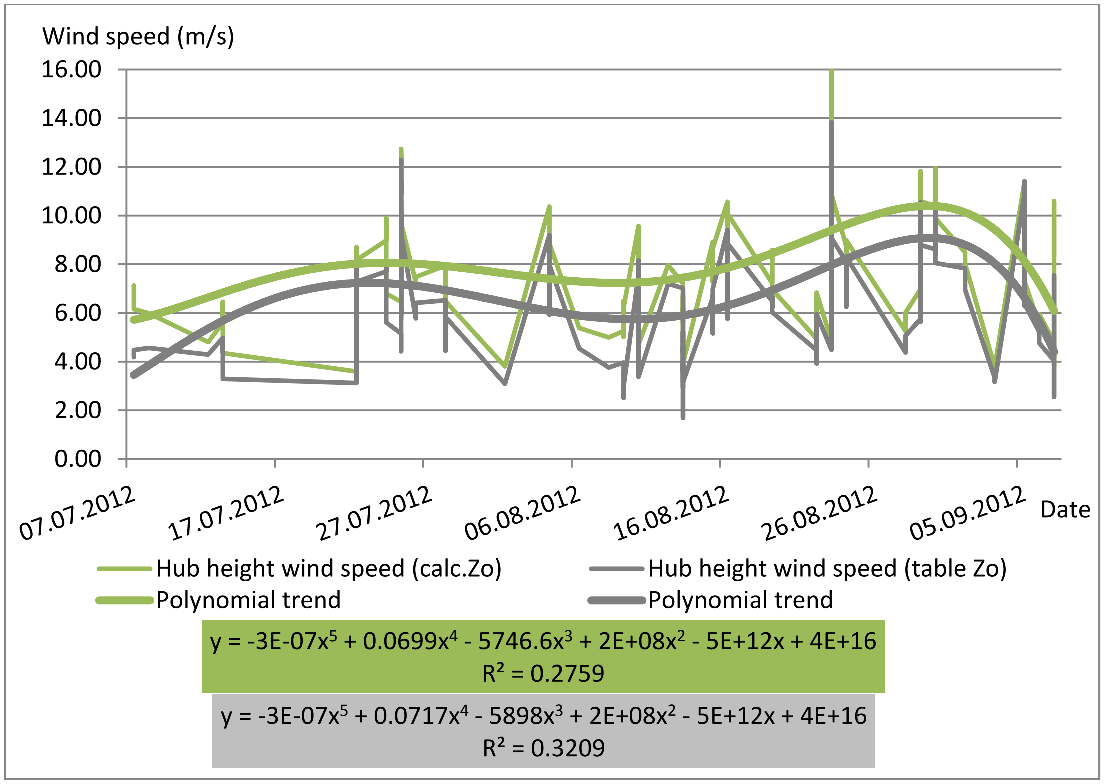

Figure 22: Distribution of calculated hub height wind speed (soybeans)

The samples of last two data sets for soybeans, containing daily aggregated data are shown on Table 12 and Table 13. Because of the nature of averaging, the number or records in these tables are almost exactly the same as in similar data for corn, which makes it easier to compare.

Calculation results for both corn and soybeans contain some extra data, which were not shown on examples above. Among these data are displacement height values (for filtered, neutral conditions data and aggregated data) and measured wind speed data (for daily aggregated tables). Full versions of all tables extended with additional columns are available for download by request to andreirby@gmail.com.

Table 12: *Average data sample (soybeans)*

	Mast 1			Mast 2		
date	Roughness	Wndspd	Wndspd_t	Roughness	Wndspd	Wndspd_t
07.07.2012	0	6.8	4.31	0.01	7.94	5.53
08.07.2012	0.01	5.99	4.56	0.05	4.49	4.03
12.07.2012	0.04	4.8	4.29	0.11	3.82	3.88
13.07.2012	0.02	5.76	4.51	0.02	6.21	4.72
22.07.2012	0.05	7.16	6.57	0.1	6.45	6.23
24.07.2012	0.03	8.19	6.94	0.03	10.03	7.94
25.07.2012	0.05	9.25	8.45	0.2	9.18	8.48
26.07.2012	0.02	11.67	8.75	0.05	13.5	10.05
28.07.2012	0.03	6.55	5.48	0.02	6.89	5.52
01.08.2012	0.02	3.8	3.09	0.01	4.78	3.54
04.08.2012	0.03	10.2	8.6	0.08	9.51	8.45

