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A CMIP5 Ensemble Assessment Of Durum Wheat Production & Climate Change In North Dakota, Usa

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A CMIP5 ENSEMBLE ASSESSMENT OF DURUM WHEAT PRODUCTION & CLIMATE CHANGE IN NORTH DAKOTA, USA

By

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Timothy D. Hochstetler Dillon

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LIST OF ABBREVIATIONS

Precip	Precipitation (mm) that falls during a 24-hour calendar period.
Temp	Temperature (ºC) measured as the maximum or minimum over a 24-hour calendar period.
N, S, E, W, NE, NW, etc.	The designations for cardinal directions used throughout this paper.
CC	Referred to as both Climate Change and CC throughout the paper. Referring to the theory of warming GMST and the associated changes in climatic parameters.
ND	Referred to as both North Dakota and as ND for simplification in certain contextual settings.
GDD	Growing Degree Day
AGGD	Accumulated Growing Degree Day

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ABSTRACT

In the United States (US), North Dakota is the largest producer of Durum Wheat (*Triticum durum*), hereinafter referred to as Durum. Durum grain has a high protein content and multiple utilities in food products. We investigated the historical trends in Durum production and yield as influenced by changes in precipitation (precip) and temperature (temp). The study accounted for variations in environmental conditions by running a dynamic crop model in thirteen Durum producing counties.

The climate of North Dakota is representative of the highly productive agricultural lands of the Northern Great Plains, encompassing five US states and two Canadian provinces. The Eastern part of North Dakota has a humid continental climate while the western part is semi-arid. Creating a distinct West-to-East precip gradient across the state. Low mean average temps (cir. +4 °C), and high-temp variability lead to the relatively short growing season (cir. 130 days). Combined with limited rainfall (cir. 350 mm in the E and 560 mm in the W), it makes agriculture highly dependent on temp and precip. Accordingly, climate change has a high potential impact on crop production in the region.

The ALMANAC crop growth model was used to simulate the production of Durum. Model performance was estimated by comparison of simulated yields with historical observations, and was found satisfactory using the Nash–Sutcliffe model efficiency coefficient (E) and Coefficient of determination (r^2) (< 0.50). Uncertainty in projected future climate is addressed using an ensemble of 17 Global Circulation Models (GCMs) run under four scenarios. GCM output data were further downscaled using MarkSim weather, and daily weather was generated for two 30-year periods, characteristic of the 2020’s and the 2050’s.

Introduction

Modern agro-technology stems from advancements in management systems cir. 1200 AD, 13,000 years after the dawn of agriculture (Harari, 2014; Standage, 2009). Some advances were based on natural observations such as a defined growing season and specific crops for each season. Other advances were in engineering such as irrigation, watermill, windmill, and, most importantly, the plow (Tudge, 2000; Harari, 2014). Farming problems of the past have been solved through the evolution of farming technologies (i.e. computers, irrigation, and greenhouses) and scientific progress (i.e. climate change, genetics, and GMO's) (Fitzgerald, 1991). Ironically, this can create a pattern of apathy in dealing with the variables that negatively impact farmers such as land use, or emissions and runoff from industry. In the past these issues have been ignored under the assumption that they will be solved by the technological innovations of the future (Fitzgerald, 1991; Harari, 2014).

Science and technology are often implemented as management tools such as guidance software for precision pesticide application or the use of satellite imagery and mapping to monitor possible weather hazards (Stafford, 2000; Pinter et al., 2003). Any part of the agricultural sector that monitors crop growth during the most vulnerable growth stages depends on accurate climatological, atmospheric, and ecological conditions that are, at best, predictable with a margin of error. Research into climate and atmospheric impacts on agricultural productivity have become increasingly important to the stability and security of many nations in the 21st century (Schwartz, 2003). The effects of climate change, hereafter CC, will alter this stability as the effects are better observed.

In several locations around the world, the evidence of CC is visible. Kelly, 2015 formed a highly plausible connection between the drought and resulting food crisis in Syria to the regional instability that began in 2011 and persists still today (Kelley, 2015). The paper posited that the drought and food crisis in Syria forced young people to migrate from rural villages to large population centers. High unemployment in cities created an unstable state of public morale and armed conflict ensued (Kelley, 2015). Humans bear the responsibility to solve CC as we are the cause of CC.

The effects of CC on temperature (temp) and precipitation (precip) regimes relevant to this study are of local or regional scale. In W North Dakota, the period within the optimal range of temps for plant growth is limited to the ~120 to ~130 days between late May to mid to late September (Enz, 2002). The location of North Dakota, the geographic center of the North American continent, creates a diverse climate with average daily temp and precip extremes as well as significant weather phenomena (ie. droughts, floods). These events occur many times a year, often during the growing season with significant impacts on the farming communities of the state (Enz, 2002). Agriculturally significant regions in western North Dakotas experience frequent periods of both high and low precip (Manske, 2012; Enz, 2002).

The current literature presents the effects of CC in North Dakota on many crops ranging from sugar beets to potatoes. However, few articles or studies exist regarding the impacts of CC on the production of Durum in North Dakota. The known effects of CC on crop growth and yield are primarily due to changes in temp and precip stresses, not necessarily the direct result of increases in CO_2 (Deryng, 2014).

The impacts of a slightly increased global temp and increased concentrations of CO_2 have been predicted to be beneficial to plant growth of certain species, due to Carbon Fertilization

(AbdElgawad et al., 2016). In several studies, increased supplies of CO_2 created increased empirical photosynthetic productivity. It was especially effective in rainfed agricultural systems like North Dakota (Nemani et al., 2003; Vanaja et al., 2017)[1].

In other studies, plants grown under compounded increases in temp exhibited signs of increased temp stress and an overall decrease in growth (Rosenzweig, 2002; Rosenweig, 2000). Adding to temp stress are potential changes in the accumulation or frequency of precip. Negative impacts of increased pCO_2, via the precip and temp changes, may be detrimental to plant growth during specific growth stages, either stimulating or retarding growth. An increase in the quantity of precip is usually beneficial, as precip is a limiting factor of growth. The exception being when too much precip falls at one time causing increased disease or damage (Rosenzweig, 2002; Rosenweig, 2000).

Global increases in the "greenness of the planet" (AKA terrestrial net primary productivity) can be associated with the climate-driven impacts such as carbon fertilization, nitrogen deposition, and forest regrowth (Nemani et al., 2003). The amount of carbon fixed in the ecosystem, species diversity, and usable biomass production across the landscape are due to global differences in photosynthetic pathways (Ehleringer, 2002). Changes in pCO_2 will also influence photosynthesis and plant growth (Nemani et al., 2003). Likewise, elevated pCO_2 and the method of carbon fixation will influence the spatial distribution of precip, temp, diseases, and plants in North Dakota (ND) (Vaughan, 2016).

pCO_2 surpassed 400 parts per million by volume (ppmv) threshold in 2013 and has continued to increase (Monastersky, 2013). The International Panel on Climate Change (IPCC), an

[1] These empirical studies only consider the benefits of additional CO_2 to photosynthesis and not the negative impacts of increased pCO_2 on climate variables.

international cooperative effort of scientists to understand our changing climate, published an assessment of Earth's atmosphere and concluded that CO_2 emissions have been increasing from pre-industrial years (the 1880's) to today (Fig. 1) (Forster, 2007).

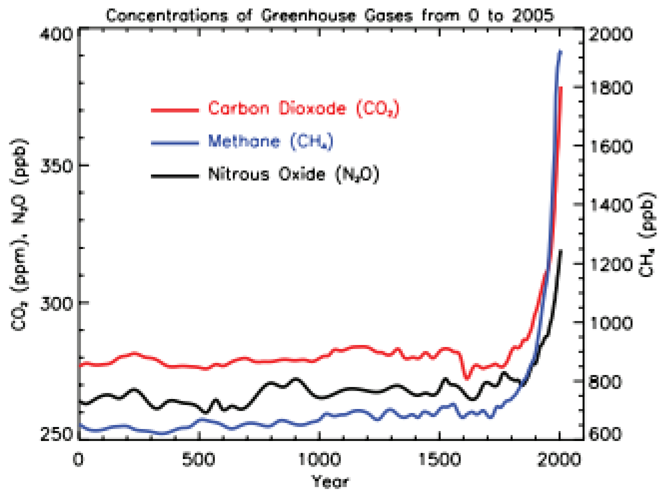


Fig. 1: The levels of three greenhouse gases from year 0 to 2005, using data from ice cores (Forester, 2007)

Under current predictions, major Green House Gas (GHG) emissions will continue to increase at a rate consistent with the actions of the emitting nations of the world (Forster, 2007).

CC theory calculates that if global GHG emissions increases, the mean annual surface temp (MAST) will increase and, in turn, the global climate will change (Adhya, 2009). Major GHG's include Carbon Dioxide (CO_2), Methane (NH_4), and Nitrous Oxide (N_2O), all of which are emitted during food production (Adhya, 2009). Over the remainder of the 21^{st} century, each nation will influence the concentrations of GHG's via policy and industrial initiatives. Affecting the global agriculture on which humanity depends (Adhya, 2009). The infinite possible futures for GHG emissions and climate were consolidated and categorized by the IPCC to form four contrasting scenarios. Each scenario was assigned to research teams in participating nations (RCP's 2.6, 4.5, 6.0, 8.5), each with various levels of interaction between humanity, industry, and climate (Barrow, 2000). Each of these scenarios represents a coherent, internally consistent and plausible description of a probable future state of the world (Barrow, 2000). These logical trajectories are based on current and historical trends in climate, agriculture, extreme weather, biology, economics, population, and social factors (Moss, 2010).

Global effects on climate will not reflect local temp or precip. Therefore, researchers employ a method known as downscaling to convert large global forces and processes (i.e. ENSO, cyclones, increasing global temps, and deep ocean convection) into local weather effects (i.e. daily maximum temp (Tmax), minimum temp (Tmin), wind speed, and precip) (Barrow, 2000). This data can then be used in research of crop/climate interactions to determine the impacts of these forces on the production of plants (Barrow, 2000).

The effects of climate on Durum is not well established for North Dakota. Wienhold, 2017 estimated that C_3 crops across the Northern Great Plains would experience increased yields and photosynthesis with decreased photorespiration in higher CO_2 environments (Wienhold, 2017). However, cereal crops that experienced increased yield often coincided with decreases in quality and protein content (Wienhold, 2017). However, certain changes in the environment could lead to decreased yield from stress factors such as increased temps during grain filling and pollination events (Wienhold, 2017). There is sufficient evidence to assume that the intensity and frequency of precip events will increase from historic levels (Kunkle, 2003). If these events occur during the critical pollination or grain filling stages, the productivity of Durum grain formation will decrease in turn affecting yield (Wienhold, 2017). This would create precip regimes that could reduce yield, promote disease proliferation, and force farmers to switch crops (Rosenzweig, 2000; Rosenzweig, 2002). Those who continue to farm will likely observe increased temp stress, disease, and potentially diminished yield (Rosenzweig, 2000; Rosenzweig, 2002). Researchers utilize models to better understand and predict plant responses to these changes (Haefner, 2012).

These models, specifically crop models, simulate crop growth and production under varying environmental and meteorological conditions.

The Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model simulates crop growth, competition and the relationship between plants and climate (Baez-Gonzalez, 2015). The main function of a model is to simulate impacts of field-level management using data defining environmental, soil, or water conditions (Baez-Gonzalez, 2015). The result is a measure of production at the farm level, reported as an annual yield measured as Tons per Hectare (t/ha) or Bushel per acre (BU/acre) (Ewert, 2007). This simulated result is the reflection of a real-world agricultural operation with similar growing conditions. These models help researchers advance agricultural productivity (Ewert, 2007).

The goal of this study is to determine the possible changes in the production of Durum (t/ha) resulting from CC in North Dakota. This study uses observed historical yields, downscaled climate data, ALMANAC crop model, and field management data to simulate the production of Durum in North Dakota. The current and simulated future trends of Durum production may be useful to lawmakers, farmers, and future research. Current production spans most of the W and N border counties and some C counties of the state.

Simulating potential yields under several projected climates will provide insight into Durum production during the 2020’s and 2050’s. This maintains the assumption that production practices remain constant and temp and precip changes are the drivers of change in Durum production.

Literature review

Growth and Structure

Plants Productivity

Melvin Calvin received a Nobel Prize in Chemistry for the discovery of photosynthesis, the process of using photons (γ), which is solar energy, to drive the production of sugars for plant growth (eq. 1) (Calvin, 1952).

$$6CO_2 + 6H_2O + [\gamma] \rightarrow C_6H_{12}O_6 + 6O_2 \qquad 01$$

The process begins using chlorophyll, a chemical within plant leaves that absorbs photons (Calvin, 1952). Photosynthesis also requires Carbon Dioxide (CO_2) and Dihydrogen Monoxide (Water/ H_2O) to stimulate plant growth (eq. 1) (Zhu, 2008; Calvin, 1952). All plants use one of three types of photosynthesis: C_3, C_4, and CAM. Each requires the same basic components of growth (Eq. 01) (Waller, 1979). C_3 and C_4 are the two dominant photosynthetic pathways of plants in North Dakota with CAM plants being more common in warmer climates (Waller, 1979).

These three photosynthetic pathways evolved over millennia to create more and more efficient primary producers (Gowik, 2011; Elheringer, 1991). Gas exchange in photosynthesis is significant and likely evolved due to changes in ancient levels of CO_2 (Ehleringer, 1991). Given this interaction between climate and plants, the efficiency of photosynthesis will increase to overcome the possible impacts of elevated CO_2 in the future. An understanding of the Calvin-Benson Cycle (hereafter C-Cycle) is required to understand how plant production will be affected under elevated pCO_2 requires (Calvin, 1952).

The C-Cycle is a set of chemical reactions that take place in the plant cell beginning when CO_2 is added to the cycle. Within the plant cell, CO_2 undergoes a series of chemical reactions each requiring the expenditure of energy in the form of ATP and NADPH (Fig.2) (Gowik, 2011; Ehleringer, 1991; Calvin, 1952). The end products of the C-Cycle are Glucose, other organic compounds, and additional RuBP for perpetuating the C-Cycle (Fig. 2) (Calvin, 1952).

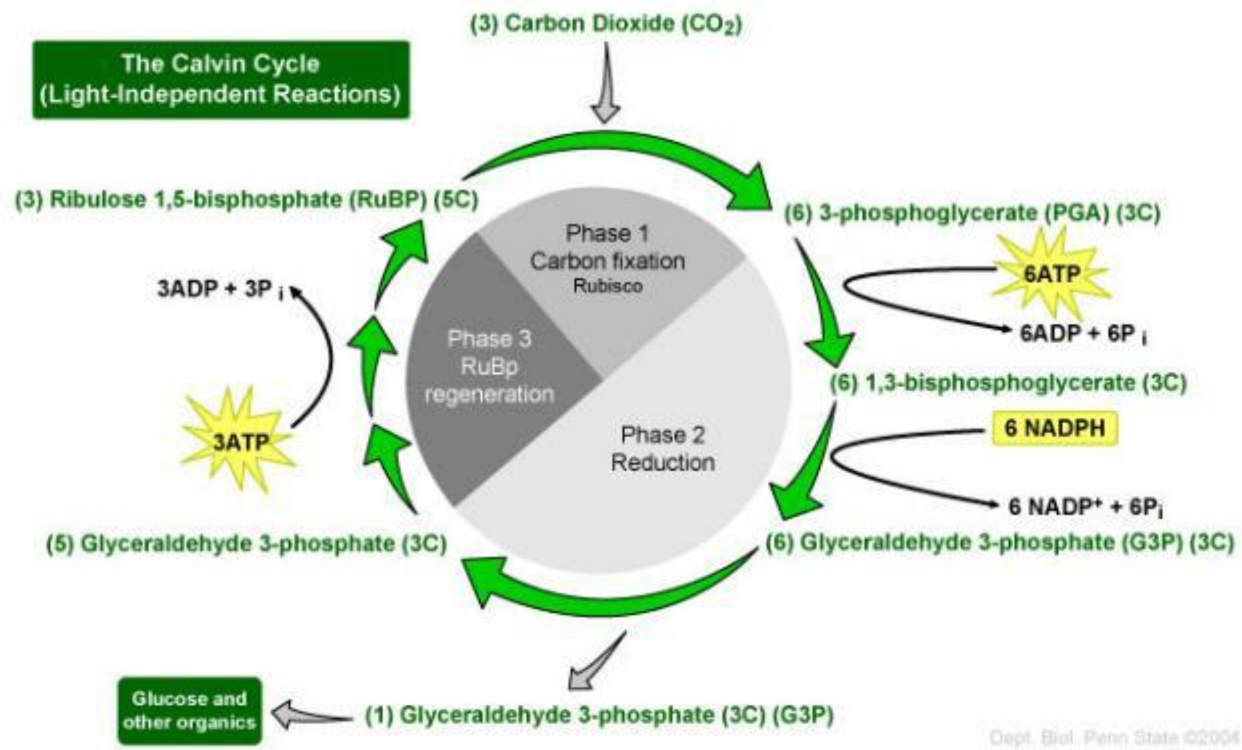


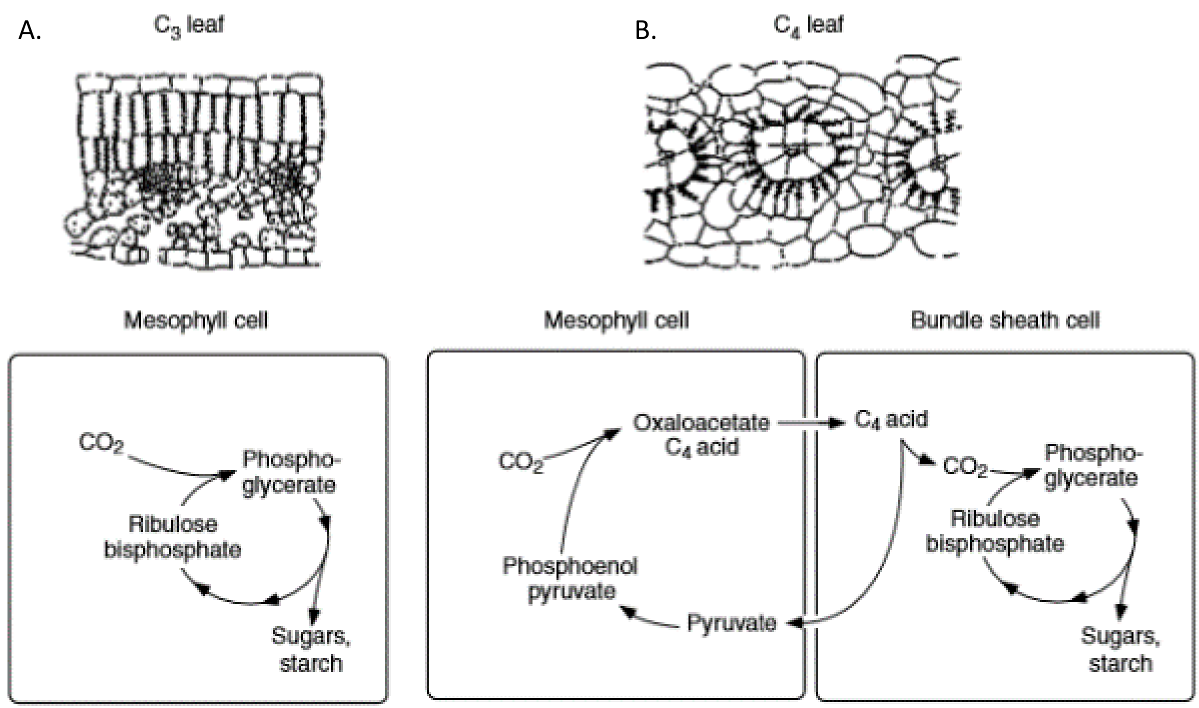
Fig. 2: The Calvin cycle is representing the transformation of CO_2 into Glucose and additional RuBp production (Dept. Biol. Penn State ©2004).

This process takes several iterations to create a Glucose molecule (AKA Sugars and carbohydrates) since only one Carbon is added per iteration of the C-Cycle. Regardless of the pathway, sugars are essential to plant growth making this process the backbone of all photosynthesis (Ehleringer, 2002). The differing pathway designations, (C_3, C_4, and CAM), refer to the method of transporting Carbon from the atmosphere to the chloroplast where the C-Cycle can begin (Ehleringer, 2002; Yamori, 2014). The two dominant pathways in agricultural plants are C_3 and C_4 (Ehleringer, 2002).

Primary Production

C_3 vs. C_4 Photosynthesis

The two most significant methods of converting atmospheric CO_2 into organic carbon (i.e., biomass) are the C_3 and C_4 photosynthetic pathways (Calvin, 1952; Ehleringer, 2002). Both vary in the method of carbon fixation, the quality of biomass production quality, and the isotopic composition of CO_2 re-released into the atmosphere (Calvin, 1952; Ehleringer, 2002). The key differences between C_3 and C_4 plants are the physiological, structural and chemical processes of carbon fixation (Ehleringer, 2002). In C_3 plants the CO_2 molecule is transported into the Mesophyll cell where the C-Cycle occurs (Fig. 3a). In C_4 photosynthesis, the CO_2 molecule is also transported into the Mesophyll Cell, but once there, the CO_2 is turned into an intermediate compound, Oxaloacetate (C_4 acid) (Fig. 3b) (Calvin, 1952; Ehleringer, 2002).



Leaf anatomy and basic photosynthetic biochemistry of C_3 and C_4 photosynthesis

Fig. 3: The key differences between C3 and C4 plants. The Calvin Cycle is the common process between the two pathways (Ehleringer, 2002).

The C_4 acid is then transported into the Bundle Sheath Cell where C_4 is converted back to CO_2, and the C–Cycle occurs (Fig. 3b) (Ehleringer, 2002). The efficiency of processing CO_2 through these pathways is based on environmental temp and the structural differences between the photosynthetic pathways themselves (i.e., Mesophilic C-cycle vs. Bundle Sheath C-cycle).

In environments with lower pCO_2 and/or high temp, C_4 plants are less likely to photorespiration making them more efficient than C_3 plants (Ehleringer, 2002). Meanwhile, in environments with elevated CO_2 or at cooler temps, the efficiency of photosynthesis is greater in C_3 plants because photorespiration is unlikely to occur (Ehleringer, 2002).

