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# AGRO-CLIMATIC AND LAND SUITABILITY MAPPING FOR SWITCHGRASS GROWN AS A BIOENERGY CROP IN NORTH DAKOTA

By

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A Thesis
Submitted to the Graduate Faculty
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for the degree of

Master of Science

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2012

This thesis submitted by Navin Thapa in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota, has been read by the faculty advisory committee under whom the work has been done and is hereby approved.

Soizik Laguette (Chairperson)

Michael J. Hill

Andrei Kirilenko

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the Graduate School at the University of North Dakota and is hereby approved.

Wayne Swisher
Dean of the Graduate School

5-2-2012

Date

PERMISSION

| | |
|---|---|
| Title | Agro-Climatic and Land Suitability Mapping for Switchgrass Grown as a Bioenergy Crop in North Dakota |
| Department | Earth System Science and Policy |
| Degree | Master of Science |

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Navin Thapa
4/28/2012

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LIST OF ABBREVIATIONS

| | |
|---|---|
| ALMANAC | Agricultural Land Management Alternatives with Numerical Assessment Criteria |
| AWS | Available Water in Soil |
| C3 | Carbon 3 |
| C4 | Carbon 4 |
| CMIP GCM | Coupled Model Intercomparison Project Global Change Model |
| CRP | Conservation Reserve Program |
| DOY | Day of Year |
| GDD | Growing Degree Days |
| GIS | Geographic Information System |
| MCAS-S | Multi Criteria Analysis Shell for Spatial Decision Support |
| NRCS | Natural Resources Conservation Services |
| ORNL | Oak Ridge National Laboratory |
| USDA | United States Department OF Agriculture |
| USDOE | United States Department of Energy |
| WGEN | Weather Generator |

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## ABSTRACT

Switchgrass (*Panicum virgatum* L), a native warm-season perennial grass, grows in Central and North American tall-grass prairie. The plant is immense biomass producer and can reach heights up to three meters or more in wet areas. Its high lignocellulosic content makes switchgrass an appropriate candidate for bio-ethanol production. Annual crops, used for bioenergy production such as corn, soybeans, often results in loss of soil organic matter and release of soil carbon, whereas perennial crops like switchgrass can help build soil organic matter and store more soil carbon due to the large amount of underground biomass they produce.

North Dakota has been identified as a potential area for perennial switchgrass biomass production for bioenergy purpose. Switchgrass is a C4 grass that has the potential as feedstock for a cellulosic based biofuels industry in the Northern Great Plains. The objective of the present study is to conduct a GIS and Remote Sensing-based land suitability evaluation for switchgrass production in North Dakota. The process involved spatial analysis of several physiographical data including climate, soil and land use. Land suitability for switchgrass was determined as a function of agro-climatic factors governing switchgrass establishment, potential biomass yield, and long term land use practice in North Dakota.

The outputs of the analysis were agro-climatic establishment risk map, switchgrass yield potential map and temporal land use variation map in North Dakota. A switchgrass suitability map was the final outcome of the analysis which was a weighted

composite overlay of the analyzed factors governing switchgrass production. The suitability map showed relative land suitability for switchgrass production in North Dakota without competing with local agriculture or negatively impacting permanent grassland. The study will be helpful for users or decision makers in planning switchgrass biomass feedstock production and policy development governing switchgrass adaptation in North Dakota.

# CHAPTER I

# INTRODUCTION

## Overview of the Study

Switchgrass (*Panicum virgatum* L.) is a warm-season perennial grass that is native to Central and North American tall-grass prairies and occurs widely in grasslands and non-forested areas (Rinehart, 2006). Switchgrass has been seeded in pastures and rangegrass in the Great Plains over several decades and has become important as pasture grass (McLaughlin and Kszos, 2005). Switchgrass has been evaluated as a potential bioenergy crop with high energy content and is potentially economically viable in the Northern Great Plains region, including the areas in central and western North Dakota (Walsh, 1998; McLaughlin et al., 2002; Berdahl et al., 2005; McLaughlin and Kszos, 2005). It grows well on a wide variety of soil types, can reach heights of 3 meters and more than 2 meters in root depths, and once established it is drought tolerant and grows well in shallow rocky soils. It has high biomass yield per unit area, low production cost, low fertilization requirement and high water use efficiency (Nyoka et al., 2007). These factors combined with a high capacity to reduce Green House Gas emissions ($CO_2$) by fixing carbon into soil, make switchgrass an important component of national energy strategy (McLaughlin et al., 2002).

Switchgrass can be used to produce cellulosic ethanol fuel. At present most of the United States' ethanol supply is coming from corn crops which raise concerns over the amount of energy required to produce the crop and competition with food crops. Planting corn as an energy crop also makes it less available for food production. Switchgrass on the other hand has potential to produce ethanol from cellulosic biomass and can be grown in land that is unfit for food crop with less fertilizer and energy input.

For switchgrass to be an economically viable option for large-scale biofuel production, a consistent supply of quality feedstock is critical. While there has been much attention regarding its suitability as a biofuel feedstock, not much is known about its overall growth suitability in North Dakota. Growth potential of switchgrass has primarily been identified based on yield results from few small plot studies that have not been extended to cover other larger areas. Expression of switchgrass growth in terms of agro-climatic and biomass yield threshold is needed to determine its production suitability. The research intends to identify the areas that could be used for uniform and consistent supply of switchgrass feedstock for cellulosic ethanol production in North Dakota.

The goal of this study is to evaluate the suitability of land area for switchgrass adoption in North Dakota based on agro-climatic parameters, estimated potential yield and land use change. The study highlights the areas that can be dedicated to switchgrass biomass production without competing with local food production or affecting permanent grassland and its biodiversity. The study integrates GIS with multi-criteria analysis technique to combine and transform spatial data into land suitability analysis decision. The procedure involves utilization and manipulation of input spatial data according to specific decision rules. It is believed that such a study can be of great help to decision makers concerned with making environmentally friendly choices in growing switchgrass for bioenergy purpose

# CHAPTER II

# LITERATURE REVIEW

## Distributions and Characteristics

Switchgrass in North Dakota occurs east of the 98$^{th}$ meridian in the Northern Great Plains in the native tallgrass prairies (Moore and Lorenz, 1985). West of 98° W longitude, switchgrass occurs as remnants of tallgrass prairies in low lying river valleys along with mixed-grass prairies (Berdahl et al., 2005). It is a versatile and adaptable plant and thrives in diverse weather conditions, growing season lengths and soil conditions. It grows well in fine to coarse textured soils, and in regions where annual precipitation falls between 380 mm and 750 mm per year or more (Rinehart, 2006).

Switchgrass is a warm-season grass that is characterized by having the C4 (Carbon 4) photosynthetic system. In C4 photosynthetic process, the first products of carbon fixation are 4-carbon acids (malate and aspartate), in contrast to the 3-carbon product (3-phosphoglyceric acid) produced by the C3 (Carbon 3) process. C4 grasses, with this C4 photosynthetic system are well adapted to arid environment. They reduce high rates of water loss during the day and use water efficiently requiring about one-third to one-half as much water to produce a unit of dry matter as do C3 grasses (Moser et al., 2004). C4 grasses grow well under high temperatures and are important in the North American Great Plains, extending to 55° N latitude (Barbour and Christensen, 1993). Switchgrass growth mainly occurs from late spring through early fall. Switchgrass becomes dormant in the winter and re-emerges in the spring once soil temperatures increase, producing new crown tillers of the plant.

## Bioenergy from Switchgrass

Switchgrass has been identified as a dedicated energy crop by USDOE because it tolerates a wide range of environmental conditions and offers high biomass yield. The high lignocellulosic content makes switchgrass an appropriate candidate for ethanol production as well as combustion fuel source for power plant (Keyser, 1994). The U.S. Department of Energy (USDOE) and the U.S. Department of Agriculture (UDSA) have been investigating the potential use of switchgrass as a bioenergy crop since the 1970s energy crisis (ORNL, 2011). The research had been focused on identifying the best varieties and management practices to optimize productivity, while developing an understanding of the basis for long-term improvement of switchgrass through breeding and sustainable production in conventional agro-ecosystems (McLaughlin and Kszos, 2005). Switchgrass has now been selected as a model bioenergy crop species for ethanol production by USDOE and has been evaluated as economically viable in North Dakota (McLaughlin et al., 2002). The demonstrated long term (>10 yrs) high biomass productivity across diverse environments, suitability to marginal lands, relatively low water and nutrients requirements, and positive environmental benefits of switchgrass makes it an appropriate candidate for bioenergy production.

## Ecotypes

Switchgrass has two distinct ecotypes, lowland and upland according to latitude of their origin (Moser and Vogel, 1995). Lowland or southern ecotypes types are mainly adapted to floodplains and other wet areas in the south where water availability is more reliable. Upland or northern ecotypes however, occur in areas that are not subjected to flooding and occur in drier soils in semi-arid climates (Vogel, 2004; Rinehart, 2006). Lowland types are taller, have longer growing season and subsequently higher biomass yield than upland types, given favorable growing conditions. Upland ecotypes flower earlier, are shorter, yield less as compared to lowlands ecotypes, and have longer winter dormant period with better winter survival when grown at the same latitude.

Ecotypes among switchgrass genotypes play an important role in the adaptation of switchgrass to specific environmental conditions. Latitude of origin is the most important factor determining area of adaptation of switchgrass. Adaptations to cold winters, hot summers, and day length are important environmental characteristics, all of which vary according to latitude. Because of this, switchgrass ecotypes should not be moved more than one hardiness zone or 500 km north of their region of origin (Moser and Vogel, 1995; Lewandowski et al., 2003).

## Growth Stages

Assessing accurate growth stages of perennial grass like switchgrass can be critical to understand biomass production and develop practices that involve establishment, productivity management, harvesting and seed production (Moore et al., 1991). Moore et al. (1991) described that the primary growth stages of any grass starts with germination and are followed by vegetative stage, elongation stage, reproductive stage and seed ripening stage. They further reclassified each of those stages into 6 secondary substages and numbered them from 0 to 5. The primary and secondary growth and development stages of perennial grasses are shown in Table 1. The substages describe specific events that occur in most grasses. The authors described that the

Table 1: Primary and secondary growth stages and their numerical indices and descriptions for staging growth and development of perennial grasses (Moore et al., 1991).

| Stage | Index | Description |
|---|---|---|
| Germination | | |
| G0 | 0.0 | Dry seed |
| G1 | 0.1 | Imbibition |
| G2 | 0.2 | Radical emergence |
| G3 | 0.3 | Coleoptile emergence |
| G4 | 0.4 | Mesocotyl and/or coleoptile elongation |
| G5 | 0.5 | Coleoptile emergence from soil |
| Vegetative-Leaf development | | |
| VE or V0 | 1.0 | Emergence of first leaf |
| V1 | (1/N)+1.9† | First leaf collared |
| V2 | (2/N)+1.9 | Second leaf collared |
| Vn | (n/N)+1.9 | $N^{th}$ leaf collared |
| Elongation-Stem elongation | | |
| E0 | 2.0 | Onset of stem elongation |
| E1 | (1/N)+1.9 | First node palpable/visible |
| E2 | (2/N)+1.9 | Second node palpable/visible |
| En | (n/N)+1.9 | $N^{th}$ node palpable/visible |
| Reproductive-Floral development | | |
| R0 | 3.0 | Boot stage |
| R1 | 3.1 | Inflorescence emergence/1st spikelet visible |
| R2 | 3.2 | Spikelets fully emerged/peduncle not emerged |
| R3 | 3.3 | Inflorescence emerged/peduncle fully elongated |
| R4 | 3.4 | Anther emergence/anthesis |
| R5 | 3.5 | Post-anthesis/fertilization |
| Seed development and ripening | | |
| S0 | 4.0 | Caryopsis visible |
| S1 | 4.1 | Milk |
| S2 | 4.2 | Soft dough |
| S3 | 4.3 | Hard dough |
| S4 | 4.4 | Endosperm hard/physiological maturity |
| S5 | 4.5 | Endosperm dry/seed ripe |

†Where n equals the event number (number of leaves or nodes) and N equals the number of events within the primary stage (total number of leaves or nodes developed). General formula is P + (n/N) - 0.1; where P equals primary stage number (1 or 2 for vegetative and elongation, respectively) and n equals the event number. When N> 9, the formula P + 0.9(n/N) should be used.

germination stage includes the events occurring between seed planting to coleoptile emergence (Fig. 1). The germination stage is followed by the vegetative stage which refers to leaves growth and development. Leaf development is followed by culm elongation which is also referred to as jointing. The elongation stage continues until the inflorescence is enclosed in the uppermost leaf stealth and referred to as boot heading. The stage culminates at flowering which marks the beginning of the reproductive stage and continues through anthesis and fertilization. The last stage is the seed development and ripening which pertains to the development of the caryopsis (Moore et al., 1991).

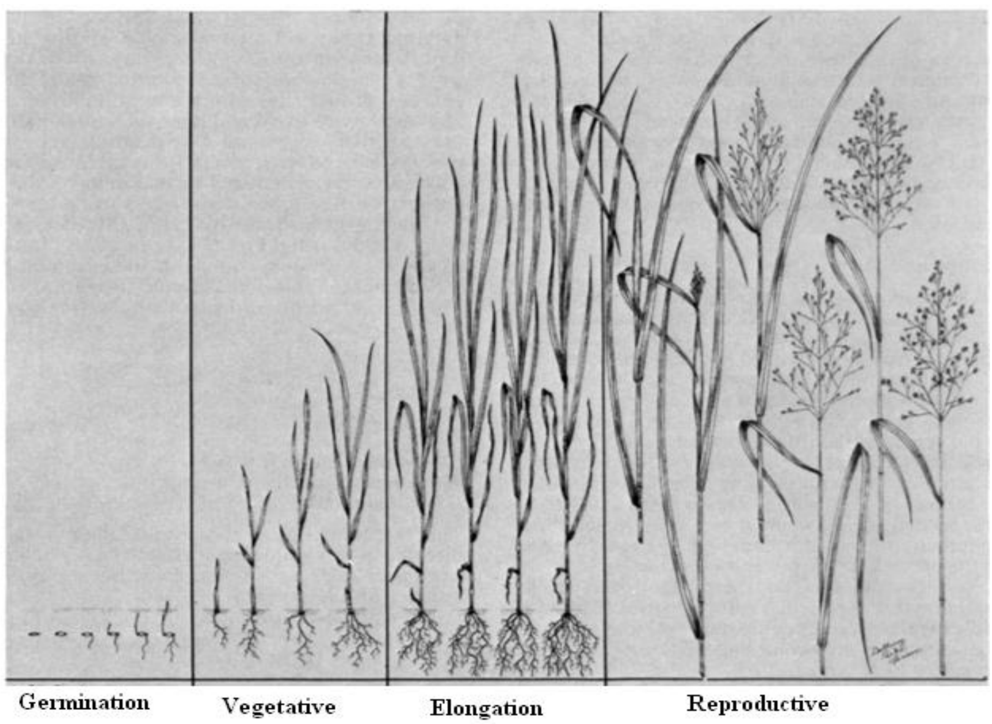



Fig. 1: Illustration of substages within the germination, vegetative, elongation and reproductive primary growth stages in perennial grasses (Moore et al., 1991).

The timing of various growth stages or phenology of switchgrass depends primarily on the photosensitivity of ecotypes, with those of northern origin maturing earlier than those of southern origin since the northern cultivars require shorter summer days to induce flowering relative to the southern cultivars (Benedict, 1941). Switchgrass genotypes are adapted to the ecological and geographical regions in which their parental germplasm evolved. In North Dakota, planting southern ecotypes may result in late flowering due to longer day length (Fig. 2). This photoperiod response also seems to be associated with winter survival. The southern ecotypes when moved to North Dakota will not survive the severe winter as they remain vegetative till late fall and ultimately get killed by subfreezing (frost) temperatures (Vogel, 2004).

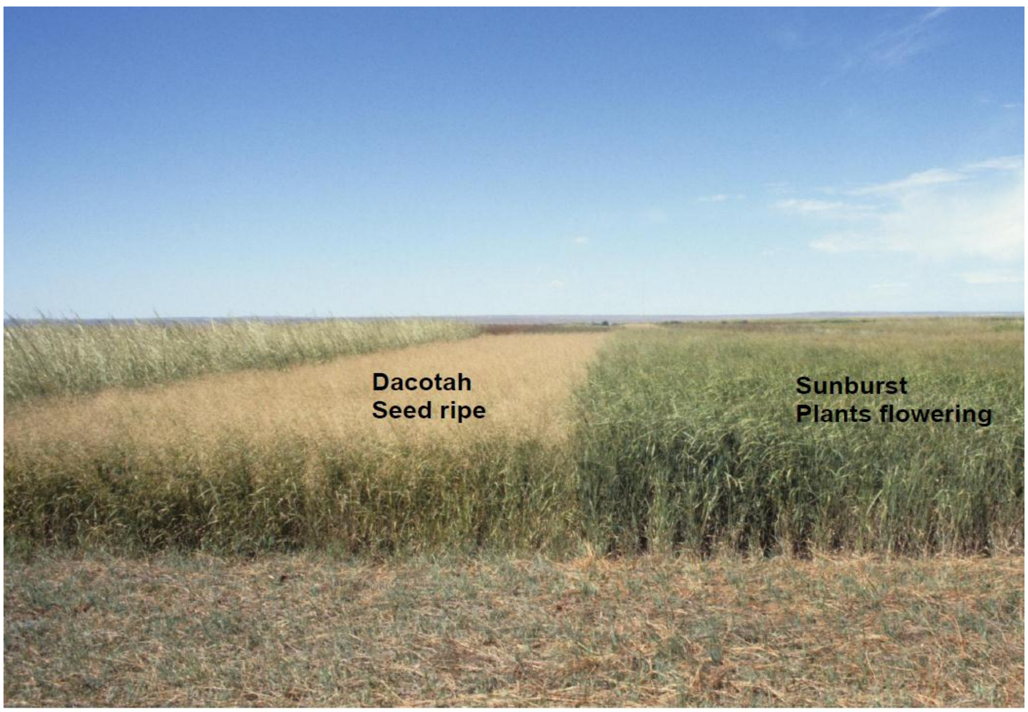



Fig. 2: Dacotah (Dakota) cultivar (left-North Dakota origin) maturing earlier than Sunburst (right-South Dakota origin) in Bismarck. (USDA NRCS Bismarck). http://www.extension.umn.edu/agroforestry/components/Grasses-Biomas.pdf

A field study by Tober et al., (2010) in North Dakota showed that Dacotah, a cultivar from North Dakota flowered 27 days earlier than Forestburg, a variety from South Dakota, and 50 days earlier than Cave in rock, Pathfinder and Blackwell, varieties from Illinois, Nebraska/Kansas and Oklahoma respectively relative to the planting date.

Dacotah reached seed ripening stage in early August while Sunburst (from South Dakota), Forestburg and Nebraska 28 were at 50% anthesis to first seed ripe. Pathfinder, Cave-in-rock and Blackwell were at stage of first emergence of inflorescence during that time which was almost the end of the growing season in North Dakota. Berdahl et al. (2005) showed that among the various switchgrass cultivars planted in North Dakota, entries from North Dakota origin were first to reach boot stage while entries from south origin had heading date close to the first killing frost. Seeding was conducted on the last week of May at USDA ARS Mandan and Dickinson experimental stations. The entries from North Dakota origin had an average heading date of July 5, sunburst from South Dakota had an average heading date of August 1, for Trailblazer (from Nebraska/Kansas) the average heading date was august 15 and for OK NU-2, the date was September 9. The later heading entries, hence could not reach maximum biomass production in most of the years in North Dakota.

Switchgrass grown for bioenergy is harvested at reproductive stage (R0-R5) or two to three weeks after the first killing frost (Schmer et al., 2006). The killing frost occurs during fall when temperatures are cold enough to kill switchgrass and represents the end of the growing season. Harvesting few weeks after the killing frost will allow the plant to recycle nutrients and likely reduce future fertilization needs as well as drying costs (Renz et al. 2009).

The early maturity of switchgrass from North Dakota origin would result in reduced number of phytomers (node, internode and leaves) and hence in reduced biomass yield (Berdahl et al., 2005). Casler and Boe (2003) found that early harvesting, at preanthesis development stage for switchgrass at northern latitudes, can result in forage regrowth. As a consequence, it will deplete carbohydrate reserve and hence reduce the ground area occupied by crown tissue in switchgrass swards. Moser and Vogel (1995) reported that switchgrass stand loss can occur if switchgrass is harvested within six weeks of first killing frost or is shorter than 10 cm stubble height. Later harvest and sufficient stubble height ensures translocation of storage carbohydrates for stand persistence. Vogel et al. (2002) found that biomass yields from switchgrass planted in central Great Plains were optimum when they were harvested at development stages from boot to postanthesis. Berdahl et al. (2005), however suggested that harvest date did not have appreciable effect on net switchgrass biomass yield and low soil moisture level and low temperature affected the survival of switchgrass in North Dakota.

There are suggestions that water deficiency may alter phenology on grasses (Sanderson, 1992). Tober et al. (2010) reported that variation in annual precipitation and temperature affected the phenology and maturity of switchgrass across the northern Great Plains. Balasko and Smith (1971) reported that switchgrass anthesis was delayed when switchgrass day/night growth temperature was reduced from 27/21°C to 21/15° C and anthesis did not occur at temperature regime of 15/10° C. Sanderson and Wolf (1995) analyzed southern cultivars of switchgrass at two locations to determine the relationship between morphological development of switchgrass and soil moisture and other agro-climatic parameters. They plotted morphological development of switchgrass into logistic and linear model to describe vegetative and reproductive developments. The results showed that the inflorescence, emergence, and reproductive development occurred at approximately the same day of the year regardless of temperature or precipitation. This indicates that growth stages of switchgrass are mostly influence by latitude of the area.

## Stand Establishment

A successful stand establishment during seeding is necessary for the production of economically viable switchgrass feedstock (Perrin et al., 2008). Establishment success and development of switchgrass stand depend on several factors including genotypes and locations. The genotypes selected should be locally adapted and sites for switchgrass production should have the potential to respond favorably to establishment and growth process. Switchgrass is established from seed and often requires two or three growing seasons to become fully established as a dense harvestable stand. Seeds normally germinate when the soil temperature is above 12°C (Kiniry et al., 2008). Within six weeks of emergence several tillers may be produced (Fig. 3).


Fig. 3: Switchgrass 6 weeks after planting in North Dakota (USDA, NRCS, Bismarck).
http://www.extension.umn.edu/agroforestry/components/Grasses-Biomas.pdf

Establishment success can be best determined considering the higher stand occurrence frequency (Vogel and Masters, 2001). Small plot research on switchgrass suggested that biomass yield would not be significantly affected by stands when established stand frequencies were more than 40%, the year after establishment (Vogel, 1987; Masters, 1997, Schmer et al., 2006). Stands with more than 40% survival would easily recuperate their stands following severe winters (Hope and Mcelroy, 1990). Agroclimatic variability in North Dakota mainly limits switchgrass establishment by affecting early survival of switchgrass stands. High risk of drought and severe winter stress are the major factors limiting switchgrass optimum yield in North Dakota. Inappropriate seeding practice and competition from weeds, insect pests, diseases, etc. could also reduce stand frequency of switchgrass during establishment year. Poor stand establishment could delay acceptable switchgrass production by at least a year (Schmer et al., 2006).

## Factors Controlling Stand Establishment and Growth

While numerous researches have been conducted on biomass production from switchgrass crop, no one has yet evaluated the combined response of switchgrass to climate, soil and crop management factors across North Dakota. The target of the switchgrass suitability analysis is the evaluation of agro-climatic conditions for switchgrass establishment based on such parameters. With regard to variation in parameters such as climatic factors, length of growing season, soil parameters, competition from weeds, seed dormancy and poor seedling vigor in North Dakota, studies related to most important of these are described in detail in the following paragraphs.

*Effect of Precipitation*

Many field trial studies have found a positive correlation between annual precipitation and switchgrass biomass yield (Berdahl et al., 2005; Lee and Boe, 2005; Madakadze et al., 1998; Nyren et al., 2010, 2011. Water availability is one of the most important factors affecting productivity in perennial grass (Epstein et al, 1996) and the efficient availability of this input is critical in switchgrass biomass production. Although very tolerant to moderate or even severe drought, switchgrass may not yield sufficient biomass for feedstock under chronic extreme drought condition (Sanderson et al., 1999). In the present study, it is assumed that on an average, annual threshold precipitation amount for switchgrass establishment and growth is about 400 mm per year. The literature cited in the following paragraphs attempts to demonstrate and support the current assumption.

Berdahl et al. (2005), on their study to ascertain biomass yield, phenology and survival of diverse switchgrass cultivars in North Dakota found that growing conditions in western North Dakota were limited by precipitation and winter related stresses. The authors measured switchgrass biomass yield for three consecutive years between 2000 and 2003 at different trial sites in Mandan and Dickinson. It was found that the biomass yield from various switchgrass cultivars were limited by the amount of total precipitation received throughout the year. Results showed that drought condition in test sites during 2002 drought year in Mandan reduced biomass yield to just 30 % compared to previous wet years. The site received annual precipitation of 350 mm during this year which was approximately 30% less than long term average precipitation. The impact of drought condition throughout the year was also intensified by severely low winter temperatures in absence of insulating snow cover (Berdahl et al, 2005).The biomass yields for all cultivars in the previous years were about 8 tons/ha with above annual precipitation of approximately 520 and 600 mm in 2000 and 2001 respectively. Similar study by the authors in Dickinson from 2001 through 2003 produced a mixed yield result. The study showed that biomass yield ranged from approximately 3 to 5 tons/ha in 2003 when total annual precipitation was about 330 mm. Abnormally high rainfall occurred in late summer of 2003 drought year which significantly initiated growth and development of plants that appeared to be in drought-induced dormancy. Yield averaged at about 5 tons/ha in 2002 when total precipitation was 380. Biomass yield averaged at approximately 4 tons/ha in 2001 despite receiving total precipitation of 480 mm. It was reported by the authors that dry and crusted soil condition after seeding resulted in lower initial stand percentages and reduced yield. The authors found that a strong relationship exist between annual precipitation and biomass yield in North Dakota and the study can support the assumption that below a certain precipitation threshold of about 400 mm drought condition could severely depress biomass yield .

The linear relationship of switchgrass biomass with precipitation was best explained by Lee and Boe (2005) in central South Dakota. The authors conducted plot research on biomass yield from 2001-2004 and found that when total annual precipitation was lowest at 193mm (46% of 30-year average in 2002), biomass yield was just about 2 tons/ha and was severely depressed by drought throughout the year. The biomass yield in the previous year was averaged at about 6 tons per ha when total precipitation was 404 mm. The biomass yield however in 2004 wet year (precipitation 457mm) was between 3-

5 tons/ha and was below expected because of negative effect on spring vigor from harvests in three previous years.

Another long term plot study was initiated by Nyren et al (2010, 2011) in 2006 to analyze production of perennial grasses for biofuel production in central and western North Dakota. The authors reported yields from various switchgrass cultivars at different sites in Hettinger, Williston, Streeter, Minot and Carrington. Yields were maximum in Carrington and peaked at 14 tons/ha in 2007 when the total precipitation was about 500 mm. Lowest yields of less than 2 tons/ha were observed in Williston in years 2007, 2008 and 2009 when annual precipitation were in the range of 320 to360 mm .

A plot of biomass yield as a function of precipitation for 25 field trial data collected from 3 literatures in North Dakota is presented in Fig. 4. The average biomass yield from the analyzed test plots was about 5.5 tons/ha The linear regression plot shows that biomass yield was not above the average yield for the state when the when the precipitation was less than 400 mm. Higher yield were observed for years when annual precipitation was more than this threshold level of 400 mm with some exceptions where a combination of other climatic factors played role on reducing yields. The plot supports the assumption that on an average, 400 mm annual precipitation would be necessary for sufficient switchgrass biomass yield for bioenergy purpose.

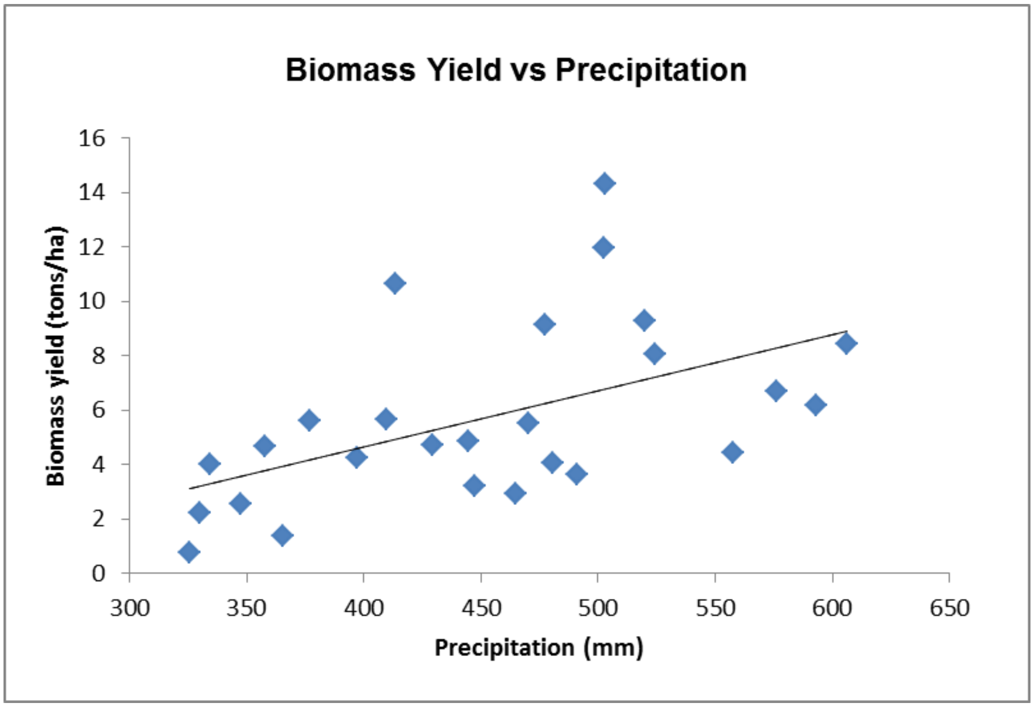



Fig. 4: Biomass yield plotted as a function of annual precipitation

*Growing Season Precipitation*

Switchgrass biomass yield as a function of growing season (April- September ) precipitation are highly variable even though low precipitation during growing season did appear to limit yield (Davis et al, 2008). Literatures suggest that sufficient rainfall must occur during critical portion of the growing season and timing and size of rainfall could be important modifiers.

Davis et al (2008) used a modeling approach based on climatic factors to predict potential switchgrass yield for continental United States. The authors used long term climate record to produce productivity maps using predictive equations and subsequently verified using crop yields within a limited geographical area. The modeling of limitation of precipitation on maximum yield with a hyperbolic regression curve reveled that biomass yield from upland cultivars of switchgrass was reduced to 36% of their maximum yield at 300mm rainfall during growing season.