Table 13: *Median data sample (soybeans)*

	Mast 1			Mast 2		
date	Roughness	Wndspd	Wndspd_t	Roughness	Wndspd	Wndspd_t
07.07.2012	0	7.12	4.27	0.01	7.61	5.65
08.07.2012	0.01	5.99	4.56	0.05	4.49	4.03
12.07.2012	0.04	4.8	4.29	0.11	3.82	3.88
13.07.2012	0.01	5.89	4.78	0.01	5.94	4.7
22.07.2012	0.05	8.18	7.56	0.09	6.27	6.87
24.07.2012	0.03	8.03	7.07	0.03	8.88	7.38
25.07.2012	0.06	9.51	8.77	0.04	9.62	8.9
26.07.2012	0.02	7.48	6.41	0.02	8.26	6.6
28.07.2012	0.02	6.46	5.46	0.02	6.65	5.34
01.08.2012	0.02	3.8	3.09	0.01	4.78	3.54
04.08.2012	0.03	9.11	7.87	0.05	7.89	7.93

4.3 Statistical Analysis

The last group of results of this research is outputs of statistical analysis. According to statistical methods applied in this study, there is descriptive statistics and comparative statistics results for each year of observation. Statistical analysis was applied to filtered neutral conditions data set and to daily aggregated data.

Descriptive Statistics

Table 14 presents the descriptive statistic results for filtered neutral conditions data set for corn (based on CWEX11 data). The table contains basic statistics for surface roughness and wind speed at the hub height, calculated for each meteo mast. Wind speeds with “t” flag stand for calculations where table surface roughness values were used. During the calculation of these statistics, several remaining outliers were removed from the table, in order to make the results more accurate.

Table 14: *Descriptive statistics for filtered neutral condition data for corn*

	N	Range	Minimum	Maximum	Mean	Variance
Z_0 mast 1	200	.40	.01	.41	.14	.01
Z_0 mast 2	200	0.29	.01	.30	.13	.01
Wndspd 1	200	7.98	4.36	12.35	7.31	2.15
Wndspd 2	200	10.14	4.48	14.63	7.85	3.68
Wndspd1_t	200	4.06	2.22	6.28	3.92	.60
Wndspd2_t	200	5.07	2.36	7.43	4.12	.78
Valid N	200					

The outcomes from descriptive statistics analysis of daily average and daily median data for corn are shown on Table 15 and Table 16 respectively. Averaged surface roughness data tend to show similar values of all statistic criteria to median data. This means that the main data set is relatively consistent and has no outlier values of Z_0, which were successfully eliminated by filtering procedures. Values of calculated hub height wind speeds follow the same trend and median wind speed values are almost exact as average ones.

Table 15: *Descriptive statistics for daily average data for corn*

	N	Range	Minimum	Maximum	Mean	Variance
Z_0 mast 1	31	.19	.04	.23	.13	.00
Z_0 mast 2	31	.18	.04	.22	.13	.00
Wndspd 1	31	5.63	4.36	9.99	6.92	1.52
Wndspd 2	31	5.99	5.09	11.08	7.40	2.31
Wndspd 1_t	31	2.66	2.26	4.92	3.65	.39
Wndspd 2_t	31	2.92	2.42	5.34	3.86	.51
Valid N	31					

Table 16: *Descriptive statistics for daily median data for corn*

	N	Range	Minimum	Maximum	Mean	Variance
Z_0 mast 1	31	.20	.04	.24	.13	.00
Z_0 mast 2	31	.18	.04	.22	.12	.00
Wndspd 1	31	5.53	4.36	9.89	6.89	1.67
Wndspd 2	31	5.55	5.09	10.64	7.42	2.31
Wndspd 1_t	31	2.70	2.26	4.96	3.62	.44
Wndspd 2_t	31	2.92	2.42	5.34	3.82	.52
Valid N	31					

Descriptive statistics for the main soybeans data set (based on CWEX12) is presented in Table 17. This table has the same structure as Table 14. Surface roughness for soybeans is generally lower than for corn. Furthermore, the variance of Z_0 values for soybeans are much smaller than for corn, although the range is about the same. The discrepancy in variance is probably caused by the difference in seasonal growth of crops.

Table 17: *Descriptive statistics for filtered neutral condition data for soybeans*

	N	Range	Minimum	Maximum	Mean	Variance
Zo mast 1	201	.10	.0000	.10	.03	.000
Zo mast 2	201	.60	.0000	.60	.05	.004
Wndspd1	201	12.57	3.60	16.17	8.53	6.27
Wndspd2	201	18.34	2.23	20.57	8.83	8.63
Wndspd1_t	201	12.15	1.69	13.84	7.17	6.07
Wndspd2_t	201	13.27	2.81	16.08	7.50	5.68
Valid N	201					

Statistical analysis for aggregated soybeans data are presented on Table 18 and Table 19. Table 18 shows daily averages of surface roughness and hub height wind speed, and daily median data contained in Table 19. Unlike the same type of statistics for corn, the average and median values of surface roughness for soybeans are nearly identical. This shows that there are not any significant outliers in data, which is also proved by zero variance of aggregated surface roughness values. Statistics for the calculated hub height wind speed shows some discrepancy between average and median data, but the values are still very close.