Wheat Physiology

The seeds that are planted by a farmer are likely produced using genetic editing or are enhanced to reduce the impacts of disease, drought, or to maximize yields (Elias, 2005). As a semi-arid crop, Durum is often produced in areas with severe weather conditions (Troccoli, 2000; Elias, 2005). A heavy dependence is placed on the adaptability of these new varieties to different environmental conditions, ensuring high yields and protein content (Troccoli, 2000). The field and seed preparations the farmer applies are based on soil conditions, past harvest knowledge, and recommendations from agencies or institutions like the United States Department of Agriculture (USDA) and North Dakota State University (NDSU) (NASS, 1997). Once planted, the seed goes through the stages of growth from seed to harvest including Germination, Emergence, Tillering, Stem Elongation, Booting, Anthesis, Milk, Dough, and Ripening (Zadoks, 1974).

Observing Wheat Physiology

Each phase of growth results in observable changes in plant physiology such as leaf development and grain filling (Nelson, 1984). Farmers use these visible signs to monitor the progress of the crop from emergence to harvest. Monitoring the crop can aid in recognizing and reducing the damage to water and temp stress. Temp stress during the early stages of growth, “may reduce the number of seeds but have minimal effect on seed [health]" (Nelson, 1984). These stresses have the most impact during the Tillering and Anthesis stages of growth (Akram, 2011). In cereal crops, the combined stress during these stages can negatively impact growth and reduce yield (Akram, 2011).

Germination

In germination, the seed takes hold of the soil and absorbs water (Almansouri, 2001). After swelling with water from the soil, the endosperm cracks the outer amber shell of the seed kernel. The structures that leave the seed via the crack include the roots and the primodia, followed by the coleoptile (Nelson, 1984). The latter grows to the surface and becomes the first leaf (Nelson, 1984). The roots grow laterally into the soil to increase the structural support of the plant (Nelson, 1984). These structures maintain a firm grasp on the soil and fortify the coleoptile while the plant emerges to the surface (Almansouri, 2001).

Emergence

After germinating, the plant accrues more biomass to grow taller, create more leaves, and emerge through the soil. Emerging plants are extremely sensitive to atypical precip events (i.e., floods, droughts, snow, hail) (Rozensweig, 2002; Rosenzweig, 2000). It has been observed that exposure to extreme precip has a negative effect on the number of seeds the plant will have at maturity (Maccaferri, 2008). A plant at the end of emergence can have up to six main roots and three leaves (Acevedo, 2006; Nelson, 1984). Once grown, these leaves absorb photons to begin photosynthesis (see Plant productivity). The Emergence phase ends when the first tiller emerges (Acevedo, 2006).

Tillering

The "Tillering Stage" has begun when the first leaves are fully formed and the first tiller has emerged from the soil. Tillers attach the leaves to the main stem and add more structural support to the plant (Acevedo, 2006). The growth of a root to support the tiller does not begin until the tiller is supporting three leaves. If a tiller fails to produce three leaves, then a root will not form, and the tiller will fall off the plant (Acevedo, 2006).

At the end of the tillering stage, the main stem will stop initiating new leaves, and the shift in plant production will be towards vertical and reproductive growth (Acevedo, 2002; Zadoks, 1974). This marks the shift from the vegetative phase to the reproductive phase.

Stem Elongation/Stem Joining

At the end of the tillering stage, the leaf nodes are stacked at the bottom of the plant. The plant stem will begin to grow taller with the nodes growing farther apart (Acevedo, 2002). The plant elongates like a collapsible telescope, and as the plant extends upward, the leaves will grow and organize to optimize light interception (Nelson, 1984). The plant develops the flag leaf to protect the grain residing in the head of the plant. The full development of the flag leaf and achieving its final vertical position ensures grain protection. The flag leaf is the primary photosynthetic organ for grain filling and indicates the start of the booting stage (Nelson, 1984; Abbad, 2004).

Booting and Anthesis (AKA Flowering)

The head of the wheat plant grows and swells with moisture throughout the booting stage and is protected by the flag leaf. At the end of the booting stage, the plant appears matured except for having smaller grains and a green color (Fig. 4, Left) (Abbad, 2004).

Durum is a self-pollinating plant which means that during anthesis/ flowering the plant uses both female and male reproductive structures that mature simultaneously within the flower (Nelson, 1984). The onset of anthesis is marked by the observation and development of the tiny white anthers (aka. Flowers) (Fig. 4, Right).

Fig.4: Plant growth including booting stage (Left) and beginning Anthesis (Right) (Miller et al., 2001).

The pollination of Durum anthers occurs within a week after flowering is complete (Acevedo, 2006). The kernel absorbs moisture and develops a rich endosperm. Endosperm development can be stunted by drought or water stress during the anthesis stage (Acevedo, 2006). This is normally the stage where additional water may be applied to reduce negative impacts of disease or illness.

A key attribute of the Anthesis growth stage is the sensitivity of the crop to photoperiod (Sanna, 2014). Photoperiod is the length of day in a specific spatial location dictating the length of the day and temp. Photoperiod is a key factor in the initiation of reproductive growth. If a plant, like Durum, is sensitive to the photoperiod then a minimum day length must be achieved to initiate Anthesis (aka flowering) (Sanna, 2014). Once this is achieved, the post-anthesis processes are considered reproductive growth including kernel development and ripening (Masoni, 2007).

Dough

In the Dough stage, the moisture collected during anthesis is mixed with the sugars produced during photosynthesis to create a starch-rich endosperm with a milky dough structure (Zadoks, 1974). During this period the starches will increase, and the endosperm will grow (Zadoks, 1974). Once this begins, the grain can be checked for moisture content by denting the outside with a fingernail or tool. Initially, the kernel is easily dented with a fingernail[2], representing the soft dough stage (Zadoks, 1974). As the grain continues to swell with starches, the kernel dries and hardens (Verma, 1998). The end of the Dough stage is easily visible by the color of the plant stem which will appear dry and amber colored.

Ripening

Ripening is the optimal time for harvesting a Durum crop. Modern mechanized harvesting techniques employ a machine called a combine harvester which requires increased moisture in the plant (16%), thus an earlier harvest date (Zadoks, 1974). The harvesting process removes the endosperm which is the desired food part consumed by humans. The engorged endosperm makes the grain kernels large and swollen. The unique amber color, large kernel size, and high protein content of the grain makes it very desirable (Fig. 5) (Zadoks, 1974).

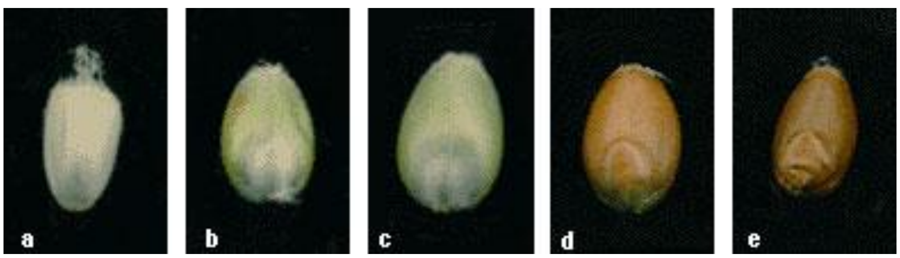


Fig. 5: Kernel growth and development during Dough and Ripening stages. These stages of development are when protein and moisture accumulation increase until the kernel is an amber color (UMN extension).

Observational Tools

Producers worldwide use observational growth stages to monitor the progress of crops, a critical task if production occurs in a hostile environment. Producing Durum in North Dakota is a challenge with several environmental and climatic variables harming or slowing growth. Therefore, close monitoring and observation is key to producing a superior harvest. Some tools

[2] A common method in cereal production is to use one's fingernail to dent the outer shell of the grain to figure out the stage of grain development and plan harvest.

developed to aid farmers in estimating the progress of their crop are growth scales based on observable changes in plant physiology.

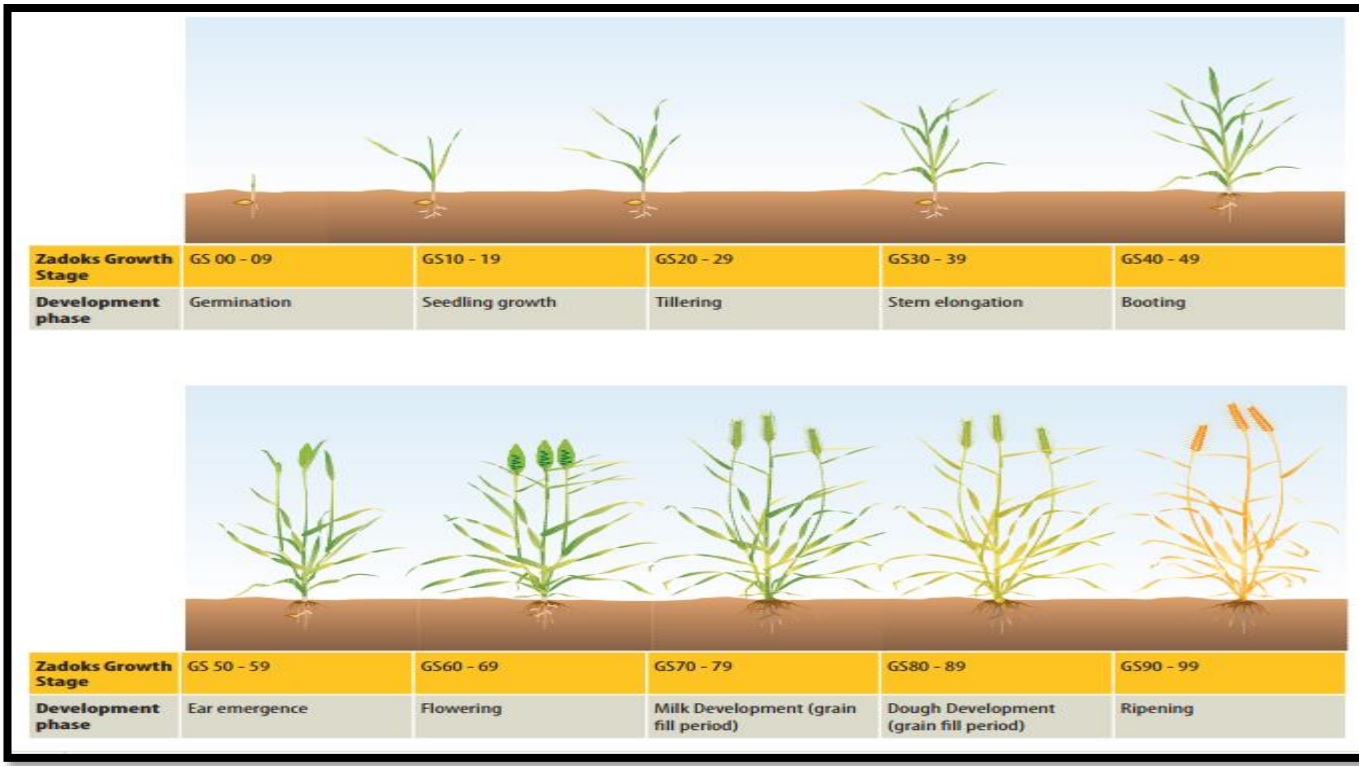


Fig.6: Zadoks decimal code for the growth of cereal crops. Each stage is identified by an observable change in crop growth that indicates the current growth stage, whether it be color or development. (Poole, 2005)

The various stages of growth are observable with the naked eye and are classified into a scale. The Zadok scale is the most comprehensive and easiest to use (Fig. 6) (Zadok, 1974). This scale shows the stages of development as well as an accompanying code classification for cereal crop development (Fig. 6). Ranging from 0 to 99, the scale is broken into four larger stages of growth, tillering, stem extension, heading, and ripening (Table 1) (Zadok, 1974). Each stage encompasses several observable changes in physiology (Zadok, 1974). These changes are indicators to the farmer to conduct certain operations such as fertilizer application. For example, the entirety of the Tillering stage is coded 20 to 29 (Fig. 6) (Zadok, 1974).

Knowing the exact stage of crop growth is essential to decision making since certain practices may be lethal to the crop during vulnerable stages. Durum is sold based on quality, a feature that is influenced by the timing and intensity of nitrogen application. Therefore, the timing of these applications needs to be timed accurately using observable scales like Zadoks.

Table 1: Code and description of various growth stages from germination to ripening. a: Winter cereals only. b: An increase in the solids of the liquid endosperm is notable when crushing the seed between fingers. c: Fingernail impression held; head losing chlorophyll

Decimal code used to quantify the growth stages in cereals

Code	Description	Code	Description
0	**Germination**		
0.0	Dry seed	38	Flag leaf ligule just visible
0.1	Start of imbibition	39	Flag leaf ligule just visible
0.2	Imbibition complete	**4.0**	**Booting**
0.3	Radicle emerged from seed	41	Flag leaf sheath extending
0.4	Coleoptile emerged from seed	43	Boots just visible and swollen
0.5	Leaf just at coleoptile tip	45	Boots swollen
1.0	**Seedling growth**	47	Flag leaf sheath opening
10	First leaf through coleoptile	49	First awns visible
11	1 leaf unfolded	**5.0**	**Ear emergence**
12	2 leaves unfolded	51	First spikelet of ear just visible
13	3 leaves unfolded	53	One-fourth of ear visible
14	4 leaves unfolded	55	One-half of ear emerged
15	5 leaves unfolded	57	Three-fourths of ear emerged
16	6 leaves unfolded	59	Emergence of ear complete
17	7 leaves unfolded	**6.0**	**Flowering**
18	8 leaves unfolded	61	Beginning of flowering
19	9 leaves or more unfolded	65	Flowering half-way complete
2.0	**Tillering**	69	Flowering complete
20	Main shoot only	**7.0**	**Milk development**
21	Main shoot and 1 tiller	71	Seed water ripe
22	Main shoot and 2 tillers	73	Early milk[b]
23	Main shoot and 3 tillers	75	Medium milk
24	Main shoot and 4 tillers	77	Late milk
25	Main shoot and 5 tillers	**8.0**	**Dough development**
26	Main shoot and 6 tillers	83	Early dough (fingernail impression not held)
27	Main shoot and 7 tillers	85	Soft dough[c]
28	Main shoot and 8 tillers	87	Hard dough
29	Main shoot and 9 or more tillers	**9.0**	**Ripening**
3.0	**Stem elongation**	91	Seed hard (difficult to divide with thumbnail)
30	Pseudo-stem erection[a]	92	Seed hard (cannot dent with thumbnail)
31	1st node detectable	93	Seed loosening in daytime
32	2nd node detectable	94	Seed over-ripe; straw dead and collapsing
33	3rd node detectable	95	Seed dormant
34	4* node detectable	96	Viable seed giving 50% germination
35	5th node detectable	97	Seed not dormant
36	6th node detectable	98	Secondary dormancy induced
37	Flag leaf just visible	99	Secondary dormancy lost

North Dakota Durum Wheat Production

The production of North Dakota Durum is best evaluated using data available from the National Agricultural Statistics Service (NASS). The average Durum production (BU) has decreased (r^2 = 0.21) an annual average of 48,672,700 BU from 1981 to today (USDA, 2017). This is connected to the similar decreasing trend in planted and harvested acres (Fig. 7). Meanwhile, yield (BU/acre) (r^2 = 0.44) has increased significantly over the same period (USDA, 2017).

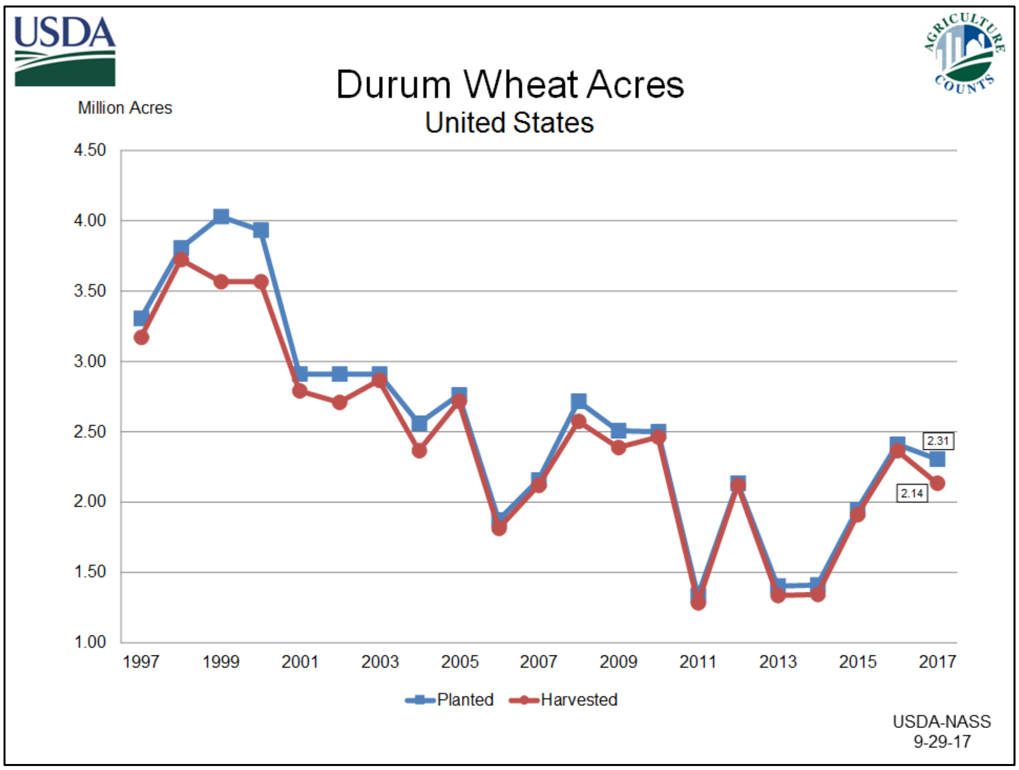


Fig. 7: National Durum wheat planted and harvested acres (USDA-NASS, 2017).

The average annual production data for North Dakota shows a decline in the average statewide production from 2008 – 2010 (USDA, 2017). The annual losses are estimated at 1.6 million metric tons, an estimated value of ~$464 million. Despite this decline, North Dakota represents 60% of national production and ~67% of planted domestic Durum hectares from 2008 - 2010 (USDA, 2017). Planted acreage decreased from ~1.50 million acres (1997) to ~2.30 million acres (2011) continuing until 2013 when acreage increased continuing to 2016 (USDA, 2017).

In North Dakota, Joppa, Tioga, Divide, Carpio, and Alkabo are the top five cultivars[3] planted in the state, representing 66% of acres planted (U.S. Wheat Associates, 2016). Each variety has different growth characteristics such as height, disease resistance, or drought tolerance (U.S. Wheat Associates, 2016). The acreage is unevenly distributed with highest Durum production in the W and lowest in the E. Meanwhile, the distribution of yields is opposite with high yield in the E and lower in the W, S, & SW (Fig., 8) (U.S. Wheat Associates, 2016). Per the NASS data yields for North Dakota have historically ranged from a low of 0.53 t/ha in Stark County during the nationwide drought in 1988 to the record highest observed yield of 4.05 t/ha in Hettinger County in 2009 (USDA, 2017).

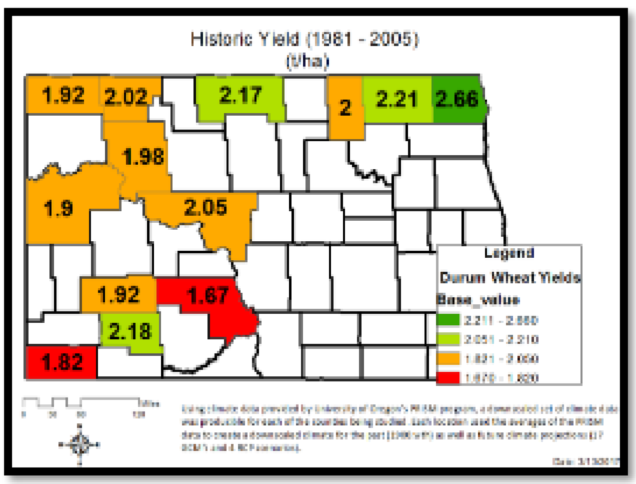


Fig. 8: The distribution of average Durum Wheat yield (1981-2005), across North Dakota (USDA, 2017).

Despite increases in yield, largely due to advances in seed engineering, the farmer's net income barely breaks even (Prat, 2017). A farmer's subpar economic return can be associated with the effect of increased diseases such as vomitoxin (VOM) in local and regional harvests (Prat, 2017; Friskop, 2017). Durum happens to be more susceptible to disease than other crops (Prat, 2017). This increased risk of disease is expressed in the price premiums they receive. Excellent quality

[3] A cultivar is a unique crop subspecies which is genetically different from the parent plant and from other genetically altered varieties.

grain is worth between $5.50 and $6.00 per bu. Grains often require cleaning to meet processors quality standards since the fetching price for VOM infected grain is between $1.8 and $3 per bu. (Triccolli, 2000).

The impact of VOM is best analyzed by looking at the cost of reversing or cleaning an infected crop. A farmer's contract with a grain buyer is contingent on the quality and the health of the crop. Should a crop fail to reach quality standards, the farmer then would have to either pay to have the grain cleaned and hope it is of proper quality, or pay out the value of the contract (Vaughn et al., 2016). The estimated economic impact of FHB outbreaks in the Midwest Durum crops is ~$1billion annually (Vaughn et al., 2016).

The cost of cleaning the infected grain is between $7,000 to $15,000 in equipment rentals to clean and create a higher-quality grain for a better market price. The risk of infection and cost of cleaning is great enough that it may currently outweigh the premium received for planting Durum (Prat, 2017). In 2016, the ND and neighboring Canadian Durum crops suffered a heavy impact from VOM (Prat, 2017).

Durum Interactions with the Environment

Durum is produced in the Mediterranean basin of Southern Europe, the desert areas of Mexico, the Northern Plains and Southeast of the US and neighboring Canada (Ranieri, 2015). Cool, dry locations where Durum is grown will be altered in response to climate changes and pCO_2 levels (Vocke, 2013). This has and will continue to force suitable planting areas to shift N and W, across the American/Canadian geopolitical border and into Montana, where temps are predicted to remain cool (Vocke, 2013).