In a similar study, Wullschleger et al. (2010) compiled published literatures on switchgrass yield from 39 field sites for both lowland and upland varieties across the United States and analyzed different climatic variables that could influence yield. Information on several factors including cultivar specific biomass yield, geographic location, climate, soil and management practices were compiled into a database and an empirical model derived to provide spatially explicit projection of switchgrass biomass based on precipitation, temperature and N fertilization. The study showed that precipitation, temperature, soil, N application, ecotype and latitude significantly impacted yield. The analysis showed that precipitation had a significant positive impact on yield and were more pronounced at latitudes greater than 38.2° N. Precipitation of less than around 300 mm during growing season had pronounced effect on limiting biomass yield to less than 5 tons/ha in the upland varieties. Yields increased with an increase in precipitation up to approximately 600 mm.

Lee and Boe (2005) found that under normal precipitation conditions, a strong linear relationship existed between growing season precipitation and switchgrass biomass production. The average biomass yield was high (10 t/ha) following higher April-May rainfall (125 mm) even though total precipitation during the remaining growing season was less than normal. The result supports the assumption by Stout et al., 1988 that switchgrass biomass production is closely related to water availability during vegetative growth season when wide fluctuation in precipitation is observed. The authors suggest that cultivars originated in North Dakota reached anthesis earlier than more southern cultivars and were able to respond to precipitation during mid-summer. Southern cultivars on the other hand, did not reach anthesis until late august and hence exhibited greater variation in peak biomass yield in response to precipitation variation during July through September. It can be concluded from the study that the precipitation before the anthesis stage or during vegetative stage (leaf development to stem elongation) could be more important for higher yield of switchgrass biomass.

Similarly, Cassida et al. (2005) showed that water availability from April to July was critical for switchgrass biomass production in south-central USA. Smoliak (1956) reported that May to June precipitation during early growth stage was a dominant factor affecting forage productivity in short grass prairie in south Alberta. Sanderson et al. (1999) also showed that switchgrass biomass production for late maturing lowland varieties in Texas was heavily affected by April to September precipitation. Sanderson and Wolf (1995) studied the effect of meteorological parameters and soil water status on the morphological development of switchgrass at two different locations at Stephenville, Texas and Blacksburg, Virginia. The result showed that the higher precipitation during the vegetative growth stage significantly increased the biomass growth rate.

All these literature reviewed on analyzing the effect of precipitation amount on switchgrass yield and the long term observed precipitation pattern in North Dakota are in favor of  the assumption that switchgrass biomass yield could be significantly affected by the precipitation amount. This provides support for the present assumption that on an average, around 400 mm of precipitation is necessary for stand establishment and viable biomass production growth.

*Effect of Temperature*

Switchgrass, because of its C4 type photosynthesis, requires elevated temperatures for growth. Switchgrass is a very persistent species with excellent cold tolerance. However, switchgrass is sensitive to exposure to extremely cold temperatures and winter kills have occurred in areas with cold winters. Owing to the lengthy below freezing winter temperatures and short growing season, the winter temperatures of North Dakota could however be an important limiting factor for switchgrass establishment (Wullschleger et al., 2010). Minimum winter temperature and its duration plays key role in determining winter survival (Berdahl et al., 2005). In the present study it is assumed that switchgrass seedlings can withstand winter temperatures as low as -15°C for short period of time but if they are exposed to this temperature or below for extended period, then it could result in winter kill. The risk associated with the occurrence of temperatures above or below this threshold value is expressed by the deviation from the mean minimum temperature. The literatures described below provide support for this assumption.

Madakadze et al. (2003) conducted growth chamber study using four switchgrass cultivars to analyze the base temperature for seedling growth and their chilling sensitivity. Seedlings at two-leaf stage were grown at 4, 8, 12, 16 and 24°C for four weeks and the growth rates were calculated for each species at each temperature. The authors correlated the base temperatures with the chilling sensitivity of the plants and conducted regression analysis which showed that seedlings of “Dakota”, a variety of switchgrass from North Dakota, could withstand a minimum temperature of 2.79°C without any visual winter injury symptoms while “Cave-In-Rock”, a variety developed from southern Illinois, “New Jersey 50” from North Carolina and “Pathfinder” from Nebraska had tolerate temperatures of 7.26°C, 5.8°C and 4.49°C, respectively. The result showed that the tolerance to physiological stresses caused by severe winter temperatures differs among different cultivars with different latitude of origin. These tolerance temperatures were considered as seedling chilling injury threshold temperature. Chilling injuries result in the visual symptoms of cellular dysfunction that are observed in plants when exposed to chilling temperatures for long period (0 to 20°C) (Raison and Orr, 1987). The injuries result in chlorosis (yellowing and purpling), browning/necrosis, and wilting (Madakadze et al, 2003). In cold areas with short growing season like North Dakota, these injuries occur in early spring or fall.

Berdhal et al., (2005) observed that switchgrass stands in North Dakota could withstand temperature below -15°C temperature for a brief period of time but when prolonged exposure to this temperature for several consecutive days, it would induce winter stress. It is concluded from these literature that the winter survival of switchgrass stand is determined by the occurrence of temperatures below this threshold minimum of -15°C and that continuous exposure to this temperature could result in stand failure.

*Growing Degree Days*

Growing Degree Days (GDD) is defined as the accumulated number of temperature degrees above a certain base temperature. Switchgrass growth is temperature driven and the rate of switchgrass growth during the growing season is reported to be correlated with accumulated heat units or GDD (Sanderson and Wolf, 1995). Development stage of switchgrass throughout the early growth period to flowering and maturity requires a certain amount of accumulated GDD (Clifton-Brown et al., 2000;

Sanderson, 1992). Accumulated GDD, if limiting, could prevent switchgrass from attaining final development stages or maturity.

As a perennial grass, switchgrass is dormant during the winter months and the regrowth does not occur until a certain amount of GDD is accumulated. The base temperature to induce growth is determined by plant's physiology and varies among crops. The effect of temperature on plant's functioning is generally brought about by enzymatic activities (Bonhomme, 2000). When temperature is too low, enzymes playing role in plant development cannot efficiently react. Similarly when temperature is too high, the enzymes coagulate and are inactivated which leads to a halt on plant development. A base temperature of 6.5°C, 10°C or 12°C is commonly used in switchgrass growth models according to their places of origin (Mitchell et al., 1997; Parrish and Fike, 2005; Kiniry et al., 2008). Based on those threshold temperatures, these growth models predict switchgrass growth stages using accumulated GDD to determine every successive development stages. For the current study, it was assumed that the base temperature to initiate switchgrass growth in North Dakota is 12°C and threshold accumulated heat units for maturity was standardized at 600°C. The following literatures provide support for the current assumption.

Kiniry et al. (2008) simulated switchgrass yield from diverse sites in the Northern Great Plains using a crop model with an aim to adjust switchgrass growth simulation parameters (potential leaf area index) and the accumulated GDD to maturity. The region is especially important since the biomass yield here is often limited by the shorter growing season. Based on agro-climatic condition of the region, the authors determined that the base temperature to initiate switchgrass growth in this region was 12°C (Van

Esbroeck, 1996) and that the standardized accumulated heat units for maturity above this base temperature was 600°C. It was also determined by personal communication with crop expert (Paul Nyren from NDSU) that switchgrass seedlings do not emerge in the spring until the last week of May when the average daily temperature is less than 12° C. It was observed that the simulated yields based on these threshold values realistically represented the measured yields in the region which supported the current assumption that the threshold temperature to initiate switchgrass growth in North Dakota is 12° C.

Test results in different regions have shown close relationships between the accumulated GDD and switchgrass growth. Sanderson and Wolf (1995) reported relationship between morphological development of switchgrass and GDD with a base temperature of 10°C for established experimental plots in Blacksburg, VA and Stephenville, TX. The authors reported that Cave-In-Rock matured 4 weeks earlier at Stephenville site, TX than at Blacksburg site, VA and the duration of the vegetative stage was shorter in Blacksburg than in Stephenville. The authors showed that switchgrass cultivars of southern origin required higher number of accumulated GDD than the 600°C GDD threshold and may not reach flowering or maturity stage during the short growing season of North. Those cultivars were more adapted to the southern agro-climatic conditions with longer growing season. They concluded that statistical models to estimate morphological developments in switchgrass based on GDD would need to be cultivar and region specific. The authors indicated that the chemical composition of switchgrass biomass for biofuel production could also be predicted by accumulated GDD.

Based on these peer reviewed journal articles evaluating the response of switchgrass development to accumulated heat units during growing season in this region especially in North Dakota, it was concluded that a base temperature of 12°C was necessary to initiate switchgrass growth and an accumulated heat units of 600°C to reach maturity. The occurrence of accumulated heat units below this value would negatively impact switchgrass establishment and biomass yield.

*Thermal Effects of Snow*

Winter survival of perennial switchgrass in North Dakota largely depends on protection from extreme climatic condition. In North Dakota, the mean monthly temperature during winter months can drop below -22°C in areas where perennial forage crops are grown. The winter survival of these switchgrass crops largely depend on the protection of their crown buds by an insulating cover. Snow cover has been found to be highly beneficial for overwintering crops such as switchgrass, alfalfa, and winter wheat by providing them insulation from extreme cold conditions and fluctuating temperatures (Aase and Siddoway, 1979; Baker et al., 1991, Steppuhn, 1981). The insulating effect of snow is due to the trapping of solar radiation and the release of latent heat. When snow cover is insufficient or absent during extreme winters, temperatures of crown surface may drop below freezing which can be damaging to plants. We estimated in the current study that a threshold snow depth of 10 cm can provide insulation against winter stress for switchgrass establishment or regrowth. The risk associated with the occurrence of a killing temperature in absence of a protective snow cover is expressed by the deviation from the mean snow cover. Following literature were reviewed to provide support for the present assumption.

A modicum of research has been conducted for assessing the effectiveness of snow cover to insulating perennial switchgrass during extreme winters. Leep et al. (2001)

assessed the insulating properties of snow as a protective cover for another perennial forage plant, alfalfa, when experimented in a research plot at Chatham, Michigan. It was found that a snow cover depth of 10 cm or greater could provide adequate protection to perennial crops against below freezing winter temperature. On average, at the canopy level, lowest minimum temperature averaged over three winter seasons was 12.1°C higher at 10 cm of snow depth than for canopy without snow treatment.

In other cases, Brun et al. (1986) showed that on fine and mixed textured soils, a minimum of 7.5 cm of snow cover was necessary to protect winter wheat from winter kill in south-east North Dakota. Aase and Siddoway (1979), working in northeastern Montana, found that at least a 7 cm snow cover was necessary to protect winter wheat crowns from lethal temperature of -16°C. Surface air temperature as low as -40°C was observed during the study period. Winter wheat and perennial forage grasses in Saskatchewan were protected from winter kill by a 10 cm snow cover (Fowler and Limin, 1986) while a 20 cm snow cover was required to prevent low-temperature injury to alfalfa (Jame et al., 1986).

Berdahl et al. (2005) assessed switchgrass performance in western North Dakota and showed that the survival percentage of switchgrass declined sharply when the minimum air temperature of a site at Mandan was below -20°C for 16 consecutive days with essentially no snow cover. The results suggest that snow cover is a good insulator for switchgrass during the severe winter months in North Dakota. Based on these results, it was confirmed that a snow depth of about 10 cm would sufficiently provide insulation to switchgrass stand against freezing winter temperatures.

### *Available Soil Water*

Soil water is the water present in the root zone of plants that can interact with the atmosphere through evapotranspiration and precipitation (Houser et al., 1998). Available soil water is the amount of soil water that could be available for use by plants. It is commonly estimated as the amount of water held between field capacity (soil moisture retained after excess water has drained away) and permanent wilting point (minimum soil moisture the plant require not to wilt) with corrections for salinity, fragments and rooting depth (Scotter, 1981). Switchgrass in North Dakota would typically be grown in marginal rainfed lands under large variability in precipitation and soil moisture conditions. Soil water holding capacity and soil water content are important factors affecting switchgrass biomass yield when precipitation is low or unevenly distributed (Stout et al., 1988; Reynolds et al., 1996). Available soil water can be an important determinant of switchgrass yield with irrigated fields averaging threefold more yields than non-irrigated fields (Koshi et al., 1982; Nyren et al., 2010). Established switchgrass has a very dense root system that may reach depths more than 1.5 m (Kiniry et al., 1999). Successful establishment of switchgrass requires moist soil. Switchgrass is generally well adapted to a wide range of soil types although it may prefer fine textured soils and are most productive on moderately well to well drained soils of medium fertility and soil pH between 6.0 and 8.0 (Blade Energy Crops 2011). For the present analysis, it is assumed that soil moisture up to a depth of 50 cm is most important for switchgrass establishment and the threshold soil moisture content at this level is assumed to be 6 mm.

Cassida et al. (2005) indicated that soil water availability during June to July was most likely to impact switchgrass yields in south-central US for lowland varieties, however, there was no such response to the timing of water availability for upland varieties. It was suggested that the genotype groups differed in their response to moisture availability. The authors also predicted that high rainfall and soil moisture near harvest time would reduce dry matter yield for northern genotypes due to decay of senesced biomass. Under water limiting conditions, switchgrass yield could be constrained by available soil moisture.

Soil moisture is important to break seed dormancy and early seedling establishments. Bardahl et al. (2005) reported that initial switchgrass stand establishment can be lowered if the soil surface becomes dry and crusted after seeding. The field study in Dickinson by the authors showed that biomass yield from established switchgrass was closely associated by the availability of soil water throughout the growing season.

## Productivity and Potential Yield

Switchgrass productivity in simple term is a measure of how much radiant energy can be captured by the plant canopy and be converted into harvestable biomass over the growth period. It is considered theoretically and physiologically possible biomass production based on biochemical conversion of solar radiation into dry matter accumulation. Assessment of productivity and the difference in yield gap between potential and actual yield in necessary before making decision on adopting switchgrass crop in North Dakota. Potential yield of perennial crop is determined by measuring solar radiation, precipitation, temperature, growth period, genotype characteristics etc. assuming that management practices, disease and pests are not limiting growth. Under rainfed situation such as switchgrass, water-limiting yield may be considered as the maximum attainable yield assuming other factors are not limiting the crop production

(Singh et al., 2001). However weather variability such as temperature, snow cover from season to season may also cause variability in potential yield.

Several studies have reported switchgrass growth and illustrated its sensitivity to variables growth conditions. Berdahl et al. (2005) conducted biomass yield, phenology and survival assessment of switchgrass in western North Dakota. The research was conducted at different test sites in Mandan and Dickinson from 2000 to 2003 and showed that stand frequency and biomass yield were often associated with survival during winters. In February 2001, a minimum air temperature of -20°C for 16 consecutive days at Mandan site with no snow cover resulted in severe winter injury and yield decline for some cultivars of southernmost origin (Shawnee, OK NU-2 and Cave-in-Rock).

Schmer et al., (2006) conducted a study to determine the relationship between switchgrass stand establishment and biomass yields in the Northern Great Plains region. Experimental biomass research plot studies were conducted in Munich and Streeter, North Dakota. The sites selected had characteristics that would have qualified them for CRP due to their marginal productivity. The fields were established in 2001and biomass harvested the following year at the plant maturity stage of inflorescence emergence to Post-anthesis/fertilization (Moore et al., 1991) or after the first killing frost. The yield results in 2002 showed that mean biomass yield from Munich site was 4.24 t/ha and from Streeter was 4.64 t/ha. The study found that the biomass yields in North Dakota were directly related to initial switchgrass stand establishment success rate and could limit yields if stand frequency were less than 40%.  The study also showed that post-establishment stands frequency and biomass yields were more likely influenced by site and environmental variables.

Latitude of origin of switchgrass cultivars has large impacts on limiting the productivity and survival of switchgrass stains, suggesting genetic variability in adaptation (Casler et al., 2004). Latitudinal adaptation of switchgrass is regulated by genetic variation for photoperiodism, growth rate or temperature stress tolerance. It is important to use germplasm that matches the environmental characteristics of a particular area. Casler et al., (2004) provided a framework for choosing switchgrass germplasm by defining hardiness zone based on 5.5$^{\circ}$ C increment of mean annual temperature. It is suggested that switchgrass cultivars should not be moved more than 500 km north of their region of origin, to protect them from winter injury (Moser and Vogel, 1995; Lewandowski et al., 2003).

Switchgrass biomass yield vary widely with fertilizer application. Switchgrass has high nitrogen use efficiency (Wedin, 2004) but responds to nitrogen fertilization by higher yield when soil water is adequate (Moser et al., 2004). Fertilizer application rates should be based on the available soil nitrogen (Mengel et al., 2006). Leaching of excess nitrogen to ground water is an important concern while determining optimum fertilizer inputs. The optimum nitrogen input for CRP lands dominated by switchgrass in South Dakota was 56 kg N/ha (Mulkey et al., 2006). Vogel et al. (2002) showed that biomass yield for an upland variety of switchgrass (cave-in-rock) in Iowa and Nebraska increased with increasing rate of fertilizer from 0 to 300 kg N /ha. They showed that the residual soil nitrogen increased when applied nitrogen exceeded 120 kg/ha. The authors concluded that the recommendation for N fertilizer should be based on anticipated biomass yield and was approximately 10-12 kg N/ha/yr for each 1 tons/ha of biomass.

In the Central Great Plains region, Phosphorous (P) fertilizer recommendations for switchgrass ranged from 0-30 kg/ha (Brejda, 2000). Phosphorus fertilizer recommended for switchgrass field depends on soil pH and soil P content (Brejda, 2000). Switchgrass did not respond to additional P in Texas (Muir et al., 2001) and showed low response in Iowa (Hall et al., 1982).

*Potential Yield Simulation*

Crop simulation models could be used to estimate the potential yields provided that the agro-climatic data for the site and crop parameters available for model execution. Yield simulation using a crop model is a succession of several predictions of physiological processes through time. The key parameters controlling the ability of crop simulation models to predict potential yields are the leaf canopy size also measured as Leaf Area Index (LAI), the efficiency of the canopy interception of solar radiation and the conversion into photosynthetic products and plant biomass (McLaughlin et al., 2006).

Kiniry et al. (2006) conducted sensitivity analysis of switchgrass simulated yield at different locations in the Northern Great Plains using temperature and precipitation variability. The analysis revealed that the reduced temperatures shortened the growing seasons which ultimately decreased yields. The higher temperature may increase water use, resulting in increased drought stress and lowering yield. Increased rainfall increased yield however increased rainfall could also negatively affect yield by leaching soil nitrogen and hence causing nutrient stress.

Nyren et al. (2010) conducted a long term biomass yield evaluation through a network of field plots at 5 different locations (Hettinger, Williston, Minot, Streeter and Carrington) starting 2006 in Central and Western North Dakota. In 2009, two additional sets of plots were established at USDA ARS experimental station in Mandan and Ducks Unlimited Ranch, north of Wing. All plots were rain fed with no irrigation except for one plot in Williston. Biomass yield results showed a wide variation in annual yields at different locations. The authors presented initial results of the study and it was found that the experimental plots in Carrington site in central North Dakota yielded the highest switchgrass biomass. Yields in Minot and Streeter were relatively moderate, while least yields were observed in Hettinger and Williston. The yield range from Carrington was about 8-15 tons/ha while for Williston, it was 0.7-3.2tons/ha. Yields from Minot and Hettinger improved in 2010 and yielded over 5 tons/ha. The yield variation could also be attributed different fertilizer inputs. The fertilizer applied were 55 kg/ha urea each spring at Carrington, 150 kg/ha of urea and 55 kg/ha of phosphate fertilizer for only one year in 2010 at Hettinger, 110 kg/ha of urea per year at Streeter and Minot, and 110 kg/ha of urea in alternate years (2008 and 2010) at Williston (personal communication).

Kiniry et al. (1996) examined radiation use efficiency (RUE), potential leaf area index and accumulated heat units from planting to maturity in Texas and showed that the changing the crop parameters to increase the potential productivity did not do much to increase yields if major limiting factors are environmental. The authors showed that an increase in radiation use efficiency and leaf area index significantly increased biomass yield but the changes were negligible when the factors such as precipitation, soil water and soil nutrients were limiting.

The case studies summarized here provide the best estimates of potential biomass yield over a broad range of agro-climatic and management conditions in North Dakota.

The small plot results reported in these literatures are the best available yield predictors for switchgrass grown as a bioenergy crop under large scale cultivation.

## Environmental Significance

Switchgrass offers various ecosystem services such as an excellent wildlife habitat, carbon sequestration in its extensive and very deep root system (Rinehart, 2006). Switchgrass fields can provide excellent nesting habitat for migratory birds (Moser and Vogel, 1995; Paine et al., 1996; Sanderson et al., 1996) and may not affect nesting suitability for birds since harvest often takes place in fall or winter (Murray and Best, 2010). Environmental significance of switchgrass can be of importance especially in the Great Plains where switchgrass is endemic.

An investigation was conducted by researchers at Iowa State University to assess responses of grassland wildlife to harvesting switchgrass established on CRP field (Murray and Best, 2010). The evaluation was based on the abundance and nesting success of grassland birds. Because birds respond to the structure of vegetation and may respond differently to different harvesting regimes, the study fields were divided into three treatment types (total-, partial-, and non-harvest). The harvested fields were cut during winter to avoid disturbance to breeding birds. The survey results showed that total bird abundance did not differ significantly between the different treatments. However, abundance of some bird species differed between harvested and non-harvested fields. Different bird species required different growth stages of grasslands. Even the harvested fields could provide suitable food habitat for many bird species. E.g. grasshopper sparrow was more abundant in short, sparse grasslands or harvested fields while northern harriers, sedge wrens were more abundant in non-harvested fields with residual vegetation.

Another significant benefit of switchgrass deployment includes the fixation of Soil Organic Carbon (SOC) by the process known as soil carbon sequestration. Soil carbon sequestration refers to “transferring atmospheric $CO_2$ into long-lived pools and storing it securely so it is not immediately reemitted” (Lal, 2004). Switchgrass can sequester large amount of atmospheric carbon to the soil (Liebig et al., 2008). A study by Liebig et al. (2008) to assess soil carbon storage by switchgrass grown for bioenergy in North Dakota showed that over 5 years of study period, soil organic carbon storage were 1.1 Mg C/ha at 0-30 cm and 2.9 Mg C/ha at 0-120 cm depth. Switchgrass is also found to restore soil organic matter lost due to prior tillage (Gebhart, et al., 1994). Perennial grasses like switchgrass maintain soil organic matter through the supply of litter and root residues, and can enhance nitrogen status of the soil and take part in recycling and translocation of nutrients in association with mycorrhizal fungi (Noble and Randall 1998). Switchgrass is deep rooted and very efficient in using nitrogen (Parrish and Fike, 2005). Literature suggests that switchgrass can be grown on soils of moderate fertility without fertilizing, or with limited additions of fertilizer, and still maintains high biomass productivity (Parrish and Fike, 2005, Hopkins and Taliaferro, 1997).

In addition, switchgrass can play an important role in reducing soil erosion in agricultural fields under cultivation, stabilizing soil along streams and wetlands (McLaughlin and Walsh, 1998). A soil erosion modeling result by Solow et al. (2005) showed that converting about 20,000 ha (50,000 acres) of cropland to switchgrass in a watershed in Iowa could reduce soil erosion by 55%.

Changes in crop management including biomass burning, ploughing and other agriculture practices are the main factors causing loss of top soil and organic matter in grasslands and croplands (Lal, 2002). Annual cropping, such as is done with soybeans, corn, and small grains often result in loss of soil organic matter and release of soil carbon to the atmosphere. Biofuel feedstock like switchgrass is compatible with conventional farming practices and can be grown in semi-arid conditions in land not optimal for agriculture (McLaughlin and Walsh, 1998).

Switchgrass substitution for fossil fuels can have significant impact on environmental quality. Solow et al (2005) conducted a study based on research by The Center for Global and Regional Environmental Research on behalf of the Chariton Valley Biomass Project (CVBP) to determine the economic feasibility of burning switchgrass as a partial substitute for coal in the production of electricity. The research was based on premise that such substitution would be more environmentally friendly as compared to a hundred percent reliance on coal fired electricity. The study by Solow et al. (2005) showed that substitution of switchgrass for coal by retrofit technology could reduce the amount of coal required by approximately five percent and could present a net greenhouse gas benefit of 163 kg (360 lbs) $CO_2$ equivalent ($CO_2$-eq) for every million btu (MMBTU) of switchgrass combusted. The study also showed reduction in emission of sulfur dioxide, nitrogen oxides, carbon monoxide, particulate, volatile organic compound, heavy metal and non-metal toxic chemicals when replacing fossil fuel coal by fuel derived from switchgrass.

## GIS Tools for Land Suitability Analysis

GIS is used as a tool to build a database for switchgrass suitability using multifactor spatial analysis. The capability of GIS for data acquisition, storage, retrieval manipulation and analysis of spatial data is of crucial importance for multi-criteria decision analysis (Chang, 2010). GIS can function as a data management tool and is useful for modeling related tasks such as exploratory data analysis and data visualization. The aim of using GIS technology in switchgrass suitability analysis is to provide support for spatial decision-making processes (Foote and Lynch, 1996). A GIS based multi-criteria spatial analysis can effectively assess the agro-climatic suitability for switchgrass planting. This approach uses multi-criteria analysis tool to combine three factors (establishment risk, potential yield and land use) to express land suitability.

Land suitability analysis is a GIS based process of land evaluation for development (NCDCM, 2005). The analysis of land suitability for switchgrass production is based on an approach involving various parameters like agro-climatic conditions, soil properties, yield estimates and land use. All these parameters may not necessarily have equal importance in determining the suitable areas for switchgrass production in North Dakota. To incorporate all these parameters that differ spatially and temporally, GIS has been identified to be the best tool. These selected parameters, presented in the form of individual GIS datasets are referred as "layers." These layers are analyzed together in a multi-criteria analysis shell (Lesslie et al., 2008). In this study, GIS based multi-criteria spatial analysis is conducted to assess the agro-climatic and land use suitability for switchgrass production. Based on the analysis, an attempt was also made to define areas suitable for switchgrass that can reduce pressure on permanent crop land and grasslands.

## Multi-Criteria Analysis Shell–Spatial (MCAS-S)

Many complex interacting factors have been analyzed in the present study to define switchgrass suitability in North Dakota. Multi-criteria analysis can help achieve natural resources management goals and decision making processes by integrating transparent and logical information on environment, society and economy (Kiker et al., 2005; Hill et al., 2005; Malczewski, 2006). A portable software MCAS-S (Multi-Criteria Analysis Shell for Spatial Decision Support) (Lesslie et al., 2008) was used for developing a switchgrass suitability model that could be meaningful to local users or firms, who are considering switchgrass adoption for bioenergy. MCAS-S is a simple, flexible multi-criteria approach that is useful in analyzing complex spatial compatibility issues in human-environment system (Hill et al., 2006). The multi-criteria approach was chosen since it is flexible and tolerant of low quality quantitative data and relies on agreed relative importance hierarchy of factors (Hill et al., 2009). MCAS-S is compatible with a wide range of GIS software and may be customized for a specific purpose in spatially explicit decision making (Lesslie et al., 2008).

MCAS-S operates with raw (primary) spatial data in a raster format of consistent spatial extent, pixel resolution and projection. Spatial data can be classified into individual class using threshold values for each parameter in MCAS-S interface.  After creating individual class also called rule set, weighted value can be applied to each parameter and construct a composite layer. The weighted combination of the selected parameters contributes to dynamically update the composite layer culminating in a final summary layer.

# CHAPTER III

# CONCEPTUAL FRAMEWORK

## Land Suitability Model

The conceptual model for the present study is based on the premise that the production suitability for dedicated switchgrass bioenergy crop in North Dakota is subject to the interactions of physical constrains imposed by severe winter, productivity and land use change. Switchgrass is believed to be the most suitable for cultivation in marginal lands or CRP lands where the federal government pays landowners annual rent for keeping out of production. Factors favoring adoption of switchgrass include selection of suitable land, favorable combination of agroclimatic conditions, high biomass yield, better environmental and economic benefits. These factors operate at a landscape level and vary with space and time and the dynamics of these factors can readily be addressed using spatial analysis tools in GIS.

In the current analysis the individual data layers and the composite of such layers that determines one of the major controlling factors for switchgrass suitability are referred to as "themes." It is determined that switchgrass suitability can be determined by combining the major themes derived from multiple GIS data layers in a spatially explicit multi-criteria framework. The conceptual framework for construction of major themes from the spatial layers and defining switchgrass suitability is shown in Fig. 7.

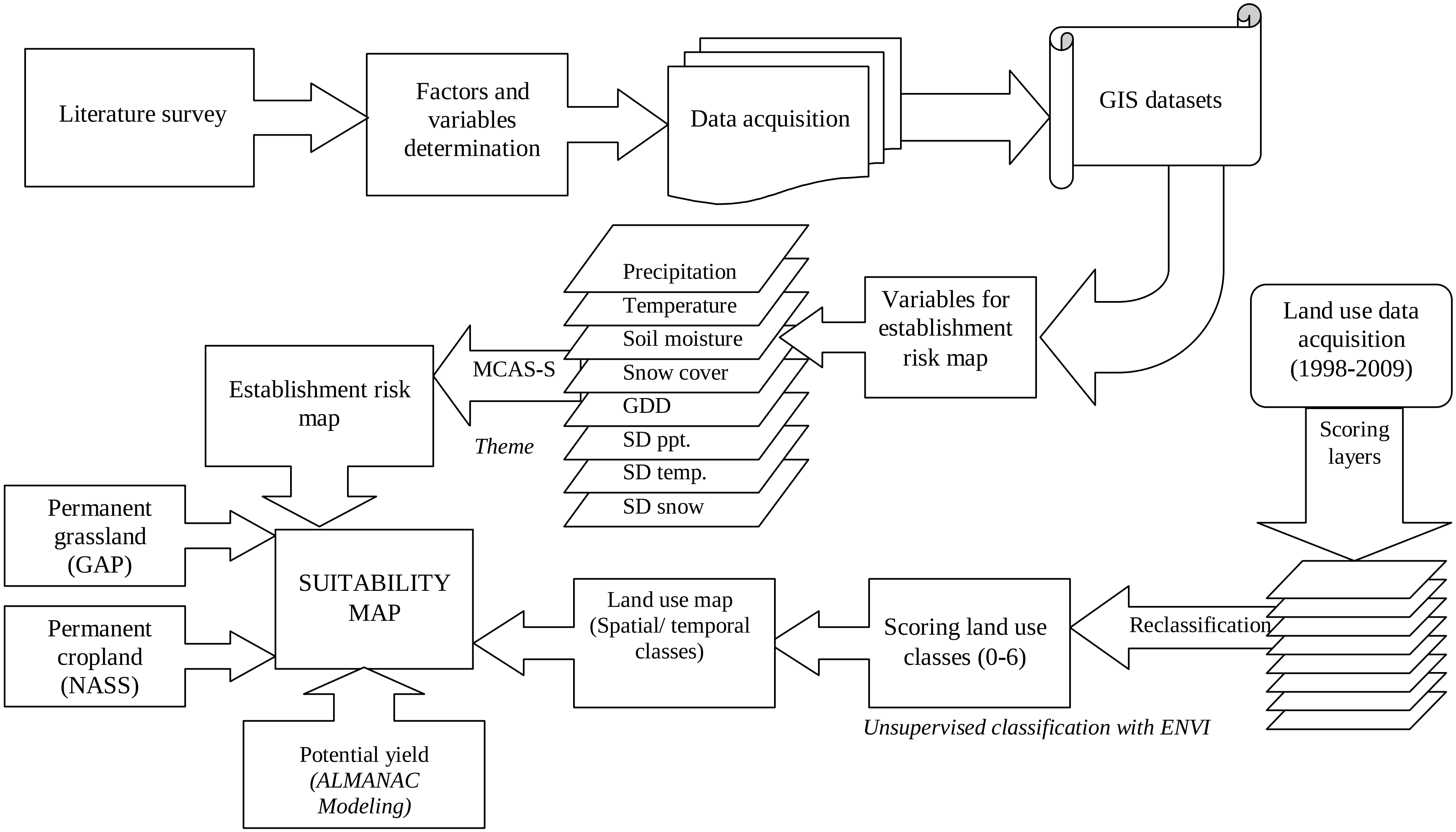



Fig. 5: Conceptual flowchart of the procedure followed to determine suitability for switchgrass production in North Dakota.