Table 18: *Descriptive statistics for daily average data for soybeans*

	N	Range	Minimum	Maximum	Mean	Variance
Z_0 mast 1	30	.05	.00	.05	.03	.00
Z_0 mast 2	30	.10	.01	.11	.05	.00
Wndspd1	30	7.89	3.78	11.67	7.35	4.61
Wndspd2	30	9.99	3.51	13.50	7.78	6.47
Wndspd1_t	30	6.52	3.09	9.61	6.04	3.97
Wndspd2_t	30	6.79	3.28	10.07	6.44	4.14
Valid N	30					

Table 19: *Descriptive statistics for daily median data for soybeans*

	N	Range	Minimum	Maximum	Mean	Variance
Z_0 mast 1	30	.06	.00	.06	.03	.00
Z_0 mast 2	30	.11	.00	.11	.04	.00
Wndspd1	30	8.28	3.78	12.06	7.27	4.22
Wndspd2	30	9.16	3.51	12.67	7.50	6.01
Wndspd1_t	30	6.92	3.09	10.01	6.92	3.88
Wndspd2_t	30	7.35	3.28	10.63	7.35	3.64
Valid N	30					

Descriptive statistics results indicate that surface roughness of soybeans is more consistent and does not change over a season as much as Z_0 of corn. Surface roughness of corn demonstrates not only higher variance, but overall higher values. Both for corn and soybeans, mast 2, which experiences more turbine influence, tends to show higher values of surface roughness than mast 1. Wind speed at hub height, calculated using table Z_0 values, tends to be lower than the one calculated using measurement derived surface roughness values. This difference in wind speed is higher for corn than for soybeans.

Comparative Statistics

The last group of results of this research is a set of independent sample t-test outcomes. The main purpose of this analysis was comparing surface roughness and hub height wind speed calculation results. Independent sample t-test allows to check whether two arrays of numbers are similar to each other or not. Results of t-test for surface roughness calculated at each mast location for corn is shown on Table 20. Based on this table, we can conclude, that there is no significant difference between surface roughness at mast 1 and at mast 2.

Results of the t-test for Z_0 at each mast for soybeans are presented on Table 21. Unlike results for corn, t-test for soybeans indicates that there is a difference in surface roughness between mast 1 and mast 2.

Table 20: *Results of T-test of Z_0 at mast 1 and mast 2 for corn*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
zz1	Equal variances assumed	,20	,652	1,44	398,00	,152	,01	,01	,00	,03
	Equal variances not assumed			1,44	396,99	,152	,01	,01	,00	,03

Table 21: *Results of T-test of Z_0 at mast 1 and mast 2 for soybeans*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
zz	Equal variances assumed	12,49	,000	-2,41	410,00	,016	-,04	,02	-,08	-,01
	Equal variances not assumed			-2,41	207,71	,017	-,04	,02	-,08	-,01

Next, wind speeds at hub height were compared. Results of this analysis are presented on tables 22 to 29. First four tables stand for the corn results and last four tables show results for soybeans. Generally speaking, independent sample t-test identifies, that hub height wind speeds for mast 1 and mast 2 can't be considered the same for corn (Table 22, 23), but there is no significant difference in estimated wind speed for soybeans (Table 26, 27) if the same source of surface roughness (either table value or calculated value) is used. The degree of similarity varies between different groups of data. There is a difference in data similarity within the same crop type. Wind speed calculated using table Z_0 values, are more similar, than the one calculated using measurement derived Z_0 for corn and conversely for soybeans.

On the other hand, results of t-test for wind speed calculated for the same mast, but using different surface roughness coefficients (table vs. calculated) in all cases indicate significant difference.

Table 22: *Results of T-test of hub height wind speed at mast 1 and mast 2, based on calculated Z_0 for corn*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd1_2	Equal variances assumed	11,55	,001	-3,15	398,00	,002	-,54	,17	-,87	-,20
	Equal variances not assumed			-3,15	372,30	,002	-,54	,17	-,87	-,20

Table 23: *Results of T-test of hub height wind speed at mast 1 and mast 2, based on table Z_0 for corn*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd1t_2t	Equal variances assumed	3,15	,077	-2,44	398,00	,015	-,20	,08	-,37	-,04
	Equal variances not assumed			-2,44	391,89	,015	-,20	,08	-,37	-,04

Table 24: *Results of T-test of hub height wind speed at mast 1 based on calculated Z_0 and mast 1 based on table Z_0 for corn*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd1_1t	Equal variances assumed	64,54	,000	28,90	398,00	,000	3,39	,12	3,16	3,62
	Equal variances not assumed			28,90	302,54	,000	3,39	,12	3,16	3,62