Growing Degree Days (GDD)

The measure of Growing Degree Days (GDD's) is used to estimate the effects of temp on crop growth and potential yield by assigning a heat value for each day of the growing season (eq. 02) (Miller et al., 2001). The calculation of GDD uses an average daily temp and a "Base Temp" (T_{Base}) to determine the amount of heat energy available for daily growth (Miller et al., 2001). T_{Base} is the point below which plant metabolism slows, and development stops, essentially entering a state of dormancy until air temps increase above the T_{Base}. The theoretical T_{Base} value for most wheat species is between 0 and 4 ℃, 0 ℃ for Durum (Miller et al., 2001) (eq. 02). To calculate the GDD for a specific day, the T_{Base} is subtracted from the daily average temp (eq. 02) (Miller et al., 2001).

$$GDD = \left(\frac{T_{Max} + T_{Min}}{2}\right) - T_{Base} \qquad (02) \qquad (Miller\ et\ al., 2001)$$

Like T_{Base}, T_{Upper} is the maximum temp for growth. T_{Upper} is a point at which, when exceeded, plant growth will stop due to water loss. In North Dakota, the frequent temp extremes often exceed the max temp thresholds causing plant stress. In areas like North Dakota, the frequent pattern of temp extremes is likely to increase in the future increasing significance of GDD and AGGD in crop growth and development (Miller et al., 2001).

As an example, a typical growing season day in North Dakota with a T_{Max} of 27℃ and a T_{Min} of 14℃ would have an average daily temp of 31℃. Using the general Durum T_{Base} value of 0℃, this day would have a GDD value of 29℃. In this example, a Hard-Red Spring Wheat plant with the GDD requirement structure as shown in table 2 would require ~4 to ~6 days of these temps to accumulate the 125 – 160 GDD℃ needed to complete the Emergence stage (Miller et al., 2001). This will continue, requiring more to reach each of the other growth stages and finally reaching the total AGGD of 1538 – 1665 ℃. The day described in this example is an optimized scenario with ideal temps and no negative weather impacts (Table 2). However, days like this are often accompanied by precipitation events and temps too hot for plant development. This makes an upper temp threshold a second barrier to plant growth.

Table 2: Examples of growth stages and GDD/AGGD requirements for a wheat crop to reach maturity. (Miller et al., 2001)

WHEAT (Hard Red) Data source: Stu Brandt, Scott, SK 1993-97 and Perry Miller, Swift Current, SK 1995-98

		Stage	GDD°C	GDD°F
Emergence	Leaf tip just emerging from above-ground coleoptyle.	1.0	125-160	257-320
Leaf development	Two leaves unfolded.	1.1	169-208	336-406
Tillering	First tiller visible (tillering of cereals may occur as early as stage 1.3, in this case continue with 2.1).	2.1	369-421	696-789
Stem elongation	First node detectable.	3.1	592-659	1097-1218
Anthesis	Flowering commences; first anthers of cereals are visible.	6.1	807-901	1484-1653
Seed fill	Seed fill begins. Caryopsis of cereals watery ripe (first grains have reached half of their final size).	7.1	1068-1174	1954-2145
Dough stage	Soft dough stage, grain contents soft but dry, fingernail impression does not hold.	8.5	1434-1556	2613-2832
Maturity complete	Grain is fully mature and drydown begins. Ready for harvest when dry.	8.9	1538-1665	2800-3029

The key difference between the maximum and minimum temp thresholds for growth are the plant responses to these extremes (Reyer et al., 2013). At the minimum temp threshold, the plant metabolism slows to a state of dormancy, and at the maximum threshold, photorespiration will occur (Reyer, 2013; Atkinson, 1996). When the GDD calculation is used in conjunction with plant growth observations, a link between growth and thermal energy is obvious (Atkinson, 1996). A well-trained farmer will become accustomed to the growth of the crops cultivated on his or her land. This will be supplemented with assistance from accurate management schedules (i.e., planting and harvesting dates) from federal and local institutions (Rosenzweig, 2002).

Laboratory studies have shown that prolonged exposure to hot temps during critical growth stages will lead to crop developmental stress, disease, increased mortality, or all the above. The plants are especially susceptible to these forcing during photosensitive stages of growth like Germination and Anthesis (Brown, 1997; Rosenzweig, 2002). A change in this GGD thermal value, a unitless measure of heat energy accumulated over a solar day, will impact the health and yield of the crop (Rosenzweig, 2002; Miller, 1997).

Growth models use artificially generated or observed meteorological data to calculate the daily GDD allocation for a specific crop, location, region, or time. In general, the spatial distribution of temp across North Dakota are hotter in the S and cooler in the N counties. Any change in the quantity or distribution of AGDD across the season will have direct impacts on the growth of the plants and the timing of growth stages (Sinclair, 2010). It is, therefore, important that models simulate the various scenarios under which a change in available GDD can occur via a change in climate (Atkinson, 1996).

In Feng 2012, the link between weather, climate, and yield was explored determining that an increase of 10 GDD's over the entire season resulted in a modest increase in yield of 0.57%. More interestingly, under extreme heat waves, it was found that yield would decrease by 6.76% for every ten days above the max temp threshold (Feng, 2012). The study confirmed that extremes in temp are a threat to growth.

The estimated changes in temp and these impacts on agriculture have driven agronomists and crop geneticists to minimize the detrimental effects of temp on growth (Feng, 2012). Energy and research objectives are being diverted from focusing on maximizing crop yield to enhancing genetic protective mechanisms from thermal and environmental damage (i.e., drought and disease resistance) (Feng, 2012; Ritchie, 1991).

Precipitation (mm)

Durum in North Dakota is produced in the Southwest (SW), Northwest (NW), and along the Northern (N) to the Northeast (NE) border with few planted acres in the rest of the state (Jensen,1998).

Precip is a critical component of plant growth and yield. On average, during the heading and filling stage, a wheat plant uses approximately 6.44 mm of water and even a slight increase of only 20 mm in the seasonally accumulated precip can greatly impact crop growth and yield (Jensen, 1998). Grain Yield (GY) of Durum was studied under several precip regimes, and results showed that the plant health varied based on the quantity, type, and temporal distribution of precip throughout the growing season (Qaderi, 2009). The physiological implications of precip changes on agriculture are not limited to prolonged drought but also to increased precip (Qaderi, 2009).

It is well documented that increased precip frequency could lead to the mortality of crops from and prolonged crop exposure to saturated soil conditions (Prat, 2017). Altogether, prolonged exposure to these conditions could promote mold growth, root rot, parasites, and fungal diseases (Rosenzweig, 2002; Porter, 2005). It has been suggested that crop diseases such as septoria leaf spot diseases (Septoria tritici and S. nodorum) will become more prevalent with excess precip and temps because of CC (Prat, 2017).

One crop disease of specific concern in ND is the Fusarium Head Blight (FHB) which affects wheat cultivars and is extremely destructive to crops causing crop mortality and grain infection (Prat, 2017; Mesterhazy, 1995). Furthermore, it is expected that warming temp coupled with increased precip may migrate these crop diseases to unprecedented locations in the northern latitudes (Smith, 2014). It is likely that precip will increase due to CC soon, with greater uncertainty later in the 21st century (McCarthy et al., 2001). Should winter seasonal precip increase, both liquid and solid, it is likely that fields may be too wet in the Spring and the planting date will be delayed (McCarthy, 2001).

In Spring 2017, farmers postponed planting until the fields dried out, and then it snowed several inches just a week later (Kennedy,2017). The struggles between agriculture and water resources are a result of the E to W precip and N to S temp gradients (Jensen, 1998). These spatial gradients are heavily influenced by geography, climate, and the movement of continental air masses (Jensen, 1998). All of which heavily influence Durum production in North Dakota.

In the W, the average annual precip is 33.0 cm and increases to 51.0 cm in the E (Munski et al., 2018). This is attributed to a higher climatological influence of the Gulf of Mexico, which is the primary source of moisture for the state, in the S of the state than the N (Jensen,1998). Historically, 50 to 60 % of annual liquid precip falls between the months of April and July. Making this period the ideal season for growing summer crops. This, coupled with often substantial amounts of solid precip in the winters, makes North Dakota an ideal location for agriculture with large spring melts (Jensen, 1998).

The spatial gradient of average annual total PRECIP is 25 to 50 mm higher in the E than in the W. The elevation slope gradually increases from W to E (Jensen 1998). Divide, Dunn, McKenzie, and Williams counties all receive greater amounts of PRECIP due to the higher elevations in those areas (Jensen 1998). The primary precip related issue facing North Dakota, both current and anticipated, is too much precip causing disease and promoting crop failure (Rosenweig, 2002; Johnson, 1982). However, this does not eliminate the effect of drought. Despite significant impacts from decreased precip, in many C_3 crops the main effect of changes in climate will be related to increased temp and in turn, decreased precip.

Temperature (^oC)

As a C_3 plant, Durum stomata will close in the event of extreme temp events, especially ongoing heat waves (Porter, 1999). This will initiate photorespiration causing a decrease in photosynthetic efficiency and O_2 production (see C_3 vs. C_4 photosynthesis) (Porter, 1999). Crops that are exposed to increased and/or prolonged temps often have decreased yield, protein, and moisture, and increased occurrences of crop mortality (Porter, 1999; Qaderi, 2009). In addition, these temps can cause decreases in plant biomass via increased evapotranspiration and stomatal conductance (Qaderi, 2009).

Like all living things, plants have a metabolism that regulates organ development, phonological processes, respiration, senescence, and nutrient uptake. The rates of these processes are influenced by several factors; one is the ambient air temp (Porter, 1999; Qaderi, 2009). Since plant function and development are heavily temp dependent, increases in temp could cause plants to develop/grow faster than under lower temps (Qaderi, 2009). The range of ideal temps for crop growth is species and spatially dependent, and any change will affect plant physiology and growth (Porter, 1999; Qaderi, 2009; Jensen, 1998). One effect that will alter plant growth changes in regional and local climate.

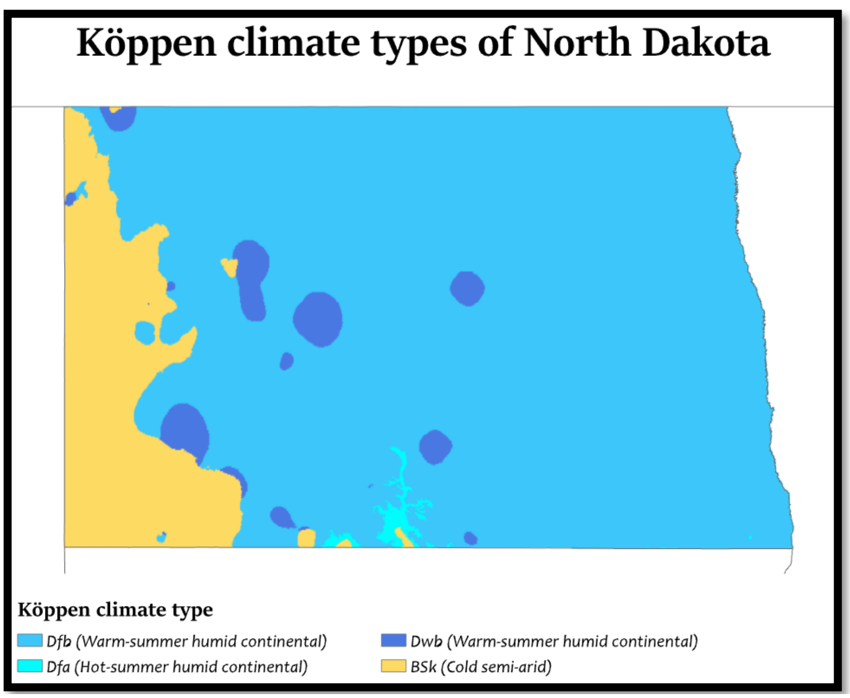


Fig. 9: Köppen climate classification of North Dakota which is a mix between semi-arid and Warm-summer humid climate. (Peterson, 2016)

There are four different climate types that make up North Dakota climate per the Köppen classification system. This system breaks climate zones into a three-part descriptive indicator consisting of the main climate group, a seasonal precipitation type, and the heat level (Fig. 9) (Kottek, 2006). However, two are dominant and occupy most the study area, Dfb (Warm-summer continental) and Bsk (Cold semi-arid) (Fig. 10) (Kottek, 2006). These climate types have frigid winters with temps frequently reaching -28.8 ^{o}C and hot summers reaching 32.2 ^{o}C (Jensen, 1998).

The western third of the state has a BSk or "cold semi-arid climate" with hot, dry summers and cold winters (Kottek, 2006). There is a greater difference in daily temp in the W than in the E. North Dakota has cold winters, hot summers, high precip in the E and lower precip in the W (Kottek, 2006).

The months with the greatest number of continuous days with temps above 90 ^{o}F occurred during the months of July and August (Jensen, 1998). There are ~8 – 14 days per year where temps reach or exceed 90 ^{o}F in the NE (Jensen, 1998; Qaderi, 2009). Meanwhile, in the SW and SC region, these temps occur more than 32 days per year (Jensen, 1998).

ND has a continental climate with light to moderate intensity precip, low humidity, and high-speed winds (Jensen, 1998). Extreme high and low temp are unique features of the ND climate. The growing season can experience long periods of prolonged hot weather and resulting drought with extreme temp variability (Kottek, 2006). ND experienced a statewide drought in Summer of 2017 which could threaten the production of some crops, including Durum.

In laboratory settings, high-temp conditions affected all stages of grain development (Altenbach, 2003). With high temps having a significant impact on the duration of water uptake, this could become damaging to ND agriculture which is mostly rain-fed (Altenbach, 2003). Lastly, it was observed that kernel health decreased as moisture accumulation in the kernel decreased (Altenbach, 2003; Jensen, 1998). These key climatological factors (i.e., temp and precip) play a significant role in the production of healthy, high-quality Durum.

Climate Change and CO_2 Concentrations

Climate Change

Weather consists of daily temp and precip while climate consists of long-term temp and precip trends and other natural phenomena related to global thermal regulation (i.e., ENSO, Deep Ocean Convection, Hadley Cells, etc.). Our understanding of the Earths' atmospheric circulation is based on decades of observation. Experts in meteorology and climatology have used these observations to establish a well-founded understanding of how the Earth regulates temp via air circulation and the global water cycle. Therefore, climatologists and meteorologists are qualified to discuss the effects of increased pCO_2 on climate. Their current scientific consensus established a link between pCO_2 and the changes in observable climate variables (i.e. Tmax, Tmin, and Precip).

The concentrations of gases in the atmosphere (CO_2, and NH_4) can be sampled from gas pockets trapped in ancient ice. The main paleoclimate GHG's were $H_2O_{(v)}$, CO_2, and NH_4. NO_x and CFC's are absent since these are sourced from anthropogenic activities. The ice core data shows that levels of pCO_2 and other GHG's have changed over millennia and global climate responds according to these changes. Higher pCO_2 and other GHG's coincide with periods of warmer average global temp.

Recent human behavior and the impact on the natural cycling of GHG's began during the industrial revolution (the 1880's). This trend continues today with steadily increasing coal, oil, and natural gas emissions. This trend of increasing pCO_2 has been observed from 1960 to 2017 and is expected to increase. Global pCO_2 increased from 316.91 ppmv to 406.42 ppmv during this period (Tans, 2016). This is a total change of 89.51 ppmv (28%) over 57 years. 37.13 ppmv (41%) of which occurred between 2000 and 2017. Other phenomena that have been observed related to CC include biotic and meteorological changes such as glacial melting and the migration of plant and animal species to regions with more suitable climates. To study the potential changes in climate, the Intergovernmental Panel on Climate Change (IPCC) created scenarios of future climate (RCP's 2.6, 4.5, 6.0, and 8.5) (Bjørnæs, 2013).

The purpose of these IPCC Climate scenarios is to identify changes in climate using radiative forcing goals without identifying a specific method of achieving said goal (Bjørnæs, 2013). These scenarios were created by several research institutions in the Netherlands, United States, Japan, and Austria with assistance from contributing scientists around the world. Each scenario is "representative" of potential practices that will result in the desired radiative forcing goal (w/m^{-2}) (Bjørnæs, 2013). These scenarios meet guidelines developed by research teams and the IPCC (Pachauri, 2014).

The research institutions that made these models analyzed the scientific and real-world implications of changes in climate over the 21st century. The areas studied include GHG emissions, energy dependence, population growth, economic growth, and technological advancement. Unlike previous generations of scenarios created by the IPCC which pigeonholed the method of achieving this goal (i.e., energy independence or population), these new scenarios do not take this approach (Bjørnæs, 2013). It allows for innovation and unique combinations of mitigation strategies that meet local or regional needs.

The original strategy was a decision maker, usually a nation's executive branch, to choose a scenario and then commit to making decisions that will achieve the target radiative forcing by

2100. This method allows a decision maker to investigate the best technologies and scientific approaches that will aid in achieving this goal for the specific nation and in turn the Earth.

The four RCP scenarios (2.6, 4.5, 6.0, 8.5) are used in conjunction with 17 General Circulation Models (GCM's) to create 68 simulations which ensure the distribution of the Earths temp and precip is not misrepresented in models by the nuanced differences between GCM's. The RCP nomenclature corresponds to increases in net radiative forcing by the year 2100 using trends in current land use and emissions identified in the literature. (i.e., "RCP 2.6"equals a net increase in radiative forcing of 2.6 W/m^2) (Bjørnæs, 2013). RCP's 2.6, 4.5, 6.0 and 8.5 create possible paths to achieving the increases in net radiative forcings for each scenario. These scenarios do not describe specific policies or practices that will achieve the goals (i.e., one-child policy, agrarian economy, etc.). Instead, these scenarios set a radiative forcing goal and communities or nations may choose the interventions, and mitigating strategies they feel are appropriate to reduce local contributions to the increasing Greenhouse Effect.

The Global Energy Budget

Earth regulates its Mean Annual Surface Temperature (MAST) of the planet using winds, ocean currents, and other forces. This process maintains a state of thermal energy balance across the planet. This natural state of balance has been and is continuously altered by human activities. Even the behavior of our ancient ancestors had a small impact on ecology and even contributed to emissions of GHG's. The small effect of our ancestors was multiplied as human populations grew and technology advanced. It was the advancement of technology and science, circa 1600's to 1880's, that allowed for the contributing human emissions to increase and detrimentally impact the climate.

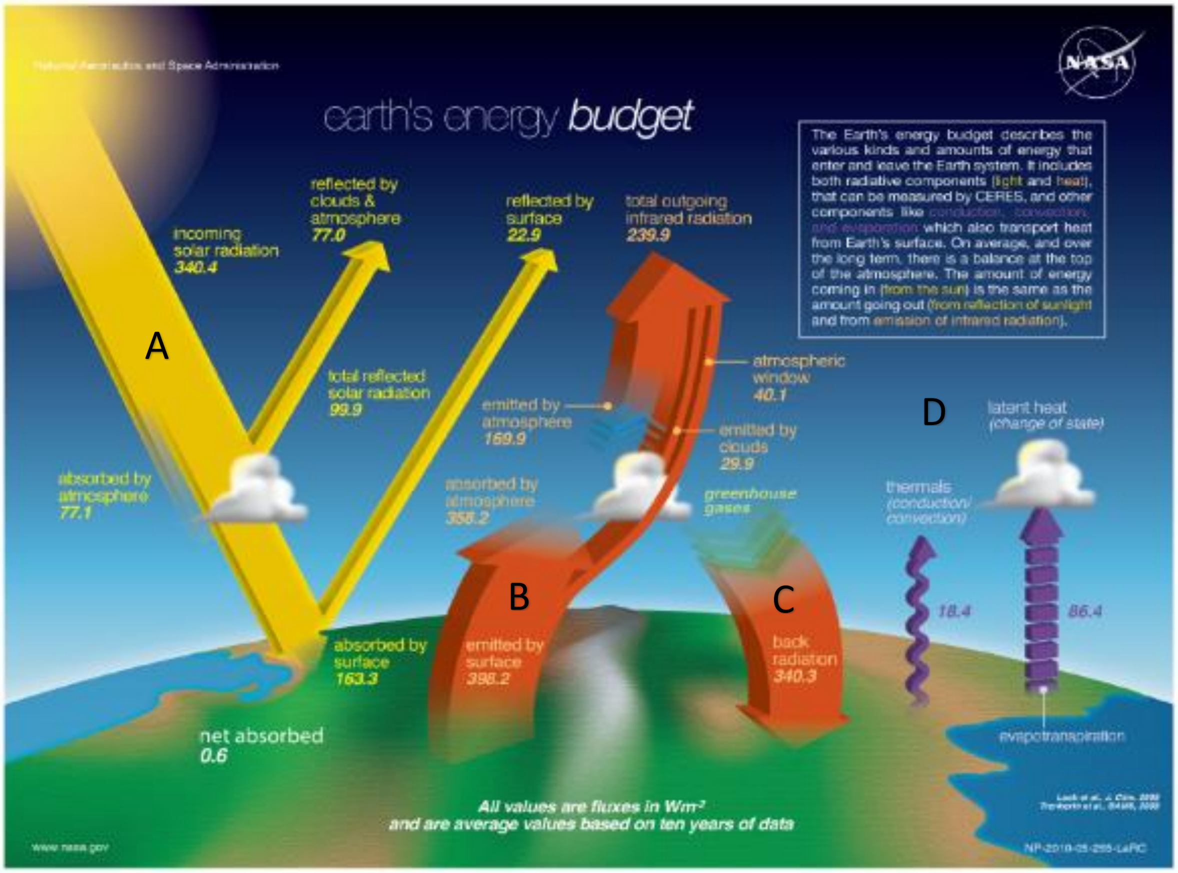


Fig. 10: The global energy budget representing the balance of incoming solar heat and energy versus the outgoing thermal and solar energy (NASA).

The Earth Energy budget describes the balance between light and heat energy that enters the Earth's atmosphere (Fig. 10: A) versus the amount that radiates off the Earth back to space (Fig. 10: B). This budget is usually balanced, so the Earth is emitting the same amount of energy as is entering the system. The methods for radiating this energy back to space occur during evaporation, conduction, and convection (Fig. 10: D). In some locations, this energy is even used to heat homes via geothermal energy.

This energy that leaves the earth's surface from this balanced energy system radiates back into the atmosphere (Fig. 10: B). This energy then interacts with chemicals in the atmosphere (GHG's), and instead of exiting into space, the energy is re-radiated back to the Earth's surface and absorbed (Fig. 10: C). The more GHG's put into the atmosphere, the greater the amount of energy re-radiated back to Earth and the greater the increase in the MAST. This theory has guided climatologists to the conclusion that the radiative forcing will increase between 2.6 and 8.5 w/m^2, an increase that corresponds to an increase of ~2 ºC in Global MAST (Bjørnæs, 2013). One way to mitigate this increase in radiative forcing and in turn temp is to mitigate and reduce the emissions of GHG's.