## Spatial Analysis and Modeling

The framework to guide the research questions and the type of analysis to be conducted is helpful to understand how suitability factors lead to the adoption of switchgrass in North Dakota. The framework illustrates complex interaction and dynamic linkage among various controlling factors for determining switchgrass production suitability. The framework we proposed draws on three different conceptual themes. It combines climatic variable with productivity and land use themes to define suitability for switchgrass production. These factors are considered spatial variables that directly or indirectly influence decision making. In the context of the framework, the theme for agro-climatic condition typically captures agro-climatic constrains with static spatial and temporal data. Productivity theme captures spatial interpolation of potential biomass yield based on model simulated value. The theme for landuse change captures the significance of particular land type in determining its suitability for growing switchgrass. The preference of marginal land that is unlikely to be used for growing food crop or biodiversity conservation is critical in avoiding landuse conflict potential.

# CHAPTER IV

## AREA OF STUDY: NORTH DAKOTA

The state of North Dakota is located in the mid-western and western regions of the Great Plains. The total area of the state is 183,272 $km^2$and it is the 19$^{th}$ largest state by area in the US. It has the third least population among all the U.S. states with about 646,844 residents as of 2009 (U.S. Census Bureau, 2009). The agriculture sector plays an important role in North Dakota where it dominates the economy and culture of the state. Agriculture accounts for one-fourth of the basic economic activity and almost 36% of all exports of goods and services (Leistritz et al., 2002). Agriculture accounts for 32% of state's economy (excluding federal payments as employee wages, social security etc.) and when combined with manufacturing and production, 44% of the state economy is directly or indirectly related to agriculture (NDFB, 2009). Approximately 160,557 $km^2$ of the state land are farmland. About 111,398 $km^2$ of land area are cropland and 45,452 $km^2$ pasture lands (excluding woodland) (Census of Agriculture, 2007). The state is the nation's leading producer for many crops, including durum wheat, spring wheat, barley, sunflower, flaxseed, canola, pinto beans and dry edible beans. North Dakota is also a significant producer of sugar beets, potatoes and oats. Since agriculture represents a significant portion of North Dakota's economic activity, the agricultural performance of the state is of significant importance.

North Dakota extends through two major U.S. physiographic regions: the Central Plains in the east and the Great Plains in the west (Fig. 6). The eastern half is generally flat and is comprised of the Red River Valley along the eastern border. This part of the state is one of the most fertile areas in the US. This area is mainly comprises of farmland. To the west of the Red River valley lies the Drift Prairie at 400-500m above sea level. The Drift Prairie is marked by stream valleys, numerous lakes and rolling hills. The southwestern half of North Dakota consists of the Missouri plateau, which is separated from the eastern drift prairie by the Missouri Escarpment, and extends approximately 160 km diagonally from northwest to southeast. The area is hilly and rich in mineral deposits.

The soils along the river floodplains are mosaics of sand, silt and clays in various combinations (Johnson et al. 1976). Williams soils are extensive in most parts of North Dakota and are economically important soils as they are naturally fertile with high organic matter content. The native vegetation on the soil consists of western wheatgrass (*Pascopyrum smithii*), blue grama grass (*Bouteloua gracilis*), green needlegrass (*Nassella viridula*), needleandthread (*Stipa comata*), and prairie junegrass (*Koeleria macrantha*) (North Dakota State Soil: USDA).

Grasslands in North Dakota are traditionally separated into two great associations, the true prairie to the east of 98° N longitudes along the floodplains of the Red River and the mixed prairie to the west (Weaver and Clements, 1938; Clements and Shelford, 1939; and others). The composition of true prairie is relatively variable and is dominated by big and little bluestem Indian-grass (*Andropogon gerardi*, *Schizachyrium scoparium)* and switchgrass (Kuchler, 1964; Risser, 1990). The dominance of C3 grasses increases from south to north including Heller's witchgrass (*Dichanthelium oligosanthes*), porcupine needlegrass (*Stipa spartea)*, prairie junegrass (*Koeleria macrantha*) and Kentucky bluegrass (*Poa pratensis*) (Ostlie et al., 1997). The mixed prairie in the west is dominated

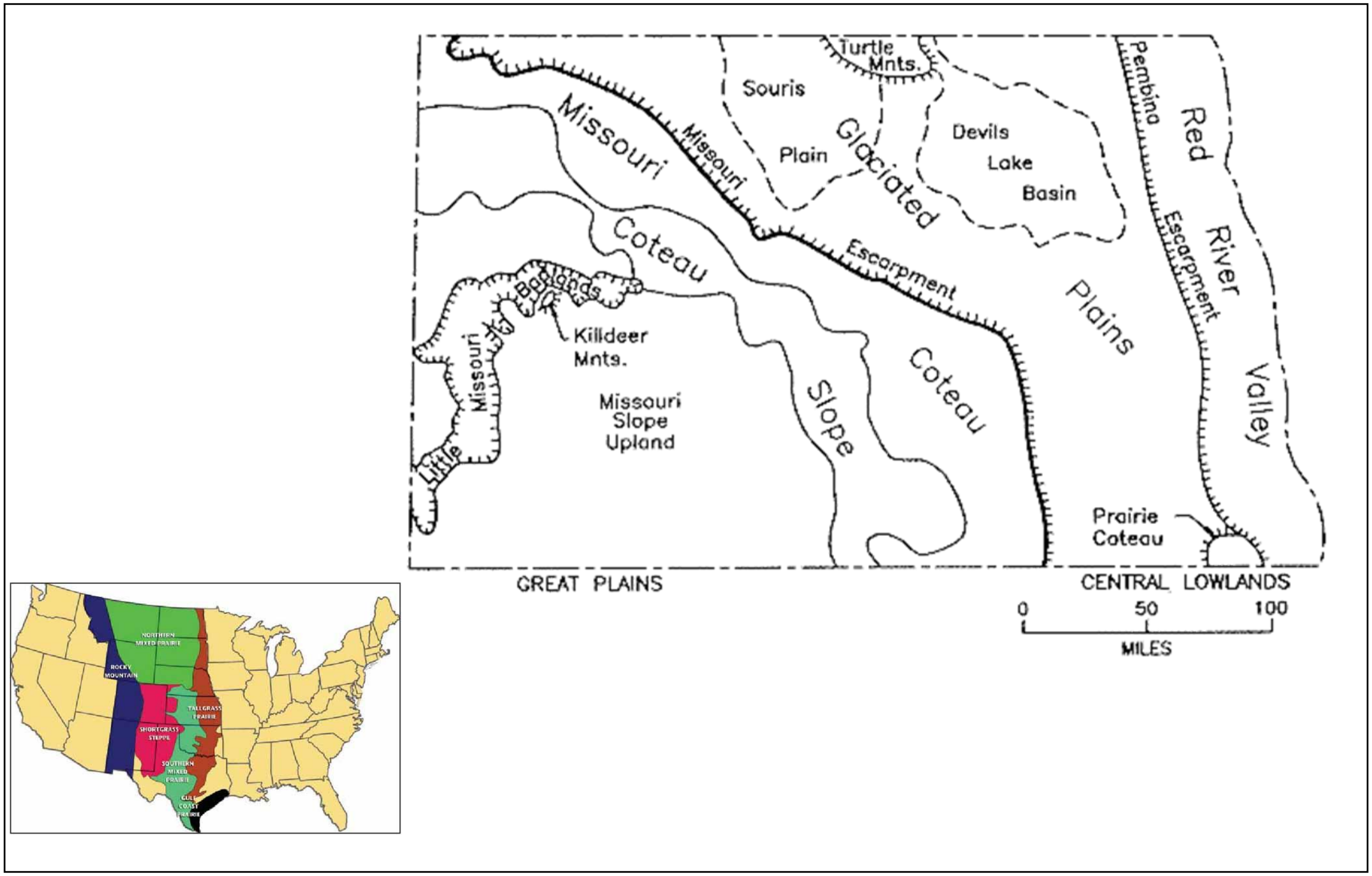



Fig. 6: Area of study with major physiographic regions of North Dakota
(Source: https://www.dmr.nd.gov/ndgs/NDNotes/ndn1.htm; Lauenroth et al., 1994)

by a combination of short and mid-height as well as some tall grasses (Bragg and Steuter 1995). Mixed grass prairie originally evolved with fire (Bragg, 1995) and fire is also being used as a management tool for prairie (Berkey et al., 1993).

North Dakota's climate is typical of sub-humid continental climate with hot summers, very cold winters and rainfalls sparse to moderate. The average annual temperature ranges from less than 2°C (37°F) in the north to about 7°C (43°F) along the southeast and southwest corners (Fig. 6). January is the coldest month, with an average temperature ranging from -16°C (2°F) in the northeast to -8°C (17°F) in the southwest. July is the warmest month, with temperatures averaging 19°C (67°F) in the northeast to 23°C (73°F) in parts of south. The highest temperature ever recorded in North Dakota was 49.5°C (121°F) at Steele on July 6, 1936, and the lowest temperature measured was -51°C (-60°F) at Parshall on Feb. 15, 1936 (NCDC, 2010). Spring and fall temperatures in North Dakota are ideal for cold season plants, but the warm summer months are also suitable for warm season grasses such as switchgrass. Annual precipitations in North Dakota ranges from around 350 mm in the northwest to more than 600 mm in parts of the Red River Valley in the southeast (Fig. 7). Winter precipitations are less important and nearly always in the form of snow. Monthly water equivalents of melted snowfall for the winter months average from 7.5 mm (0.3 inches) to 15 mm (0.6 inches), but January amounts range upwards to 22 mm (0.9) inches in the northeast (Jensen, 2006). Precipitation is 2.5 mm (0.1 inches) to 5 mm (0.2 inches) higher in the east than in the west for all months (Jensen, 2006). Approximately 75% of the annual precipitation falls in the six-month period from April through September (Fig. 8 and 9). Rainfall is light in the spring, but the melting snow keeps soil wet in the field. Average daily rainfall increases until late June, facilitating the early establishment of crops, and gradually declines until December. The declining rainfall during the late growing season is favorable for maturing and harvesting crops.

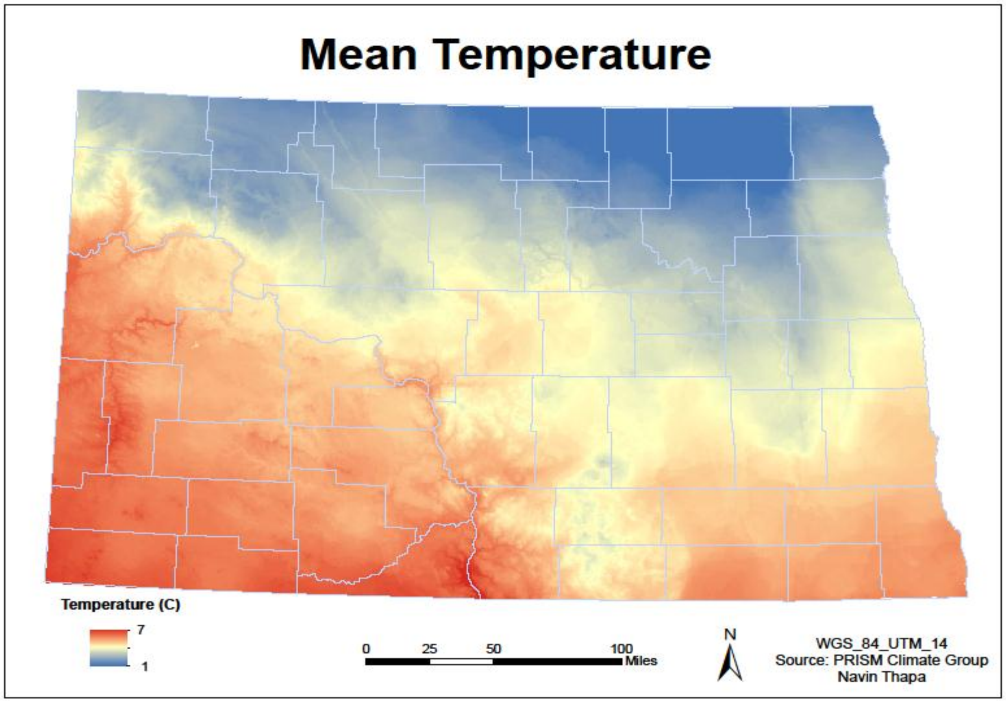



Fig. 7: Mean annual surface air temperature in North Dakota (1971-2000)

North Dakota has considerable fossil fuel reserves and has substantial lignite coal, crude oil and natural gas reserves in the western half of the state. North Dakota is the eight largest oil producing state in the US (Comprehensive State Energy Policy, 2008-2025), and accounts for 2% of the nation's crude oil production (USEIA, 2011). North Dakota is a substantial producer of wind energy and is among the leading states in the US in potential wind power capacity. North Dakota is being considered as a potential producer for perennial grasses and other dedicated bioenergy crops. There is one biodiesel plant functional in Velva, North Dakota. The plant processes canola for biodiesel production and has a production capacity of 322 million liters per year (Ethanol

Producer Magazine, 2009). Research on cellulosic ethanol production using switchgrass biomass is in acceleration in North Dakota. At present, 6 corn-based ethanol plants (Located in Underwood, Richardton, Grafton , Walhalla , Hankinson, Casselton) are functional in North Dakota with a total annual operating production of nearly 1600 million liters (Renewable Energy Fuels Association, 2011).

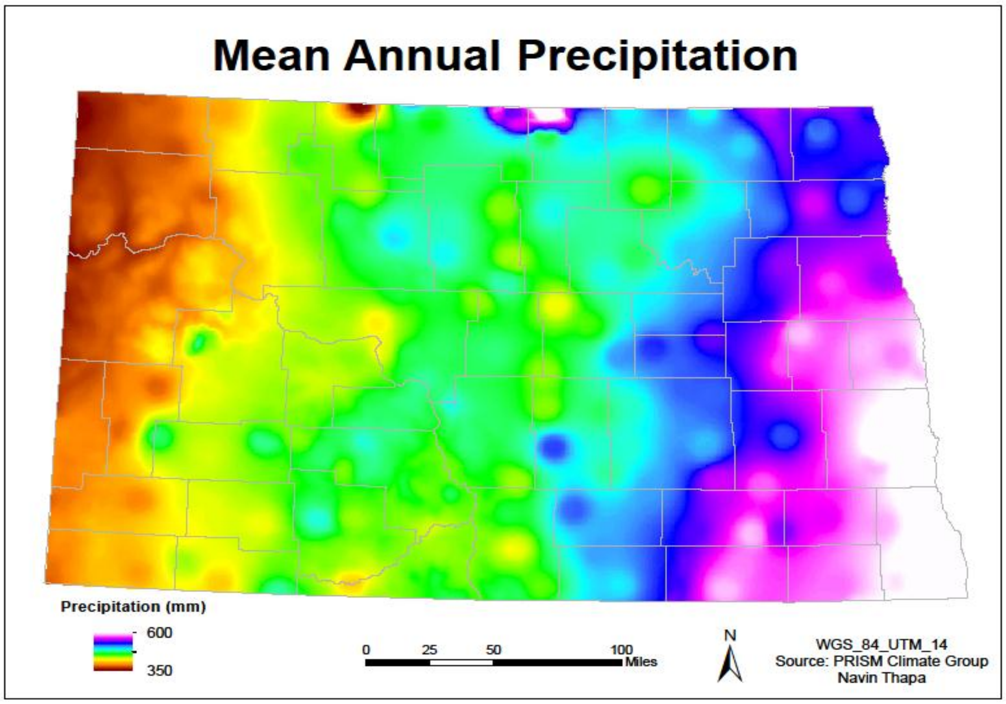



Fig. 8: Mean annual precipitation in North Dakota (1971-2000)

# CHAPTER V

# ESTABLISHMENT RISK MODELING

## Switchgrass Establishment

Successful establishment of switchgrass stand in seeding year is an important requirement for its production as a bioenergy crop. First year establishment of the crop stand is critical as the stand failure resulting from unfavorable agro-climatic conditions will hamper economic viability of the crop for successive years. The risk factors associated with switchgrass establishment in North Dakota are site specific and dependent on the severity of climatic parameters and soil characteristics. To date, no studies have specifically focused collectively on these variables to analyze risks associated and their severity. So far, studies are mainly focused on analyzing factors such as seed dormancy, seed density, drilling dates and seedling sensitivity to soil and weed conditions to determine establishment success. This study attempts to analyze various agro-climatic parameters and their threshold levels in defining stand establishment risk of switchgrass in North Dakota. For this, five agro-climatic parameters are analyzed:

1. Precipitation
2. Temperature
3. Snow depth
4. Soil water potential
5. Growing Degree Days

## Data Collection

First, the various agro-climatic variables that determine stand establishment and their threshold value for establishment determined. The parameters were described in earlier chapters and identified as the major limiting factors affecting switchgrass establishment and survival in North Dakota. Data Layers for all these parameters were collected from various data sources, clipped to North Dakota, gridded at 787.4m spatial resolution for analysis by using GIS tool and overlaid in the workspace of MCAS-S to create a composite theme for establishment risk. The detailed methodology of data collection for each layer is described below.

### *Precipitation*

Average annual precipitation data and annual precipitation for a period of 2000-2009 were downloaded for a 30 years time-period (1971-2000) from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) Climate Group at Oregon State University. The standard deviation between 30-years annual average precipitation and mean precipitations for the period 2000 to 2009 was computed to analyze the trend and variation of precipitations in the region. Mean annual precipitation for the 30 years normal ranged from 350 mm to 600 mm. The general trend of total annual precipitations showed that it was lower in the western part of the state and gradually increased to the east seemingly making eastern side more favorable for switchgrass establishment and growth (Fig. 9). The highest rainfall occurred in the southeast part of the state, along the Red River Valley. The average growing season precipitations (April to September) ranged from 270 mm in the west to 400 mm or above in the southeast along the Red River Valley. A threshold precipitation level of 400 mm per year was established for defining the minimum precipitation requirement for growing switchgrass.

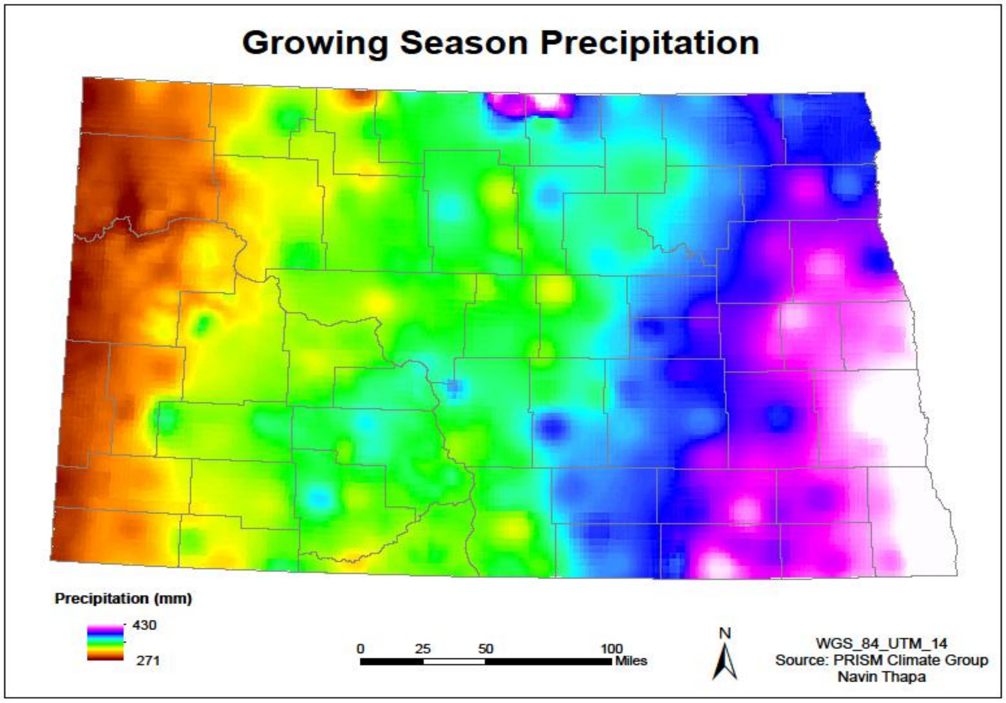



Fig. 9: Mean growing season precipitation (Apr.-Sept) in North Dakota (1971-2000)

*Temperature*

Temperature data for the present analysis were collected from the PRISM Climate Group. The monthly normal minimum temperature (Tmin) data for 30 years (1971-2000) and for a period of 2000-2009 were downloaded for three winter months (January-March) and for the growing season (April-September). The average Tmin during the winter period ranged from -5°C to -22°C (Fig. 10). Tmin for winter months during the period 2000 to 2009 were collected and standard deviation calculated from the 30 years mean. Tmin threshold for winter kill was established at -15°C as it was assumed that extended exposure of about three weeks or longer to this temperature (Berdahl et al., 2005) would result in winter kill of switchgrass.

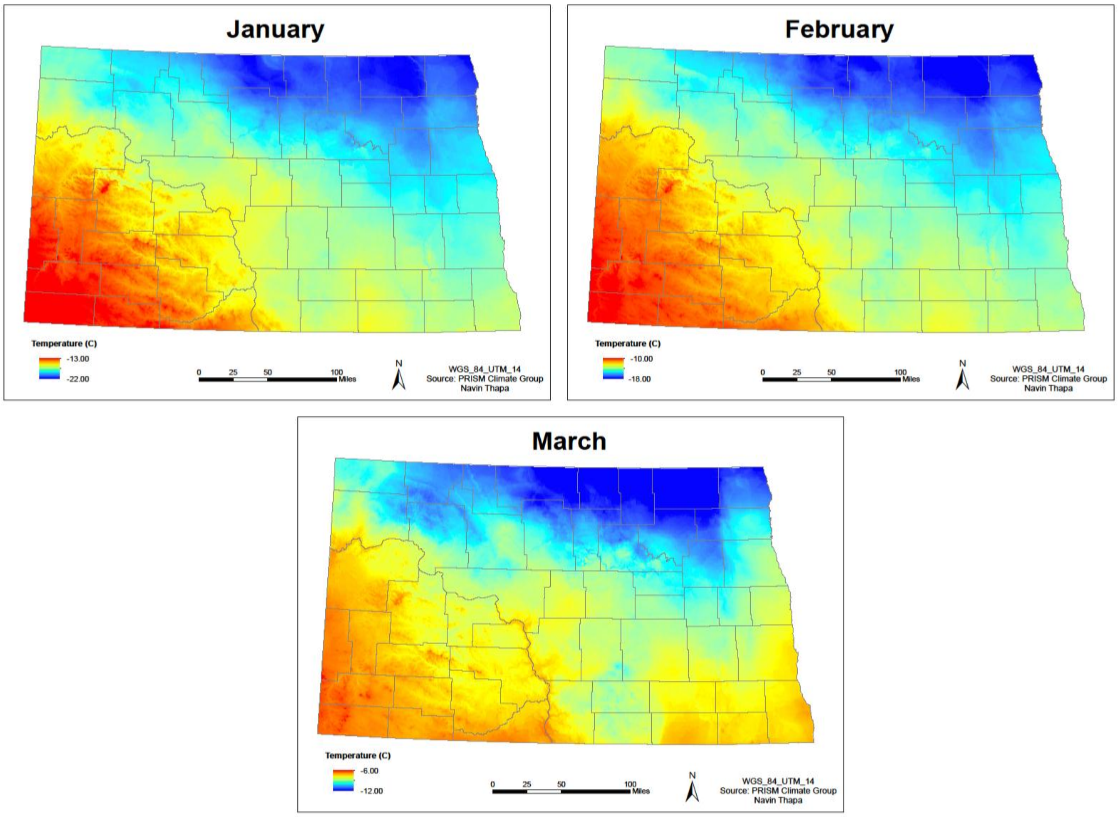



Fig. 10: Average minimum daily air temperature (Tmin) during the winter months (Jan., Feb., Mar.) in North Dakota (1971-2000)

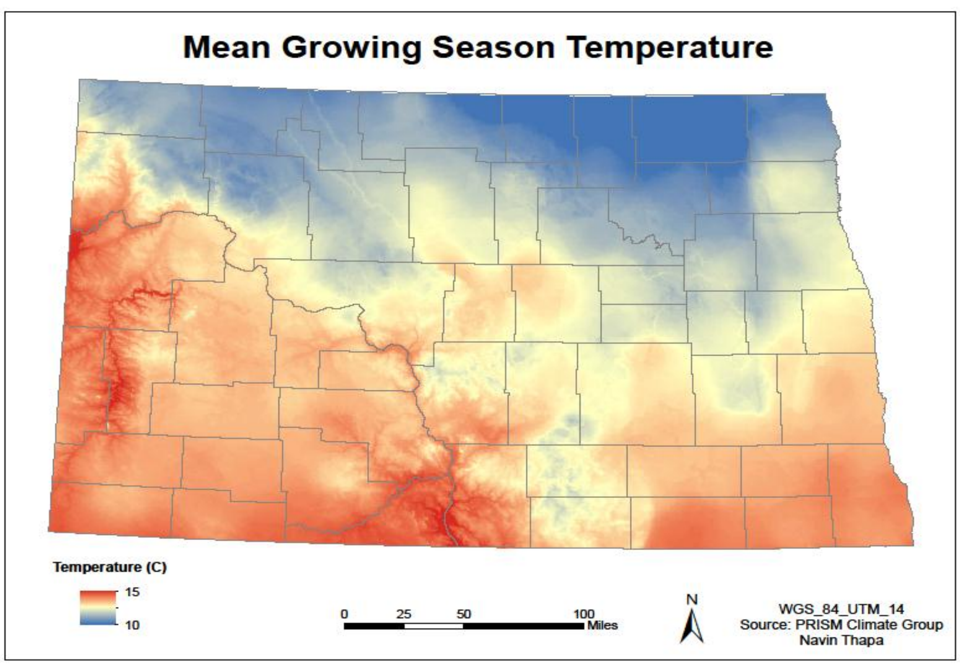



Fig. 11: Mean growing season (Apr.-Sept) air surface temperature in North Dakota (1971-2000)

The temperature pattern across the state shows that the southern parts are relatively more protected from severe winter temperature compared to northern parts. January is the coldest month while July is the warmest. The growing season temperature in North Dakota, from April to September, showed the same general pattern as the average annual temperature (Fig. 11), with an average ranging from near 10°C in north-east to 15°C in the southeast and southwest border.

*Snow Depth Data Collection*

The snow depth data for North Dakota were obtained from the Snow Data Assimilation System (SNODAS) data products at the National Snow and Ice Data Center (NSIDC). SNODAS is a modeling and data assimilation system developed by the National Operational Hydrologic Remote Sensing Center (NOHRSC) to provide the best possible snow depth estimates from satellite data, airborne platforms and ground stations (Carroll et al., 2001). The data set contained output from the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service's NOHRSC (NOHRSC, 2004). Data was collected for three winter months, January to March from 2004 to 2010 with 10 days intervals.

Snowfalls are significantly low as compared to nearby states in the east or west (Minnesota or Montana) (Jensen, 2006). The average snow cover depth in North Dakota during the three winter months (January, February and March) ranges from a few mm in the south western part of the state to about 500 mm at some eastern locations (Fig.12).

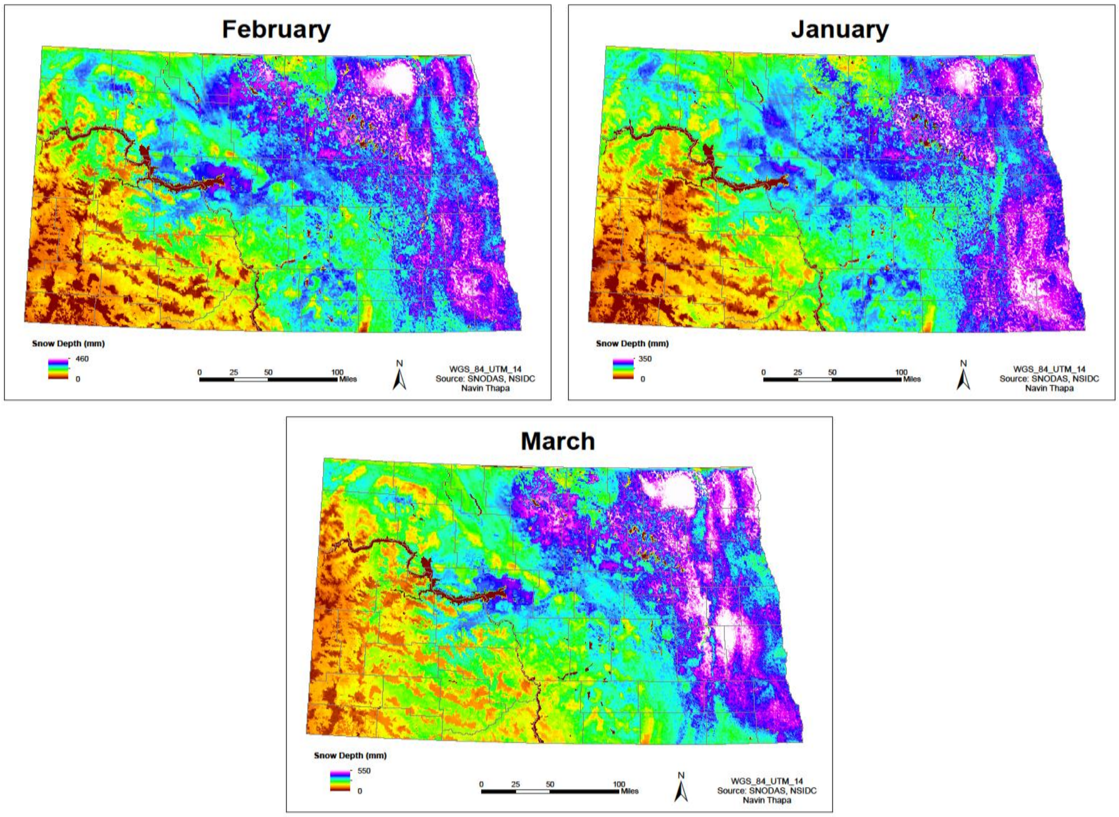



Fig. 12: Average snow cover depth during winter months (Jan., Feb. Mar.) (2004-2010)

*Available Water Storage (AWS)*

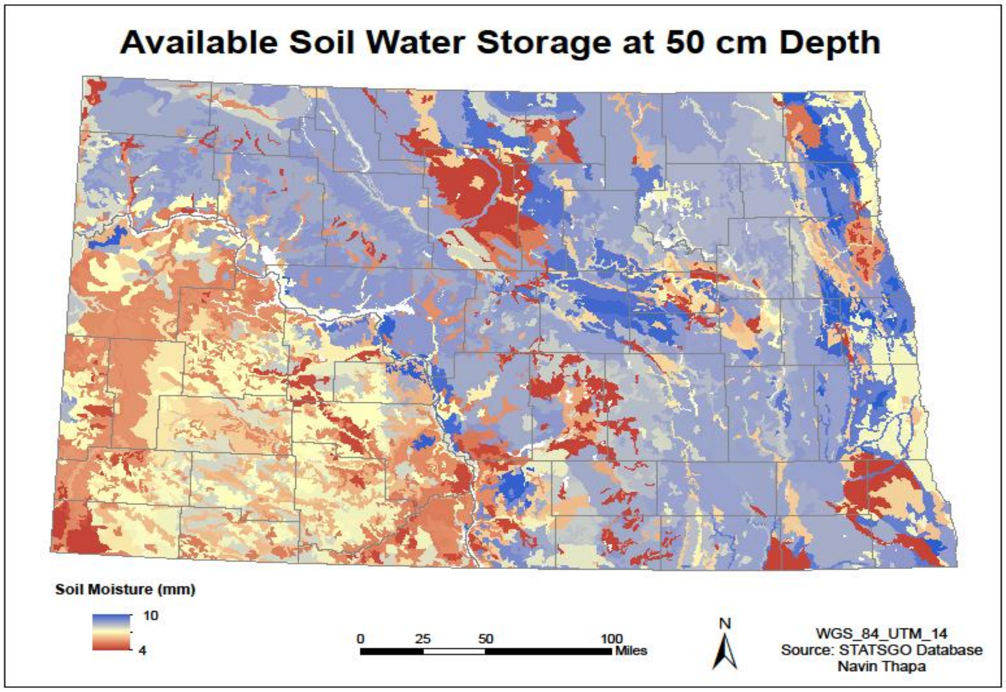
Available Water Storage (AWS) data for North Dakota was obtained from the U.S. General Soil Map database (Soil Survey Staff, 2010). The map was developed by the National Cooperative Soil Survey and supersedes the State Soil Geographic (STATSGO) dataset published in 1994. The dataset consisted of AWS that was commonly estimated as the difference between the water contents at field capacity (1/10 or 1/3 bar) and permanent wilting point (15 bars) tension, adjusted for salinity and soil fragments. AWS in soil up to depths of 50cm was used to determine the initial establishment condition and 150 cm depth to determine the potential yield of switchgrass yield in North Dakota (Fig. 13). The available soil water storage model data for depth 0-

50 cm was selected while considering switchgrass establishment and divided into 3 different soil water classes (Table 2). This helped to analyze the effect of variability in soil water content upon switchgrass growth.