Table 25: *Results of T-test of hub height wind speed at mast 2 based on calculated Z_0 and mast 2, based on table Z_0 for corn*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd2_2t	Equal variances assumed	83,08	,000	24,96	398,00	,000	3,73	,15	3,43	4,02
	Equal variances not assumed			24,96	279,27	,000	3,73	,15	3,43	4,02

Table 26: *Results of T-test of hub height wind speed at mast 1 and mast 2, based on calculated Z_0 for soybeans*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd1_2	Equal variances assumed	2,67	,103	-1,16	410,00	,248	-,35	,30	-,94	,24
	Equal variances not assumed			-1,16	396,53	,248	-,35	,30	-,94	,24

Table 27: *Results of T-test of hub height wind speed at mast 1 and mast 2, based on table Z_0 for soybeans*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd1t_2t	Equal variances assumed	,16	,694	-1,39	410,00	,167	-,35	,25	-,85	,15
	Equal variances not assumed			-1,39	410,00	,167	-,35	,25	-,85	,15

Table 28: *Results of T-test of hub height wind speed at mast 1 based on calculated Z_0 and mast 1 based on table Z_0 for soybeans*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd1_1t	Equal variances assumed	,28	,596	5,28	410,00	,000	1,39	,26	,87	1,91
	Equal variances not assumed			5,28	408,29	,000	1,39	,26	,87	1,91

Table 29: *Results of T-test of hub height wind speed at mast 2 based on calculated Z_0 and mast 2, based on table Z_0 for soybeans*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	*Sig.*	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std. Error Difference*	*Lower*	*Upper*
wndspd2_2t	Equal variances assumed	5,91	,015	4,73	410,00	,000	1,39	,29	,81	1,97
	Equal variances not assumed			4,73	386,16	,000	1,39	,29	,81	1,97

Summary

Results of this research allow to make the following conclusions. First, there is a noticeable seasonal trend in surface roughness change of corn. Second, calculated hub height wind speed is different when using table and measurement derived values of Z_0. Third, surface roughness shown by a wind mast which experienced more impact of surrounding turbines tends to be somewhat higher than surface roughness calculated for the other mast. At the same time, comparative statistics shows that hub height wind speed calculated for each mast, can be considered to be the same for soybeans but not for corn. This means that higher surface roughness of corn has a stronger impact on hub height wind speed.

CHAPTER 5

DISCUSSION

5.1 Surface Roughness of Corn and Soybeans

Data Quality Factors

Calculation of surface roughness length based on wind speed measurements is a well-known procedure implemented in various research (De Bruin, & Moore, 1985; Driese, & Reiners, 1997; McInnes et al., 1991; Nakai et al., 2008). This study highlights some methodological specialty for using field measurements within a wind farm. First, a strong influence of the wind turbines was identified. Calculations for all wind sectors contained some meaningless results, but the highest amount of unrealistic or unphysical values of Z_0 were registered for wind coming from the main part of the wind farm. Figure 23 illustrates the degree of filtering applied to different wind sectors. Sectors shown in red correspond to location of the wind farm. Green sectors correspond to wind coming from relatively open area, least affected by wind turbines. Existence of these “bad” sectors allows answering one of the research questions. Turbulence produced by wind turbines leads to unphysical Z_0 values calculated based on near surface measurements. This also supports the hypothesis that wind farm has a significant influence on wind flow, which leads to meaningless values of Z_0 calculated for northern wind sector.