Agriculture & Climate Change

Land use significantly contributes to CC. Agricultural, Forestry, and Other Land Use (AFOLU) activities emit significant amounts of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide

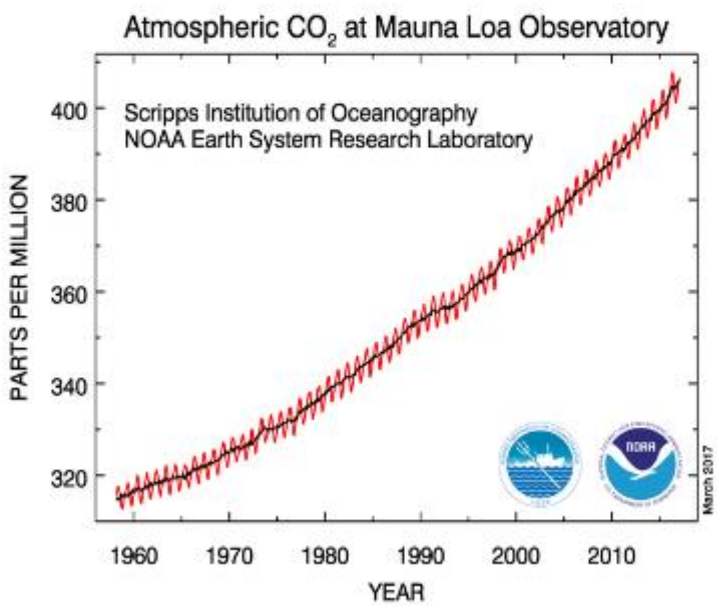


Fig. 11: Observed pCO2 levels at the Mauna Loa monitoring station, Hawaii

(N_2O) into the atmosphere (Smith, 2014). From pre-history to the 1800's, the main sources of agricultural GHG emissions are from deforestation and agriculture land conversion via slash and burning methods. Since the 1800's these GHG emissions have increased and were furthered in 1909 with the advent of industrial nitrogen fixation. This increase has continued well into the 21st century (Fig. 11). North Dakota cereal crops use such nitrogen fertilizers, the strategic application of which can have a significant benefit to increasing yields.

The final agricultural contributions to GHG emissions are from seed production, transportation, and end-user waste (i.e., packaging). These contributions are difficult to estimate and are considered negligible when compared to other sources of agricultural emissions such as machines and fertilizer. Taking a look at how carbon moves throughout the Earth, we observe that fossil fuels contribute ~9 GT of carbon a year. It is well established that natural carbon sequestration, the storage of carbon from the atmosphere in the ocean and in biotic life, does not occur as quickly as the annual release of additional carbon into the atmosphere. The current contributions of agriculture to CO_2 emissions will increase as fertilizers and demand for agricultural land use increases. The reality is only exacerbated by increased food demand from a burgeoning global human population.

Effects of Climate Change on Food Availability and Security

Food availability is defined as the production and health of food commodities, while food security is the distribution of and access to these commodities for a given population. The effects of CC on food security will be significant. Droughts and floods are expected to be more frequent

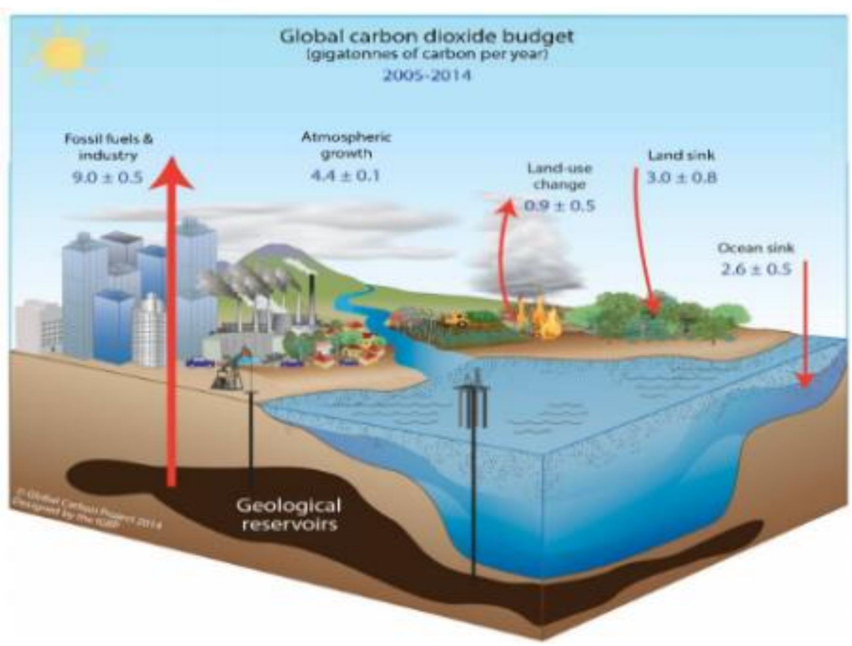


Fig. 12: The pCO2 budget of sources and sinks in the Anthropogenic/Environmental system. (Le Quéré, 2016)

causing damage to crops. Heat waves will cause temp stress and kill plants. These changes in climate will alter the distribution and availability of food in the future. One non- climate-related challenge affecting food availability is the number of humans on Earth. As of April 2017, the human population has reached 7.25 billion individuals, and the United States is the third most populated nation with 326.6 million. The population is growing and, when coupled with the impacts of CC, many people will see changes in diet and food resources (Rozenberg, 2015). These changes will place additional strain on the production, transportation, storage, and distribution of food commodities. Increases in food demand will force producers to use more fertilizers and increase irrigation to produce higher yields on fewer available hectares of land (Fig. 12). Changes from a climate that affect the distribution of food will also affect the distribution of human populations. Under future climate change affects coastal areas will experience flooding and permanent inundation. These inundated coastal areas will force populations to migrate from cities suffering under increasing population and negative coastal climate effects (i.e., hurricanes, tsunamis, winter storms) (Neumann, 2015).

Table 3: Changes in land use and GHG emissions under the four RCP's (Hartman, 2013).

Scenario Component	**RCP 2.6**	**RCP 4.5**	**RCP 6.0**	**RCP 8.5**
GHG Emissions	High Mitigation Very Low Baseline	Medium-low Mitigation Very Low Baseline	High Mitigation Medium Baseline	No Mitigation High Baseline
Agricultural/ Land Conversion	Medium (Cropland & Pasture)	Very Low (Cropland & Pasture)	Medium (Cropland) Very low (Pasture)	Medium (Cropland & Pasture)
Air Pollution	Medium- Low	Medium		

The effects of CC such as sea level rise, air pollution, and other effects outlined in the RCP's will likely alter our behavior in land management and food production (Table 3). Since the increasing global population is a key driver of CC it begs the question, how will the population be fed?

CC in regions where agricultural production or processing is a key economic sector can be devastating. In North Dakota, ~40% of the population is employed in the agricultural sector with many towns and cities centered near highly productive agricultural land. The National Agricultural Statistics Service (NASS) ranked North Dakota as one of the top ten producers of wheat for grain, soybeans, corn for grain, and forage land for hay (NASS, 2017; Stoval, 2016). North Dakota is also the top producer of Durum used for pasta despite a production decrease from 2010 to 2014 when production reached a low of 18 million Bushels (BU) (NASS, 2017). The 2016 North Dakota Durum harvest it was the largest since 2000 reaching 58 million Bu (NASS, 2017). The production significance of North Dakota should incentivize the research and development of methods to increase resilience to the effects of CC.

Increases in yield may continue for several years despite the overwhelming biological evidence that agricultural systems will be negatively impacted by CC (via drought and heat stress). The efforts of research institutions like the NDSU Durum Breeding Program which produces cultivars that are disease resistant and high yielding to protect the agricultural industry from environmental damage.

Impacts of Climate on Plant Pathology

Disease accounts for no less than 10% of global food production losses estimated at ~220 billion USD. The economic significance alone justifies the mass of literature on the topic. When the conditions are perfect, the relationship between illness, environment, and the host plant create disease. Changes in environmental conditions are likely to enhance the creation of disease in the future. This is based on anticipated changes in temp and precip. However, the numerous disease types and extensive diversity in regional climates where the plants are produced creates a wide range of plant – disease relationships. Many of the negative effects of CC and increased CO_2 are related to changes in plant physiology that in turn benefit disease transmission and infection. For example, the increase in photosynthetic behavior in the plant from enhanced pCO_2 will create more biomass (i.e., roots, shoots, and leaves). However, this will provide additional glucose and tissue for sugar dependent pathogens such as rusts or mildews (Ghini, 2008). Likewise, increases in the crop canopy density can promote the spread of diseases via leaf to leaf transfer. There are some positive effects of CC on combatting disease such as the decreased spread of stomata invading pathogens by decreasing the frequency of stomal opening periods.

One of the biggest threats are the impact change in climate will have on the frequency of disease favorable climate conditions. Increased extreme temp and precip events will increase the frequency of disease and crop mortality. Increased climatic variability will make accurate crop moisture and soil management difficult. Disease is likely to proliferate given difficulties managing or predicting these critical components of growth.

In North Dakota, cereal crops and livestock are commonly infected with diseases which can affect yield as well as animal and human health (Friend, 1982). The primary disease affecting Durum crops in North Dakota is Fusarium Head Blight (AKA Scab, FHB). FHB alone can harm crop yield, but more importantly, it produces a toxin called Deoxynivalenol (DON or VOM) (Bond, 2017). Per the Food and Drug Administration (FDA), VOM concentrations allowed for safe consumption must not exceed 1 ppm in products for human consumption, 5 ppm for swine feed, and 10 ppm for poultry feed (Bond, 2017). In large quantities, it will make humans and animals sick.

It has been argued that CC will enhance the ability of agro-systems to respond to diseases by implementing biocontrols (Ghini, 2008). This reality would require enhanced technology and increased awareness of the complexity within the agro-system. The necessary technology is advancing and can now identify crop diseases early allowing for the culling individual sick plants to preserve crop health (i.e., disease identifier for an Android phone) (Xie, 2016). Due to CC, technologies like this and public awareness of disease impacts will become more important in the future. However, the development of such technology is dependent on the continued study of the impact CC has on disease.

Representative Concentration Pathway 2.6

The Netherlands Environmental Assessment Agency developed RCP 2.6 which has the lowest increase in net radiative forcing of the four scenarios (2.6 w/m^2) by 2100 (Monastersky, 2013). These increases in net radiative forcing are estimated at ~ 3 W/m^2 (~490 ppmv pCO_2) by 2050. Under this scenario, the trend will decrease into the latter half of the century to 2.6 W/m^2 (~445 ppmv pCO_2) in 2100 (Bjørnæs, 2013). If successful, this scenario would represent several important changes in pollution and GHG emissions such as decreased NH_4 emissions (Bjørnæs, 2013; Van Vuuren, 2011).

The peak and decline trend in pCO_2 under RCP 2.6 can be achieved via the application of stringent policies to reduce GHG emissions. These strategies will counteract the increasing demand for energy and fuel from the growing population (Bjørnæs, 2013).

Under RCP 2.6, the use of land for agricultural and pasture production is expected to increase by 2100. An increase that is accelerated by the increased demand for bioenergy and biofuel production (Fig. 13) (Thomson, 2011; Van Vuuren, 2011). The 2.6 scenario also estimates the state of several socioeconomic factors compared to the other four scenarios such as:

1. A global human population of 10.1 billion individuals by 2100
2. The greatest increase in Gross Domestic Product (GDP)
3. The greatest decrease in oil consumption
4. The greatest increases in global energy efficiency per person (Bjørnæs, 2013)
5. Increase in GMST of 1°C by 2100 (Newbold, 2015)

It should be noted that as of Spring 2017, pCO_2 is 409 ppm. Decreasing industrial or agricultural emissions will decrease net radiative forcing. Due to the ambitious nature of RCP 2.6, the number of socioeconomic and political changes required will be greater than any other scenario. However, the reward of containing temp increases would significantly benefit humanity and the best-case scenario for global climate.

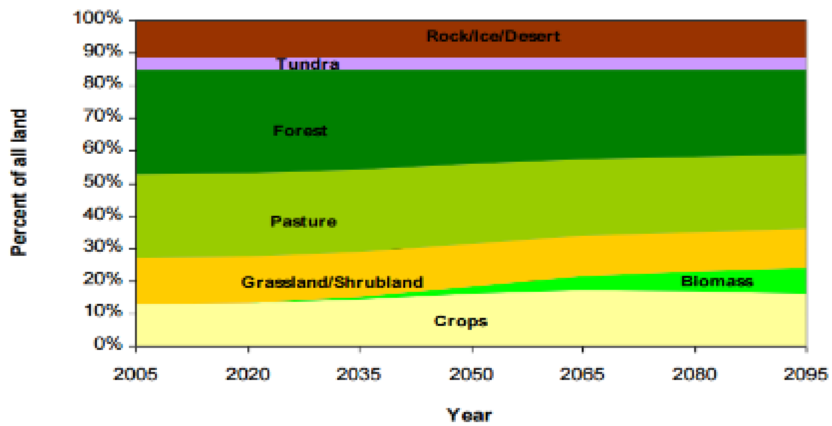


Fig. 13: The projected changes in land use under RCP 4.5 (Thomson, 2011).

Representative Concentration Pathway 4.5

The RCP 4.5 scenario was developed by the US Pacific Northwest National Laboratory. The 4.5 literature represents several policies and measurable changes to reach the radiative forcing goal including:

1. Low CO_2 emissions
2. Stable CH_4 emissions
3. Decreased fossil fuel dependence

4. Increases in GMST of 1.75°C by 2100 (Newbold, 2015)

In the RCP 4.5 scenario, GHG emissions and air pollution are mitigated with a medium level of strategies and very low starting pCO_2 baseline values (Bjørnæs, 2013; Van Vuuren, 2011; Thomson, 2011).

The increasing development of crop and pastureland acres from previous levels remains lower under RCP 4.5 than scenarios 6.0 and 8.5. RCP 4.5, like 2.6, still requires extensive agricultural production to support the growing global population. This increased demand will likely change the human diet by 2100 (Bjørnæs, 2013; Van Vuuren, 2011; Thomson, 2011).

A 4.5 W/m^2 increase in net radiative forcing translates to a pCO_2 level of ~538 ppm by 2100 (Van Vuuren, 2011; Thomson, 2011). The differences between the RCP 2.6 and 4.5 scenarios mainly aim at fossil fuel use and land management. These differences create different trajectories in radiative forcing. The objectives of the RCP 2.6 scenario include the greatest decrease in fossil fuel use while RCP 4.5 has a smaller decrease in use. Under the RCP 4.5 scenario, there is an increasing global demand for bioenergy crops and food use. By mid-century, the primary driver of land use change will likely be for land intensive meat production. The scenario then expects that as population growth stabilizes, demand for food-producing land would decrease accordingly (Thompson, 2011).

It should be noted that the stringent demands of RCP 2.6 may not be fiscally feasible within the current United States political and economic system making RCP 4.5 a more realistic goal for decision makers.

Representative Concentration Pathway 6.0

RCP 6.0 is a second intermediate scenario with some of the same changes seen in RCP 4.5 such as a medium level of climate mitigation and a medium starting pCO_2 baseline (Van Vuuren, 2011). The socioeconomic status and behavior under RCP 6.0 relative to the other scenarios in 2100 include:

1. A human population of 8.7 billion individuals
2. Heavy oil consumption
3. Intermediate energy intensity per person (Bjørnæs, 2013)
4. An increased GMST of 2.5 °C (Newbold, 2015)

This scenario has a heavy reliance on fossil fuels comparable to current demand. Under this scenario, CO_2 emissions rise and peak near 2060. After reaching 175% of today's levels in 2060, the pCO_2 decreases to 125% of today's value in 2100 (Bjørnæs, 2013; Van Vuuren, 2011). Ineffective climate mitigation strategies, combined with a medium level of land conversion to cropland, creates an increase in GHG emissions from the agricultural sector. With these increases in emissions and fossil fuel dependence, a net increase in radiative forcing and temp is likely. A net radiative forcing 6.0 W/m^2 translates to pCO_2 level of ~ 670 ppm by 2100 (Bjørnæs, 2013; Van Vuuren, 2011).

Representative Concentration Pathway 8.5

The 8.5 scenario represents the greatest increase in radiative forcing, reaching 8.5 W/m^2 by 2100 (Riahi, 2011). This scenario represents very little economic development departing from business as usual. RCP 8.5 deserves the most attention because of the serious implications a do-nothing strategy would have on climate and agriculture. Some of the possible socioeconomic factors for the RCP 8.5 scenario include:

1. A total global economic growth by 2100 of $321.5 trillion in 2017 USD.
2. A human population of 12 billion individuals
3. A "medium" level of land conversion for agricultural or pasture use (Fig. 16) (Neumann, 2015; Riahi, 2011)
4. High-energy and fossil fuel demands (Riahi, 2011)
5. Increased GMST of 5 – 6 °C by 2100 (Newbold, 2015)

The most extreme scenario of future climate, RCP 8.5, has a net radiative forcing of 8.5 W/m^2 equaling a pCO_2 of ~ 550 ppm (Riahi, 2011). These pCO_2 increases continue throughout the 21st century with relatively unmitigated emissions of GHG's.

This scenario is driven by a 20% increase in agricultural land use by 2100, an increase necessary to support the growing population thereby amplifying the amount of N_2O required by global

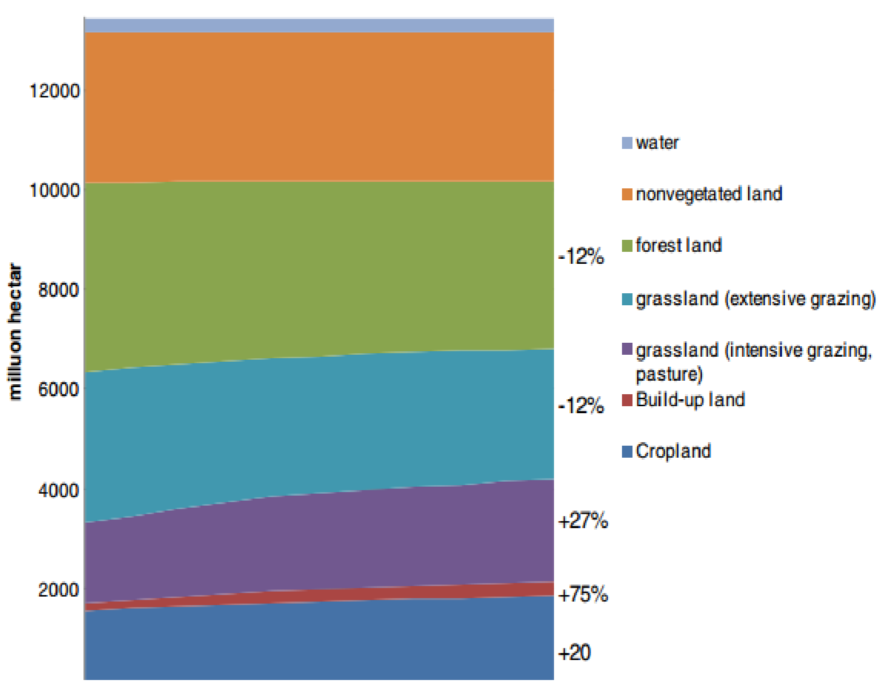


Fig. 14: The changes in land use from 2000 to 2100 for RCP 8.5 (Riahi, 2011).

agricultural operations and enhancing the role of agriculture as a driver of CC (Fig. 14) (Riahi, 2011).

RCP 8.5 is not entirely dismal, with some positive changes being made such as a decrease in SO_2 emissions of 25% by 2030 (Riahi, 2011). This positive change in SO_2 is overshadowed by the negative impacts of such a scenario. RCP 8.5 has increased relevance in 2017 given the recent changes to the structure of the United States federal government regarding environmental and natural resource management policies. To achieve this radiative forcing, funding, and implementation of climate mitigation strategies would have to be widely ignored as is indicated under the scenario policy guidelines for RCP 8.5. Through unregulated emissions, a policy approach that ignores CC and contributing factors are one of the most significant drivers of CC.

The impact of 8.5 on coastal communities will cause inundation of coastal areas possibly requiring the relocation of millions of individuals. Coastal areas have always been ideal locations for settlement due to water access, and of the cities above 5 million individuals, 66% are settled along the coasts of Earth's continents (Abadie, 2016). In 19 coastal European cities, the estimated annual cost of preserving these ancient cities is $40 billion USD (Abadie, 2016). There are 13 similar American cities that are projected to reach over 4 million individuals by 2100 (A total of ~52 million individuals). These include coastal cities such as New York, Los Angeles, Miami, Houston, Boston, Washington D.C, Detroit, Chicago, and Seattle (Neumann, 2015). Should the population increase and the sea level rise, then these 52 million individuals in the 13 coastal American cities would need to be relocated inland (Hoornweg, 2013). This coastal inundation poses a threat to all land managers. Even sparsely populated inland communities (i.e., North Dakota, Montana, South Dakota, Wyoming) are at risk of an even larger problem, inland migration.

Representative Concentration Pathway: Conclusions

The simulations of future climate and the potential impacts on Durum production in North Dakota is primarily based on the changes in climatic parameters during the growing season. The season from May to September covers most of the process from fields drying/planting to harvest. Therefore, historical production is based on the distribution of daily Tmax, Tmin, and Precip during these months.

Many of the estimated impacts of RCP 8.5 are apocalyptic while RCP 2.6 has a relatively unaltered climate. RCP 2.6 reverses many of the anthropogenic impacts on climate while 8.5 does not. These two scenarios are opposite, and therefore the net changes in climate are opposed. Given the knowledge that the effects of CC will affect the most vulnerable population first, an applicable litmus test for any CC-related policy approach can be adapted from the words of Vice President Hubert Humphrey. He said, "The moral test of [a policy] is how that [policy] treats those who are in the dawn of life, the children; those who are in the twilight of life, the elderly; those who are in the shadows of life; the sick, the needy and the handicap." As previously stated, under the effects of CC, the frequency and intensity of diseases, famines, and droughts will increase (Rozenberg, 2015). These climate changes increase the mortality of the homeless and impoverished population, a population that is expected to grow in the future. The WHO estimates that the effects of CC on regional weather alone will kill an average of 150,000 individuals annually. (Patz, 2005). It is reasonable to predict that changes in the distribution and frequency of regional weather will change disease outbreaks, crop management, food security, and yield. The compelling accumulation of research eludes to a future of negative heat-related impacts on human health and daily life.