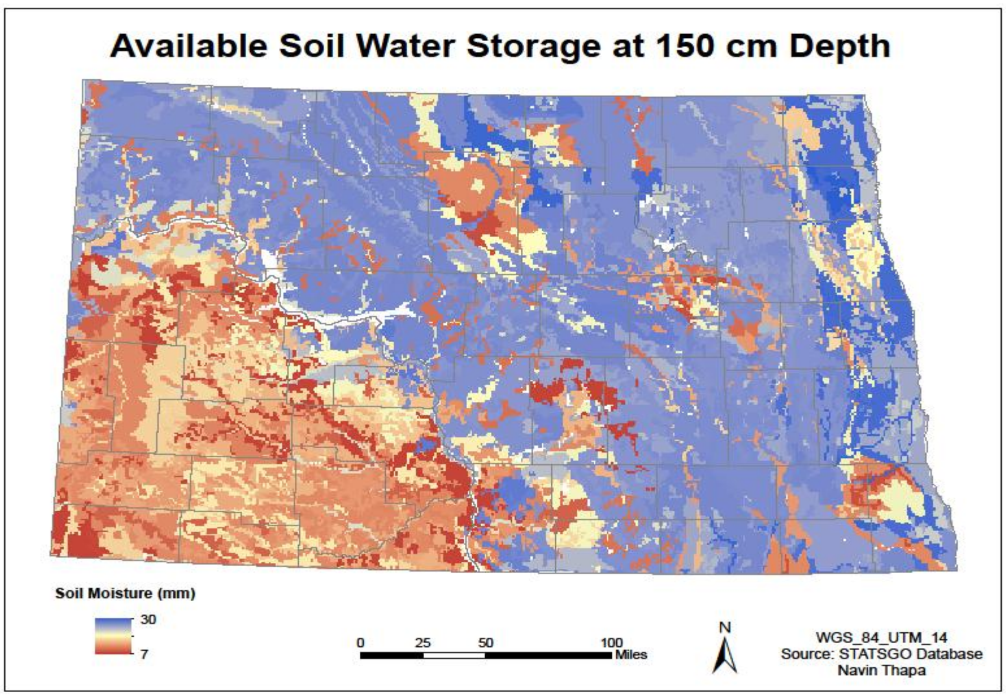
Table 2: Available Water Storage Classes in North Dakota

| | Available water storage (mm) (0-50 cm) | | Available water storage (mm) (0-150 cm) | |
|---|---|---|---|---|
| AWS Class | From | To | From | To |
| 1 | 4.58 | 6.48 | 7.76 | 16.50 |
| 2 | 6.48 | 8.39 | 16.50 | 22.35 |
| 3 | 8.39 | 10.3 | 22.35 | 28.79 |

The AWS value ranged from 4.58-10.3 mm/m up to a depth of 50 cm and 7.76-28.79 mm/m for depth up to 150 cm. Moisture content showed similar patterns at both depths but the value increased with increased depth. The map showed that the moisture content in the southwestern portion of the state, west of the Missouri river escarpment, was less as compared to other areas. The southwestern portion of the state received less precipitation throughout the year and the snow accumulation was less in this area. The lower soil moisture also coincides with the reduced amount of precipitation in the area. The moisture content was relatively high along the eastern border of the state along the Red River Valley.




a.




b.

Fig. 13: Soils Available Soil Water Storage (AWS) in North Dakota at depth 50 cm (a) and 150 cm (b) from the surface level

*Growing Degree Days (GDD)*

The purpose of calculating GDD is to explain the relationship between switchgrass development and accumulated heat units or GDD. GDD is calculated by calculating the mean daily temperature and then subtracting the base temperature needed for switchgrass growth under North Dakota agroclimatic condition (McMaster and Wilhelm, 1997).

$$\text{Accumulated GDD} = \sum \left[ \frac{(Tmax + Tmin)}{2} - Tb \right]$$

Where

Tmax is the daily maximum air temperature,

Tmin is the daily minimum air temperature and

Tb is the base temperature (12°C)

The daily temperature data were collected from the Coupled Model Inter-comparison Project Global Change Model (CMIP_GCM) for 30 years (1971-2000). The calculated GDD values for each year was spatially interpolated at 0.5' resolution and later resampled to 787.4 m (x, y) to maintain uniformity with other important agro-climatic layers for further analysis.

The distribution of accumulated GDD in North Dakota showed that the total heat units value was relatively higher in the south-eastern parts of North Dakota and lower in the north-west. The accumulated GDD (Tb=12°C) required by switchgrass to reach maturity was standardized at 600° C. Fig. 14 shows that certain areas in the northeastern region of the state have lower than threshold level of accumulated GDD to reach maturity.

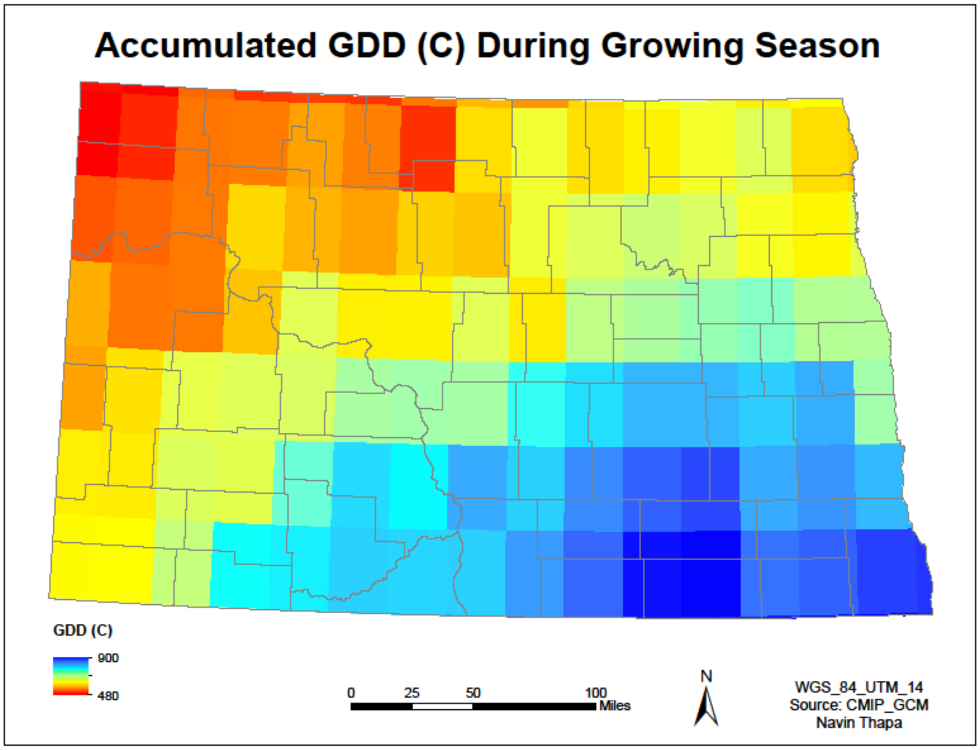



Fig. 14: 30 years average daily GDD accumulation during growing season (Apr.-Sept.) (Tb= 12°C) in North Dakota (1971-2000)

## Establishment Risk Analysis

The creation of a composite layer or theme for switchgrass establishment risk required combining those parameters in MCAS-S. Table 3 shows the layers used for assessing establishment risk and land use. The process required assigning a numerical relative weight value to each agro-climatic layer based on their relative importance for switchgrass establishment. In many situations, it is difficult to assign relative weights to the different criteria involved in making a decision on risk factor analysis for a particular agro-climatic condition. It is therefore necessary to adopt a technique that would allow estimation of such weighted value. A technique known as Analytical Hierarchical Process (AHP) technique (Saaty, 1977) was used to determine the weights.

Table 3: Layers used for switchgrass suitability analysis

| | Themes | Layers used | Description |
|---|---|---|---|
| 1 | Land use | Land classification | Time series Land use classification (1998-2009) |
| 2 | Establishment risk | Snow depth | Mean snow depths for winter months (January - March) (2003-2010) |
| 3 | | Total precipitation | Normal precipitation (1971-2000) |
| 4 | | Minimum temperature | Normal minimum temperature for months (January – March) (1971-2000) |
| 5 | | Average soil moisture | Available soil water at depth 0-50cm |
| 6 | | GDD | Growing degree days with base temperature 12°C |
| 7 | | SD snow | Standard Deviation in mean snow depth |
| 8 | | SD precipitation | Standard deviation between normal precipitation and 2000/09 data |
| 9 | | SD temperature | Standard deviation between normal minimum temperature and 2000/09 data |

AHP is one of the most widely used multiple criteria decision-making tool. This method is an approach to calibrate a numerical scale for the measurement of quantitative and qualitative parameters (Vaidya and Kumar, 2006). The essence of AHP is to construct a matrix expressing the relative importance values of a set of input variables or attributes. The first step in the AHP process is to build a hierarchy or a stratified system of ranking variables based on the understanding of their importance. The method assigns odd integers for each parameter based on its relative importance (Table. 3). Even number is assigned for intermediate importance. Once the hierarchy is constructed, the variables are analyzed through a series of pairwise comparisons against the goal for importance, and priorities are derived as numerical scales of measurements. These scales are used during the multi-criterion decision making process.

The AHP technique was used to develop a numerical scale for each parameter defining the establishment risk theme. The parameters affecting switchgrass establishment were arranged in hierarchical order for pairwise comparison, and a computed numerical relative weigh (importance) was assigned to each of them. Without AHP, decision makers might base their decisions only on a subset of important criteria without understanding the hierarchical importance of the layers and the possible interactions between them in decision makings (Handfield et al., 2002). Table 4 shows the relative value assigned to pairwise attribute layers according to the relative importance of each layer for determining establishment risk. A higher relative rank (weighting) implies that the parameter has a more significant role in moderating establishment of switchgrass in an area. Similarly the lower relative rank value implies that the parameter was relatively less important in influencing switchgrass establishment.

Table 4: Scale for comparing attributes for attributes for AHP (Saaty and Vargas, 1991)

| Relative rank | Attributes |
|---|---|
| 1 | Both attributes are equal importance |
| 3 | Attribute on horizontal axis is slightly more important that the attribute on the vertical axis |
| 5 | Attribute on horizontal axis is moderately more important that the attribute on the vertical axis |
| 7 | Attribute on horizontal axis is significantly more important that the attribute on the vertical axis |
| 9 | Attribute on horizontal axis is much more important that the attribute on the vertical axis |
| 2,4,6,8 | Intermediate values |
| Reciprocals | For inverse comparison |

The attribution of relative weightings, the evaluation criteria and hierarchical structuring were mainly based on literature survey and discussions with experts in the related field. Heaton et al. (2004) analyzed several peer reviewed publications and showed that switchgrass responded positively to precipitation and nitrogen fertilization. Berdahl et al. (2005) found that high N application did not guarantee increased biomass yield when water availability was reduced. When rainfall is not sufficient or below threshold level, switchgrass cannot extract sufficient nutrients from the soil potentially leading to nutrient stress. Similarly very high rainfall could increase leaching of soil nutrients from root zone and cause nutrient deficiency. Precipitation amount is most important especially during the early stand establishment period and during the critical portions of the growing season. Based on these factors and previously described literature, total precipitation amount was considered the most important parameter among the climate data for switchgrass establishment in North Dakota.

The northern distribution of switchgrass is shown to be at least partially a function of cold winter temperature (Vogel et al., 2002; Berdahl et al., 2005). Berdahl et al. (2005) showed that cool temperature and short growing season in North Dakota could limit switchgrass growth potential. Minimum temperature could impose considerable risk if there is not sufficient insulating cover such as snow cover to protect switchgrass stands from winter injury. Snow cover could provide significant protection when severe below freezing winter temperatures impose threat to switchgrass survival (Berdahl et al., 2005). Minimum temperature and protective snow depth both play equally important role in determining winter survival of switchgrass in North Dakota and were both ranked as second important factors in establishment risk assessment.

Table 5: Relative rankings of layers to establish priorities among winter risk mapping themes

| Risk map. | Total ppt. | Tmin | Snow depth | Soil moisture | GDD | SD ppt | SD Tmin | SD snow |
|---|---|---|---|---|---|---|---|---|
| Total ppt. | 1 | 3 | 3 | 5 | 5 | 7 | 9 | 9 |
| Tmin | 1/3 | 1 | 1 | 3 | 3 | 5 | 5 | 7 |
| Snow depth | 1/3 | 1 | 1 | 3 | 3 | 5 | 5 | 7 |
| Soil moisture | 1/5 | 1/3 | 1/3 | 1 | 1 | 3 | 3 | 5 |
| GDD | 1/5 | 1/3 | 1/3 | 1 | 1 | 3 | 3 | 5 |
| SD Ppt | 1/7 | 1/5 | 1/5 | 1/3 | 1/3 | 1 | 1 | 3 |
| SD Tmin | 1/9 | 1/7 | 1/7 | 1/5 | 1/5 | 1/3 | 1 | 1 |
| SD snow | 1/9 | 1/7 | 1/7 | 1/5 | 1/5 | 1/3 | 1/3 | 1 |

Switchgrass when managed for biomass purpose is normally not irrigated. Available soil water for switchgrass use can hence be an important factor affecting the establishment of switchgrass when rainfall is irregular. Total rainfall is one important factor contributing to soil moisture, but the timing and size of rainfall events are the important modifiers (Wullschleger et al., 2010). So the interaction between rainfall and soil texture could affect soil water holding capacity and its water availability with implication for seedling establishment and yield. Based on this, soil moisture within the root zone of switchgrass was considered the third important factor assessing establishment risk.

Close relationship has been observed between developmental morphology of switchgrass and GDD (Sanderson and Wolf, 1995; Heaton et al., 2004). The shorter growing season in North Dakota often limits the accumulated GDD required to reach maturity, resulting in late maturity of certain cultivars from southern origin. Due to this effect, GDD was also ranked as third in importance.

The deviations of precipitation from long-term mean were analyzed to assess the risk associated due to change in precipitation pattern and was assigned fourth rank in importance. The deviations in the value of minimum temperature and snow depth were ranked as fifth in importance.

The relative ranking assigned to each layer was normalized in the form of a matrix as shown in Table 6. The horizontal rows in the normalized matrix showed the calculated importance value for each layer in relation to other, the average of which showed the final weighting of the layer.

Table 6: Normalization of matrix (Table 5) for each cell with respect to the total of their respective column. The average value of each row gives percentage weighting for each layer.

| Risk map | Total ppt. | Tmin | Snow depth | Soil moisture | GDD | SD ppt | SD Tmin | SD snow | Avg. × 100% |
|---|---|---|---|---|---|---|---|---|---|
| Total ppt. | 0.41 | 0.49 | 0.49 | 0.36 | 0.36 | 0.28 | 0.33 | 0.24 | 37.06 |
| Tmin | 0.14 | 0.16 | 0.16 | 0.22 | 0.22 | 0.20 | 0.18 | 0.18 | 18.36 |
| Snow depth | 0.14 | 0.16 | 0.16 | 0.22 | 0.22 | 0.20 | 0.18 | 0.18 | 18.36 |
| Soil moisture | 0.08 | 0.05 | 0.05 | 0.07 | 0.07 | 0.12 | 0.11 | 0.13 | 8.74 |
| GDD | 0.08 | 0.05 | 0.05 | 0.07 | 0.07 | 0.12 | 0.11 | 0.13 | 8.74 |
| SD Ppt | 0.06 | 0.03 | 0.03 | 0.02 | 0.02 | 0.04 | 0.04 | 0.08 | 4.10 |
| SD Tmin | 0.05 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.04 | 0.03 | 2.47 |
| Total ppt. | 0.05 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 2.17 |
| Total | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 100.00 |

After evaluating the relative weights of the agro-climatic parameters defining switchgrass establishment criteria, the second step was the construction of composite establishment risk theme. An integration of AHP in MCAS-S to determine weighting for establishment risk analysis produced promising theme. In MCAS-S interface, the weighted agro-climatic layers were combined to form a composite winter establishment risk map. Each agro-climatic layers affecting switchgrass survival were classified taking into account their respective minimum establishment threshold condition. Threshold values were defined as the minimum agro-climatic condition required for switchgrass establishment. Two to five equal interval classes were defined for each of the eight layers impacting switchgrass establishment (Table 7). The relative weights assigned to each of the eight layers were incorporated into MCAS-S workspace and a composite map was produced for establishment risk (Fig. 15).

Table 7: Class intervals for agro-climatic parameters defining switchgrass establishment

| Class\layers | Class 1 | Class 2 | Class 3 | Class 4 |
|---|---|---|---|---|
| Total ppt (mm) | < 400 | 400 to 450 | 450 to 500 | >500 |
| Tmin (°C) | > -10 | -10 to -15 | -15 to -18 | < -18 |
| Snow depth (mm) | < 100 | 100 to 200 | 200 to 300 | > 300 |
| Soil moisture (mm/m) | < 6.48 | 6.48 to 8.39 | >8.39 | |
| GDD (°C) | <600 | >600 | | |
| SD ppt | > 35 | 35 to 25 | 25 to 15 | <15 |
| SD Tmin | >1.20 | 1.20 to 0.85 | 0.85 to 0.50 | < 0.50 |
| SD snow | >225 | 225 to 150 | 150 to 75 | <75 |

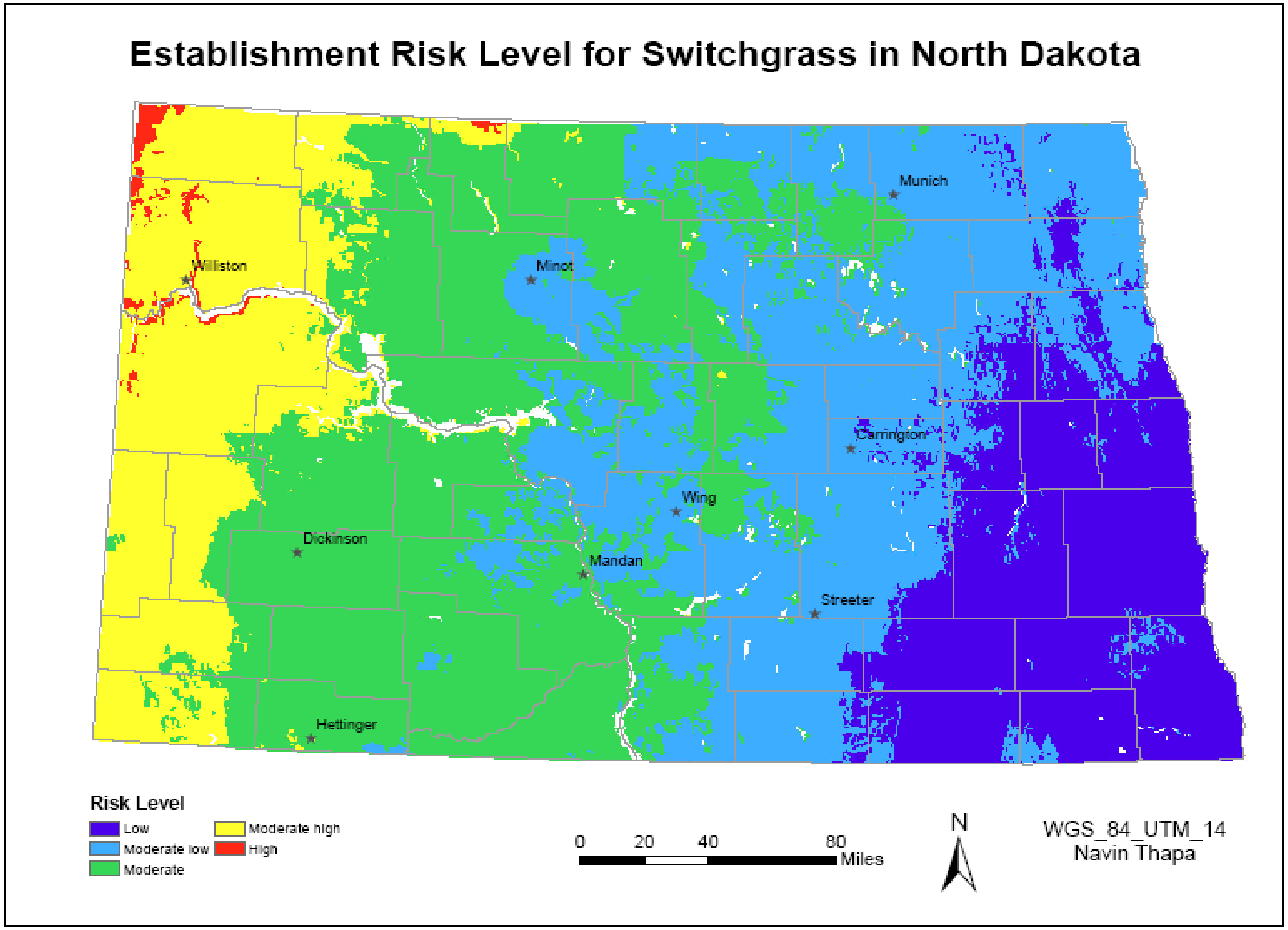



Fig. 15: Establishment risk for switchgrass in North Dakota based on various agro-climatic parameters

## Discussion

The combination of AHP and GIS tool in multi-criteria risk factors analysis proved to be a promising method that can be applied for switchgrass stand establishment risk analysis. The analysis result showed that the central and eastern parts of the state offer a favorable combination of agro-climatic factors for switchgrass establishment as compared to the western regions. The result was mainly dependent on the intellectual judgment of the weightings attributed to each agro-climatic layer. Due to the higher importance of total annual precipitation amount, it is the most significant parameter in the establishment risk assessment. The histogram in Fig. 15 shows the percentage of area falling in every class characterizing establishment risks. The largest proportion of the state area (35%) lies in moderate risk zone. About 16% of the area in the east is classified as low risk zone while 1% of area in the west is considered as high risk zone. The western part of the state is also not the area of natural occurrence of switchgrass owing to its agro-climatic severity. Western North Dakota is subjected to periodic drought and fluctuating precipitations that hinder the capability of the region to successfully establish switchgrass stands and provide a consistent supply of switchgrass biomass for bioenergy purpose. This risk pattern matches the dominant land use pattern in North Dakota and reflects the close relationship between the existing land use and agro-climatic suitability. Switchgrass is found to be less sensitive to winter stress in the southeast part of the state which is also the area mostly dedicated to cash crops production.

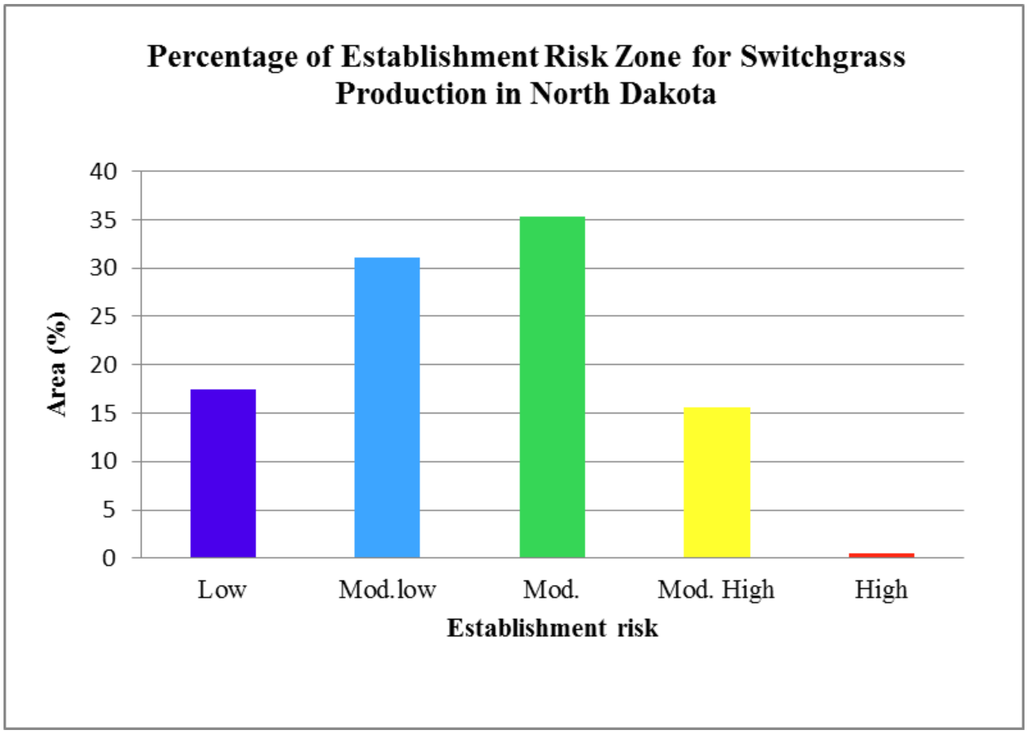



Fig. 16: Distribution of switchgrass establishment risk zones in North Dakota

# Chapter VI

# LAND USE SUITABILITY

## Land Suitability and Switchgrass Adoption Factors

USDOE selected switchgrass as a model crop for bioethanol production due to its demonstrated high productivity across a wide range of climatic condition, its suitability for marginal land, its low water and nutrients requirements and positive environmental benefits (Lynd et al., 1991; McLaughlin, 1993). Land areas that are less favorable for growing cash crops would be appropriate for switchgrass. Availability of such lands could therefore be important when adopting switchgrass as a perennial herbaceous crop for bioenergy purpose. Land that can be dedicated for switchgrass production in North Dakota is expected to come from marginal land currently in crop production, pastures or idle land enrolled in conservation programs such as Conservation Reserve Program (CRP) (McLaughlin et al., 2002; Mitchell et al, 2010). With about 1.2 million ha of land under CRP and 3 million ha of erodible marginal land, North Dakota offers great potential for perennial bioenergy crop production.

Much of the recent debate about bioenergy viability has focused on the competition between cropland use for food production or for bioenergy production. There are increased concerns that introducing perennial switchgrass into cropping could lead to switching permanent crop land and grassland into switchgrass fields due to their higher productivity. This can result in competition with local food crop production, cause loss of different types of grassland habitat for wildlife, and have other environmental consequences such as loss of soil organic carbon, nutrients during tillage, etc. The current analysis assumes that the low agricultural productivity marginal lands or intermittent agricultural lands or grasslands are highly desirable for growing switchgrass in North Dakota. It is assumed that growing switchgrass in these land categories should not affect food productions or cause biodiversity loss as they are not preferred for growing food crop or provide suitable habitat for wildlife. Permanent croplands or permanent grasslands are excluded for this reason as they are considered least suitable for bioenergy switchgrass production and potentially they may never be used for bioenergy purpose.

## Land Use Data Collection and Analysis

Land use data for North Dakota was obtained from the crop data layer database (USDA/NASS). Annual land use classification data from 1998-2009 were used. Data layers for each year were first reclassified to develop a common classification cross reference system. Four broad classes were selected and they were: 1. Cropland; 2. Grassland/Woodland; 3. Wetlands and 4. Developed land/Water bodies. The 12 annual raster layers with these classes were stacked to create a single 12-bands stacked layer. An unsupervised classification was run using ENVI on the stacked layers to characterize temporal land use pattern. The classification resulted into 11 different undefined classes which were then refined with a low pass filter. The filtered layer was then reclassified into 7 different classes based on temporal land cover pattern during the analysis time-period, 1998-2009 (Fig. 5). The layer was gridded at 787.41 m (x, y) resolution for further analysis of switchgrass production suitability in MCAS-S.