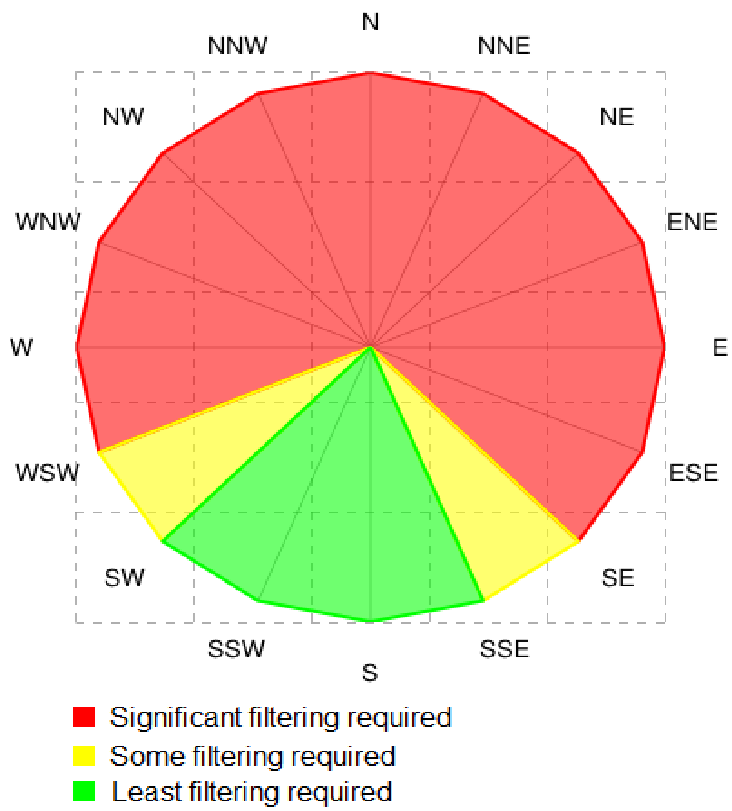

Figure 23: Data quality according to wind direction

Next important factor of data quality is registered wind speed. First of all, cases with very low wind speed tend to demonstrate meaningless Z_0 values. Most of these cases were eliminated by applying 2 m/s filter, the others were found and deleted from calculations manually. Based on this fact, we can say that higher registered wind speed is better for surface roughness length calculation. Another effect of wind speed is connected to the difference between wind speed measured at height 1 and height 2. If this difference is close to zero, it is likely to get unrealistic Z_0 values.

Atmosphere stability can be considered as another factor of calculated surface roughness quality. Using non-neutral conditions for Z_0 estimation makes calculations more complex, which increases a chance of an error. Furthermore, according to the results of this study, number or erroneous values of Z_0 calculated for neutral conditions is less than for stable or unstable conditions.

Seasonal Change of Surface Roughness

One of the goals of this research was identifying if there is any seasonal trend in surface roughness change for corn and soybeans. Based on Figure 24, we can answer research question concerning seasonal change in Z_0 for a corn field during growing period (02/07 – 16/08).

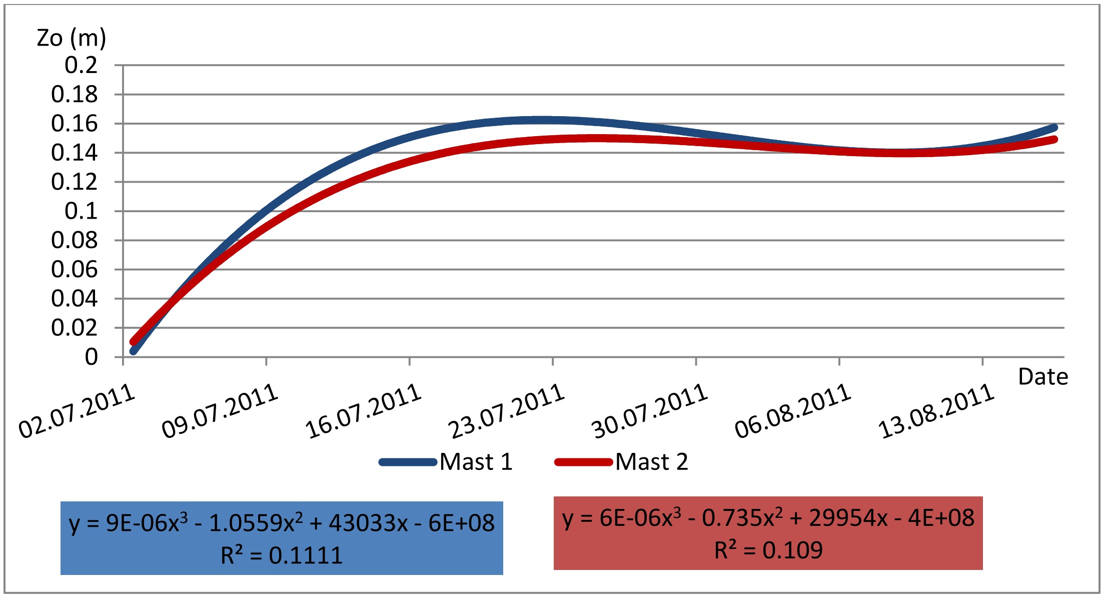

Figure 24: Seasonal trend of Z_0 for corn

The conclusion is that there is a distinct growing trend at the first part and almost constant values of Z_0 for the rest of studied time period. Trend line reaches plateau approximately between July 16th and July 23th. These dates match the period when corn reaches its maximum height (Rajewski et al., 2013). This fact supports a hypothesis that Z_0 has a growing trend respectively to corn growth. When corn reaches its maximum size, mean value of surface roughness becomes a constant value. Trend line shown by mast 2 is not exactly the same as the one for mast 1 and has slightly less variation and overall smaller values. It might be caused by the wake effects of surrounding turbines. However, initial assumption was that wake from turbines will lead to higher fluctuations and overall higher values of Z_0, which is disproved by the results of the study. Nevertheless, comparative statistics (Table 20) indicates that there is no significant difference between the values of mean surface roughness in these two points.

According to Figure 24, Z_0 of full sized corn is about 0.16 m, which is lower than a table value for high crops (Table 2). This does not support a hypothesis that Z_0 for full sized corn is close to table values. Due to the lower surface roughness of corn at early phenology stages, mean value of Z_0 for studied period is even lower (0.13-0.14 m).