These scenarios were created based on human behavior and the climate-altering decisions made regionally and nationally. Likewise, agriculture is heavily linked to changes in human behavior and land management techniques. Therefore, changes in the agricultural sector can either contribute to increasing the net radiative forcing (i.e., increased mechanized farming, land clearing for agricultural use, and poor water conservation techniques) or decrease the net radiative forcing (i.e., using biofuels instead of fossil fuels, and using tilling methods that reduce erosion).

Methodology

Crop Modelling

A crop model represents a real-world system, using parameters of growth and available resources to represent agricultural production of a crop commodity over a land area (Haefner, 2012). Their versatility and wide application make crop models essential for research into food production, security, and associated land use studies (Haefner, 2012). Practitioners and researchers in the areas of food security, crop/plant science, and meteorological science depend on the ability of crop models to determine the impact of possible changes in crop growth characteristics (i.e. maturation timing), environmental factors (i.e. GDD), or human behavior (i.e. planting and crop rotation schedules) (Haefner, 2012).

Models are commonly used to solve crop production problems. In this study, the area of production is a county spatial level, and the crop is the cereal crop, Durum. One of the main objectives of using this crop model is to determine the impact of changes in climate variables on Durum production in 13 North Dakota counties. Crop modeling and yield calculation estimation techniques are often successful at estimating the potential yield (Y_p) of a crop or agrosystem (Kiniry, 1992). However, Y_p represents yields under pre-defined/ideal growing conditions. Compared to Y_p, observed yield (Y_o) suffers from extraneous factors not accounted for in the model (Kiniry, 1992). These include factors such as pests or disease that the model cannot predict or replicate without more data. One of the more common applications used in this study of crop modeling uses pre-developed modeling scenarios to replicate historical yields and then simulate future yields. (Haefner, 2012).

Agroecosystem management is modeled using parameters defining agricultural practices and plant growth/physiology (Xie, 2003). For example, planting density (plants/m^2), fertilizer application (lbs/acre), and planting depth (mm) are all determined by the farmer and have a significant impact on plant growth (Xie, 2003). Interspecies competition is regulated in the agricultural system via weeding, herbicide, or other chemical applications and is also regulated in the model using a plant population density (Xie, 2003).

Estimates of the climatological impact on growth are used as guidelines for cropping systems. A model can simulate historical and forecasted yields using general parameters for crop physiology (Xie, 2003). The model used for this study is the Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model which simulates annual yield (t/ha) (Kiniry, 1992).

The Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) Model

Crop models are used to understand the production of agroecosystems in the future. One of the key benefits of using a crop model is simulating plant growth and climate scenarios without needing field experiments, test sites, or even plants. The model used for this study is the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model which employs a deterministic approach to plant growth (Kiniry, 1992). Modeled relationships between physical states (i.e. growth stages) and natural resources use a variety of mathematical functions of growth. For example, ALMANAC and its predecessor EPIX have very strong replication of water stress on biomass production. In ALMANAC, these include, "light interception by leaves, biomass accumulation, partitioning of biomass into the grain, water use, nutrient uptake, and growth constraints such as water, temp, and nutrient stress" (Kiniry, 1992). Parameters of crop growth and development use subroutines to compute certain variables key to crop growth (i.e., Beers Law). These variables, in turn, influence the distribution of resources to other processes in the model such as allocating basic resources for growth (i.e., directing biomass to be structural or reproductive growth or Precip to various parts of the plant) (Xie, 2003).

Modeling with ALMANAC

The amount of crop model literature dedicated to the calibration and validation of crop models outweighs the amount of literature on the application of these models. The key processes simulated in ALMANAC are related to plant growth and field management. The discrepancy is likely caused by the daunting data requirement, parameters, and complexity of running models (Kiniry, 1992). One such model with extensive input requirements is the ALMANAC model.

For instance, the fraction of light intercepted by the leaf canopy is described using Beers Law and the Leaf Area Index (LAI) (Kiniry, 1992). LAI is the measure of leaf area divided by the ground area covered by shaded by the leaves (eq. 03). This describes the light interception by leaves the proportion of which declines exponentially as total leaf density and the distance from the top of the canopy to the ground increases (eq. 03) (Flenet, 1996; Baez-Gonzalez, 2015).

$$Fraction = 1.0 - \exp(-k \times LAI) \qquad (03)$$

(Flenet, 1996)

In eq. 03, “k” is the extinction coefficient representing the quantity of light per unit of photosynthetic leaf area. The extinction coefficient is a measure of photosynthetic efficiency that varies by plant species (Flenet, 1996; Johnson, 2009).

All model parameters use equations like the one for light interception. The result of one equation will sometimes be used as an input for other parameter equations. All of these parameters and equations are combined to create an annual value of crop production referred to as potential yield (Y_p), sometimes called “grain yield” or “harvestable yield.”

Y_p is the biomass accumulated in the harvested portion of the plant as a percentage of total biomass (grain biomass/total biomass) (Sinclair, 2010). Harvested yields are reported annually by farmers and summarized on a county basis by the NASS and the U.S. Dept. of Agriculture (USDA).

This study uses ALMANAC and annual Y_o from NASS to simulate a modeling environment like operations in the real world. Environmental and management data are used to test different variables that may be sensitive to the modeling of Durum Wheat and may have a significant impact on Y_p (Haefner, 2012).

To model crop yields in ALMANAC, it is important to first replicate historical yields for a multidecadal period. Like the 25-year period from 1981 to 2005 used for this study. Modeling Y_p only simulates yield based on the data provided and the model capabilities. Due to these limitations, information regarding pest infestations, disease, changes in politics or management practices would need to be incorporated in a unique way that ALMANAC cannot currently accommodate.

Model Calibration and Validation

Models require calibration and sensitivity analysis to determine the effects of individual parameters on yield (Kiniry, 1992). Y_o values are compared to Y_s to ensure that the model reflects a realistic agricultural operation over time. A sensitivity analysis uses model parameters and determines how Y_s responds to the changes (i.e., changing parameter A will cause a reaction in Y_s or not). This process uses ALMANAC based literature to determine the impact, range, and response of parameters to crop physiology (i.e., PHU, HI). Nevertheless, several parameters still require "tuning" to replicate historical crop Y_o from 1981-2005. These parameters are related to plant physiology and are frequently changed with each new cultivar produced resulting in increased yields due to ~30 years of genetic modification. Parameters are generalized to represent this change in genetics and, to overcome this issue, several parameters are adjusted to reflect this modification, mainly HI and PHU/AGGD.

Parameters such as PHU and HI change with time and are adjusted or averaged to replicate historic yields (1981-2005). HI is a calculation related to the distribution of photosynthetically created biomass within the plant. A plant that allocates as much biomass to reproductive growth as possible (high HI) is likely to be shorter, due to the decreased biomass assigned to structural growth. The diversity of short dwarf and semi-dwarf Durum cultivars being produced are examples of cultivars with modified HI values and high yields. HI is a popular parameter for genetic modification. having increased from only 32% in the early 1900's to 49% in the 1980's and continuing to increase today (HI ≈0.50) (Rasmusson et al., 1984). In these simulations, several of the counties had HI values ~0.40. Meaning, ~40% of total available biomass is partitioned to reproductive growth. Meanwhile, PHU/AGGD is averaged from estimated planting dates and data available from the North Dakota Agricultural Weather Network (NDAWN). NDAWN calculates these values using daily Max and Min temps (See Growing Degree Days).

Lastly, the parameters defining the management of North Dakota Durum production can be defined as constants via "best management practices." This guidance comes from federal agencies and academic research institutions (e.g., Optimal application of fertilizer [kg/m^2], planting/harvesting dates and management practices) (Haefner, 2012).

The process of changing these crop physiologies and management parameters to replicate a specific set of spatially specific historic yields is called model calibration. The calibration of yield production was completed for the 13 counties in the study area. The simulations were temporally representative of 1981-1995 and 1996-2005 for calibration and validation respectively. After "tuning" the model parameters to replicate the yields of the calibration period and the results are statistically significant, the validation process can begin. To help confirm that the model functions independently of what temporal or weather data is being inputted, the process needed to be replicated for the second period using the same parameters. These simulations are evaluated just as with the calibration process.

After computing a successful statistical relationship between Y_S and Y_O, forecasted climate data can be applied. With its base parameters held constant, the model will represent the changes in the input Tmax, Tmin, and PRECIP under four RCP 2.6, 4.5, 6.0, 8.5. The simulations utilized 17 Global Circulation Models (GCM's) to represent differing models of the Earths complex climate system. The specific forcing's from future climate data are then applied to the ALMANAC model.

Model Calibration and Validation Statistics

After simulating county yields for calibration or validation, it was important to determine the statistical accuracy of the simulation via comparing the Y_s to the Y_o. It was important also to have multiple statistics to prevent from falsely equating any relationship, cause, or effect. Historical yields from 1981 – 2005 were split into two equal time periods. One period was for calibration (1981 – 1995) and one for validation (1996 – 2005). When the ALMANAC model was being calibrated for a county, the Y_s and Y_o were compared using the Pearson Correlation (ρ), Nash Sutcliffe coefficient of model efficiency (E_{NS}), and the Root Mean Square Error (RMSE). Each of these statistics serves unique purposes in ensuring the data are not misinterpreted. However, as a means of expediting and removing inadequate simulations, a linear regression was the first statistic applied to allow for visual data analysis (Fig., 15)

For graphical representations of yield comparisons and associated residual plots see Appendix A.

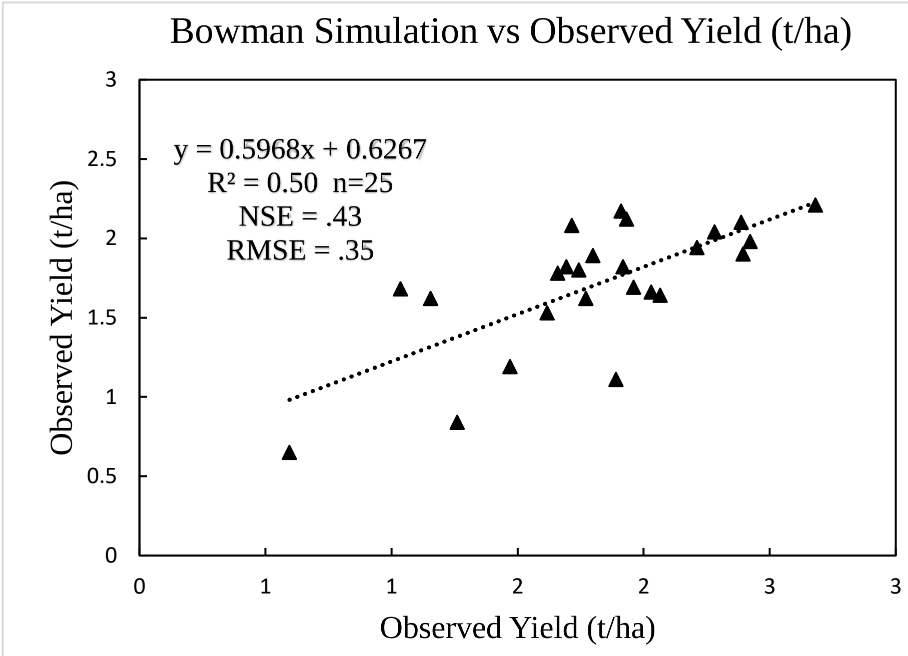


Fig. 15: Comparison of simulated and observed yield for Bowman County (1981-2005)

Pearson Correlation Coefficient

The Pearson Correlation Coefficient (ρ) is a measure of the linear relationship between two datasets. Computed using the Pearson function in excel, this measure establishes the association between the two variables being tested. A value closer to one indicates a strong positive correlation between the two sets of values, meaning that changes in one dataset (Y_s) are like the change in (Y_o).

Nash–Sutcliffe model efficiency coefficient

The Nash–Sutcliffe model efficiency coefficient (E_{NS}) is a measure of the predictive power of a model. This statistic is commonly used in hydrological models such as SWAT. For this study, E_{NS} was used to determine ALMANACs ability to predict yields. E_{NS} values closer to one indicate a more powerful ability to predict the next years' value.

Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) is a measure of predictive error between the Y_s and the Y_o. This statistic uses the difference between Y_s and Y_o as a "residual value." The standard deviation of these values measures the distance the values are from the regression line. This value indicates the difference between a typical Y_s and Y_o within the dataset. RMSE also has the unit of measure associated with the data being examined. For this study, it is measured in t/ha, and an adequate Y_s value will be within 1.00 t/ha of Y_o values.

Statistical Values for the Calibration & Validation Combined Datasets

(1981-2005)

The simulated yields for 1981 – 2005 used E_{NS}, Pearson, and RMSE statistics as the basic thresholds for determining simulation adequacy. For Pearson and E_{NS}, the standard value for an adequate simulation uses a level of 95% confidence (0.05). Meanwhile, RMSE was considered adequate if within 1.00 t/ha.

The simulations for 1981-1995 were tested with these statistics, and each county passed the thresholds for statistical significance. The simulations for the validation period were then added as extensions to the calibration period, thus, creating a dataset of Y_s from 1981-2005 which could be compared to Y_o values. The three statistical tests were then applied to the entire data period (1981 – 2005) (Table, 4). Successful application of these statistics should indicate a suitable modeling environment for 2020's and 2050's simulations.

Using the parameters which created the historical simulations with adequate statistical correlations ensured that the modeling environment remained unchanged. The only changing factors are the climatological data and the time period being simulated.

Table 4: Statistical values for 1981-2005 representing data for both calibration and validation.

	Avg. Yo (t/ha)	Avg. Ys (t/ha)	E_{NS}	Pearson	RMSE (t/ha)
Bottineau	2.08	2.09	0.14	0.51	0.43
Bowman	1.82	1.72	0.43	0.71	0.35
Burke	1.96	2.06	0.39	0.67	0.33
Cavalier	2.21	2.24	0.17	0.41	0.60
Divide	1.92	1.67	0.37	0.79	0.41
Hettinger	2.18	2.11	0.36	0.63	0.43
McKenzie	1.90	1.71	-0.17	0.68	0.49
McLean	2.01	1.96	0.27	0.54	0.42
Morton	1.67	1.68	0.58	0.76	0.29
Mountrail	1.95	1.97	0.45	0.69	0.33
Pembina	2.66	2.71	0.11	0.45	0.59
Stark	1.92	1.88	0.45	0.67	0.38
Towner	2.01	2.07	0.17	0.46	0.41

The statistical measures of these parameters indicate that all 13 counties had adequate statistical values for the calibration period (1981-1995). For validation, 12 of the 13 counties had adequate statistical measures, McKenzie County being the exception. When evaluated as a continuous dataset of Y_s values, the data from 1981 – 2005, these statistics indicate the ability of the model to simulate historical yields.

Model Processes

The essential functions of the model used in this study are the crop physiology and field management parameters. The model can overlay these parameter groups with external climate and geographical/soil data to produce yields for these areas.

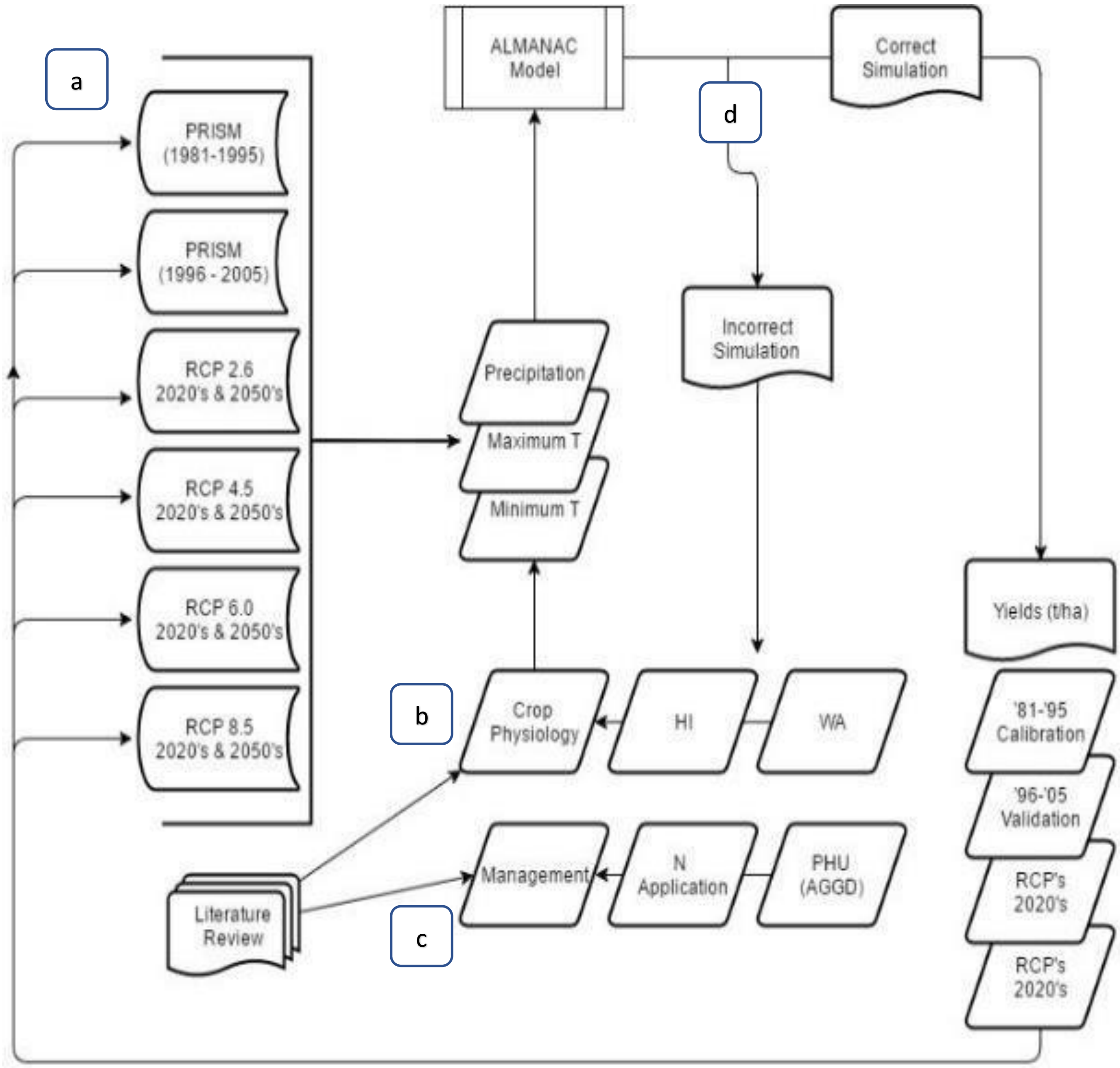


Fig. 16: Conceptual flow chart of data input and determination functions for Durum Wheat estimation.

The conceptual flow chart (Fig. 16), incorporates various data sources such as climate data (a), crop physiology (b), management parameters (c), as well as model corrective processes (d) (adjusting parameters and re-simulation).

Model Equations

Almanac was designed for simulating the competition for resources between two plant species. The model procedurally inputs the external data into key equations that dictate plant growth and behavior. The key equations include competition for light, LAI curve, PHU curve, and other parameters which aid in simulating growth. For example, the fraction of daily incoming solar radiation that is intercepted by the leaf canopy is expressed as:

$$Fraction = 1.0 - \exp(-k \times LAI) \quad eq. 04$$

The relationship between LAI and the extinction coefficient (k) creates a curve of light interception that increases as the plant grows and LAI increases (eq. 04, Fig. 17). This curve of light interception is a function of plant height, population density, and growth stage. Older plants have a larger LAI, and a greater quantity of light intercepted by leaves.

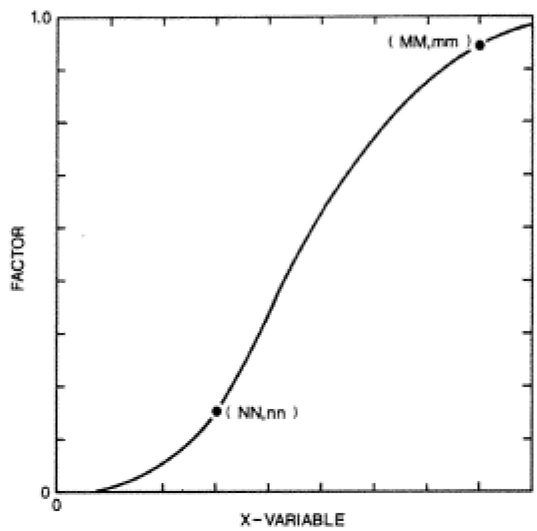


Fig. 17: The S curve representing the increase in LAI over the growing season. The curve is restricted by the extinction coefficient and population density (Kiniry, 1992).

The accurate simulation of light interception and photosynthetic activity depends on the equations of LAI (Eq. 05, Fig. 17).

$$F = X \,/\, [X + \exp(Y1 - Y2 \times X)] \quad eq. 05$$

In eq. 05, X is the population density, Y1 and Y2 are points along the curve, and K is the extinction coefficient. These parameters influence the amount of light intercepted by leaves as the plant grows and the LAI increases.

The ALMANAC model then uses functions for plant height, HI, and population density to determine crop growth and competition between individual plants. As the season progresses, the model assigns the number of preset GDD’s for the simulation and then computes the annual yield.

Study Area

The North Dakota climate is unique because of the state’s geographic location as the center of North America between 45º56,’ and 49º00’ N. This location is a significant driver of the climate, influencing the length of the day, temp distribution, and precip gradient. It is this angle of incoming solar radiation that creates the differences in temp and day length that we observe moving from the hot equatorial regions to the cold polar regions.

North Dakota is the 39th state in the United States and was largely settled for natural resources and a large flat landscape deemed suitable for agriculture. The Regions of Interest (ROI) for this study include 13 of the 53 counties in North Dakota. County selection is based on the top Durum producing counties in North Dakota. They are primarily located in the W, N, and NW (NASS, 2017). Historical climate variables in North Dakota are observable using weather data. For example, average T_{min} values are colder in the N half of the state than in the S half of the state with a higher Avg. Tmax in the S half than in the N half.

The angle of incoming solar radiation in North Dakota is important for selecting crops that grow well in the region. Day length or “Photoperiod” is dictated by the solar angle and, in North Dakota, results in nine-hour winter days and up to 16-hour summer days (Jensen, 1998). This contributes to the extreme seasonal variation in temp and dictates the N to S temp gradients (Millet, 2009). The interaction of large continental-scale air masses is unhindered with little topography to reduce wind speed. These mixing air masses create a range of extreme temps that frequently exceed 40°C in the summer and drop below -40°C in the winter (Millett, 2009). The W to E precip gradient has an average annual accumulation of ~350 mm in the W and ~500 mm in the E (Laird et al., 1996). This precip accumulation is a combination of liquid precip and snowmelt. Snow is an important source of moisture for early spring crop growth representing nearly a quarter of the annual total.