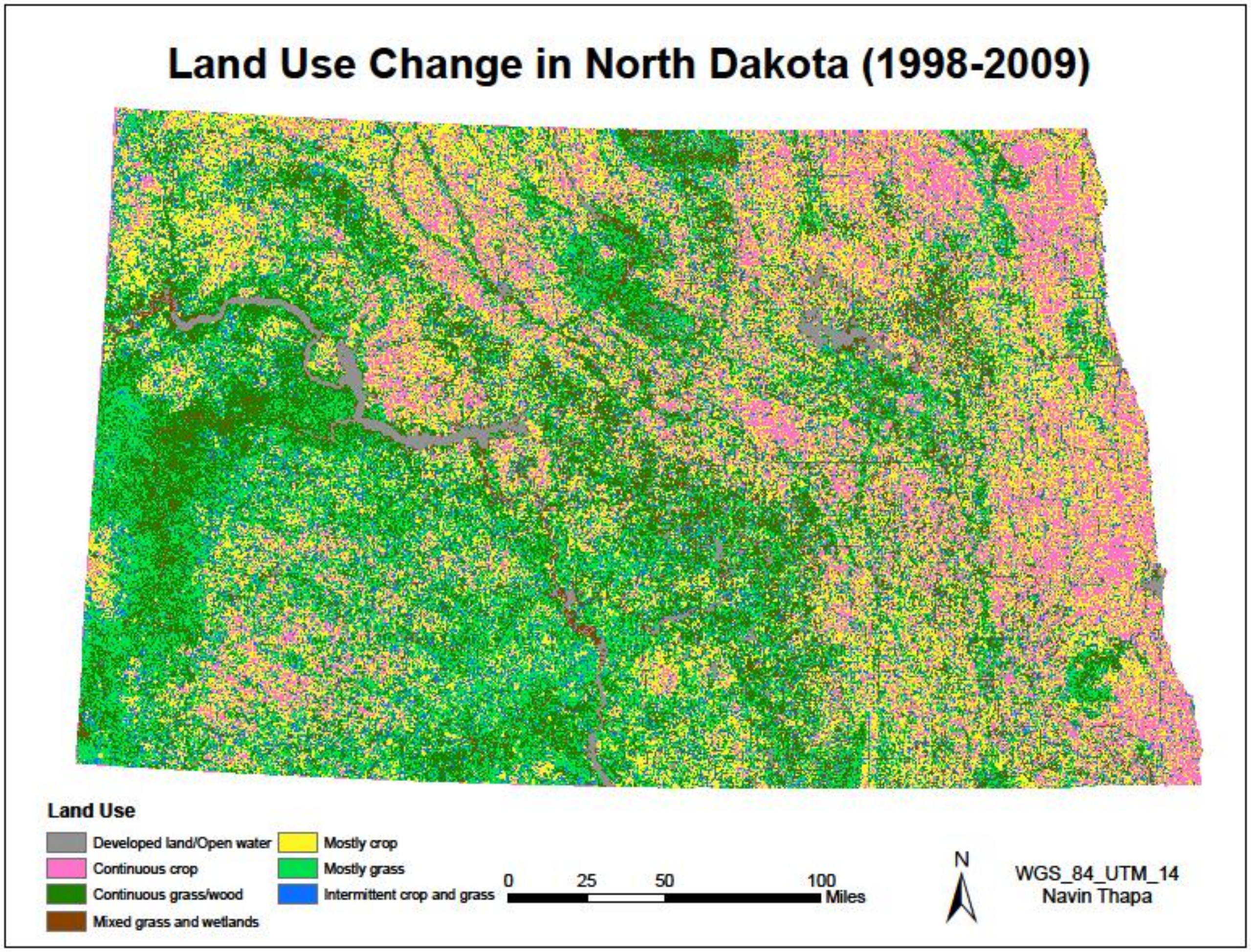



Fig. 17: Land use change in the past 12 year period between 1998-2009 in North Dakota (NASS). (Mostly crop or mostly grass includes area under crop or grass for 7-9 yrs respectively; intermittent crop and grass include 5-7 yrs under crop or grass).

## Importance Determination for Each Land Cover Class

The general process of land-use suitability determination is based on analyzing necessary conditions to adopt switchgrass in a particular land-use type. Landuse to determine the land classes were judged based on criteria on past use. Paine et al. (1996) recommended growing switchgrass on marginal lands such as highly erodible land, or poorly drained soils, thus avoiding competition with food crops. Land parcels that have been under continuous agriculture or continuous grassland were considered of low importance for switchgrass plantation as those lands would hardly or never be used for such purpose. These are mostly the productive lands that are highly suitable for agriculture crop production or for biodiversity conservation. Land area that are preferred for switchgrass are former agriculture fields, fallow lands that may or may not be in agricultural production currently but has such potential with some restrictions. Such lands are the marginalized lands with less opportunity for cash crop to be profitable due to lower potential productivity. These types of land could also be highly erodible and would require erosion control measures such as reduced or no tillage, contour strips etc. Such marginal category lands with significant erosion or drought hazards are considered best for growing switchgrass. The lands under intermittent cropping and grasscover likely fall under this category since they may not remain productive when continuously cropped and often tend to be underutilized.

## Relative Ranking of Land Class Importance

A numerical raster value was assigned for each landuse class in ascending order with lowest value representing land class with least priority and highest value representing highest priority for conversion to switchgrass field (Table 8). The land area that had been under agriculture for more than 10 years in the last 12 years of assessment were the continuous agriculture land and were considered least favorable for growing switchgrass to avoid any possible competition with established croplands. Similarly land area under continuous grassland/woodland were second least priorities after continuous agriculture as conversion of such permanent grassland would affect local biodiversity and release soil carbon to the atmosphere. Land areas with wetland or grassland were given third least priority. Higher priorities were given to the land areas that have been under intermittent land class that have been under crop and grass cover for 5-7 years each during the assessment period. The open water bodies and urban developed lands are excluded from the present consideration for bioenergy use. The histogram in Fig. 18 shows the total land area under each category of land-use classification. A large portion of the land cover falls under intermittent use category, i.e. under both crop cover and grasscover in the past for 5 to 7 years. These lands are often underutilized due to low productivity and are marginalized. The abundance of such category offers high opportunity for switchgrass adoption in North Dakota.

Table 8: Raster layers for various land use classes

| Land use | Raster Class |
|---|---|
| Developed structures and open water | 0 |
| Continuous crop (10+ yrs) | 1 |
| Grassland/woodland (10+ yrs) | 2 |
| Mixed grassland/woodland and wetlands | 3 |
| Mostly crop (7-9/12 yrs) + few grassland | 4 |
| Mostly grassland (8-9 yrs) + intermittent crops (2-3 yrs) | 5 |
| Intermittent crop and grassland | 6 |

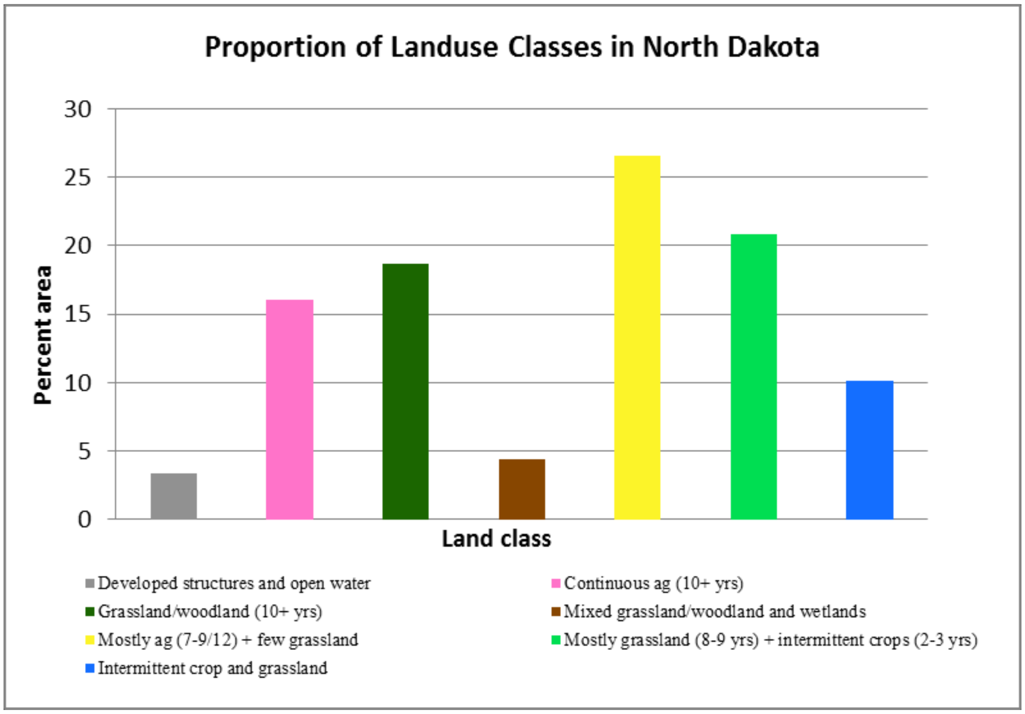



Fig. 18: Proportion of various land use classes in North Dakota resulted from unsupervised land use classification

# CHAPTER VII

# PRODUCTIVITY MODELING

## Productivity and Potential Yield

Crop productivity is determined by a large number of factors such as weather parameters, soil types, genetic potential of crop cultivar and crop management variables which significantly vary across time and space. The year-to-year crop yield variability for a given area can be normally estimated through empirical or crop simulation approach using weather, soil and cultivation practices.

Process based models such as ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) (Kiniry et al., 1992) holds promise as a realistic tool for simulating switchgrass biomass yield and simulates daily plant growth through LAI, light interception and a constant for converting intercepted light into biomass (radiation-use efficiency). ALMANAC has already been validated for switchgrass yield simulation in North Dakota and does not require local calibration of plant parameters or hydrology components (Kiniry et al., 2008).

## Model Description

ALMANAC is a physiologically based process-oriented crop growth model that takes into account switchgrass growing conditions and support management decisions, to predict yields over large areas. ALMANAC was designed to quantify productivity based on key plant-environment interactions (Kiniry et al., 1992). The parameters used for switchgrass productivity simulation in ALMANAC are based on work done with Alamo cultivar of switchgrass at different locations in Texas (Kiniry et al., 1996). The model is relevant for the present simulation of switchgrass productivity in North Dakota since it has been parameterized to work at several locations in the Northern Great Plains. Appropriate soil parameters have been developed to characterize soil water and nutrient supply, and the model parameterizes LAI to provide realistic yield simulation (McLaughlin et al., 2006).

The model includes subroutines and functions from the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1984) that shares components for simulation of crop growth. ALMANAC simulates the water balance, the nutrient balance and the interception of solar energy for switchgrass. The model has daily time step and is designed to simulate yield on the basis of analysis of weather inputs. The model uses readily available daily weather data and a wide range of USDA-NRCS soil data for predicting switchgrass yield. The model simulates light interception by using Beer's law (Monsi and Saeki, 1953), LAI of the total canopy and the potential daily biomass increase with a species specific value of radiation use efficiency (RUE) (Kiniry, 2008). ALMANAC has the option to generate weather or read daily weather input data. A weather generator subroutine, based on the concepts of the WGEN (Weather Generator) model (Richardson and Wright, 1984), is capable of estimating multiple years of daily weather. For long term yield simulation and decision making, it is suggested to use generated weather data, while for model testing, measured daily weather is usually inputted (Kiniry and Spanel, 2009). The basic weather components entered are solar radiation (langleys/day), maximum temperature ($^{\circ}$C), minimum temperature ($^{\circ}$C), precipitation (mm), wind speed (m/s) and relative humidity. Missing values for rain and temperatures could be generated if the value is set to 999. Solar radiation could be generated if the value is set to zero of left blank. Growth parameters for upland switchgrass are available within the model. Field location, soil type and crop management schedules are selected or edited manually.

## Methodology: Potential Yield/Productivity Analysis

ALMANAC simulation of switchgrass yield was carried out under prevalent water-limiting condition (in non-irrigated fields) to represent the most common management practice followed for planting perennial crops in North Dakota. The weather and soil inputs were readily available. Weather inputs were downloaded from the nearby weather station. The soil parameters for these locations were derived from soil database. Parameters specific to the growth of upland switchgrass variety were available within the model. Management input parameters such as planting and harvest date, planting density, row spacing, etc. were derived from literature description of field experiments across North Dakota. Information on parameters for nutrient inputs, soil types for each site were obtained from field researchers working at different NDSU Research Extension Centers (REC). Daily weather input data for yield simulation were derived from nearby NDAWN weather stations and the ND cooperative weather observers archive. The degree days from planting to maturity (PHU) were computed for each site taking a 30-years average GDD with a base temperature of 12°C (Kiniry et al., 2008).

## Simulation Error and Yield Validation

Several previous works have attempted to evaluate switchgrass biomass yields in North Dakota through a network of established field plots studies (Schmer et al., 2006; Nyren et al., 2010, 2011; Berdahl et al., 2005). The yields observed at those plots in different years were used as references to evaluate the accuracy of the ALMANAC model yield simulations (Table 9). The ALMANAC model realistically simulated the mean switchgrass yields for several sites. The simulated and observed yield results showed higher yields along the central-eastern side of the state and gradually decreased toward the west. The average yield at Carrington was the highest, while Williston in the far west was the lowest. The mean difference of observed and simulate yields were compared for each site. The mean simulated yield was approximately 8% higher than the mean measure yield. A positive correlation coefficient (r) of 0.79 was found between the observed and simulated switchgrass yield (Fig. 19). The root mean square error (RMSE) for simulation was 2.08 and rRMSE (relative-RMSE) (ratio of RMSE and mean simulated yield) was 35%. The significance test (t-test) of the correlation coefficient shows that the result is significant at 95% confidence limit. The mean error of prediction (simulated minus measured yields) for all simulated value was -0.48 tons/ha. The negative value in mean error prediction implied that the model has overestimated the biomass yield. The model has significantly underestimated yields for site in Carrington by 2.36 to 3.54 t/ha between years 2007 and 2010. The model has overestimated yield from sites such as Streeter, Minot, Hettinger etc. The residual plot in Fig. 20 showed that the model tends to underestimate yield for higher observed values especially when the observed yields were more than 9 tons/ha. The positive residue value (error of prediction) in the plot implies that simulated yields underestimated the actual yields while negative residue reflects that the yields were overestimated. The plot also showed that the model mostly overestimated yield where the mean observed yields were less than 5 tons/ha.

Table 9: Observed and simulated switchgrass yield and associated error

| Locations (N) | Year | Site Names | Measured yield (t/ha) | Estimated yield (t/ha) | Error ($D_i$) |
|---|---|---|---|---|---|
| 1 | 2000 | Mandan | 8.06 | 7.18 | 0.88 |
| 2 | 2001 | | 8.43 | 8.74 | -0.31 |
| 3 | 2002 | | 2.55 | 2.84 | -0.29 |
| 4 | 2010 | | 6.19 | 6.37 | -0.18 |
| 5 | 2007 | Minot | 4.86 | 6.95 | -2.09 |
| 6 | 2008 | | 3.64 | 6.23 | -2.59 |
| 7 | 2009 | | 5.67 | 4.96 | 0.71 |
| 8 | 2010 | | 9.27 | 7.15 | 2.12 |
| 9 | 2001 | Dickinson | 4.06 | 6.04 | -1.98 |
| 10 | 2002 | | 5.61 | 3.62 | 1.99 |
| 11 | 2003 | | 3.98 | 5.08 | -1.10 |
| 12 | 2007 | Williston | 0.77 | 2.4 | -1.63 |
| 13 | 2008 | | 1.36 | 3.27 | -1.91 |
| 14 | 2009 | | 2.19 | 1.48 | 0.71 |
| 15 | 2010 | | 2.90 | 4.2 | -1.30 |
| 16 | 2007 | Carrington | 14.3 | 11.94 | 2.36 |
| 17 | 2008 | | 11.98 | 8.83 | 3.15 |
| 18 | 2009 | | 10.63 | 7.91 | 2.72 |
| 19 | 2010 | | 9.13 | 5.59 | 3.54 |
| 20 | 2002 | Streeter | 4.64 | 5.01 | -0.37 |
| 21 | 2007 | | 4.44 | 6.59 | -2.15 |
| 22 | 2008 | | 1.83 | 6.66 | -4.83 |
| 23 | 2009 | | 4.71 | 7.15 | -2.44 |
| 24 | 2010 | | 6.7 | 8.81 | -2.11 |
| 25 | 2009 | Hettinger | 3.18 | 4.03 | -0.85 |
| 26 | 2010 | | 5.52 | 8.27 | -2.75 |
| 27 | 2002 | Munich | 4.24 | 6.12 | -1.88 |
| 28 | 2010 | Wing | 2.92 | 3.66 | -0.74 |
| | | | Mean= 5.49 | Mean= 5.97 | Mean = -0.48 |

The simulated yield result for each year showed that the model did not perform very well in accounting for year-to-year variability in yields for some of the locations. Several factors could be attributed to the variation in switchgrass yield simulation in North Dakota. The accuracy of any crop model in simulating yield is determined by the preciseness of the algorithm describing the real processes as well as by the quality of its input data (Fodor and Kovac, 2003). The simulation of crop yield by ALMANAC model requires extensive input datasets. ALMANAC model would not be able to precisely simulate the process if the data input is not entirely accurate or available. Weather and soil data are important inputs for switchgrass simulation using ALMANAC. Daily weather data and soil data were collected from the nearest available weather stations for each test site which at several instances were several miles away from the actual test site. Parameters such as solar radiation, temperature might not change significantly within that distance but precipitation amount data could vary even within a small spatial variation. Precipitation is considered the most important parameter determining switchgrass biomass yield in North Dakota and even a small change in input weather data at some locations could resulted in some uncertainties in yield simulation. The simulation result would have been more precise if the weather data were available from individual sites throughout the study period. Similarly, soil data used for the simulation were the model derived generic data for each soil type. The actual field measured data on soil characteristics from each plot would have reduced some error that might have been inherited by the generic soil data derived from ALMANAC model.

ALMANAC model simulated yields from drier sites such as Williston was almost double the actual observed yields. This also seems likely for such sites that the model did not precisely simulate yield under the circumstances where mean precipitation is too low than threshold level.

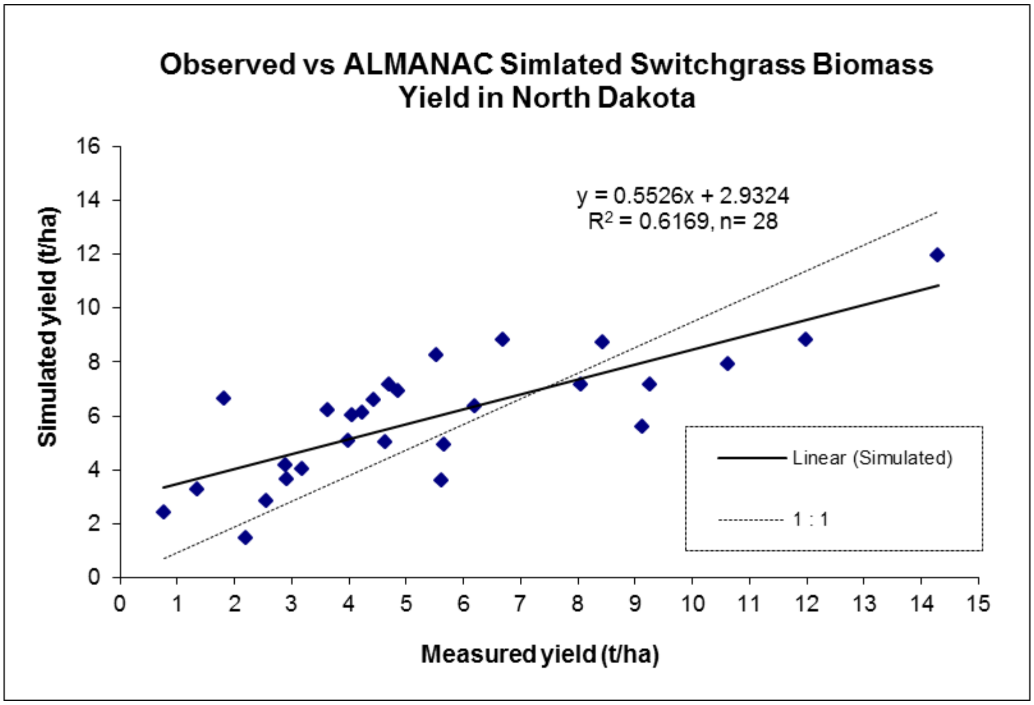



Fig. 19: Observed and simulated switchgrass yield at different years for nine locations across North Dakota

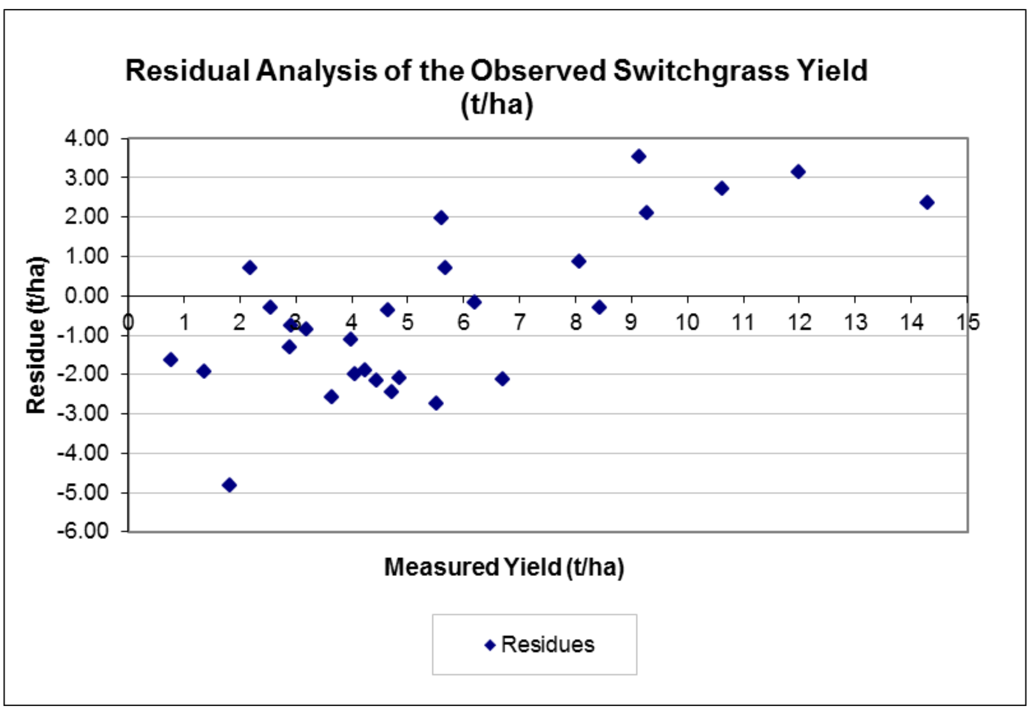



Fig. 20: Residual analysis of ALMANAC simulated biomass yield at different field sites

## Spatial Interpolation of Switchgrass Yield

The long term potential yield of switchgrass across North Dakota was spatially interpolated using ALMANAC simulated yield values from 17 different sites (Fig.21). Potential yield was simulated for 12 years (1998-2009) with variable soil types and weather conditions. Co-kriging method in ArcGIS was used for multivariate spatial interpolation of switchgrass yield across the state using variation in rainfall, temperature and available soil water. The interpolation method had the lowest RMSE of 0.7987. The spatial interpolation of simulated yield however, does not consider topography and landscape variations across the locations that could be associated with soil type, weather pattern etc.

The spatial interpolation map of simulated yield shows that the yield potential of switchgrass biomass is high along the along the Red River Valley in the south east part of the state and decreases gradually to the west. A large proportion of land area approx. 34% in the west had lowest yield of less than 4.5 t/ha (Fig. 22). Less than 5% area in the east had potential yield of more than 7.5 t/ha. Switchgrass yield was lower towards west and was highly variable as any occurrence of severe weather conditions during the establishment or growth period could significantly impact the stand survival and total biomass yield.

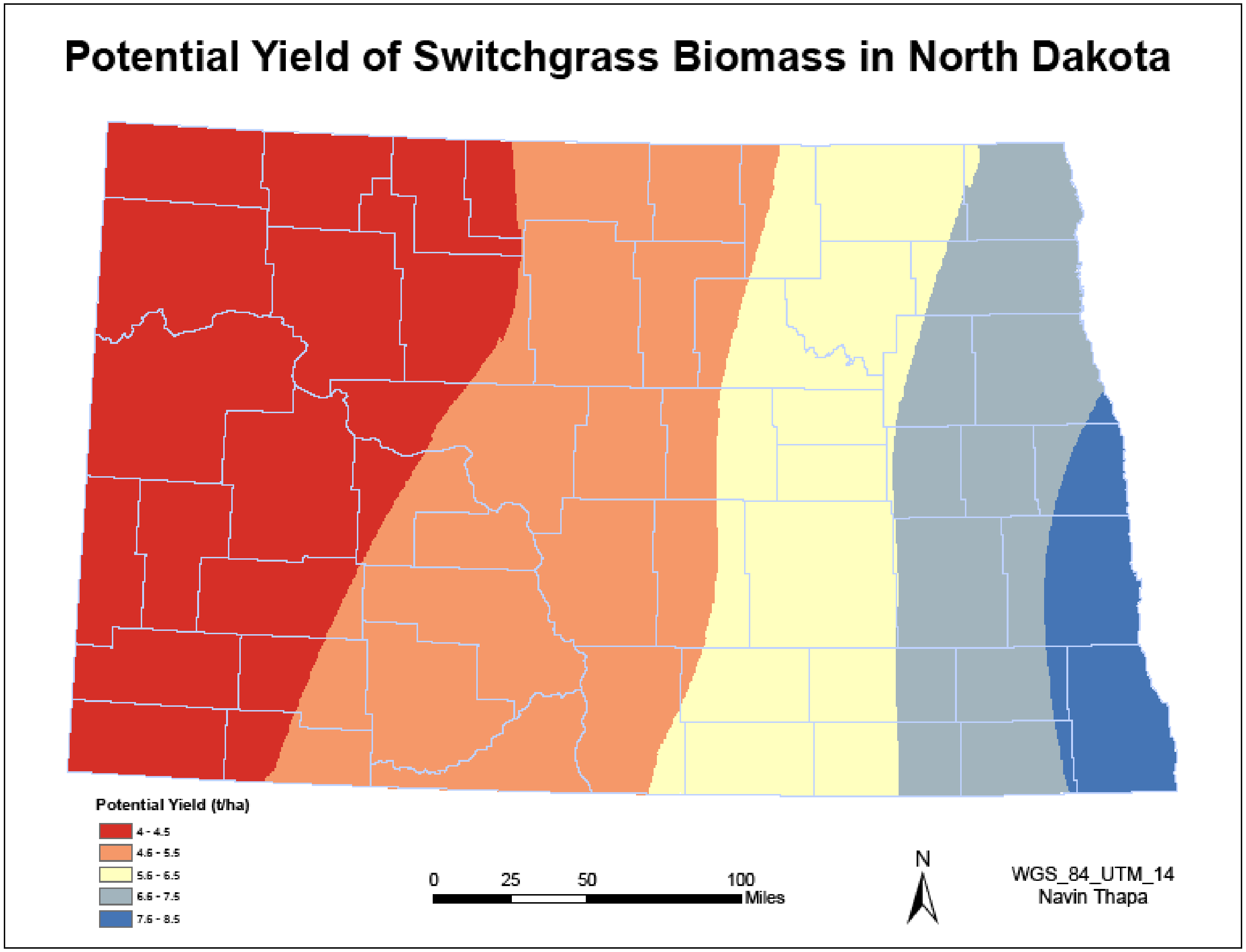



Fig. 21: Potential yield of switchgrass in North Dakota based on ALMANAC simulated values

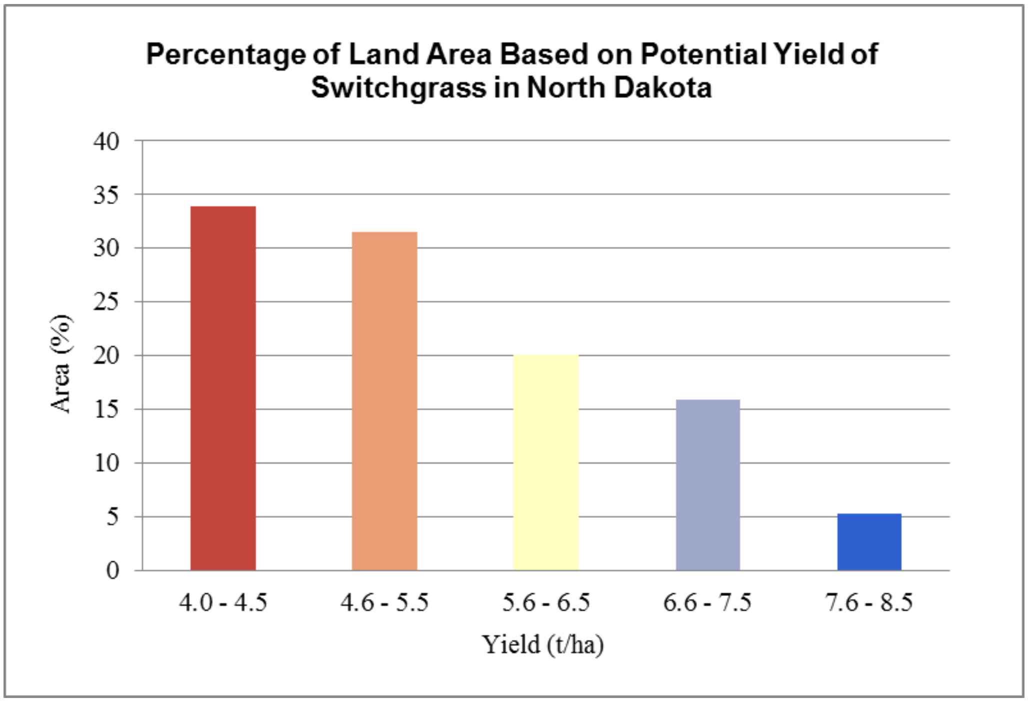



Fig. 22: Percentage of land area based on spatially interpolated potential yield of switchgrass

Production Challenges for Cellulosic Ethanol Production

Several environmental and economical challenges could impose limitations on sustainable switchgrass feedstock production for bioenergy purpose in North Dakota. For switchgrass production to be sustainable, it must be productive, protective of environmental resources and profitable to the producers. A reliable and consistent supply of switchgrass feedstock is necessary for running cellulosic switchgrass based bioethanol plant. Based on the present study, it is assumed that it is reasonable to expect an average of 5 tons per ha per year or more of switchgrass in North Dakota on a commercial scale although wide disparities in yields exist among sites at different years. It is generally assumed that in the first year of production, yields are estimated to be 30 percent of the full potential while in second year it is normally seventy percent and in the third year, yields should be at the hundred percent level (Garland, 2008). It is known that an average of 88 gallons of ethanol could be produced per tons of switchgrass feedstock (Mitchell et al, 2010) (80 gal from 1 US tons; 1 US tons = 0.9071 metric tons). Based on this value, it can be estimated that an ethanol plant with 50-million gallon production capacity per year would require about 567,000 tons (625,000 US tons) of switchgrass feedstock per year (Table 10). Around 113,400 ha of land will be required to produce this much switchgrass feedstock from a land area with an average yield of 5 tons/ha. If all this available land is to be used for switchgrass feedstock production, 2,575 million gallons of ethanol could be produced. Table 10 below shows the potential biomass yield and ethanol production from different regions in North Dakota based on potential yield estimated using ALMANAC model. The average yields for each yield class were analyzed to calculate total feedstock based on available land area. This feedstock was then converted to ethanol production using the conversation function suggested by Mitchell et al (2010). The analysis shows that about 28% of ethanol production in North Dakota would be from moderate quality land with biomass yield of about 5 tons/ha (Fig. 23).