Correlation analysis between surface roughness and near surface wind speed for corn reveals that surface roughness is negatively related to wind speed (at 9 m) with a Pearson correlation coefficient of $r = -0.374$ for mast 1 and $r = -0.386$ for mast 2. According to $p = 0.01$, correlation is significant at 99% level. This correlation probably means that there is an effect of wind surface roughness due to corn plants flexibility.

Seasonal behavior of surface roughness of soybeans is different from corn. First of all, the variance of Z_0 for soybeans is much lower than for corn (Table 14, Table 17).

Next, polynomial trend line (Figure 25) shows some changes of surface roughness values, but there is no distinct pattern as shown by corn Z_0. If we compare linear trends of soybeans surface roughness shown by mast 1 and mast 2, we will notice that they are not as similar as Z_0 trends of corn. Also, linear trend of mast 1 is slightly increasing, while trend at mast 2 is decreasing, which is an evidence of lacking overall trend during the period of observations. A possible explanation of this might be that studied period (July 7 to September 7) was not long enough to accumulate enough statistical data to reveal the pattern in seasonal Z_0 change of soybeans. Higher values of Z_0 at mast 2 might be explained by stronger effect of turbines on mast 2, or some external factor, as amount of precipitation, might have caused variations of Z_0 within study area.

Figure 26 illustrates the difference of mean values of surface roughness between corn and soybeans for both mast1 and mast 2. Generally speaking, surface roughness of soybeans shows less seasonal changes and overall smaller values than Z0 for corn.

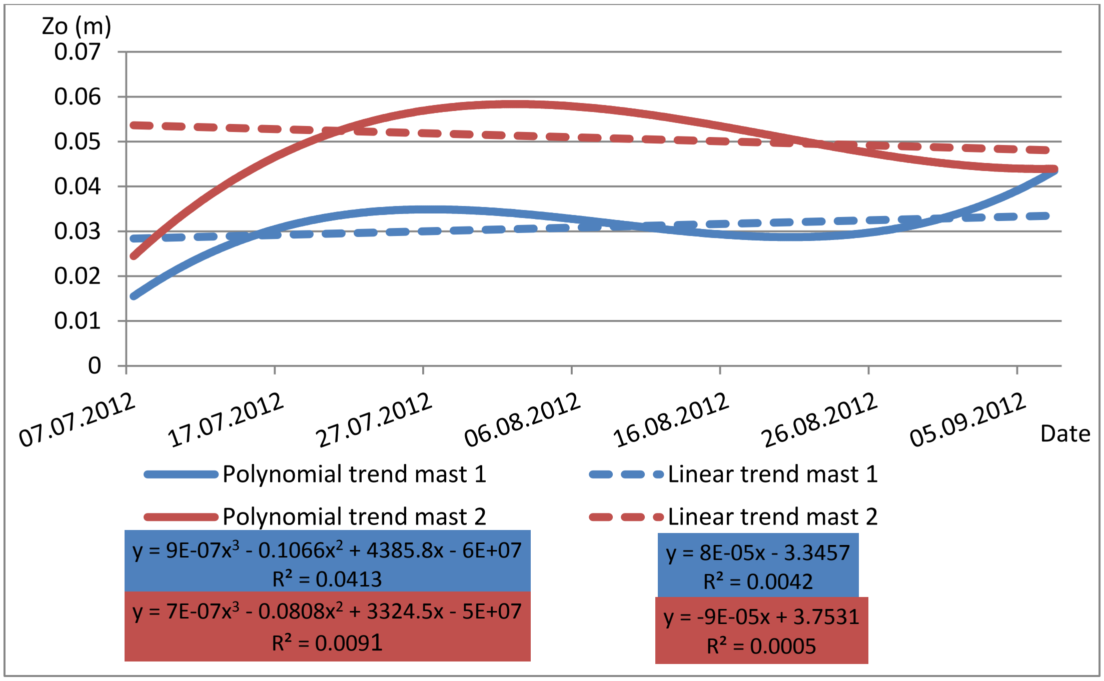

Figure 25: Seasonal trend of Z_0 for soybeans

It is interesting, that the results of t-test, comparing surface roughness at mast 1 to surface roughness at mast 2, are different for corn and soybeans. Table 20 indicates that Z_0 at mast 1 and 2 for corn can be considered to be the same. However, t-test for soybeans (Table 21) indicates that there is a difference between surface roughness at mast 1 and mast 2. A possible explanation of this happening might be the effect of some external factors or just some random calculation error.

Correlation analysis between near surface wind speed and surface roughness for soybeans did not indicate any significant relationship. Mast 1 showed positive correlation coefficient of r = 0.159 while mast 2 demonstrated negative correlation of r = -0.130. The significance of correlation is lower that for corn, only 95% (p = 0,05). This means that the effect of wind speed on surface roughness of soybeans is insignificant, probably due to overall smaller size and less flexibility.