The Winter months from ~Nov. to ~Mar. play a significant role in the preparation of the land for a Spring and Summer growing season. The accumulation of snow, high winds, and low soil temp are common features of North Dakota winters. When the melted snow permeates into the soil and temps increase, the available moisture is stored for the Spring/Durum season. The unique geographic position, continental wind interactions, and topography of North Dakota are indicative of the agricultural commodities produced.

North Dakotas' chief agricultural commodities include *Barley*, *Canola*, Corn, *Dry Beans*, *Flaxseed*, *Honey*, Livestock, Potatoes, Pulse Crops, Soybean, *Sugarbeets*, and *Spring/Durum Wheat*. Of these, North Dakota is the top producer of 8 commodities (*italicized*). Per the North Dakota Department of Agriculture, the agricultural production and associated industries sector employed 42% of North Dakotans and represented roughly $4.1 billion in cash receipts in 2010.

North Dakota is a large producer of several globally consumed agricultural commodities, and the production capability is based on the climate and geography. Changes in these factors place North Dakota in a position of significance in agricultural production.

Climate of North Dakota

The historical climate of North Dakota has a distinct spatial distribution tied to changes in elevation and geographic features which define the precip distribution. North Dakota has hotter

Tmax and Tmin values in the SW and S with cooler values in the N and NE (Fig. 18). Meanwhile, daily precip (May-Sept) is generally higher in the E and NE than in the W and SW (table 5).

Table 5: Daily Avg. Tmax, Tmin and Precip 1981-2005 for months encompassing the Durum season (May to Sept) 1981-2005.

Region	Ag District	County	1990's_Tmax: (ºC)	1990's_Tmin: (ºC)	1990's_Precip: (mm)
NW	10	Burke	23.30	8.70	1.92
	10	Divide	23.12	8.63	1.72
	10	Mountrail	23.14	8.29	1.88
NC	20	Bottineau	23.71	8.71	1.88
NE	30	Cavalier	21.72	8.69	2.16
	30	Pembina	23.23	9.74	2.13
	30	Towner	22.54	8.85	2.07
WC	40	McKenzie	24.76	8.60	1.70
	40	McLean	23.55	9.20	2.04
SW	70	Bowman	24.31	9.31	1.64
	70	Hettinger	24.90	9.26	1.70
	70	Stark	24.15	8.87	1.90
SC	80	Morton	24.23	9.91	1.97
Statewide Avg.		(ºC)	23.59	8.98	1.90

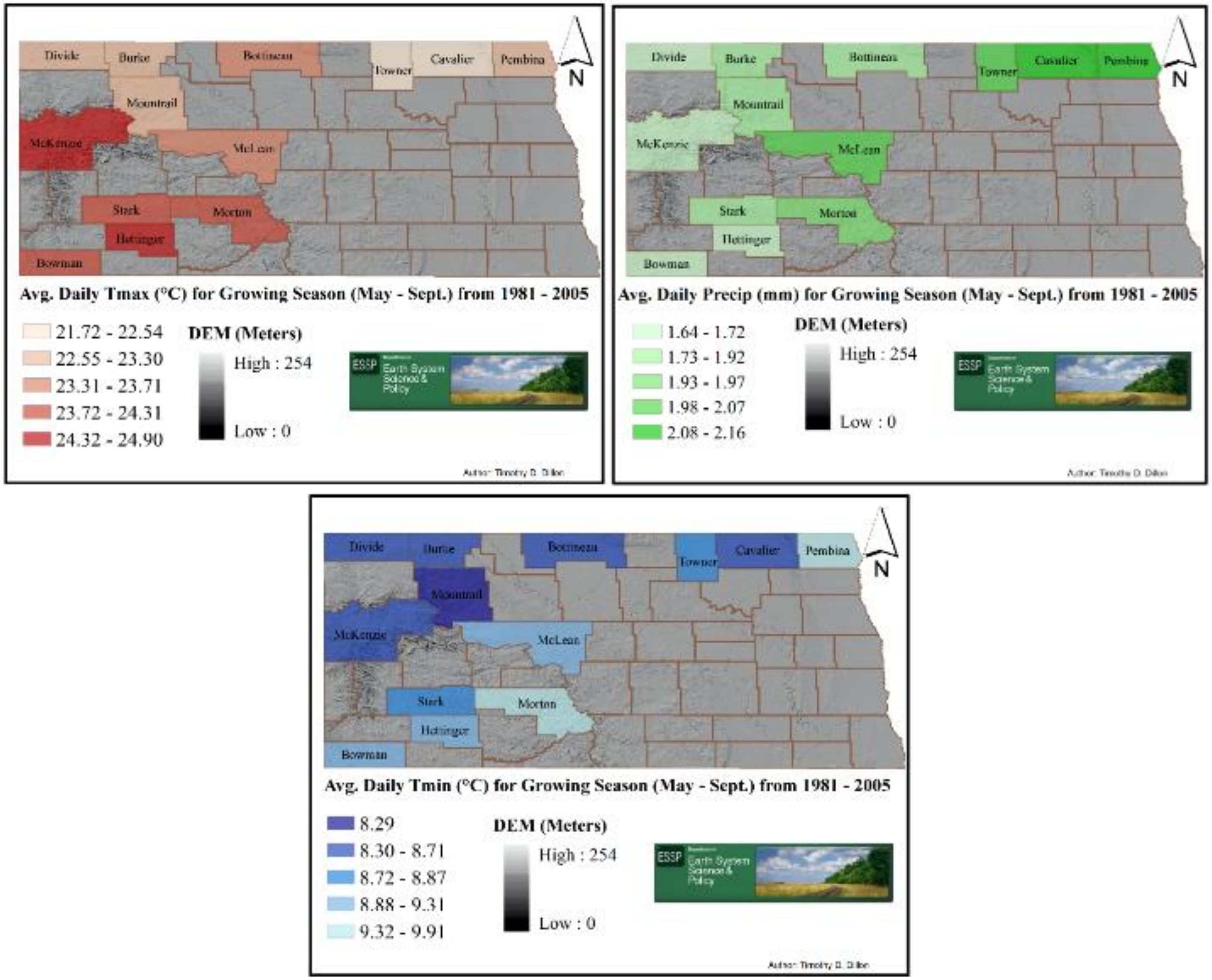


Fig. 18: The climatological data for Tmax, Tmin, and Precip for 1981 - 2005

Climate of the 2020's

In the simulations of the 2020's, the view of climate in the near future is focused the W, C, SW, NC, and NE study regions primarily. The climatological variables of the growing season[4] provide insight into the distribution of plant growth resources (i.e., thermal energy and moisture).

In the historical climate data (1981 – 2005) average daily precip ranged from a low of 1.64 mm in the W to 2.16 mm in the E/NE. The spatial distribution of higher daily precip in the E and lower in the W is a feature that is observed in historical climate data (1981 – 2005), and the four RCP climate scenarios. It should also be noted that the Northern Divide, a geographic feature, crosses from the NW corner of the state and cuts across to the SE corner (Gonzalez, 2003). The Northern Divide separates the major drainage systems with all water to the E of the Divide going to the Hudson Bay Drainage and everything to the W going to the Missouri Drainage. This is a likely driver of the precip distribution across the state.

The historical trend of temp is cooler daily Tmax and Tmin in the N and NE of the study area with hotter values in the C, S, and SW (Table 7). The distribution of daily Tmax values did not change from historical values to the predictions of the 2020's. The Tmax values under the four scenarios had increased from the historic Tmax values (~22.00 – 25.00 ^{o}C) to 2020's values (~23.00 – 26.00 ^{o}C) for each scenario (RCP's 2.6, 4.5, 6.0, 8.5). Tmin values historically ranged between ~8.00 – 10.00 ^{o}C. This increased to a Tmin low of ~10.00 ^{o}C and highest of 11.79 ^{o}C. These scenarios of the 2020's represent a drier and hotter state (decreases in precip, increases in Tmax and Tmin).

[4] Growing season covers the period of May to September. This is to accommodate the variety of days in which farmer's plant crops. These planting days depend on soil moisture content and the occurrences of field flooding and could span from mid-late May and even early June.

The historical distribution of Tmax and Tmin remained unchanged across all RCP's in the 2020's with hotter counties in the S and SW and cooling in the NE and N border which remained cooler. Daily Tmin during the growing season increased across all counties and scenarios ranging from a low of ~1.40 ^{o}C in Bowman County (RCP 6.0) to the greatest increase of ~2.00 ^{o}C in McLean County (RCP 8.5).

Tmax increases were greatest under RCP 8.5, lower in 4.5 and 6.0, and the lowest in RCP 2.6 with the greatest increase in daily Tmax occurring in Towner county (RCP 8.5 of ~2.00 ^{o}C). Meanwhile, Bowman county in the SW had the lowest increase in Tmax of ~1.50 ^{o}C. Lastly, changes in daily precip varied from county to county. However, overall daily precip decreased in the intermediate and upper scenarios (4.5, 6.0, and 8.5) and increased in many counties in the RCP 2.6 scenario.

Table 3: Changes in the daily Growing Season (May-Sept) Tmax, Tmin, and Precip from historical values (1981-2005) to the simulations of the 2020's climate.

	Tmin: 2020's/Hist				**Tmax: 2020's/Hist**				**Precip: 2020's/Hist**			
	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Bottineau	1.62	1.53	1.51	1.91	1.62	1.64	1.65	2.06	0.04	-0.11	-0.10	-0.30
Bowman	1.45	1.51	1.37	1.72	1.48	1.68	1.69	1.94	0.01	-0.06	-0.05	-0.01
Burke	1.58	1.59	1.49	1.82	1.57	1.70	1.65	2.03	0.16	-0.09	0.12	-0.08
Cavalier	1.60	1.46	1.43	1.83	1.69	1.65	1.61	2.09	-0.04	-0.02	0.05	0.03
Divide	1.58	1.61	1.49	1.80	1.53	1.66	1.62	1.98	0.35	0.22	0.14	0.19
Hettinger	1.48	1.50	1.41	1.77	1.52	1.65	1.72	1.98	0.16	0.03	-0.14	0.07
McKenxie	1.56	1.62	1.49	1.79	1.53	1.71	1.70	2.01	0.27	0.00	0.03	0.01
McLean	1.61	1.63	1.52	1.93	1.61	1.69	1.72	2.09	-0.02	-0.03	-0.22	-0.24
Morton	1.57	1.56	1.49	1.88	1.61	1.67	1.75	2.06	0.10	0.12	-0.05	0.00
Mountrail	1.60	1.67	1.51	1.88	1.57	1.71	1.68	2.06	0.07	0.20	0.04	-0.02
Pembina	1.58	1.43	1.41	1.76	1.69	1.66	1.57	2.06	-0.16	-0.18	-0.24	-0.02
Stark	1.50	1.56	1.43	1.80	1.54	1.71	1.73	2.04	0.18	-0.03	-0.10	-0.20
Towner	1.63	1.52	1.47	1.89	1.67	1.67	1.63	2.10	0.11	-0.07	0.01	-0.20

Climate of the 2050's

The growing season precip of the NE and C part of the state (i.e., Morton, McLean, and Stark) had more wet/moderate precip under each scenario. Meanwhile, the rest of the counties surrounding the C region as well as the SW and NW region had low precip in each scenario. Under the RCP 2.6 scenario, only three counties experienced decreases in precip with others experiencing mild increases or little to no change. Under the other three scenarios (RCP's 4.5, 6.0, 8.5) seven or eight counties had decreases in precip. The counties with the greatest decreases from the 2020's to the 2050's were in the NE with Pembina, Cavalier, and Towner having significant decreases in daily precip across all RCP's. Meanwhile, Bowman and Hettinger remained the lowest in daily precip from May – September. Across each scenario of the 2050's only Divide County had increases in each RCP simulation with Morton increasing in the 2.6 and 6.0 scenarios and McKenzie in the 2.6 scenarios.

Daily temp maximums (May-Sept) increased in the 2050's compared to the 2020's from ~0.60 ^{o}C in RCP 2.6, to ~1.00 ^{o}C in RCP 6.0. The RCP 4.5 and 8.5 scenarios had the greatest increases of ~2.00 ^{o}C and ~2.40 ^{o}C respectively. The daily growing season temp distribution remained unchanged only with the SW regions becoming hotter. Meanwhile, temp minimums decreased by ~0.45 ^{o}C (RCP 2.6), ~1.45 ^{o}C (RCP 4.5), ~1.00 ^{o}C (RCP 6.0), and ~2.00 ^{o}C (RCP 8.5) (table 8).

The daily minimum temp increased from the 2020's to the 2050's in all counties. The greatest Tmin increases between scenarios were in the RCP 8.5 (~0.43 ^{o}C) and the lowest increases in the RCP 2.6 (~2.10 ^{o}C). The minimum Tmax increase was ~0.52 ^{o}C in Pembina county (RCP 2.6) and a maximum increase of 2.94 ^{o}C in Morton county (RCP 8.5). The spatial distribution remained the same as the 2020's and historical data with hotter temps in the S and SW and cooler temps in the N and NE for both Tmax and Tmin.

Precip decreased unilaterally across all scenarios with only a few counties in each scenario having no or little to no change. The greatest decrease in daily precip was 0.43mm in Pembina county (RCP 8.5). At a maximum, precip increased by 0.19 mm in Morton county (RCP 6.0).

Table 4: Changes in the daily Growing Season (May-Sept) Tmax, Tmin, and Precip from simulated 2020's climate to the simulations of the 2050's climate

	Tmin: 2020's - 2050's				**Tmax: 2020's - 2050's**				**Precip: 2020's - 2050's**			
	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Bottineau	0.47	1.5	0.95	2.19	0.66	1.93	1.00	2.84	-0.09	-0.04	0.00	0.16
Bowman	0.47	1.29	0.93	1.98	0.68	1.90	1.19	2.88	-0.02	0.02	0.03	-0.09
Burke	0.49	1.47	0.93	2.15	0.71	1.97	1.06	2.79	-0.20	-0.03	-0.15	0.04
Cavalier	0.4	1.42	1.02	2.19	0.56	1.90	0.97	2.83	0.00	-0.25	-0.24	-0.22
Divide	0.5	1.49	0.96	2.14	0.75	1.99	1.07	2.80	-0.17	-0.10	-0.05	-0.06
Hettinger	0.42	1.4	0.92	2.03	0.62	1.97	1.20	2.93	-0.18	-0.15	0.07	-0.10
McKenxie	0.49	1.46	0.93	2.12	0.74	2.05	1.13	2.87	-0.16	-0.10	-0.07	-0.08
McLean	0.4	1.48	0.93	2.11	0.60	1.96	1.08	2.88	-0.03	-0.22	0.18	-0.03
Morton	0.35	1.45	0.92	2.09	0.53	1.96	1.13	2.94	-0.07	-0.22	0.19	-0.07
Mountrail	0.45	1.45	0.95	2.11	0.68	2.00	1.10	2.86	-0.15	-0.37	-0.05	-0.15
Pembina	0.34	1.33	1.03	2.14	0.52	1.87	0.93	2.80	-0.02	-0.11	0.12	-0.43
Stark	0.45	1.4	0.94	2.03	0.65	2.00	1.19	2.90	-0.19	-0.04	0.05	0.17
Towner	0.42	1.44	1.01	2.19	0.60	1.92	0.99	2.85	-0.13	-0.13	-0.20	-0.08

Data

There are distinct differences in model inputs that will alter Y_s outcomes (i.e., crop physiology parameters). The relevant parameters, determined from the literature are relevant to plant physiology and interactions with the environment. Estimated yield outcomes (Y_S) represent the production of a potential real-world agroecosystem. However, each model type has strengths and weaknesses. To determine the accuracy of ALMANAC Y_S must be compared to Y_O from the NASS records. To model $Y_{S,}$ a significant amount of data must be tailored to the specific location being modeled.

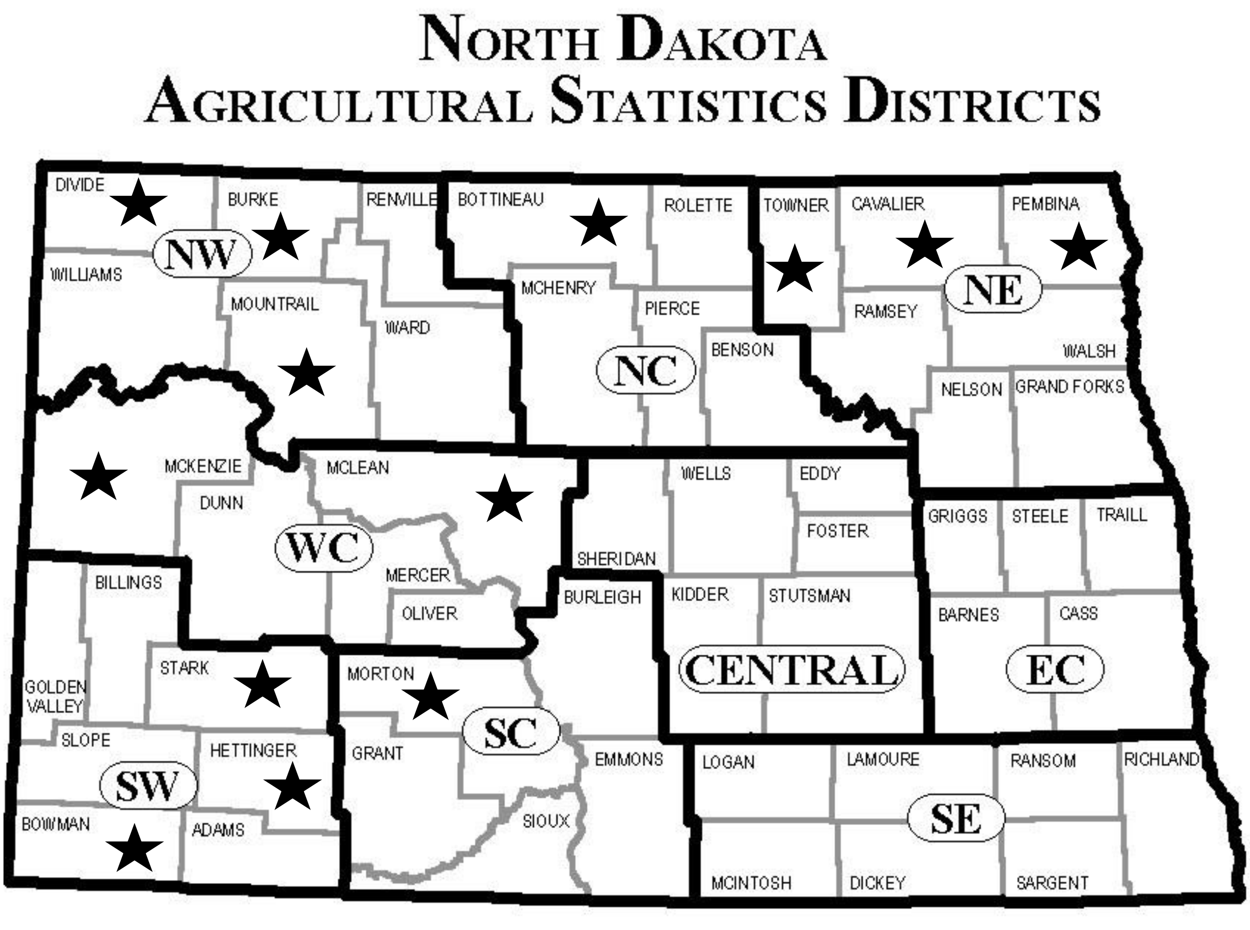


Fig. 19: Counties in the study area. Each defined as a top producer of Durum with data for 1981 - 2005.

The ALMANAC model utilizes data like soil types from the USGS Web Soil Survey (WSS) program. For example, WSS data is provided as a set of folders containing tabular, spatial, soil, and geographic data which must be confined within the model to the coordinates of the region of interest. For this study, this was focused on the SW, SC, WC, NC, NW, and NE regions of the state (Fig. 19).

The soil data is then mapped with either historical daily weather data from the PRISM climate group at the University of Oregon or with forecasted future weather data from a previous study. Climate data from the University of Oregon PRISM climate group must be formatted using specific cell by cell rules to create compatible files for use in the model. This spatially specific data is available from a multitude of government and NGO resources (i.e. PRISM, NASA, WorldClim, NOAA). Crop physiology and field management are gathered from a variety of literary sources (Xie, 2003). The model simulates plant growth by incorporating atmospheric, soil, and management data to determine the amount of biomass the plant will accumulate and then turn into yield.

The Management parameters are derived from the literature (i.e., scientific articles, newspaper resources, federal agency recommendations, educational instructions and annual production reports). Some of the key parameters gathered from these sources to replicate historical yields include nitrogen/fertilizer application and available potential heat units (PHU/AGGD). PHU/AGGD were acquired from the North Dakota Agricultural Weather Network (NDAWN) which provides an AGGD calendar based on historical weather data. The NDAWN website uses a set planting date and then calculates the AGGD from that day onward for the rest of the year. The AGGD for the location is then chosen based on the harvest date set in the model. Other required parameters include tilling, planting, harvesting dates, and population density (Table 9). The management parameters are applied to the model informing how the field is to be cared for during the growing season.

Table 5: List of parameters used in the ALMANAC modeling process

Operations	Parameter	Definition	Actual Value
Management	Year, Month, Day of Operation	Operation schedule (i.e., irrigation, fertilizer application, tilling).	
	Fertilizer (FNO & FPO)	Amount of Organic Nitrogen and Phosphorous applied (Kg/HA)	FNO = 200 FPO = 50
	PHU	Potential Heat Units/ Accumulated Growing Degree Days	
	Plant Population	Plant population density/Seeding Rate (plants/m^2)	330
Crop Physiology & Growth	Biomass-Energy Ratio (WA)	The potential (unstressed) growth rate (including roots) per unit of intercepted photosynthetically active radiation (PAR).	
	Harvest Index (HI)	The ratio of grain yield to total plant biomass (%), and is mostly constant for a species of plant but can vary between different cultivars of the same species.	
	DLAI, DLAP1, DLAP2	DLAI – The fraction of the growing season in heat units divided AGGD. (maturity is the point where Leaf Area Index starts to decline). DLAP1 & DLAP2 – two points along the DLAI growth curve representing a nonlinear rate of change.	DLAI = 0.60 DLAP1 = 31.07 DLAP2 = 57.950

Crop physiology parameters represent specific functions of plant growth and include the Harvest Index (HI), Biomass Energy Ratio (WA), and Leaf Area Index (LAI) (Table 9). These determine the distribution of available biomass, water resources, and photosynthetic efficiency of each plant in the crop. Each of these parameters is defined as fractions of the total value, allowing expression as a percent. These parameters restrict or enhance the growth of the plant to achieve the desired result (e.g., direct or restrict biomass regulation) (Fig. 16).