Table 10: Land area required to grow 567,000 tons of dry matter per year switchgrass biomass to provide 50-million gallon cellulosic ethanol plant for North Dakota

| Yield (t/ha) | Average yield (t/ha) | Available/suitable land area (ha.) | Land area (ha.) needed to produce 567,000 tons/yr of feedstock | Potential biomass production (t/yr) | Potential Ethanol production (million gallons) |
|---|---|---|---|---|---|
| <4.5 | 4 | 6,019,729 | 141,750 | 24,078,916 | 2,123 |
| 4.5-5.5 | 5 | 5,838,400 | 113,400 | 29,192,000 | 2,574 |
| 5.6-6.5 | 6 | 3,700,944 | 94,500 | 22,205,593 | 1,958 |
| 6.5-7.5 | 7 | 2,924,960 | 81,000 | 20,474,654 | 1,806 |
| 7.5-8.5 | 8 | 1,158,061 | 70,875 | 9,264,488 | 817 |

Ethanol produced from cellulosic sources is viewed by many to be a prospective alternative energy source since that is more abundant and environmentally friendly. Production technology for cellulosic ethanol production is not yet commercialized, but switchgrass holds potential for the latent commercial conversion processes (Perrin et al., 2008). The simulation result presented here provides decision makers and researchers an opportunity to opportunity to understand extent of potential yield effect of climate and, soil variability, management practices on switchgrass production. The evaluation process of potential yield carried out at different field measurement sites revealed that the model holds promise as a yield simulation tool in North Dakota.

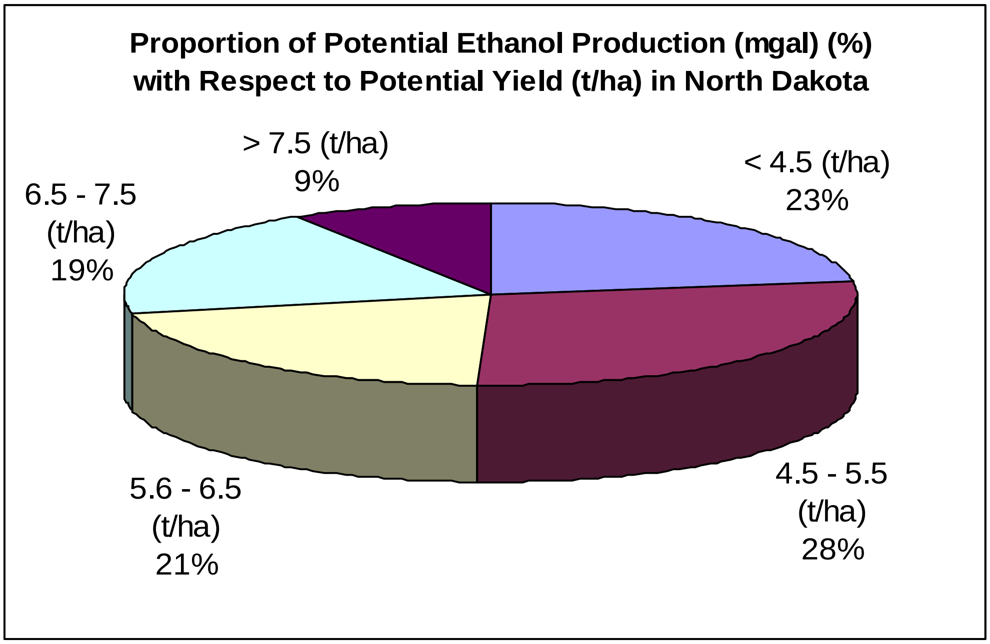



Fig. 23: Proportion of potential ethanol production (million gallons) in North Dakota according to the potential switchgrass yield

# CHAPTER VIII

# SUITABLILITY MODELING

## Introduction

The agro-climatic and land suitability modeling of switchgrass is important in the process of achieving optimum utilization of land area for bioenergy production. The process involves making knowledgeable decision taking into account the agro-climatic thresholds, biomass yield potential and land use. A multi-criteria interactive approach was adopted for suitable site selection for bioenergy purpose using GIS tools.

The suitability requirements and constrains of the overlaying themes were used as the basis for establishing the evaluation criteria for decision making. A set of algorithms was employed to match the quality of land by assigning numerical ranking to the major themes. The matching procedure was based on importance of the themes for suitability. The final outcome of the analysis was a map that portrayed the divisions of the area of interest into suitability classes for switchgrass feedstock production.

## Methodology: Suitability Analysis

The themes for suitability analysis (establishment, potential yield and landuse) were independently examined and importance rated using AHP model. Each theme was rated with a value according to its suitability for biomass production. The themes were then imported into the visualization workspace of MCAS-S and classes for each layer were defined to represent threshold value for ordinal data, and equal interval classes for continuous data. A composite layer based on weighted combinations of the selected major layers was then created, which utilizes the criterion weights (Table 11 and 12) to form a composite map. The composite layer was constructed by summing the pixel values for each pixel multiplied by weighted value. This operation could permits tradeoff balances between the analyzed themes. For example, low land productivity could be compensated for by low agro-climatic risk to some extent depending on the weighting assigned to each theme. The resulting composite overlay of the themes was presented in the form of a suitability map which was expressed in continuous values, ranging from least suitability to most suitability (Fig. 24).

Table 11: Relative ranking of the layers for switchgrass suitability analysis

| Themes | Potential yield | Establishment risk | Land use |
|---|---|---|---|
| Potential yield | 1 | 3 | 5 |
| Establishment risk | 1/3 | 1 | 3 |
| Land use | 1/5 | 1/3 | 1 |

Table 12: Normalization of matrix (Table 11) for each cell with respect to the the total of their respective columns and then averaged horizontally to get percentage weighting for each layer.

| Themes | Potential yield | Establishment risk | Land use | Avg.×100 |
|---|---|---|---|---|
| Potential yield | 0.65 | 0.69 | 0.56 | 63.33 |
| Establishment risk | 0.22 | 0.23 | 0.33 | 26.05 |
| Land use | 0.13 | 0.08 | 0.11 | 10.62 |
| | | | | 100.00 |

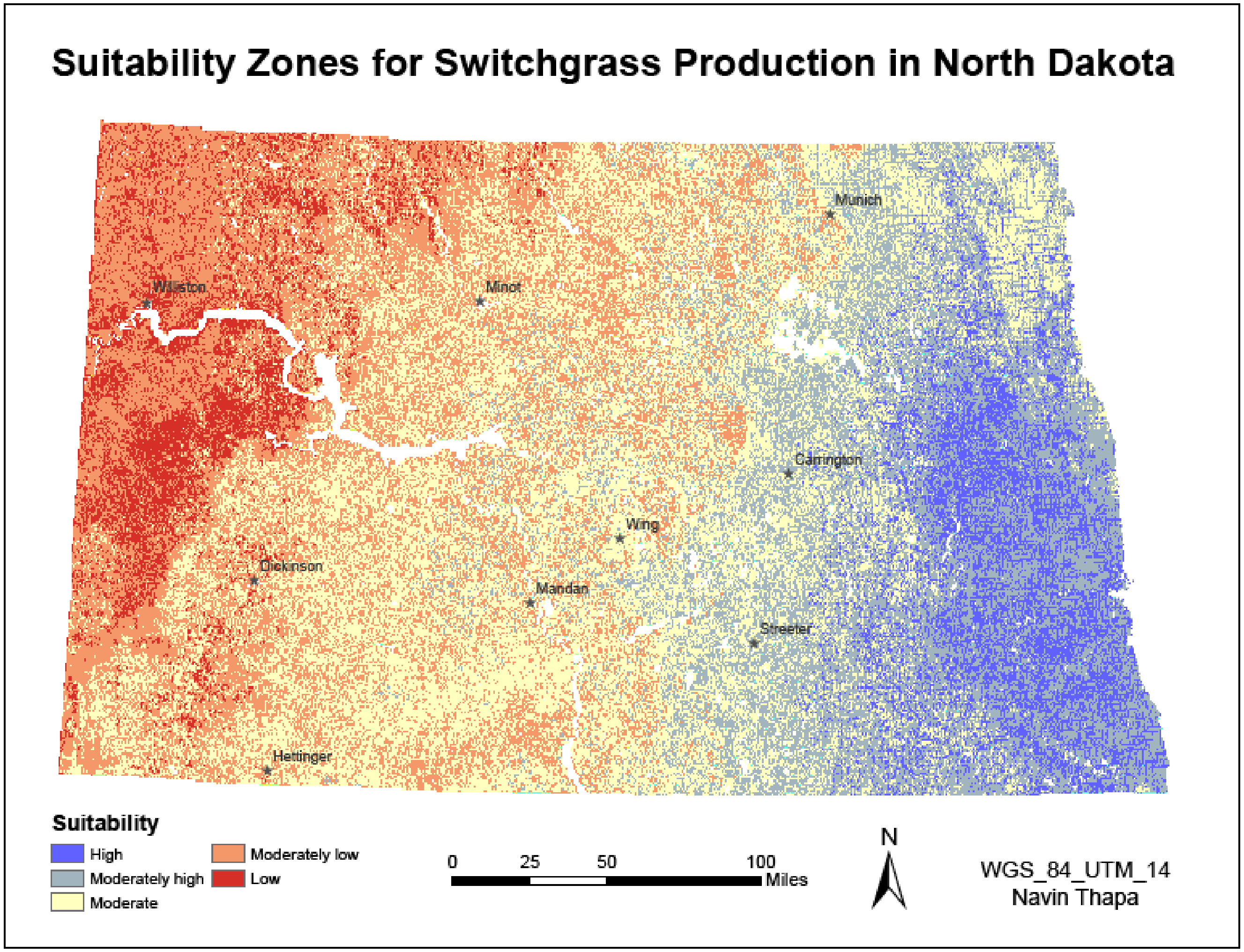



Fig. 24: Suitability mapping for switchgrass in North Dakota based on various agro-climatic parameters, potential yield and land use change

## Results and Discussion

The overlay of switchgrass suitability was classified into 5 equal interval suitability classes on a scale of 0-1 (Fig. 25). Many regions in North Dakota are fairly suitable for switchgrass production with most of the area falling between moderately low and moderately high suitability classes. The areas defined ideally as high suitability were land areas with low level of agro-climatic stress, high potential yield and marginal land category that were not normally under continuous cropping or grass cover. Areas identified as highly suitable for switchgrass production were predominantly located in the east central part of the state along the Red River Valley. Land areas identified as less suitable for were mostly in the western region which were areas characterized by low annual biomass yield high and agro-climatic stress for switchgrass establishment.

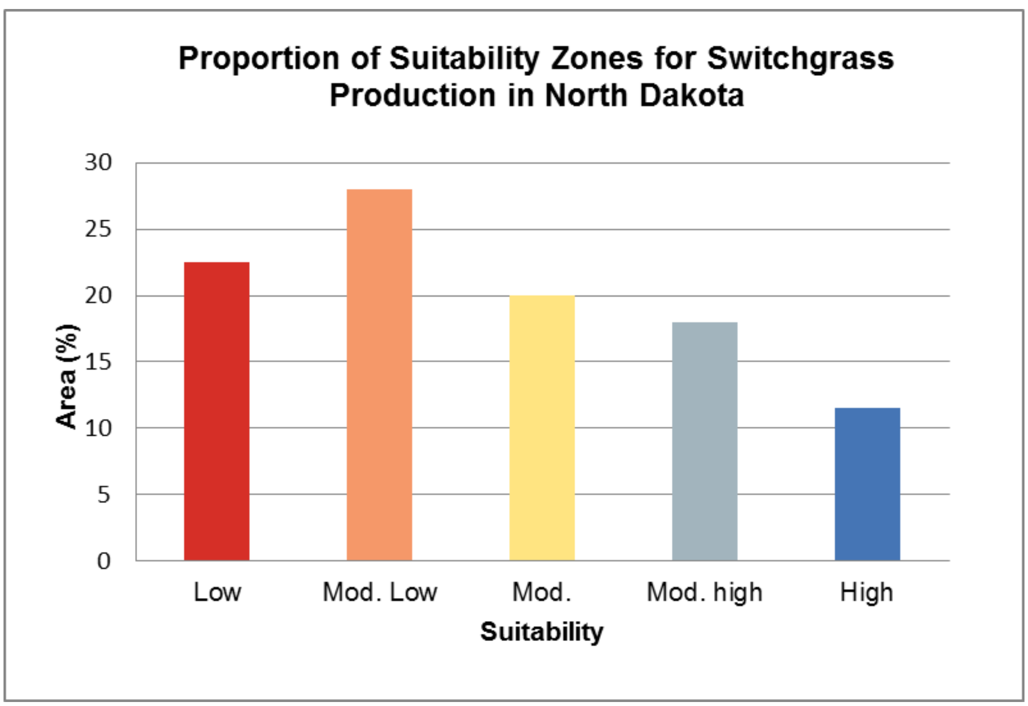



Fig. 25: Percentage of suitability zones for Switchgrass production in North Dakota based on agro-climatic risk factors for establishment, potential yield and land use

This result of the land suitability analysis is consistent with the natural occurrence of switchgrass which is east of 98° meridian along the Red River Valley (Moore and Lorenz, 1985). The present research assumes that the decision to implement switchgrass production is the result of complex tradeoff balances between bioenergy crop and native prairie. Switchgrass production is environmentally friendly only if it does not intensify negative impacts on native prairie lands or displaces cropland necessary for meeting human nutritional needs. Many of the regions that are classified as suitable for switchgrass growth are subjected to intense cash crops agriculture. Use of such lands for switchgrass growing would compete with the local agriculture production. It is not likely that such cropland would be used for bioenergy purpose owing to their necessity and suitability for food crop production. A raster layer for continuous cropland was derived from the NASS land use map and was overlaid on the switchgrass suitability map to mask the continuous (permanent) cropland in North Dakota (Fig. 24). This would avoid the worries about food cropland being diverted for ethanol production. This also promotes selection of site suitable for switchgrass that is considered unfit for food crops.

The suitability map was subjected to additional evaluation to exclude areas that could have important implications for native prairie restoration and conservation. Such grasslands have many important benefits such as providing land for grazing and wildlife habitat for may be at-risk species. The exclusion of those areas would lead them to be unsuitable for switchgrass production unlike how they originally appear. As part of our analysis, we assumed that grassland with more than 50% crown cover represents pristine native prairie and should not be prioritized for conversion to switchgrass production. The grassland mainly occurs in the central and western part of the state including a small dense portion of the Cheyenne National Grassland in southeast. A raster layer for grassland (more than 50%) from USGS GAP land use map was overlaid to mask the grassland (Fig. 26).

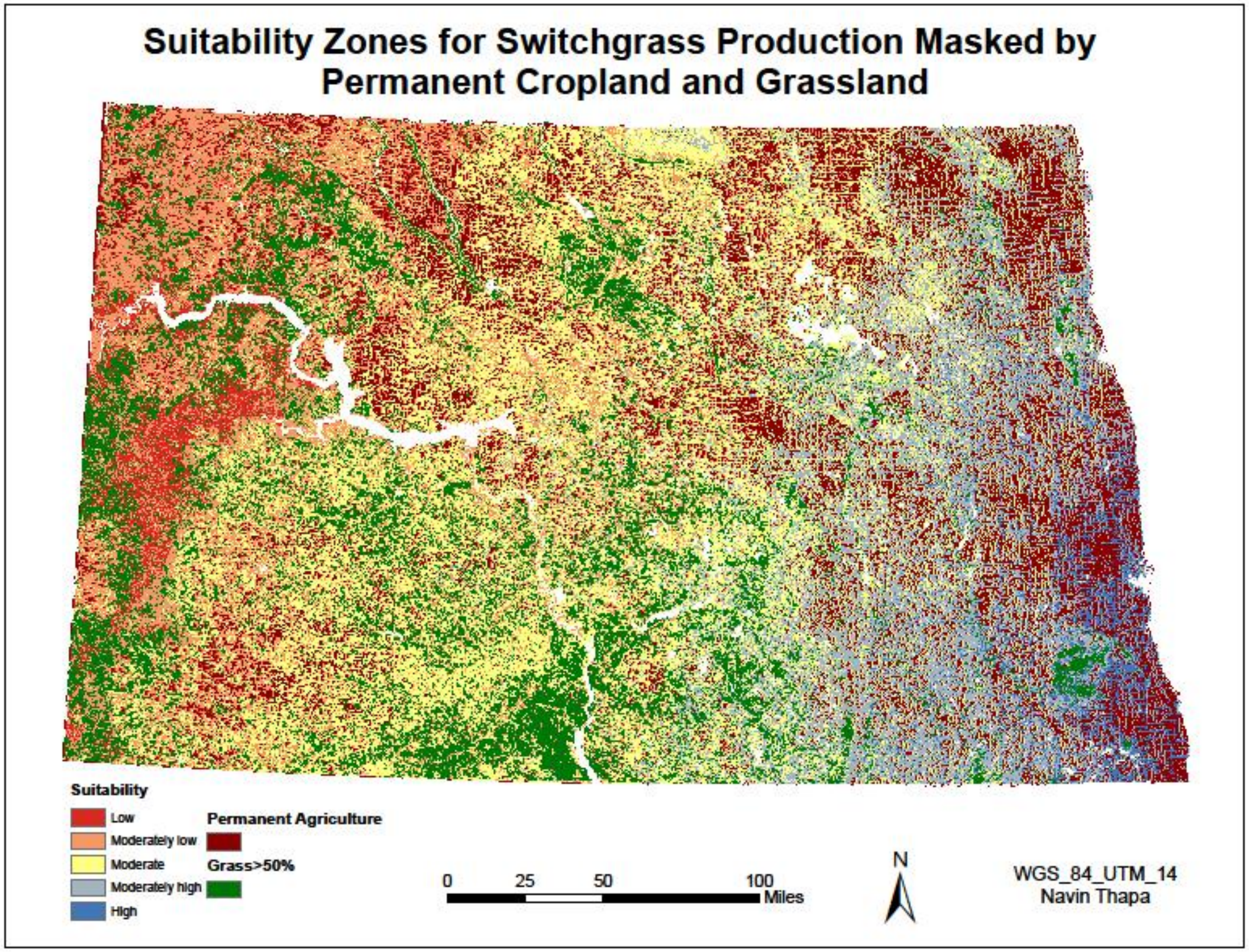



Fig. 26: Suitability map for switchgrass production in North Dakota excluding permanent cropland and grassland (canopy cover >50 %).

# CHAPTER IX

# GENERAL DISCUSSION

The current land suitability assessment determines how appropriate it is to grow switchgrass as a source of bioenergy cellulosic ethanol in North Dakota. The assessment for switchgrass production suitability is based on objective analysis of climate variables and land characteristics. The factors considered when assessing the suitability of a particular location were based on proponents' choice, experts' discussion, and literature survey that would qualify a location as suitable for switchgrass. The framework of a GIS based multi-criteria decision support model has been applied for three independent, main objective suitability parameters: agro-climate, productivity and land-use. Each parameter is comprised of factors selected from experts and literatures. The approach emphasized the importance of agro-climatic and land constrains and could provide rationale to develop sustainable switchgrass production program.

The study offers a broad overview and synthesis of factors determining the growth and yield potential of switchgrass in North Dakota (Nyren et al., 2010, 2011; Schmer et al., 2006; Madakadze et al., 2003; Berdahl et al., 2005). The results of the observed biomass yields from these studies and the current simulation in central and western part of the state are shown in Table 13. The yield simulation results presented would however need further refinement and should be expanded over larger area so that they could aid in determining realistic yield goals between and among fields.

Table 13: Switchgrass yields from various locations along with the input agro-climatic parameters and stress factors in North Dakota

| | | | | Inputs | | | | | Simulated (days) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Year | Measured Yield range (T/ha) | Simulated yield(t/ha) | S. Radn (las/d) | Tmax_avg (C) | Tmin_avg (C) | Ppt (mm) | N (Kg/ha) | Temp stress | N stress | Drought stress |
| Mandan | 2000 | 5.27-8.81 | 7.18 | 346.92 | 12.14 | -0.71 | 524.47 | 67 | 125 | 24 | 93 |
| | 2001 | 4.75-10.52 | 8.74 | 357.07 | 13.02 | -0.05 | 606.04 | 67 | 230 | 24 | 98 |
| | 2002 | 2.00-3.28 | 2.84 | 328.33 | 12.51 | -0.54 | 347.64 | 67 | 235 | 4 | 120 |
| | 2010 | 6.05-6.33 | 6.37 | 338 | 11.23 | -0.45 | 593.2 | 110 | 123 | 21 | 99 |
| Minot | 2007 | 3.81-5.91 | 6.95 | 312 | 11.9 | -0.58 | 444.6 | 110 | 114 | 20 | 108 |
| | 2008 | 3.26-4.03 | 6.23 | 330 | 10.7 | -2.07 | 491 | 110 | 111 | 20 | 89 |
| | 2009 | 5.51-5.83 | 4.96 | 325 | 9.15 | -2.04 | 409.8 | 110 | 103 | 32 | 75 |
| | 2010 | 8.60-9.93 | 7.15 | 316 | 10.09 | -0.52 | 519.9 | 110 | 118 | 32 | 95 |
| Dickinson | 2001 | 3.20-5.62 | 6.04 | 360.53 | 13.34 | 0.03 | 480.74 | 56 | 115 | 35 | 91 |
| | 2002 | 3.76-7.59 | 3.62 | 356.64 | 12.63 | -0.64 | 376.65 | 56 | 115 | 27 | 83 |
| | 2003 | 2.94-5.25 | 5.08 | 348.16 | 12.97 | -0.54 | 334.11 | 56 | 141 | 27 | 83 |
| Williston | 2007 | 0.67-0.86 | 2.4 | 309.02 | 13.06 | 0.05 | 325.32 | 0 | 107 | 34 | 97 |
| | 2008 | 1.24-1.48 | 3.27 | 333.56 | 11.87 | -1.26 | 365.45 | 110 | 112 | 5 | 112 |
| | 2009 | 2.08-2.30 | 1.48 | 328.38 | 10.57 | -1.48 | 329.93 | 0 | 100 | 34 | 87 |
| | 2010 | 2.55-3.26 | 4.2 | 329.46 | 10.9 | -0.33 | 464.82 | 110 | 120 | 16 | 112 |
| Carrington | 2007 | 13.24-15.35 | 11.94 | 299 | 10.82 | -1.29 | 502.85 | 55 | 111 | 58 | 67 |
| | 2008 | 11.29-12.68 | 8.83 | 351.8 | 10.43 | -2.4 | 502.43 | 55 | 113 | 33 | 75 |
| | 2009 | 9.12-12.13 | 7.91 | 325.21 | 8.79 | -2.75 | 413.19 | 55 | 116 | 39 | 77 |
| | 2010 | 8.28-9.98 | 5.59 | 321.15 | 10.24 | -1.01 | 477.12 | 55 | 138 | 32 | 72 |
| Streeter | 2002 | 3.1-7.4 | 5.01 | 345 | 10.9 | -1.08 | 357.9 | 0 | 103 | 42 | 64 |
| | 2007 | 4.23-4.65 | 6.59 | 344 | 11.01 | -0.9 | 557.4 | 110 | 122 | 25 | 95 |
| | 2008 | 1.83- NA | 6.66 | 325 | 9.73 | -2.91 | 575.6 | 110 | 114 | 23 | 78 |
| | 2009 | 4.52-4.89 | 7.15 | 348 | 8.97 | -2.14 | 429.1 | 110 | 102 | 22 | 95 |
| | 2010 | 6.67-6.72 | 8.81 | 339.18 | 10.23 | -0.32 | 576.23 | 110 | 112 | 37 | 64 |
| Hettinger | 2009 | 2.62-3.73 | 4.03 | 348 | 11.08 | -1.87 | 447.1 | 0 | 108 | 22 | 88 |
| | 2010 | 5.04-6.00 | 8.27 | 336 | 11.68 | -0.94 | 470.4 | 165 N+55 P | 108 | 10 | 101 |
| Munich | 2002 | 1.5-7.9 | 6.12 | 318 | 8.35 | -2.54 | 397.3 | 67 | 111 | 22 | 74 |
| Wing | 2010 | 2.32-3.51 | 3.66 | 338 | 11.23 | -0.45 | 593.2 | 110 | 118 | 23 | 107 |

## Biomass Yield and Agro-climatic Suitability

The yield results showed that biomass is more adapted to the central and eastern region of the state than the far west. The analysis of the agro-climatic and land conditions governing switchgrass growth and productivity at the study sites showed that regions in the central North Dakota were characterized by the highest mean annual precipitation while western parts received the lowest. In the central region, Carrington was located in between low to moderately low establishment risk zone and the next nearby moderately low risk area was Streeter. Switchgrass biomass varies as a function of precipitation and the relationship is more prominent in the upland regions where precipitation is limited (Wullschleger et al, 2010). Wullschleger, et al. (2010) showed that biomass yield for upland ecotypes increase with increase in April to September precipitation. Carrington and Streeter received nearly 25% more than their average precipitation during the 2007 growing season (Fig. 27). The rainfall decreased in the following years which were followed by subsequent decrease in yield except in 2010 when both rainfall and yield peaked again. Carrington being located at relatively higher latitude had slightly colder winter temperature than Streeter (Fig. 29) but both sites received a significantly high amount of snow during the winter months to get protected from extremely cold winter temperatures (Fig. 28). Streeter was characterized by better climatic conditions for switchgrass production but the available water in soil (AWS) was lower compared to Carrington (Fig. 13).

Yields in Carrington and Streeter were underestimated in Carrington while overestimated in Streeter. The residual analysis of estimated yield (Fig 20) showed that ALMANAC had high prediction error above the biomass yield of about 9 tons/ha and below 5 tons /ha. Switchgrass yield reported from Streeter in 2008 was less than 2 tons/ha while the simulated yield was 6.6 tons/ha. The yield was lowest from the site during the study period and could have been due to occurrence of an isolated extreme weather event which was not reported by the authors. The average observed yields in Carrington during the study period ranged from 9 to 14 tons/ha while the simulated yields were between 5 and 11 tons/ha. Yields in Carrington and Streeter might have varied as a function of precipitation and other weather events during the growing season which was not precisely simulated by ALMANAC.

The far western region of Williston observed the least biomass yield due to its extreme agro-climatic condition. Williston occurred along highest risk area for switchgrass establishment and was characterized by below threshold and highly variable agro-climatic parameters such as precipitation, temperature and soil water, least snow cover protection from extremely low winter temperatures and low heat units accumulation. Smoliak et al (1956) and Curie and Peterson (1966) reported that biomass yield from perennial crop would be limited by precipitation if it is less than 300 mm during growing season. The average growing season precipitation in Williston during the study period was about 275 mm which suggested that the region would be unfavorable for growing switchgrass. The precipitation during the growing season of 2007-2009 was lowest and close to 250mm and the resulting biomass yield was the least biomass during the period. The simulated yields were almost twice the observed values which suggest that the model did not precisely simulate yield when precipitation value was very low. An experimental irrigated plot in Williston produced significantly high biomass yield that peaked at 15 tons/ha in 2008. This only irrigated site in Williston yielded the highest biomass despite occurrence of most extreme climatic condition among all sites. This demonstrates that the water availability is the most important limiting factor for higher biomass production of switchgrass in North Dakota.

Minot being located in the northwest region was also characterized by less favorable growing condition. The site is characterized by potential switchgrass yield ranging between 4.5 and 5.5 t/ha. The rainfall in Minot in 2006 during switchgrass planting was much lower than the long term average. This could have resulted in low establishment success rate of switchgrass stand. The biomass yield in 2007 was 4.85 tons/ha but declined slightly in the subsequent year following decreasing rainfall. In 2010, the growing season precipitation was more than 60% above average and the yield increased to 9.26 tons/ha during that year.

The yields observed at the newly established sites in Mandan (USDA-ARS) and Ducks Unlimited Ranch North of Wing were variable in comparison to the nearby locations in Minot and Streeter. Mandan and Ducks Unlimited site both occurred in moderate to moderately low establishment risk zone. The snow depth at Mandan sites during winter months averaged at approximately 13 cm from 2004 to 2010 (Fig. 26). Mandan experienced high variations in snow depths that ranged from less than 1 cm in 2006 to over 50 cm in 2010. There were possibilities that switchgrass fields could be free of sufficient snow cover for several consecutive days. This high variation in snow depth combined with severely cold temperatures could result in winter injury (Berdahl et al., 2005). Spatial interpolation of ALMANAC simulated yield showed that Mandan occurred in the second least potential yield class for switchgrass biomass while the Ducks Unlimited site occurred in between second least potential yield class and the median yield class (Fig. 20).Yield from ducks unlimited site was low compared to the simulated yield. The reason for the reduced yield could be due to low stand establishment ratio in the seeding year. The yield results from subsequent years would explain the reduced yield in more detail.

Dickinson occurred in the region with moderate establishment risk and the observed biomass yield range was about 4-5.6 tons/ha Dickinson had low stand establishment because of dry and crusted soil condition after seeding. Switchgrass requires stand frequency level of 40% or more during the establishment year for adequate biomass yield (Schmer et al., 2006). The current study supports the assumption that low stand establishment for test cultivars in Dickinson resulted in low yields. The average growing season precipitation in Dickinson during the study period was below the long term average. The reduced rainfall created drought condition in soil during seedling establishment and result in lower stand establishment. The simulated yield in Dickinson was ranged from 3.6 to 6 tons/ha and tended to overestimate the observed value. The overestimation of the yield was probably due to occurrence of the dry soil condition which was not precisely simulated by the model. The average snow depth at the Dickinson site varied widely and averaged at approximately 7 cm. It was concluded that periodic drought conditions with wide fluctuation in snow cover and sub-freezing winter temperatures significantly affected the survival of switchgrass stands in the area. It was also observed that the cultivars from North Dakota origin usually showed high post winter survival while southernmost entries suffered the greatest decrease of stand survival in later years as suggested by Moser and Vogel, (1995) and Lewandowski et al., (2003).

Munich was located in moderately low establishment risk zone and had observed yield of about 4 tons/ha. Munich received significantly high rainfall during the growing season of 2002. The present analysis showed that the snow cover depth was above threshold during this winter, protecting switchgrass stand from extremely cold winter temperatures. Despite relatively more favorable growing conditions at Munich site, the mean biomass yield from Munich in 2002 was less compared to nearby site Carrington or Streeter. One reason for the reduced yield at Munich site could be the shorter length of growing season and lesser accumulated GDD due to its more northward location. It was reported that the Munich farm cooperators lacked a grassland drill, but instead broadcasted switchgrass seed and incorporated it into the soil by shallow tillage which resulted in inferior seedling development conditions (Schmer et al., 2006). This could also be a reason that the simulated yields were over estimated as was about 6 tons/ha.

The sites in Hettinger were subjected to extreme climatic conditions and needed to be reseeded in 2008. The biomass yield in the following two years were 3.2 and 5.5 tons/ha. The simulated yield value for those years were 4 and 8.2 tons/ha and were slightly overestimated.  Hettinger occurred in moderate establishment risk area and the weather adversities for stand establishment or some extreme weather phenomenon may have resulted on stand loss and low biomass yields from this site.