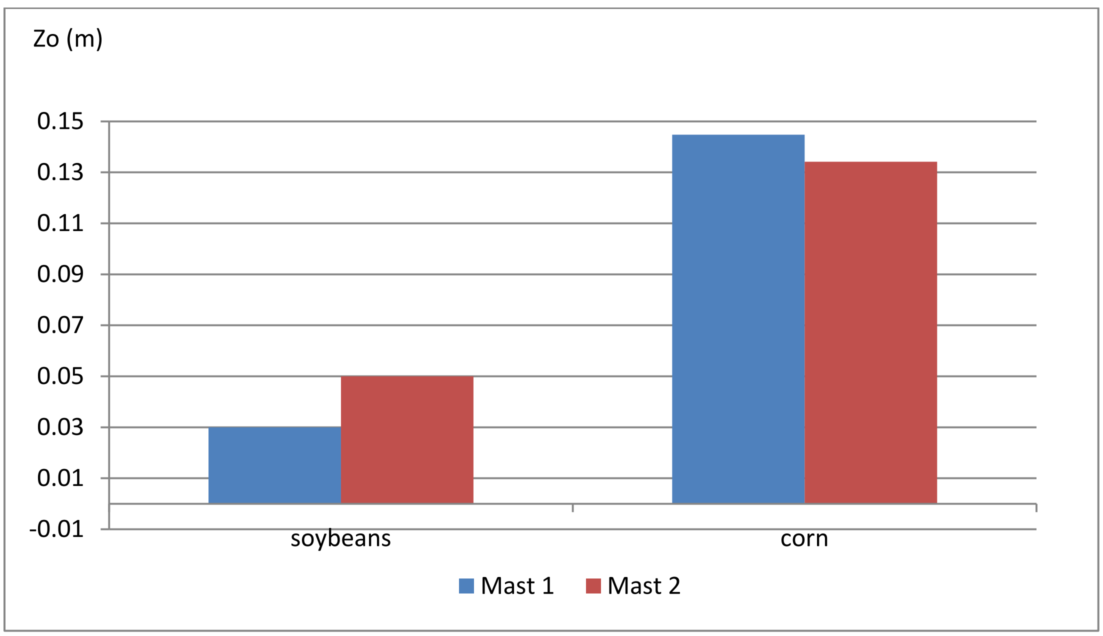

Figure 26: Mean surface roughness of each mast for corn and soybeans

5.2 Calculated Hub Height Wind Speed

Results of this study highlight a significant difference in calculated hub height wind speed for table and measurement derived values of surface roughness (Table 23, Table 24, Table 27, Table 28). This difference is illustrated on Figure 27, which shows the ratio of mean hub height wind speed in meters per second at each mast for corn and soybeans, calculated using Z_0 derived from measurements and table values of surface roughness.

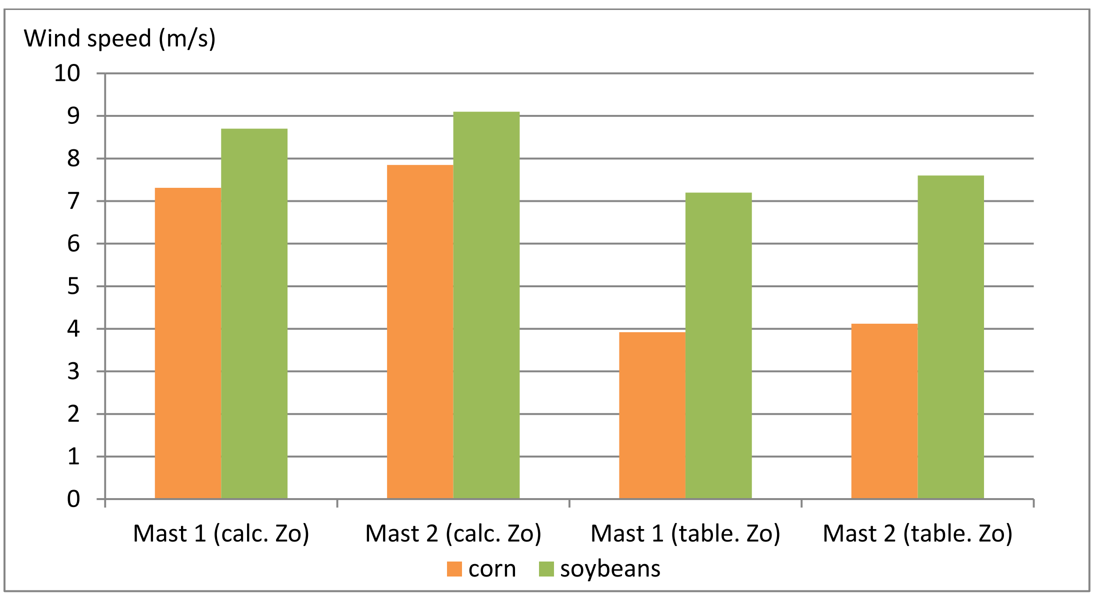

Figure 27: Ratio of calculated mean hub height wind speed

First what we can identify from Figure 27 is that wind speed is significantly higher for calculations using measurement derived surface roughness. The difference in wind speed is about 47% for corn and about 18% for soybeans. Also, as we see from Figure 27, wind speed calculated for soybeans is overall higher than for corn. Since field measurements were conducted at the same time of the year, the reason for higher wind speed for soybeans is most likely lower values of surface roughness length.