PHU, WA, and HI values are adjusted in ALMANAC to create Y_s values that accurately replicate Y_o. This is to increase the statistical significance of E and ρ between Y_s and Y_o for datasets from 1981 – 2005.

Downscaled Climate Data

Measuring the production on a county or local scale requires downscaled climate data because global climate data is not adequate for simulations at smaller scales (i.e., counties). The method for transforming global data into county data is known as downscaling (Maurer, 2008; Jones, 2013. The production of this data is essential to including local-scaled weather into the modeling of county yields. For example, daily precip is generated using "latent heat balance as air is transferred from cell to cell" (Jones, 2009). This creates daily weather data (i.e., precip, Tmax, Tmin). The MarkSim™ software for downscaling climate data uses a statistical downscaling method simulating the lengths of wet and dry spells (Trzaska, 2014). This downscaling methodology was replicated for this study area based on a previous research project that used downscaled climate data for the Devils Lake region. This methodology created future climate data for two 30-year periods representing the climate of the 2020's and the 2050's. The methodology for the downscaling process is best described as follows:

"The [climate] *scenarios were developed using synthetic weather patterns* [and] *computed with* [the] *Marksim weather generator (Jones et al., 2008). …* [These scenarios] *us*[e] *the standard 30-year climate period (WMO, 1983) of 1981 – 2010."*

"Future climate scenarios were generated using projections of 17 CMIP5 GCMs included into the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programme. For details see MarkSim model documentation (Jones, 2013). Multiple GCM runs

under four different radiative forcing scenarios were used to generate a statistical ensemble of projections, accounting for model uncertainty (Arnell et al., 2004), which is an accepted way of dealing with GCM biases (for a list of previous studies see Faramarzi et al., 2013). Four Representative Concentration Pathways (RCPs) were used for the radiative forcing scenarios: RCP2.6, RCP4.5, RCP6, and RCP8.5 (Moss et al., 2010), with the numeric part of the name indicating the additional radiative forcing in 2100 relative to the base climate (W/m^2). Further, to account for the spatial bias in the GCM climate ensemble, the projections were statistically downscaled with Marksim weather generator (Jones et al., 2008) with the 1981–2010 Weather patterns used for the base climate. Furthermore, to account for the climate variability, the weather samples were grouped into 1-year periods and then reshuffled multiple times.

This process, when applied to this study of Durum producing countries in North Dakota, created 68 simulations representing the four RCP's and 17 GCM's for each county for a total of 1,768 30-year weather samples characteristic of 2020's and 2050's climates. Each provides the minimum weather data requirement of daily Tmax, Tmin, and precip.

Results

Historical Yield Replication Results

Prior to use in creating trusted results, the crop model must be calibrated and validated using historical data. Calibration and validation, hereafter C & V, of ALMANAC used adjusted parameters to create Y_S values that are compared to Y_O. All 13 counties were stimulated for 1981 – 2005 with adequate statistical relationships using the Ens and r^2. An Ens or r^2 value ≥ 0.05 is considered statistically significant, with higher values indicating a stronger relationship between Y_o and Y_s. The successful calibration of county yields for 1981 – 1995 resulted in adequate correlations. Using the same parameters with different weather data (representing 1996-2005) the validity of the C process is confirmed. The statistical measures for this period represent the uninterrupted simulation of Durum yields for 30 years, 1981 – 2005 (Table 10).

Table 10: List of counties and the associated yield change Yz = (Ys - Y0, r^2, and E for 1995 – 2005 period.

Name	**Avg. Diff in** Y_o and Y_s	**r^2**	**Nash**
Bottineau	-0.01	0.26	0.14
Bowman	0.10	0.50	0.43
Burke	-0.10	0.45	0.39
Cavalier	-0.03	0.17	0.17
Divide	0.25	0.62	0.37
Hettinger	0.07	0.39	0.36
McKenzie*	0.19	0.46	-0.17[5]
McLean	0.05	0.30	0.27
Morton	-0.01	0.58	0.58
Mountrail	-0.02	0.48	0.45
Pembina	-0.06	0.20	0.11
Stark	0.04	0.45	0.45
Towner	-0.09	0.22	0.17

[5] The McKenzie County simulations for 1996 to 2005 were the only non-significant results. This county had a successful calibration but validation was unsuccessful. It is possible that after 1995 a new variable may have affected yields causing poor correlation between Y_o and Y_s for 1996 – 2005.

North Dakota Durum production in the 2020's and 2050's is based on 68 simulations per county for each period. The baseline for these simulations uses historical average yields from 1981 – 2005. Historical yields are generally higher in the NE in Pembina (2.66 t/ha), lower in the SW in

Average Y_o (t/ha), Historic (1981 – 2005)

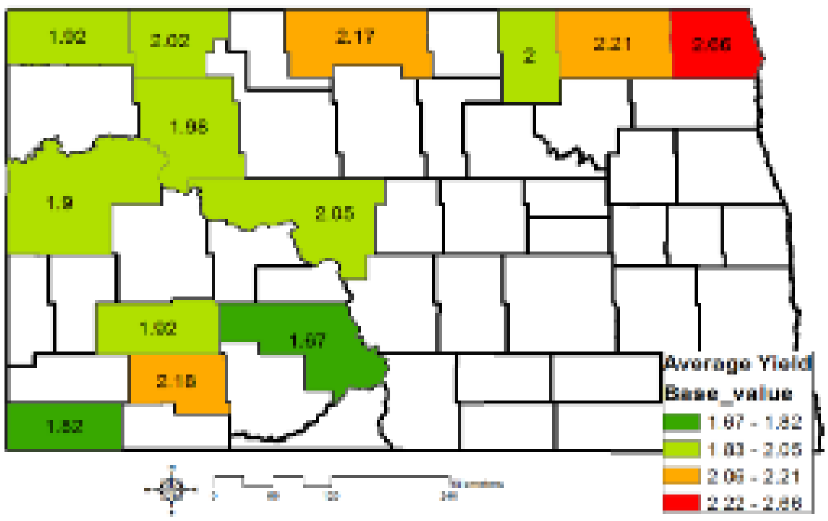


Fig. 20: Durum Historic Average Yields from (1981-2005).

Bowman (1.82 t/ha) and milder average yield in the NW in Divide (1.92 t/ha) (Fig. 20). The distribution of crop yield is heavily linked to the spatial distribution of Tmax, Tmin, and PRECIP. As we will recall, the NE of the state has increased precip compared to the drier W and SW region of the state. Meanwhile, the N is cooler than in the S (Table 11).

Table 11: Climatological data of 1981 – 2005 color-coded with red and orange as smaller values than the yellow and green color-coded cells.

Historic 1981-2005				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	10.39	-2.67	1.06
NC	20	10.48	-2.93	1.18
NE	30	9.16	-2.78	1.25
WC	40	11.97	-1.67	1.07
SW	70	12.99	-0.91	1.07
SC	80	11.21	-1.64	1.14

RCP Simulations of the 2020's

RCP 2.6 Changes

The Avg.Ys increased from historical average yields (1981-2005) in the counties that follow the Missouri River such as Morton, McLean, and Mountrail (Fig. 21). All other counties had a decrease in 2020's yields (Fig. 21). Average statewide yields decreased ~3.0 % from 2.01 to 1.95 t/ha. The spatial distribution of yields in the 2020's is still higher in the NE and decreasing in the central region of the state to ~2.00 t/ha ± 0.25. The lowest yields for RCP 2.6 are in Divide, Burke, and Bowman counties which were below 1.66 t/ha.

Average Y_s (t/ha), RCP 2.6 (2020's)

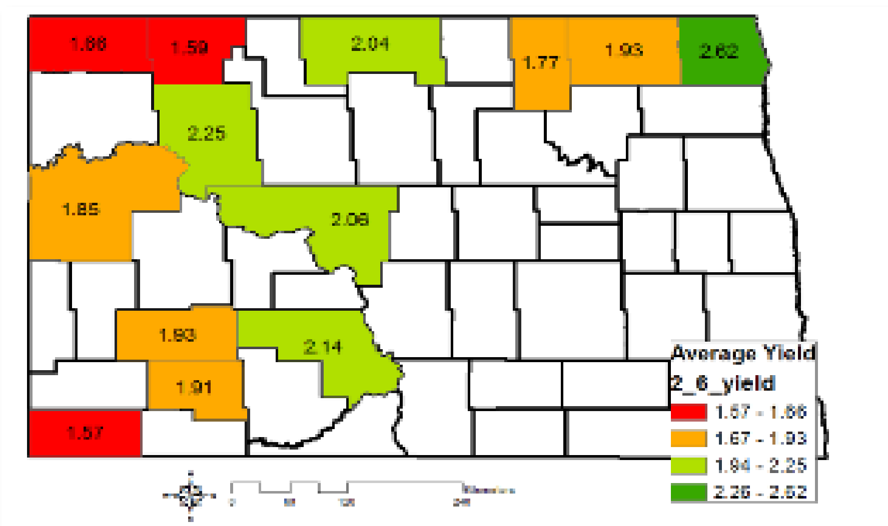


Fig. 21: Simulated Average Yield (t/ha) RCP 2.6.

RCP 4.5 Changes

The second climate scenario, RCP 4.5, represents a change in emissions and mitigating policies to reduce the human influence on CC. The increases in Tmax and Tmin, coupled with the changes in precip, create the conditions for decreases in Durum yield under RCP 4.5 in the 2020's. Estimated yields in the 2020's, ranged from 2.02 t/ha to 1.59 t/ha with a statewide trend of decreasing yield from 2.01 to 1.96 t/ha, a 2.49% decrease. Yield distribution remains unchanged with higher yields in the NE and lower yields in the W and SW under RCP's 4.5, 2.6 and under historical conditions (1981 – 2005). The same four counties along the Missouri River saw increases in yield as in RCP 2.6 (Fig. 22).

Average Y_s (t/ha), RCP 4.5 (2020's)

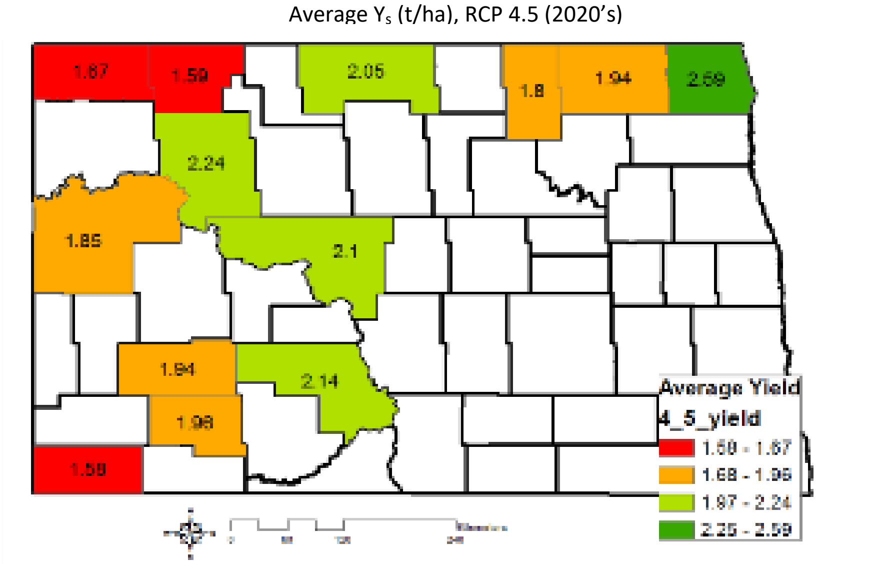


Fig. 22: Simulated Average Yield (t/ha) RCP 4.5.

RCP 6.0 Changes

In RCP 6.0, the second intermediate scenario, the radiative forcing is expected to stabilize by 2100 resulting in a net increase of 6.0 W/m^2. This scenario is consistent with a heavy reliance on fossil fuels and increased demand for agricultural land conversion to feed the growing global population.

These changes coupled with changes in precip and temp will affect the climate of North Dakota and in turn yield (Fig. 23). The statewide Tmax and Tmin increased by 1.20 and 1.30 °C respectively with Tmax and Tmin remaining higher in the S and lower in the N (Fig. 23). The trend of lower temps in the NE and higher temps in the SW is consistent for RCP 6.0 in the 2020's.

Average Y_s (t/ha), RCP 6.0 (2020's)

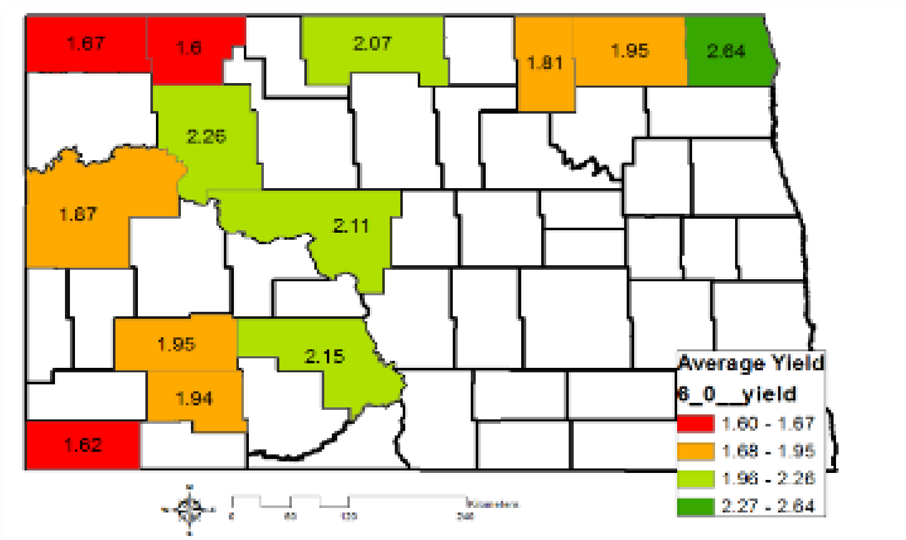


Fig. 23: Simulated Average Yield (t/ha) RCP 6.0.

In the 2020's avg. Y_s increased in 8 counties ranging from 0.01 to 0.41 t/ha. McKenzie, McLean, Morton, Mountrail, and Stark, had decreases in yield ranging from 0.05 and 0.47 t/ha. The climate of North Dakota is hotter and drier and may be the cause of decreased Y_s in most counties. The statewide average yield decreased by 0.04 t/ha from the historical value of 2.01 t/ha (1981 – 2005) to 1.97 t/ha in the 2020's (table 12).

Table 6: County Yields with the greatest deviations from the statewide average (1.97 t/ha).

County	RCP 6.0 Y_s – 2020's
Burke	1.60
Bowman	1.62
Divide	1.67
Mountrail	2.26
Pembina	2.64

RCP 8.5 Changes

RCP 8.5 is a scenario with the greatest increase in radiative forcing, 8.5 W/m^2 by 2100. This change will likely increase GMST anywhere from 2.0 to 2.6°C. The increases in Tmax, Tmin, and changes in precip make the RCP 8.5 scenario the hottest and driest scenario provided by the IPCC. This scenario is the greatest threat to the production of North Dakota Durum in the 2020’s. The Avg. Y_s decreased from 2.01 t/ha (1980 – 2005) to 1.93 t/ha in the 2020's. Despite this statewide decrease, 8 counties experienced an average increase of 0.23 t/ha with the other five counties decreasing an average of 0.16 t/ha. The spatial distribution of yield has not changed with higher yields in the NE and C regions and lower yields in the W and SW (Fig. 24).

Average Y_s (t/ha), RCP 8.5 (2020’s)

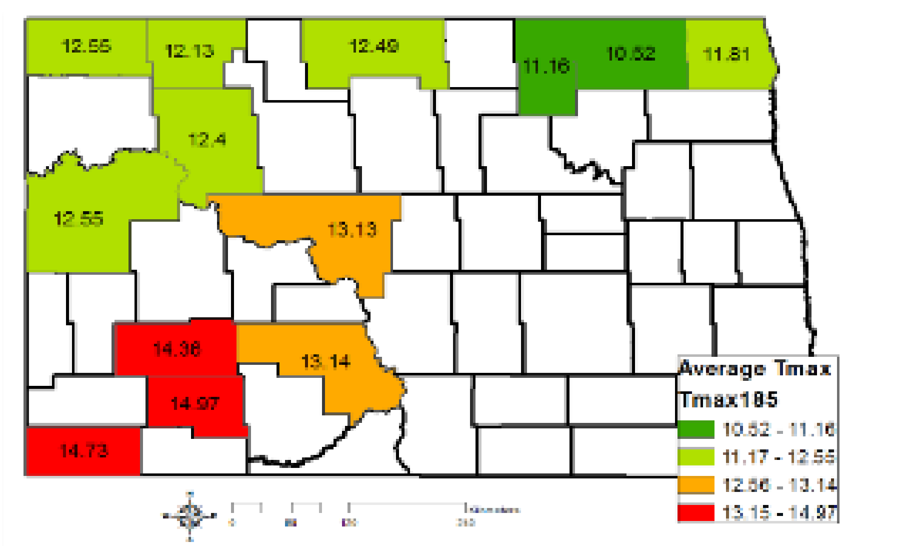


Fig. 24: Average Ys RCP 8.5

RCP Simulations of the 2050's

The 2050's represent a period midway through the end of century estimates. The repercussions of increases in radiative forcing manifest as daily observable factors. The IPCC AR5 scenarios represent changes in temp, precip, ENSO, PDO and many other climate variables (Pachauri, 2014; Hartman, 2013). Trends observed in the 2050's are not guarantees of 2100 values. For example, in the RCP 2.6, 4.5, and 6.0 scenarios, radiative forcing increases to a certain decade and then decreases until 2100. The only scenario with continued increases throughout the 21st century is RCP 8.5.

RCP 2.6 Changes

Under the RCP 2.6 yield decreased by an average of 0.08 t/ha from the 2020's to the 2050's in the NE counties. For example, Pembina decreased from 2.66 to 2.53 t/ha and, in the NW, where Divide decreased from 1.92 to 1.62 t/ha. The greatest changes were in McKenzie and McLean counties which increased from the historical (1981 – 2005) values to the 2020's (Fig. 25). 2050's yields maintain the same distribution with higher Y_s in the NE and decreasing as you move W and SW (Fig. 25).

Average Y_s (t/ha), RCP 2.6 (2050's)

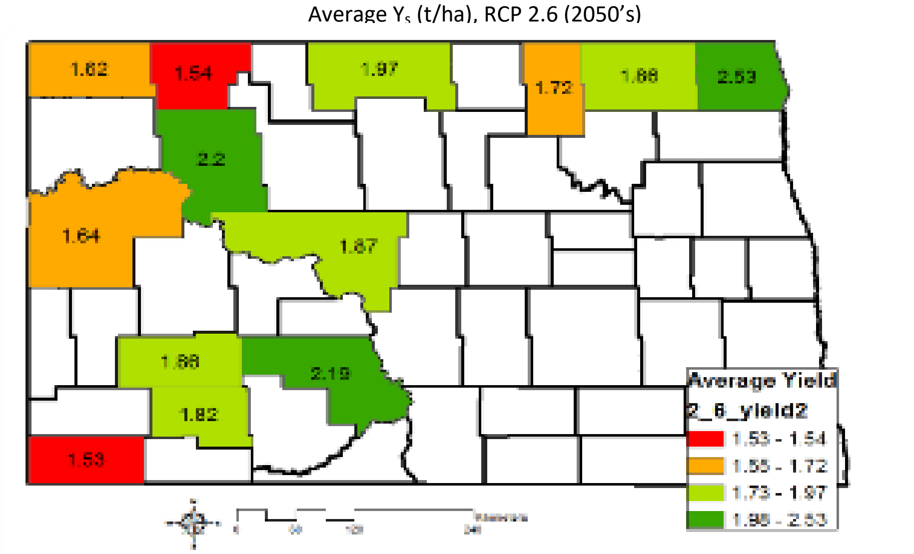


Fig. 25: Average Yields RCP 2.6 in the 2050's.

RCP 4.5 Changes

Precip in the 2050's decreased under the RCP 4.5 from 2020 levels. Increases in Tmax and Tmin will continue creating a drier and hotter North Dakota climate in the 2050's. Thus, the Y_s continued to decrease from 1.95 t/ha in the 2020's to 1.87 t/ha in the 2050's. Meanwhile, Mountrail, Morton, and Pembina still produce yields above 2.00 t/ha. The only county with Y_s increases from 2020's to 2050's was Morton with an increase of 0.01 t/ha (Fig. 26).

Average Y_s (t/ha), RCP 4.5 (2050's)

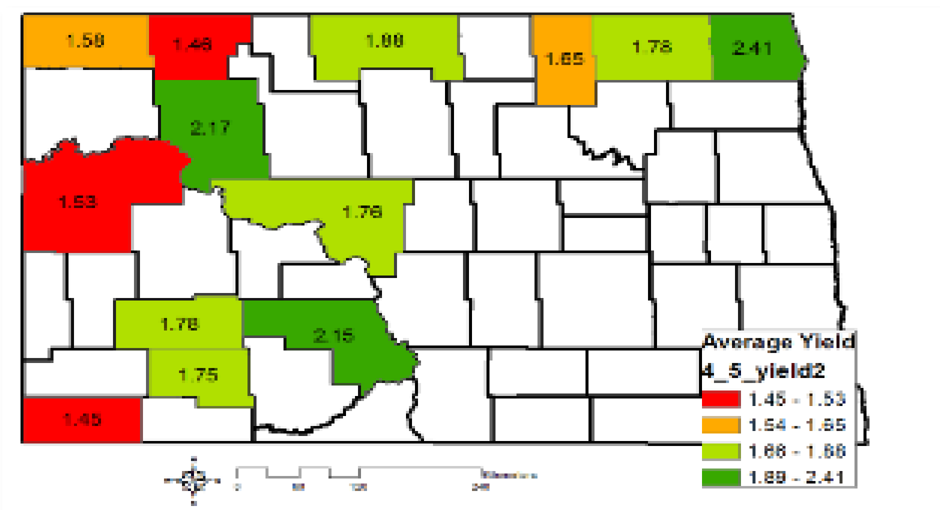


Fig. 26: Average Yields RCP 4.5 in the 2050's.