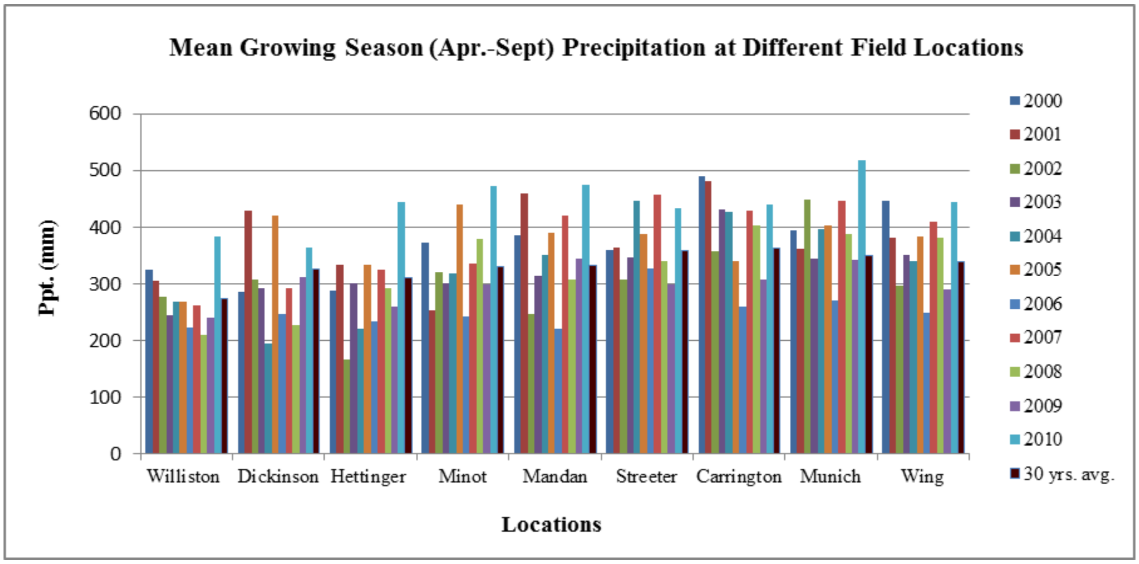



Fig. 27: Mean growing season precipitation (Apr.-Sept.) at different field test locations

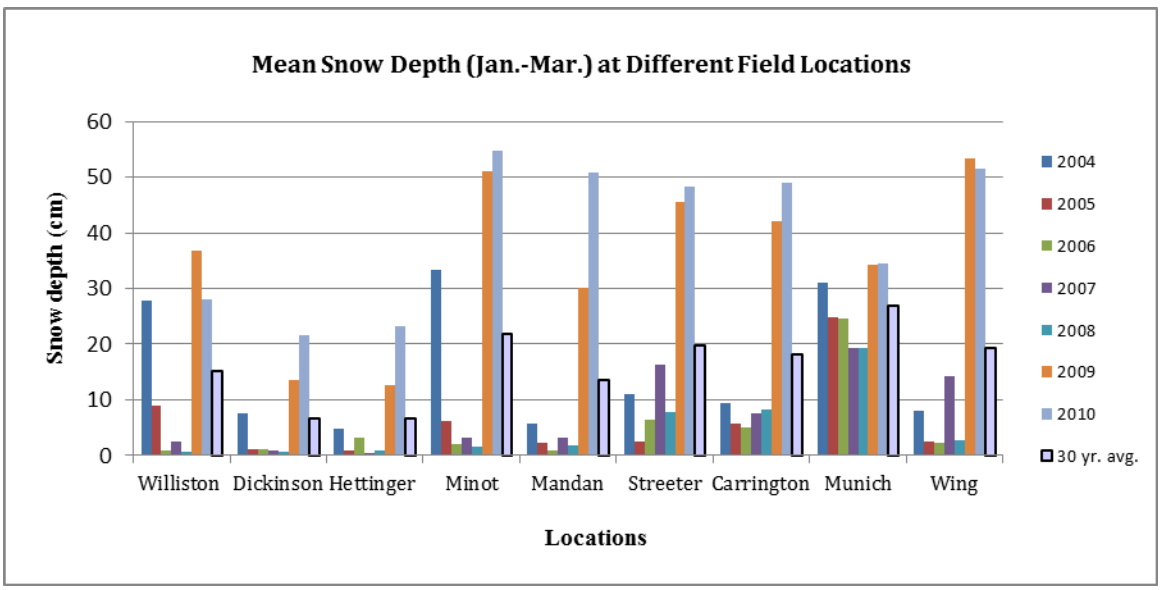



Fig. 28: Means snow depth at different field test locations during winter months (Jan.-Mar.)

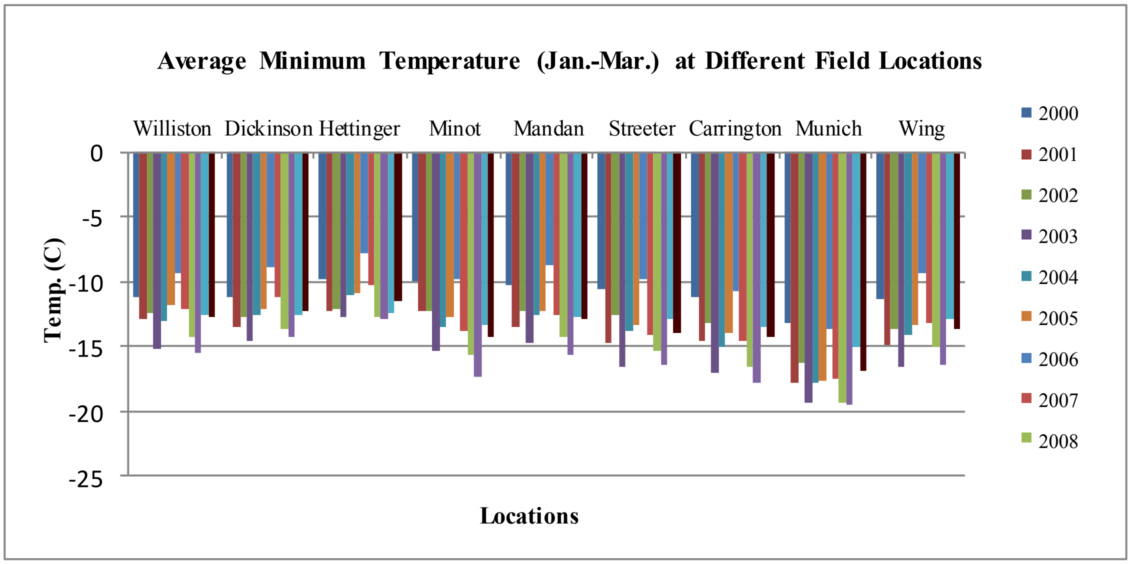



Fig. 29: Average minimum temperature during winter months (Jan.-Mar.) at different filed test locations

The simulation of switchgrass yields using ALMANAC model seemed sensitive to stress caused by temperature (heat units), $NO_3$ uptake and drought condition at all locations. Higher number of temperature stress days at Carrington site in 2008 and 2010 seemed to have reduced the yield despite normal precipitation and nutrient stress. Switchgrass cannot yield high biomass if water stress is high (Berdahl et al., 2005; Wullschleger et al., 2010). For example in the study by Berdahl et al (2005), Mandan received below average precipitation during 2002 growing season which triggered high drought stress (Fig. 30/Table 13). Thus the factors related to water supply such as rainfall, available heat units to maturity, soil moisture, soil profile, drained upper after rainfall and lower limits after depletion of the soil moisture affected yield of switchgrass. Temperature stress was also highest during the year which resulted in high reduction in yield. The low temperature in absent of sufficient snow protection due to low precipitation might have resulted in higher temperature stress in Mandan that year.

Similar plots with variable temperature and precipitation values during the study period for other field locations are shown in Appendix G (Fig. 36).

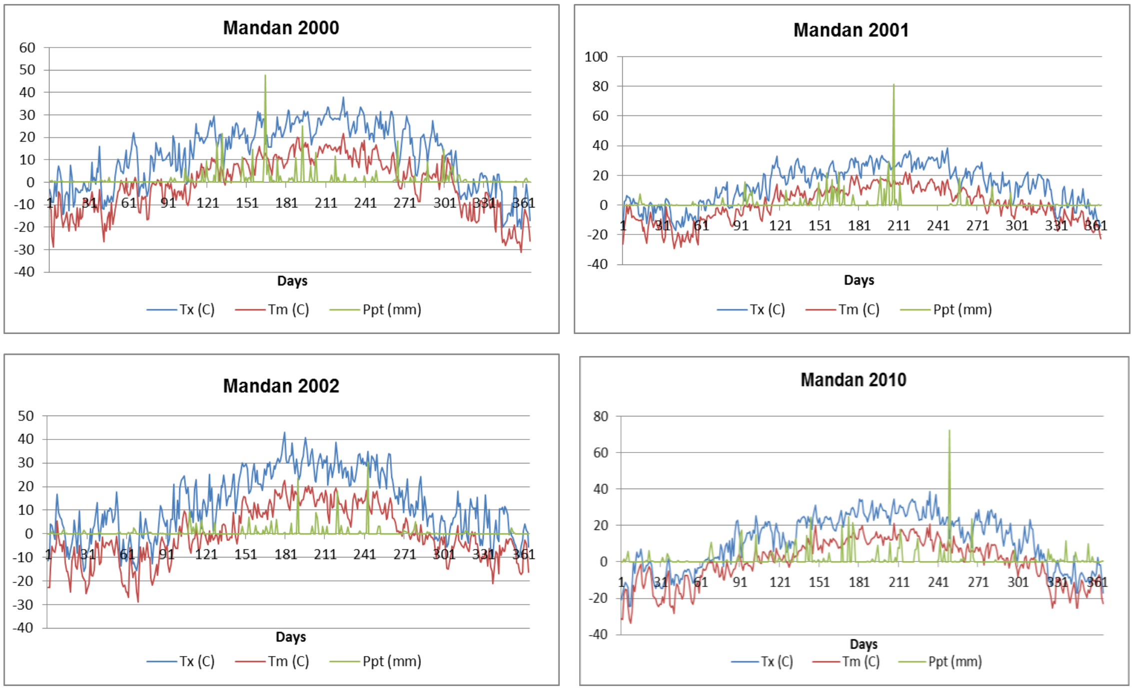



Fig. 30: Daily maximum (Tx) and minimum (Tm) temperature and precipitation data at Mandan site during the study period

The limited heat units to maturity due to shorter growing season seem to have pronounced effect on biomass yields in North Dakota. ALMANAC calculates accumulated heat units for the period between planting and yield harvest. The lower amount of accumulated GDD at north western locations such as Williston imposed pronounced impact on biomass yield throughout the study period. Lower GDD accumulation during 2002 growing season in Mandan could have significantly reduced biomass yield.

Increased solar radiation could also trigger drought stress in an area when the rainfall is near average. Water stress decreased biomass products per unit of light intercepted. The effect was more pronounced in lower latitude areas such as Dickinson, Mandan, Hettinger and Streeter where higher average incoming solar radiations could have triggered drought stress and reduce biomass accumulation when rainfall was limited. Fig. 31 shows the plot of monthly data for average input solar radiation along with simulated heat units, $NO_3$ uptake, leaf area index and biomass accumulation.  The plots of other test sites are shown in Appendix H (Fig. 37).

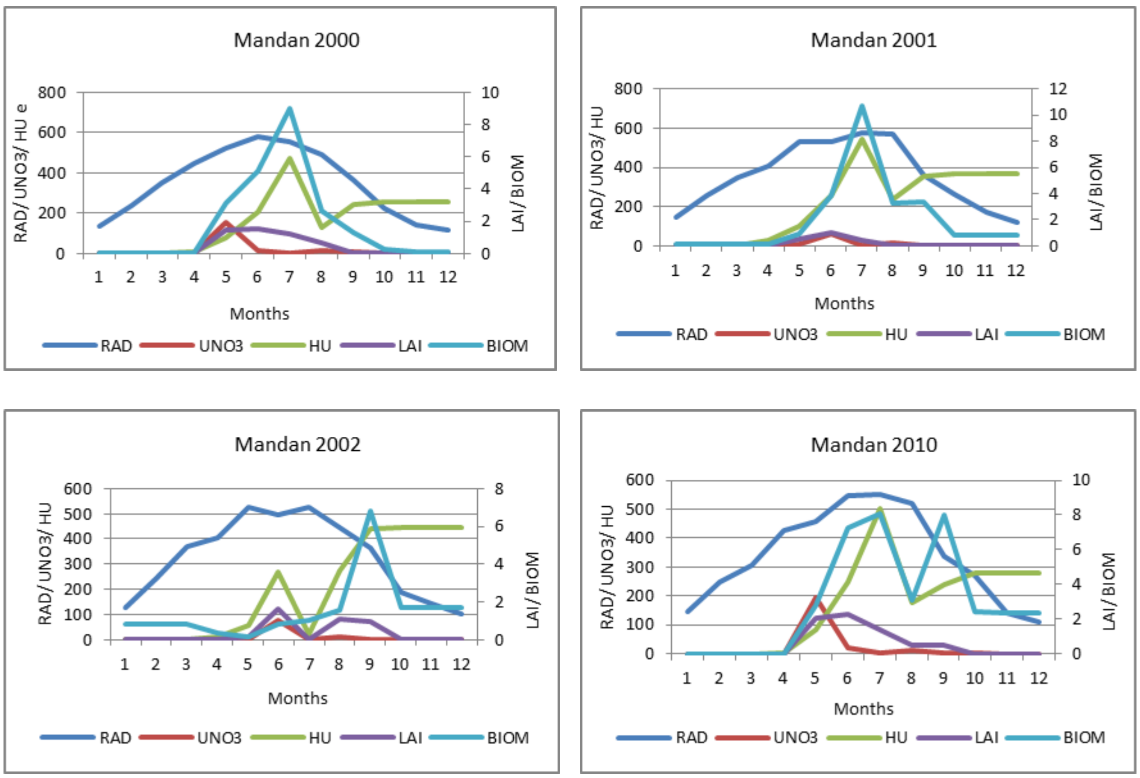



Fig. 31: Radiation input {RAD (lan)}, nitrogen uptake {$UNO_3$ (g/t)}, heat units {HU (°C)}, leaf area index (LAI) and biomass accumulation {BIOM (t/ha)}, for Mandan site.

## Production Challenges and Environmental Significance

Biofuel production has environmental costs associated with and is environmentally beneficial only if it is produced sustainably. The environmental sustainability of switchgrass production largely depends on the type of land being used. This research assumes that the areas under permanent (or native) grassland vegetation should not be prioritized for conversion to bioenergy switchgrass fields. Switchgrass fields are ecosystems partially influenced by human activities in comparison to native permanent grasslands. The naturalness rating of these managed grasslands lies between land untouched by humans (wilderness area) and land completely transformed by humans (urban center) (Brentrup et al., 2002). The conversion of permanent grasslands to switchgrass would require plowing of grassland, which releases much of the carbon previously stored in plants and soil through decomposition into the atmosphere (Searchinger et al., 2008). Land use change by conversion of native ecosystems to crops can hence cause substantial loss of soil organic carbon soon after land conversion and might take several decades to recover (David et al., 2009). Unlike annual crops, switchgrass needs soil tillage only in the establishment year, which can significantly reduce soil degradation (Vaughan et al., 1989; Kort et al., 1998). However, producers often try to boost yields through addition of fertilizers, improved drainage and irrigation which have their own environmental consequences on air, water and land quality.

Since switchgrass is adaptable to marginal lands and can be economically profitable in many locations, it can be a motive to restore marginal lands to avoid conversion of native prairie. The profitable use of switchgrass as a bioenergy crop requires sufficient understanding of the agro-economic aspects of its production. At the landscape scale, multiple physical, environmental and economic factors /constraints affect bioenergy production. Along with environmental performances, switchgrass bioenergy systems will largely depend on production cost, cost of technological conversion to usable energy and cost of the competing fuels. For switchgrass to compete with other fuels, it must be grown in cost-effective manner, which can be done by increasing the productivity without significant increase in production cost. It is necessary to determine the breakeven price needed for switchgrass grown under average growing conditions to provide incentives to grow (Khanna et al., 2008).

At present the actual production cost of switchgrass throughout North Dakota is unknown but given the adaptability and environmental benefits of switchgrass, it is likely that potential public subsidies and market will encourage its production. The socio-economic analysis of sites selected for switchgrass production may also be influenced by the accessibility of this production sites and their proximity to urban centers or biofuel processing plants. Matching current land suitability classification and proximity to processing facility can reduce transportation cost and increase the net economic return. The detailed analysis of this socio-economic component for switchgrass production in North Dakota is however not within the scope of the present research. The suitability map presented in this study can be a useful input to model the environmental significances and economic constrains on switchgrass production in North Dakota.

The current suitability map shows the potential land area for switchgrass production without negatively affecting prairie or competing with food crops production. Effective decision making regarding agricultural land suitability is vital to achieve optimum land productivity and ensure environmental sustainability (Kurtener et al., 2004). The value of switchgrass as a bioenergy crop can be enhanced by accurate estimation of potential environmental benefits (McLaughlin et al., 2002). Biofuels are considered one solution to global energy security concerns and climate change. Using switchgrass for bioenergy production is of significant importance due to its long term productivity (>10 yrs) (Fike et al., 2006), suitability to marginal lands (Evanylo et al., 2005), low water and nutrient requirements and positive environmental benefits (Vogel, 1996; McLaughlin et al., 2002). The flows of these benefits (services) rely on how the ecosystems are managed at the site scale and on the diversity, composition and functioning of the surrounding landscape (Tilman, 1999). These perennial ecosystems contribute to reduced runoff and erosion which helps to restore soil nutrients and organic matter, fix atmospheric carbon dioxide into biomass and increase fixation of soil carbon, which improves soil quality. They can also contribute to reduce the use of chemicals in agriculture and thereby reduce pollution of streams and groundwater.

# CHAPTER X

# CONCLUSION AND RECOMMENDATIONS

Through this study, we conducted a GIS based land suitability analysis for growing dedicated bioenergy crop switchgrass in North Dakota. The study demonstrates favorable growth potential for non-irrigated switchgrass crop mostly in the central and western regions of the state. The important beneficial characteristics of switchgrass such as high yield, adaptability to marginal areas, efficient use of water and nutrients and other multiple environmental benefits makes it an ideal candidate for bioenergy. The agro-climatic suitability, economically viable yield potential and availability of large amount of land area suitable for switchgrass growth makes North Dakota a privileged region for cellulosic ethanol derived from switchgrass.

The study analyzed various agro-climatic factors that pose risk for switchgrass establishment and limit sustainable production. Rainfall was evaluated the most important limiting factor for switchgrass establishment and growth in North Dakota. The other important factors included temperature, snow cover, GDD, available soil moisture and land use. Agro-climatic factors were combined into a composite major theme defining risk areas for switchgrass establishment. AHP technique integrated in MCAS-S proved to be highly useful in determining the relative weights for each of the individual agro-climatic layers and creating composite theme during risk analysis.

Productivity simulation was conducted to identify areas that could support economically viable switchgrass feedstock for cellulosic ethanol production. ALMANAC crop model was used to simulate potential yield of switchgrass at different locations using weather inputs and soil characteristics. The resulting yields were validated against field measured values and were spatially interpolated using co-krigging function with variables precipitation, temperature and soil moisture in ArcGIS. The evaluation of the yields revealed that the model holds promise as switchgrass biomass yields simulation tool in North Dakota. The model performed well when observed yields were moderate in the range of 5 - 9 tons/ha. But when the observed yields were more than 9 tons/ha and less than 5 tons/ha, the model tended to underestimate and overestimate yields respectively. It was concluded from the analysis that the model might not be sensitive to extreme weather events such as precipitation while simulating yields from regions with highly variable weather patterns. Based on the current observed and simulated yield values, it is reasonable to expect an average of 5 tons per ha of switchgrass biomass on a commercial scale at the central regions with slightly higher yields in eastern part and lower in the western parts despite disparities in yields between years.

A switchgrass suitability map was the final outcome of the analysis which was a weighted composite overlay of the analyzed factors governing switchgrass production. Results indicated that integration of GIS, AHP and MCAS-S proved to be useful for switchgrass suitability analysis. The research identifies permanent cropland and grass cover and then masks them from the suitability map since they would hardly or never be used for growing switchgrass. It would exclude any competition between bioenergy and food production or degradation of permanent grassland. The study will be helpful for users or decision makers in planning switchgrass biomass feedstock production and policy development governing switchgrass adaptation for cellulosic ethanol production in North Dakota.

## Recommendations

The research can help improve our understanding of agro-climatic and land suitability for upland switchgrass cultivars in North Dakota. While we have improved our knowledge of adaptation of existing and new switchgrass cultivars in North Dakota, there still remains several constrains to integrate switchgrass into cropping systems, including reliable establishment methods, fertilizer management techniques and efficient methods to convert to biofuel (Sanderson et al., 2006). Research on improving yield through improved switchgrass stand establishment and adaptation in a region should continue to expand existing knowledge. Considering the current suitability conditions, it is important to expand the current research to incorporate information on socio-economic and environmental performances of switchgrass in North Dakota in future.

Biofuels have hidden environmental costs associated with their productions and are beneficial only if they are cultivated in sustainable and environmentally friendly manners. Excluding permanent grasslands from conversion to switchgrass production field would help protect critical habitats to native wild animals, birds and promote ecological services of grasslands. The study recommends that the policies promoting sustainable bioenergy productions need to provide considerable guidance to encourage best practices in such feedstock production.

Biofuels are viable substitutes to fossil fuels and these substitutes should have beneficial effects in terms of ecology, energy balance and economy. The next step to expand the current research would be to analyze the environmental performance of switchgrass in terms of ecosystem value and services such as soil stabilization, carbon sequestration and habitat enhancement for wildlife. The research should be able to analyze the tradeoffs and balances between bioenergy production and ecosystem services of switchgrass grown as a bioenergy crop.

APPENDICES

## Appendix A

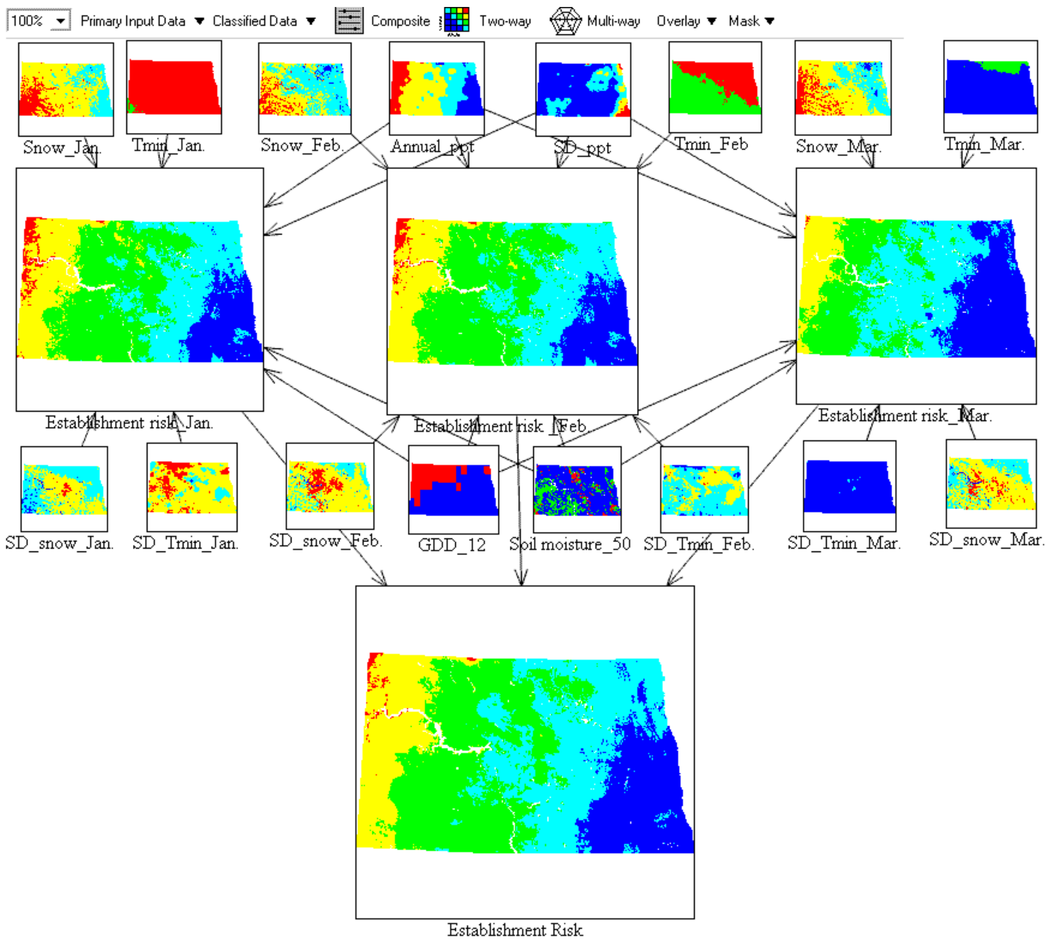



Fig. 32: Theme creation for switchgrass establishment risk in North Dakota using MCAS-S

## Appendix B

Table 14: ALMANAC simulation of switchgrass biomass at different sites

| County | Long. | Lat. | Weather stations | N-(kg/ha) | Soil type | PHU | Yrs of Simulation | Yield (t/ha) |
|---|---|---|---|---|---|---|---|---|
| Cass | -96.9922 | 46.9894 | McLeod 3e | 50 | Southam silty clay loam, 0 to 1 percent slopes | 750 | 12 | 8.42 |
| Emmons | -100.2618 | 46.2796 | Nepoleon | 50 | Aastad-Forman loams, 0 to 3 percent slopes | 750 | 12 | 5.53 |
| Benson | -99.7425 | 48.3079 | Leeds | 50 | Heimdal-Esmond-Sisseton loams, 6 to 9 percent slopes | 650 | 12 | 5.18 |
| Burke | -102.501 | 48.8638 | Powers lake | 50 | Vallers loam, saline, 0 to 1 percent slopes | 530 | 12 | 3.95 |
| Dickey | -98.2925 | 45.9872 | La Moure | 50 | Barnes-Cresbard loams, 3 to 6 percent slopes | 800 | 12 | 6.34 |
| Grand Forks | -97.293 | 48.18 | Mayville | 50 | Dovray clay | 750 | 12 | 7.28 |
| Richland | -96.6725 | 46.1837 | Rothsay | 50 | Southam silty clay loam, 0 to 1 percent slopes | 750 | 12 | 8.44 |
| Mc Lean | -101.5677 | 47.7469 | Underwood | 50 | Williams-Bowbells loams, 6 to 9 percent slopes | 600 | 12 | 4.53 |
| Hettinger | -102.668 | 46.002 | Mott RR | 50 | Beisigl-Lihen loamy fine sands, 0 to 6 percent slopes | 660 | 12 | 4.37 |
| Burleigh | -100.2901 | 47.1428 | Mc Clusky | 50 | Wabek soils, undulating | 680 | 12 | 3.97 |
| Cavalier | -98.7719 | 48.6583 | Edmore 1 W | 50 | Barnes-Svea loams, 0 to 3 percent slopes | 600 | 12 | 5.5 |
| Foster | -99.1308 | 47.5239 | Fessenden | 50 | Parnell silty clay loam, 0 to 1 percent slopes | 750 | 12 | 7.72 |
| Morton | -100.9 | 46.832 | Carson 2 S W | 50 | Parshall fine sandy loam, 0 to 2 percent slopes | 740 | 12 | 5.61 |
| Stark | -102.8 | 46.89 | Dunn | 50 | Flasher-Vebar-Parshall complex, 9 to 35 percent slopes | 650 | 12 | 4.36 |
| Stutsman | -98.9991 | 47.2001 | Napoleon 2 SE | 50 | Savage silty clay loam, 2 to 6 percent | 800 | 12 | 5.02 |
| Ward | -101.2889 | 48.2216 | Foxholm Wildlife RF | 50 | Williams loam, level | 560 | 12 | 4.19 |
| Williston | -103.5792 | 48.2468 | Grenora | 50 | Lihen loamy fine sand, 0 to 6 percent | 520 | 12 | 3.86 |

Appendix C

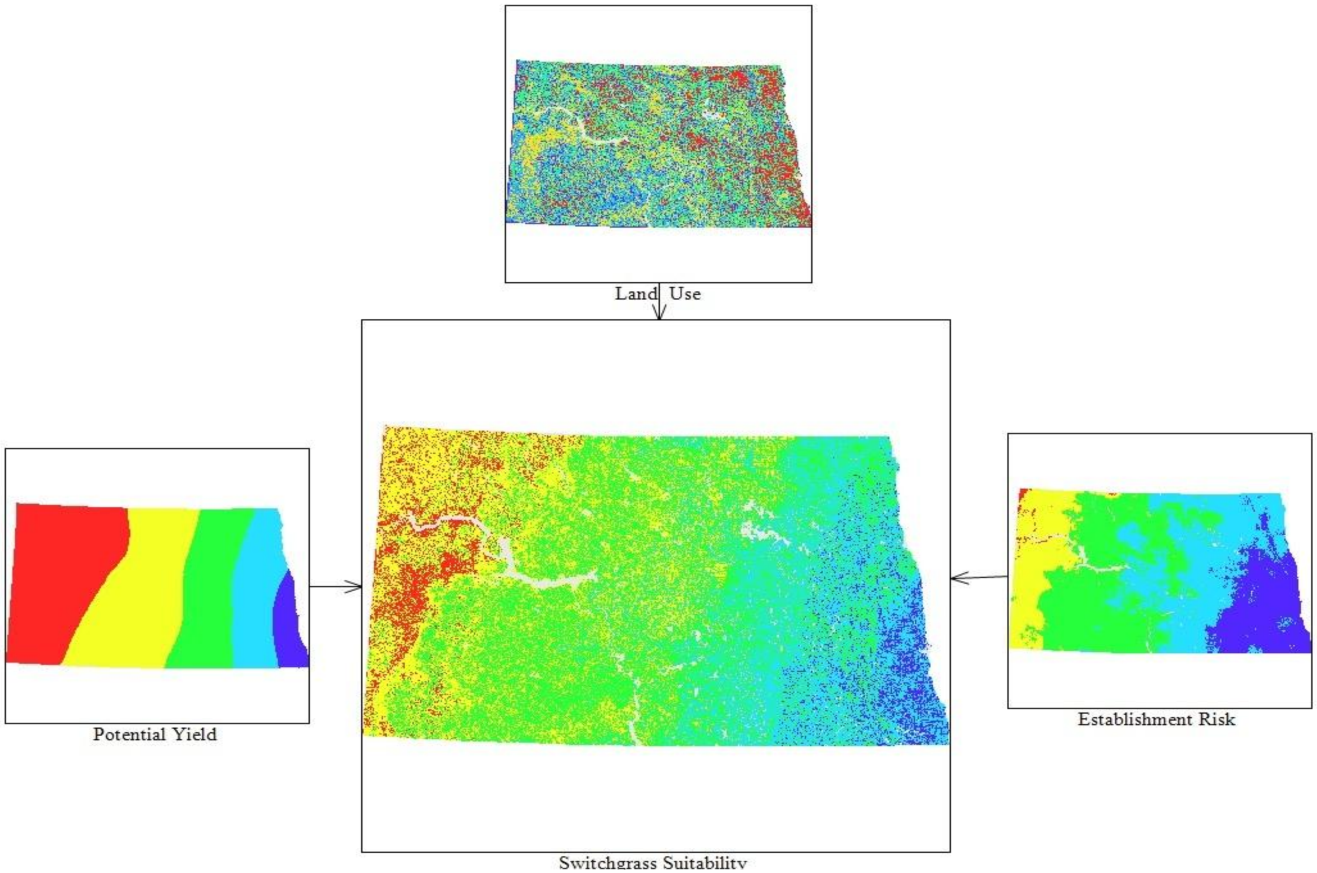



Fig. 33: MCAS-S Interface for defining land area for switchgrass suitability by overlaying establishment risk, potential yield and land use classes in North Dakota