The next conclusion, which can be made from looking at Figure 27, is that mean wind speed calculated using the same source of surface roughness values is very similar and, as confirmed by t-tests, even can be considered the same in case of corn. Although the histogram shows that mean wind speed both for soybeans and corn is slightly higher at mast 2. A possible explanation for this might be the impact of surrounding turbines. Turbulence caused by rotating blades might lead to better air mixing and bringing faster wind from upper layer closer to the earth surface. The difference in estimated wind speed is higher if calculated Z_0 is used. Also, wind speed estimated for corn shows slightly higher differences between mast 1 and 2 than for soybeans.

5.3 Conclusions

If countries hope to reach their renewable energy production goals, this requires precise estimates of wind resources. This research addressed the effects vegetation on surface roughness length, and inquires seasonal aspect of surface roughness change in Iowa. Current approach of using limited amount of predefined Z_0 coefficients might be insufficient for accurate wind speed and thus wind resource estimations.

Calculations of surface roughness based on micrometeorological field measurements were performed in this research. Then hub height wind speed was calculated using both obtained values of Z_0 and table coefficients. Resulting data were compared using descriptive statistics and independent samples t-test. The goal of this research was determining enhanced-quality surface roughness values, which will help to increase accuracy of local and regional wind resource characterization in Iowa.

Specific landcover types, experience significant changes during their lifecycle. For example, corn field changes from bare earth at spring to dense, almost 3 m height vegetation by the end of summer, and ends as bare earth after harvest at fall. Hence, surface roughness of a corn field can’t be considered as constant. This study reveals that (1) both corn and soybeans demonstrate changes of surface roughness during studied period. Soybeans featured 0.01 m to 0.03 m roughness change, and Z_0 of a corn field grew from 0.03 m to 0.18 m. (2) Surface roughness of corn demonstrates distinct growing trend, which corresponds to growth of corn. Negative correlation between Z_0 of corn and near surface wind speed is noticed. Surface roughness of soybeans doesn’t show any clear trend, but some variation exists. There is no significant correlation between Z_0 of corn and near surface wind speed. (3) An evidence of the impact of turbulence, caused by wind turbines, on data quality in measuring surface roughness is noticed. The impact of wake from individual turbines also takes place, but has to be further investigated. (4) Calculated values of Z_0 are lower than corresponding table values. This leads to a significant difference between hub height wind speed calculated using table and measurement derived values of surface roughness. Based on this, a conclusion can be made, that the use of surface roughness coefficients provided by tables lead to underestimation of hub height wind speed and available wind resources.

Therefore, research suggests that for more accurate assessment of local wind resources, surface roughness should be determined from field measurements. For the most accurate assessments of wind speed, seasonal aspect of surface roughness change should be taken into account. It is especially important for landcover types such as crops, which experience explicit seasonal changes. This study provides enhanced surface roughness coefficients for the most common landcover types in Iowa. Aside from just mean values of Z_0, data for different grow stages of vegetation are available. The use of surface roughness length coefficients enhanced by field measurements will be also beneficial for wind farm suitability modeling and turbine micrositing.

Limitations

Among the limitations of this study are: (1) The height above the ground of available anemometers, which was not optimal for surface roughness calculations. Especially for measurements over corn, when only top anemometer was above the roughness sublayer, which means that lower anemometer experienced additional turbulence. (2) Different types of sensors were used – cup and sonic anemometers. (3)

Field measurements were available for relatively short period of observations. Longer studied period would help to reveal more accurate seasonal change in surface roughness. (4) No measured hub height wind speed was available to values of estimated wind speed.

Further Directions

Possible future work in this research could consist of the following: (1) Combine high resolution landcover with obtained surface roughness data into a surface roughness map and perform wind resource modeling. In doing so, available wind power assessment can be improved because accurate wind speed is a crucial factor of wind resource estimation. (2) Develop an enhanced wind speed map of Iowa and run a site suitability modeling. (3) Validate estimated hub height wind speed using measured wind speed.(4) Conduct more filed measurements for extended time period and for more landcover types and develop tables of seasonal surface roughness coefficients for the most common landcover in Iowa.

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