Appendix D

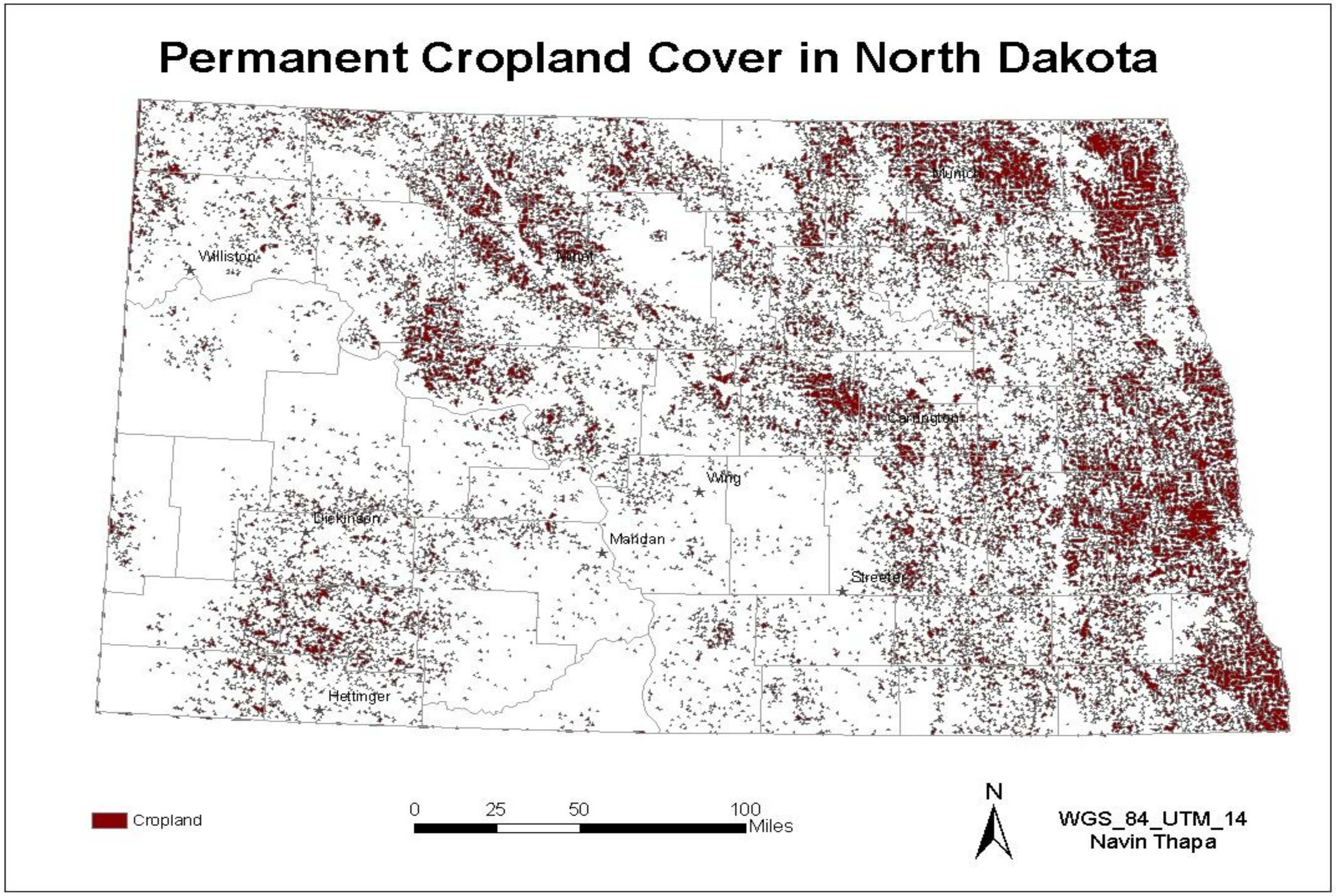



Fig. 34: Distribution of permanent croplands in North Dakota. Land area under continuous agriculture for the last 12 years (1998-2009) was used to mask the switchgrass suitability land area in North Dakota (Source: NASS)

Appendix E

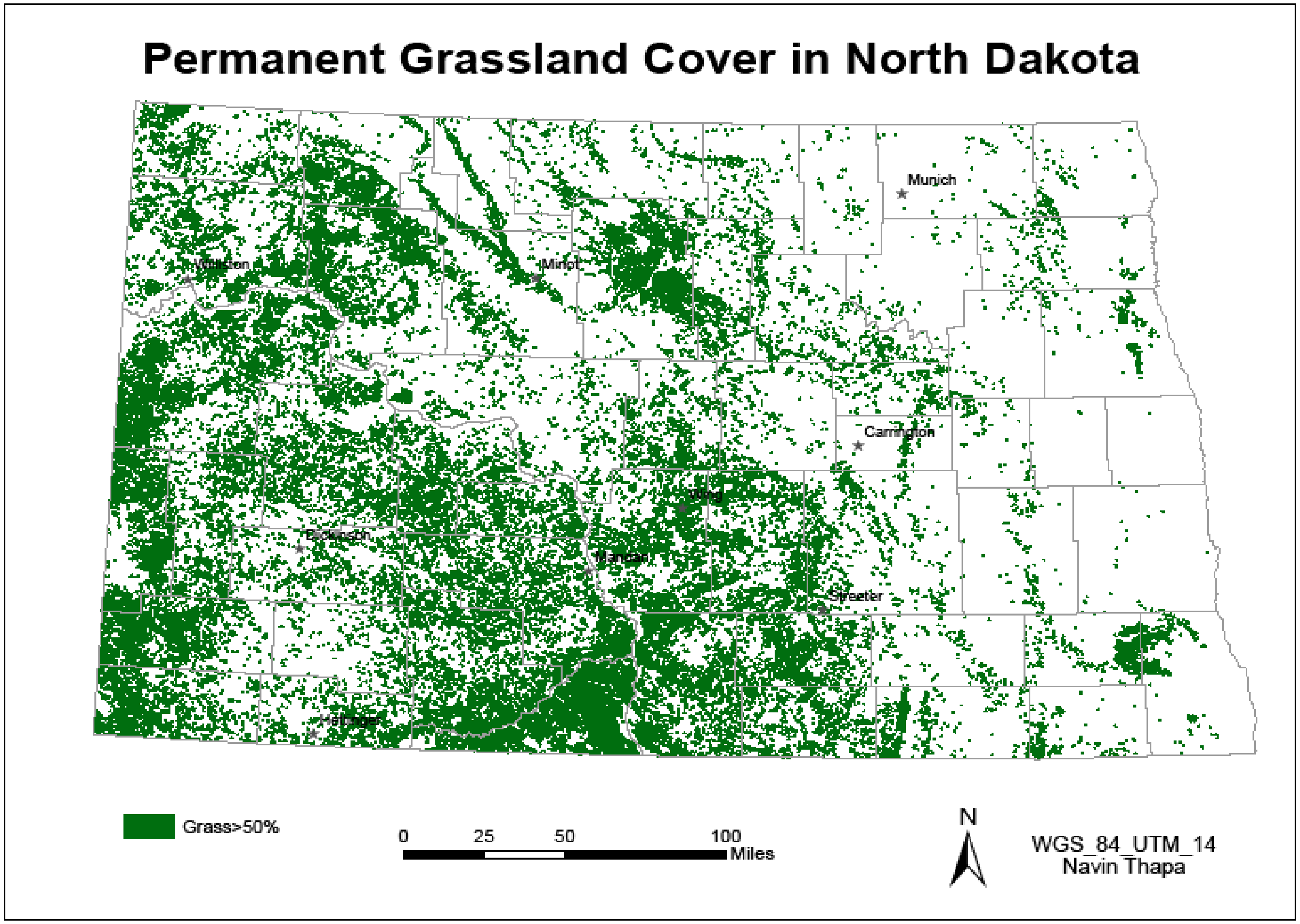



Fig. 35: Distribution of permanent grasslands in North Dakota. Land area with grass cover more than 50% was used to mask switchgrass suitability land area in North Dakota (Source: GAP)

Appendix F

Table 15: Summary table for the statistical analysis of observed and estimated (simulated) yield of switchgrass in North Dakota

| Year | Location | Measured yield (t/ha) | Simulated yield (t/ha) | Difference (t/ha) | Prediction bias | Di^2 | MSE | RMSE | rRMSE |
|---|---|---|---|---|---|---|---|---|---|
| 2000 | Mandan | 8.06 | 7.18 | 0.88 | | 0.77 | | | |
| 2001 | | 8.43 | 8.74 | -0.31 | | 0.10 | | | |
| 2002 | | 2.55 | 2.84 | -0.29 | | 0.08 | | | |
| 2010 | | 6.19 | 6.37 | -0.18 | | 0.03 | | | |
| 2007 | Minot | 4.86 | 6.95 | -2.09 | | 4.37 | | | |
| 2008 | | 3.64 | 6.23 | -2.59 | | 6.71 | | | |
| 2009 | | 5.67 | 4.96 | 0.71 | | 0.50 | | | |
| 2010 | | 9.27 | 7.15 | 2.12 | | 4.49 | | | |
| 2001 | Dickinson | 4.06 | 6.04 | -1.98 | | 3.92 | | | |
| 2002 | | 5.61 | 3.62 | 1.99 | | 3.96 | | | |
| 2003 | | 3.98 | 5.08 | -1.10 | | 1.21 | | | |
| 2007 | Williston | 0.77 | 2.4 | -1.63 | | 2.67 | | | |
| 2008 | | 1.36 | 3.27 | -1.91 | | 3.65 | | | |
| 2009 | | 2.19 | 1.48 | 0.71 | | 0.50 | | | |
| 2010 | | 2.90 | 4.2 | -1.30 | | 1.68 | | | |
| 2007 | Carrington | 14.3 | 11.94 | 2.36 | | 5.57 | | | |
| 2008 | | 11.98 | 8.83 | 3.15 | | 9.92 | | | |
| 2009 | | 10.63 | 7.91 | 2.72 | | 7.40 | | | |
| 2010 | | 9.13 | 5.59 | 3.54 | | 12.53 | | | |
| 2002 | Streeter | 4.64 | 5.01 | -0.37 | | 0.14 | | | |
| 2007 | | 4.44 | 6.59 | -2.15 | | 4.62 | | | |
| 2008 | | 1.83 | 6.66 | -4.83 | | 23.33 | | | |
| 2009 | | 4.71 | 7.15 | -2.44 | | 5.95 | | | |
| 2010 | | 6.7 | 8.81 | -2.11 | | 4.45 | | | |
| 2009 | Hettinger | 3.18 | 4.03 | -0.85 | | 0.72 | | | |
| 2010 | | 5.52 | 8.27 | -2.75 | | 7.56 | | | |
| 2002 | Munich | 4.24 | 6.12 | -1.88 | | 3.53 | | | |
| 2010 | Wing | 2.92 | 3.66 | -0.74 | | 0.55 | | | |
| | | 5.49 | 5.97 | -0.48 | -0.48 | 120.94 | 4.32 | 2.08 | 0.35 |

# Appendix G

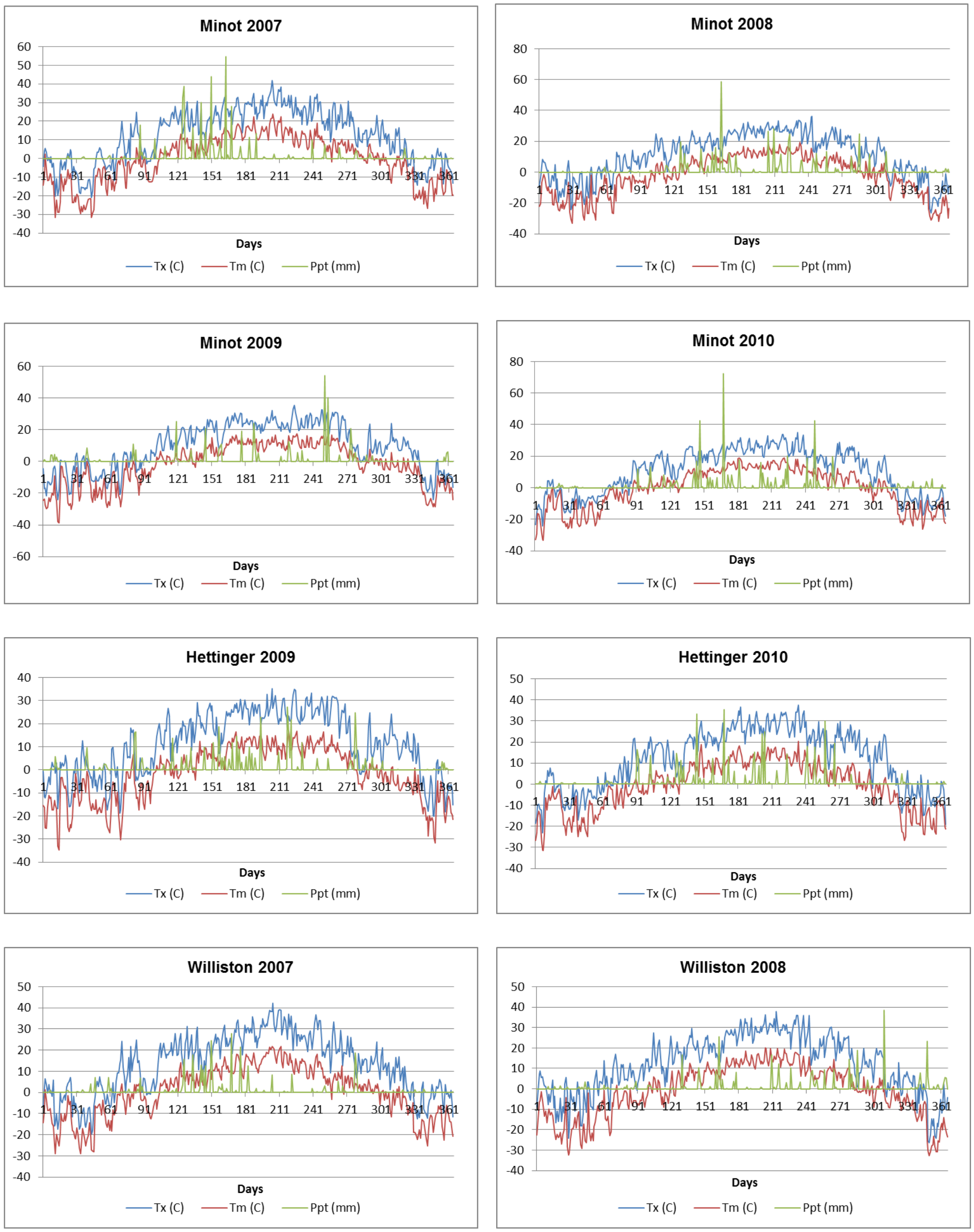
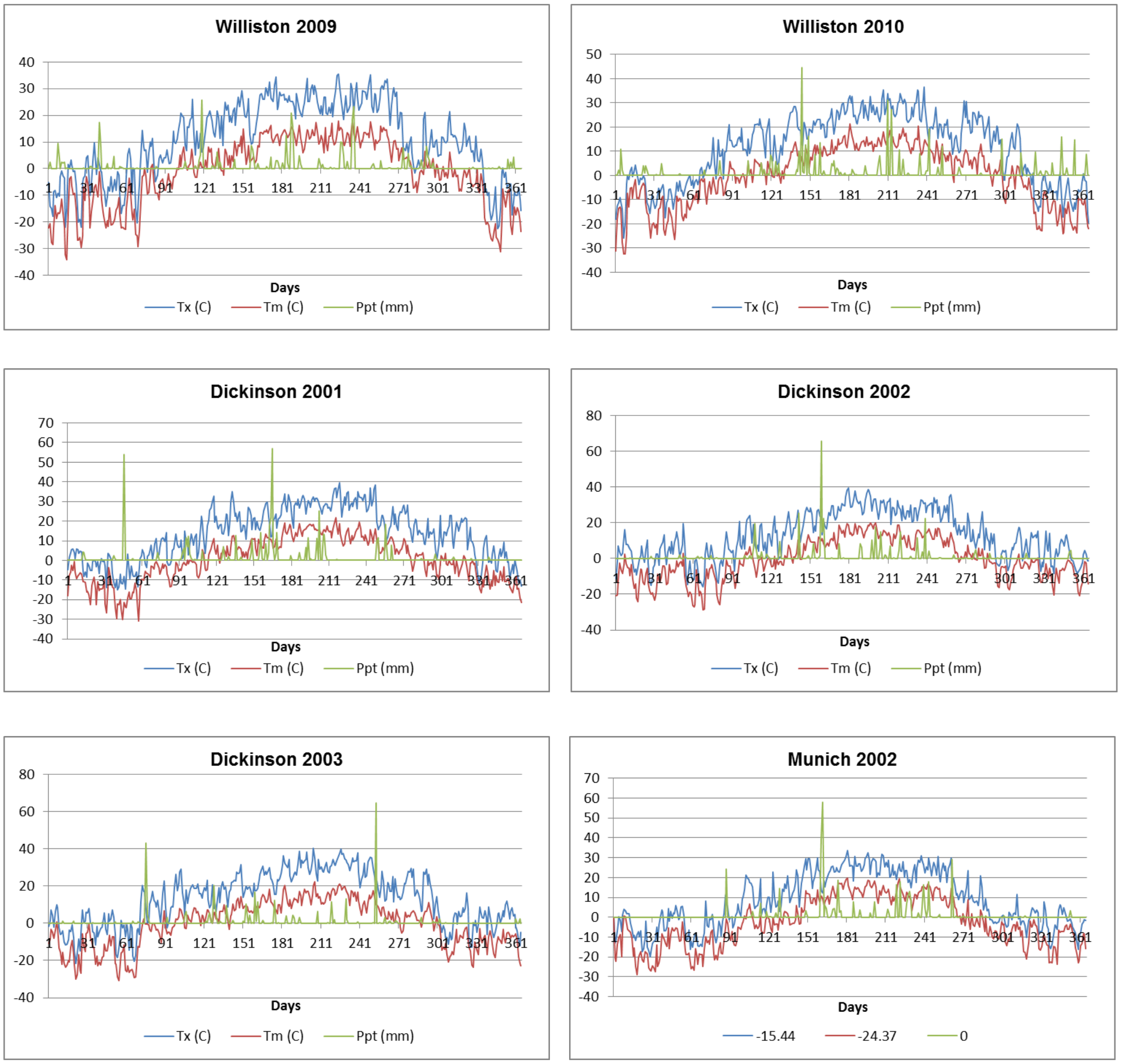



Fig. 36: Daily maximum (Tx) and minimum (Tm) temperature and precipitation data at different study areas during the study period

Fig. 36 contd…


Williston 2009
Days
Tx (C)
Tm (C)
Ppt (mm)
Williston 2010
Days
Tx (C)
Tm (C)
Ppt (mm)
Dickinson 2001
Days
Tx (C)
Tm (C)
Ppt (mm)
Dickinson 2002
Days
Tx (C)
Tm (C)
Ppt (mm)
Dickinson 2003
Days
Tx (C)
Tm (C)
Ppt (mm)
Munich 2002
Days
-15.44
-24.37
0

Appendix H

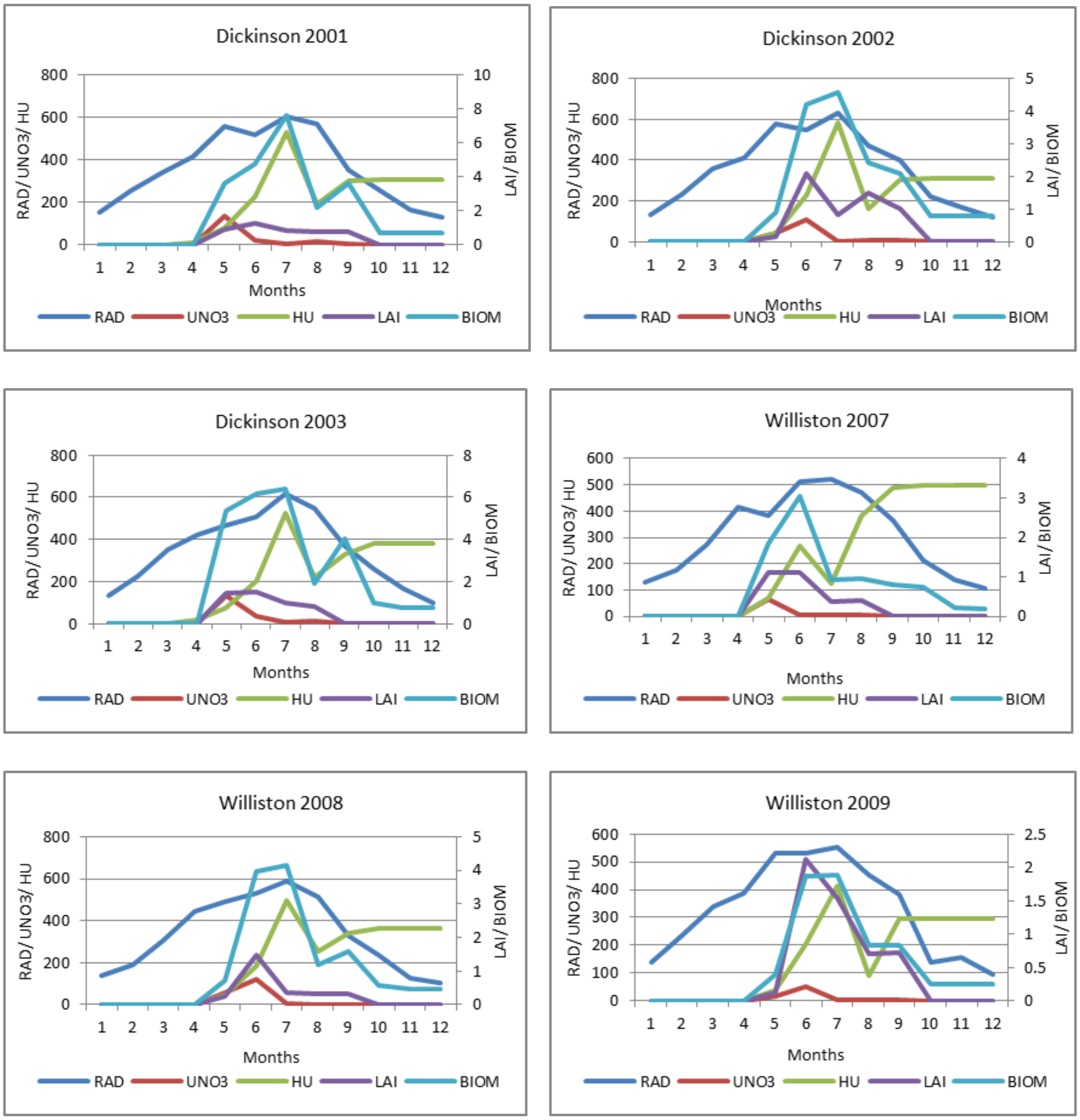



Fig. 37: Radiation input {RAD (lan)}, nitrogen uptake {$UNO_3$ (g/t)}, heat units {HU ($^{\circ}$C)}, leaf area index (LAI) and biomass accumulation {BIOM (t/ha)}, for switchgrass simulation sites in North Dakota.

Fig. 37 contd…

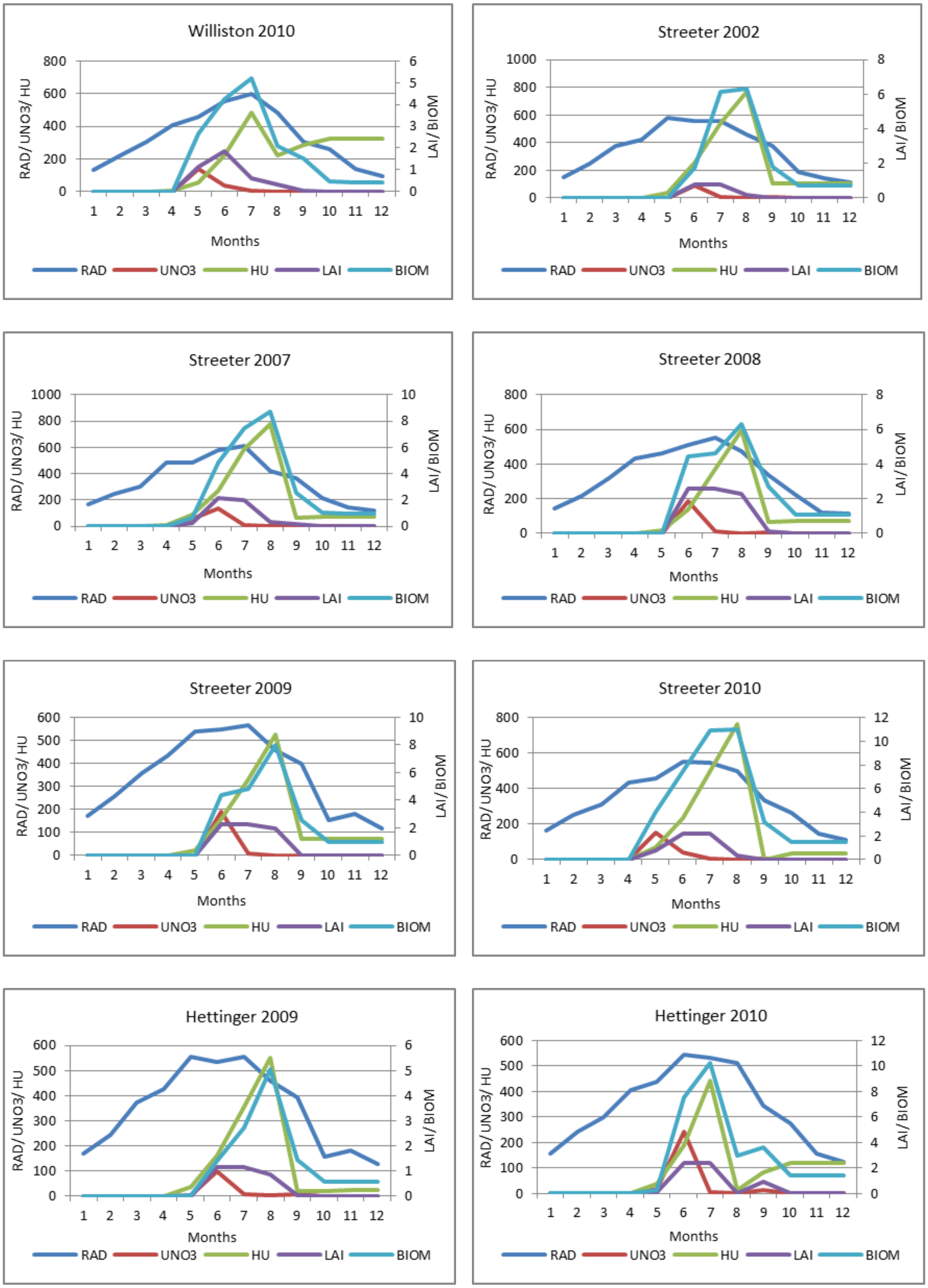

Williston 2010
RAD/ UNO3/ HU
LAI/ BIOM
Months
RAD UNO3 HU LAI BIOM
Streeter 2002
RAD/ UNO3/ HU
LAI/ BIOM
Months
RAD UNO3 HU LAI BIOM
Streeter 2007
RAD/ UNO3/ HU
LAI/ BIOM
Months
RAD UNO3 HU LAI BIOM
Streeter 2008
RAD/ UNO3/ HU
LAI/ BIOM
Months
RAD UNO3 HU LAI BIOM
Streeter 2009
RAD/ UNO3/ HU
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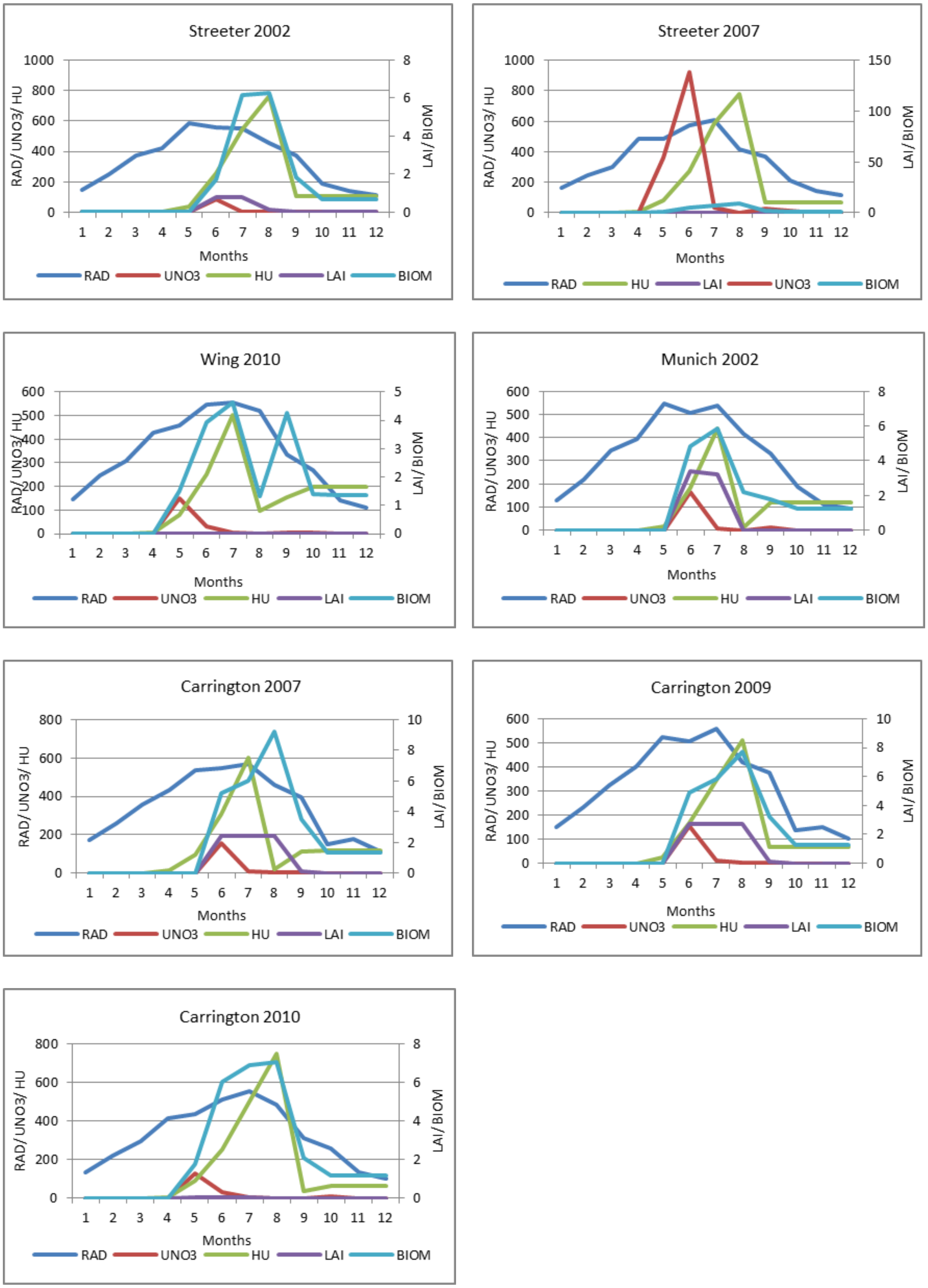
Fig. 37 contd…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