RCP 6.0 Changes

The second intermediate scenario (RCP 6.0) aims for a net radiative forcing of 6.0 W/m^2 by 2100 (Van Vuuren, 2011). Y_s decreased an average of 0.17 t/ha under RCP 6.0 from the 2020's to the 2050's. These yields reflect a dry, hot climate with only four counties achieving average yields above 2.00 t/ha in the 2050's compared to 3 counties in the 2020's and 6 counties for the entire period from 1981-2005 (Fig. 27).

Average Y_s (t/ha), RCP 6.0 (2050's)

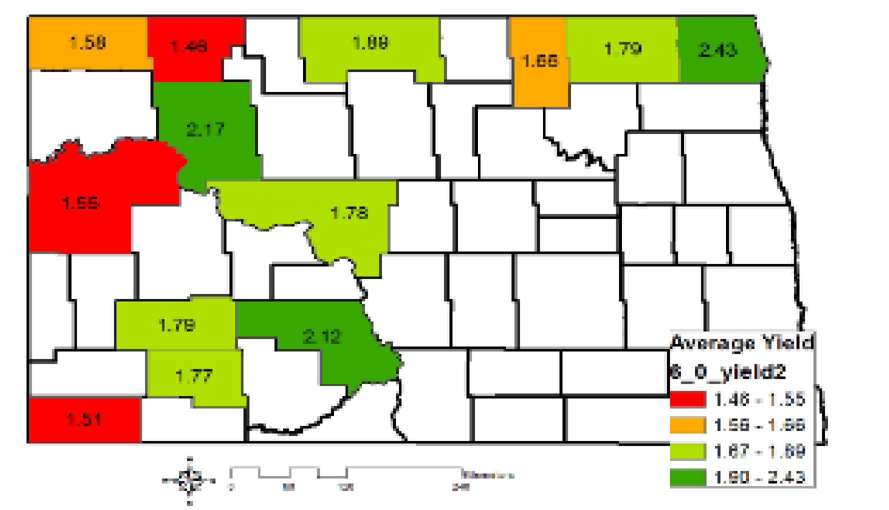


Fig. 27: Average Yields RCP 6.0 in the 2050's.

RCP 8.5 Changes

The final scenario, RCP 8.5, is considered a do-nothing scenario representing the most extreme effects of unmitigated CC on North Dakota. The temp increases and precip decreases under 8.5 make it the hottest and driest scenario. These climatic changes make this scenario the greatest threat to Durum production. Under RCP 8.5, Y_s decreased an average of 0.28 t/ha from the 2020's to the 2050's. Like other scenarios, the distribution of yields remained unchanged with lower yields in the W and SW, and higher yields in the NE (Fig. 28).

Average Y_s (t/ha), RCP 8.5 (2050's)

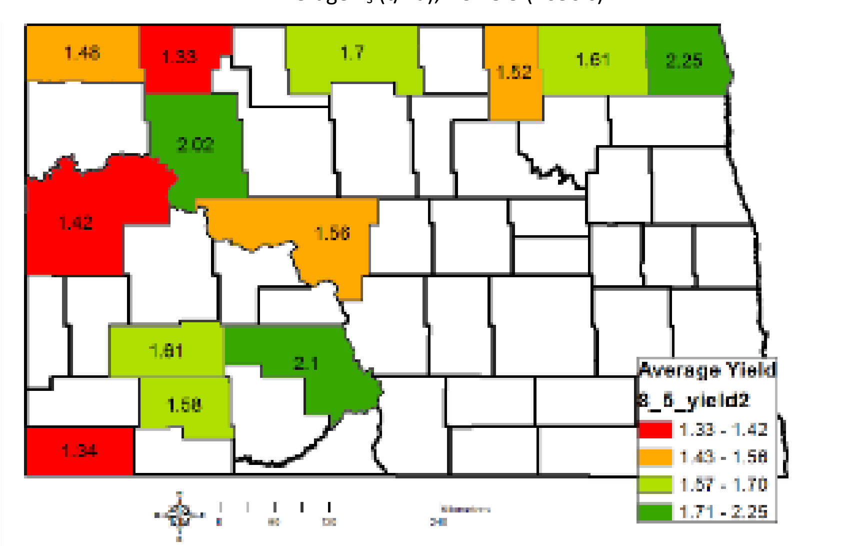


Fig. 28: Average Yields RCP 8.5 in the 2050's.

Discussion

This study of North Dakota Durum used a model to replicate historical yields for a 25-year period (1981 – 2005). Several observations of historical climate and agricultural trends were revealed in the study, such as the increasing number of acres planted with high yielding cultivars. Another observation from the study was the statewide production response to a nationwide drought like the one from 1988 – 1989 which caused significant decreases in yield and production. Using modeling and the projected trends of multiple key factors, an assessment of Durum production trends is possible.

Model Sensitivity Analysis

The simulation of historical yields, 1981 – 2005, was achieved using three parameters which are important to the replication of past Durum production. Xie et al. 2003, discussed that certain parameters in ALMANAC have significant effects on yield compared to other parameters. Those with the greatest effects on yield include

- Harvest Index (HI) which determines the amount of biomass partitioned to the grain
- Radiation Use Efficiency (WA) which is the amount of dry matter per unit of intercepted light.
- Potential Heat Units (PHU) which is the total amount of heat/thermal energy available to the plant growth process over the season.

These parameters dictate plant growth within the simulation and have a considerable influence on grain/yield formation. The PHU parameter is key to the transition from one growth stage to another (See Durum Interactions with the Environment). Knowing the range of common HI, WA, and PHU values are helpful in simulating yields. HI values ranged from 0.25 to 0.30 at the turn of the century. This seems laughable compared to the varieties planted in the latter part of the 20th century with HI values of 0.35 to 0.40. These parameters, (HI, WA and PHU) were altered in the study one at a time to determine the response of yield (t/ha) to each parameter change. Increasing HI caused an increase in harvestable yield and decreasing HI had the opposite effect. Increasing WA means more biomass is being distributed to grain/yield production and less to structural growth causing an increased yield response. One example was in Bottineau County which served as a test area for simulating (table 13).

Table 13: Example of parameter settings used for sensitivity analysis, WA (Biomass partitioning ratio), PHU (Potential Heat Units/AGGD), and Harvest Index (HI)

Bottineau Sim: '81 - '95			
Sim	WA	PHU	HI
1	35	1783	0.42
2	35	1783	0.40
3	35	1783	0.39
4	35	1783	0.38
5*	35	1783	0.37
6	35	1783	0.36
Bottineau Sim: '96 - '05			
1*	35	1783	0.37
2	35	1783	0.40

Unlike HI and WA, PHU is not a malleable parameter available for genetic manipulation. Instead, this parameter is dictated by the daily thermal energy available to the plant and totaled throughout the growing season (i.e., Growing Degree Day calculation) from the climate data. The range of the PHU parameter was selected from the North Dakota Agricultural Weather Network (NDAWN) where a GDD's schedule for wheat is generated from historical weather data. After providing the simulation planting date, the GDD's are tallied from planting to harvest. This schedule provides a cumulative total for a given growing season. However, AGDD/PHU totals are computed for each growing season using weather data meaning annual PHU values can vary from year to year.

This parameter was altered in many simulations to encapsulate the best fitting average PHU/AGGD values for each county. Generating an average PHU value required the range of PHU totals for each year and using this range to calibrate the model. PHU is a climatological and management parameter in ALMANAC. While PHU does represent the amount of thermal energy available to the plant over the growing season, this parameter is also used as a management tool for monitoring the progress of the crop. Often influencing management decisions (i.e., water and fertilizer operation schedules). After generating an average PHU range for each county, possible values for the PHU parameter were tested often ranging between 1600 and 1800 °C,

A simulation of historical yields, only altering the PHU, shows the total amount of PHU achieved in that specific year. This represents how much thermal energy was available from the weather data (i.e., Tmax and Tmin) for the year. This annual PHU value is "capped" or limited by the model input value (ex. if the PHU parameter is set to 1785 °C, then the PHU available for any year of the simulation is ≤1785 °C). The yield response to alterations in PHU varied depending on the magnitude of the alteration.

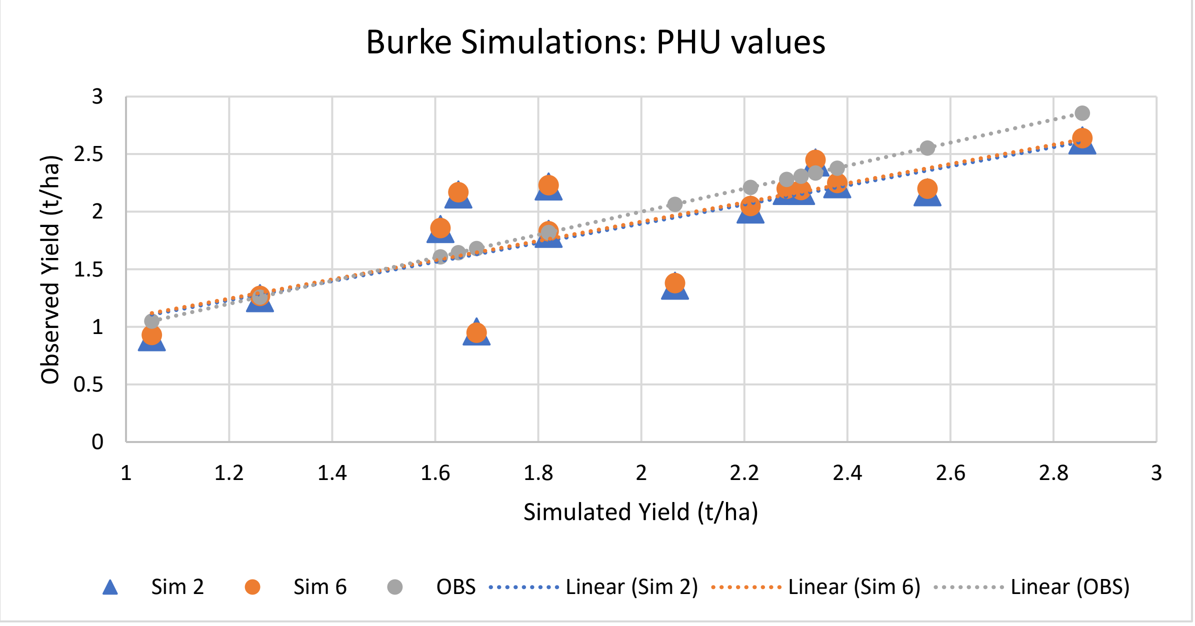


Fig. 29: Slight changes to the PHU parameter in Burke County shows that yield (t/ha) did not significantly change when altered by a small number of thermal units (~50 °C).

For example, in Burke County, it was simulated that a slight change in PHU did not have a significant impact on Y_S (Fig. 29). These two simulations used the same HI and WA values of 0.28 and 35% respectively. PHU was adjusted from the 1783 °C in Sim 2 to 1800 in Sim 6 with minimal effect on yield (Fig. 29). Observing this response in multiple counties indicated that a minor change in PHU has minimal effect in altering yields. This makes sense because a small variation in PHU values happens every year.

However, larger changes in PHU had a more significant impact on simulated yield. In many counties, the PHU values were adjusted at wider intervals when the NDAWN range for the PHU parameter settings was largely making a good simulation of past yields difficult (Fig. 30). Using multiple simulations in these counties, it was observed that lower PHU values had lower simulated yields than higher ones. For example, Cavalier County was evaluated using 14 simulations, six of which had the same HI and WA with altered PHU values. These simulations used a wide range from 1444 °C to 1800 °C and as PHU increased so did Y_S (t/ha) (Fig. 30).

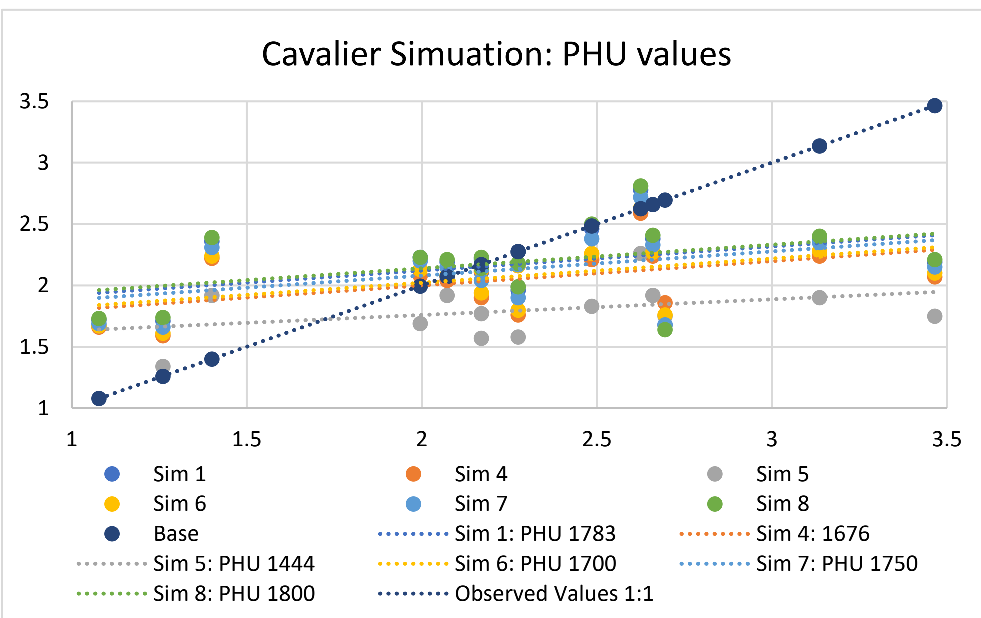


Fig. 30: These simulations (above) and the associated trend lines represent changes in the PHU parameter. The lowest (grey) had a PHU of 1444 and increased with each trend line to the top of 1800.

While evaluating parameters for sensitivity to change, it was deemed prudent to evaluate the impact of altering key management and timing values. Simulations were run to see if reducing or increasing the field prep period influenced yield. Lastly, simulations tested the effect of moving the planting date forward and backward.

Simulations use preset management parameters such as a planting and fertilization schedule that incorporates a field preparation process prior to seeding. To test the significance of this parameter, the planting date was moved forward by increments of five days in Bowman county, resulting in three simulations with earlier planting dates. In each of these simulations, the field preparation day remained one day prior to seeding. Yields in these simulations varied with preset parameters or using modified planting dates. However, using an analysis of variance test (ANOVA), it was determined that these three simulations with modified planting dates were not significantly different from each other (F<F crit) (Table 14). This indicates that altering the planting date by ± 5 – day increments, for a total of 15 days did not result in a statistically significant change in yield (Table 14).

Table 14: Analysis of Variance (ANOVA) test for the differences between simulations with earlier and earlier planting dates (i.e., moved forward by 5, 10, and 15 days).

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
5-day increase	10	17.05	1.705	0.089294
10-day increase	10	17.34	1.734	0.079471
15-day increase	10	17.72	1.772	0.061751

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.02258	2	0.01129	0.146931	0.864039	3.354131
Within Groups	2.07465	27	0.076839			
Total	2.09723	29				

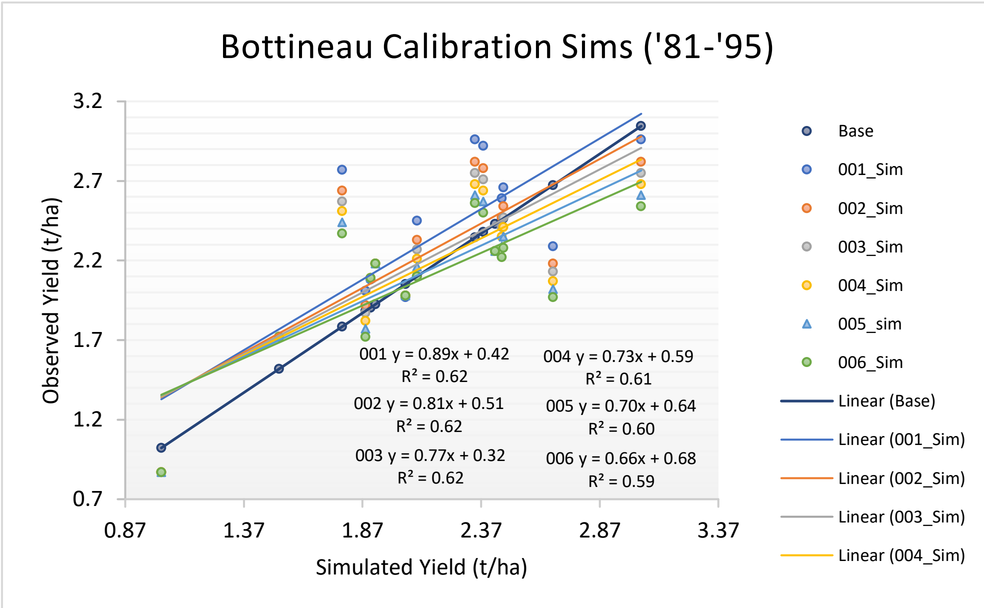


Fig. 31: Simulations of '81 to '95 for Bottineau County comparing simulated versus observed yields (t/ha).

After this was tested, an examination of moving the field prep day was tested by changing the field day prep from 1 day prior to seeding to 5 and 10 days prior to seeding. It was found that setting the field preparation earlier than the planting date had no effect on yield (Fig. 31).

After altering these parameters, a simulation of 1981 to 1995 created a series of simulations which were compared to the Y_o values and evaluated using ρ and the E_{ns}. A simulation with high ρ and E_{ns} has yields that generally follow the same pattern as the Y_O values. This is indicative of the model's ability to replicate historical yields for 1981 – 2005.

For example, while simulating Bottineau historic yields, the simulation number 005 had the best replication of historical yields (t/ha) with a ρ = 0.78 and an E = 0.59. The E value was the highest of the six simulations performed. This simulation had lower yields than observed values eight of the 15 years from 1981 to 1995 and over simulated seven years of the period. Using the parameters for this 1981 –1995 simulation, (WA: 35, PHU: 1783, HI: 0.37), a second simulation of the 1996 to 2005 period was conducted. The results of this simulation were added to the original simulation (4981 – 2095) to create a continuous simulation from 1981 to 2005 (Fig. 23). The simulation overestimated the observed yields (t/ha) 11 times and underestimated 14 times.

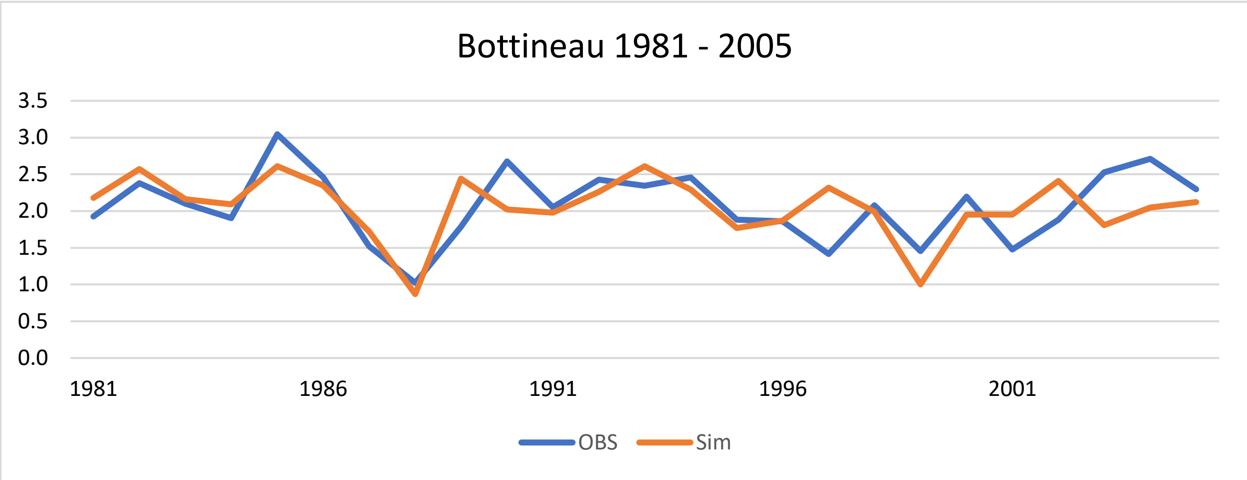


Fig. 31: These simulations of Bottineau County 1981 – 2005 compared to Observed values measured in (t/ha).

Methodological limitations

Limitations of this methodology are either mathematical or systematic in nature. An example of a mathematical limitation within ALMANAC is the lack of a parameter to represent disease or pest stresses on crop physiology and growth. It is possible to incorporate these effects into the model by altering growth characteristics to replicate the effect of these stressors but were not for this study. A systems limitation is the model's ability to quantify a concept (i.e., accept future simulation dates or alternate management or genetic profiles mid-simulation). Some models may tackle these issues, but ALMANAC does not. Adding variables to the model will occur over time with new knowledge of agronomy or modeling. This limitation is inherent and does not invalidate other aspects of the study. These factors that are extraneous to plant growth (ex. pollution impact on growth) can be considered after modeling. The investigator can replicate the impact of the variable by applying common knowledge of the stressor based on the literature. For example, it is known that molds and diseases negatively affect crops and proliferate under "ideal" climatic conditions. If these "ideal" conditions increase in the future, then it can be predicted that the occurrences of molds and diseases will also increase. If these insect or disease stress factors can be expressed as different stress factors such as water stress, then these external factors might be folded into the model. The systemic limitations of modeling are unknowns and impacts devoid of data/research. These can be socio-political uncertainties including government regulation or war. These uncertainties create so many variables the error and data would be overwhelming.

An appropriate systemic target would look at the trends in current sociopolitical events and attempt to predict specific decadal trends (i.e., What will the rise of nationalism do to agriculture in a specific nation?). However, this methodology would require titanic amounts of data, some of which is not available. This would require an understanding of phenomena and processes that remain too complex to our understanding. The understanding of methodological limitations allows for insight into areas of potential improvement or development. Results of a scientific study are often provided with an error which does not represent a lack of foundational scientific understanding but rather a mathematical error which guides the interpreter along with a general trend or conclusion that is likely to occur. If the limitations and error are appropriate for the study, then the study has statistical merit and may be valuable.

Historical Trends in Climate & Agriculture

Global CC is analyzed using a variety of temporal resolutions ranging from brief monthly or daily intervals like GHG emissions or long-term geologic periods like the millennia of countless ice ages (Hartmann, 1994). However, this study focuses on the short-term trends in agriculture (<100 years) meaning any discussion should be curtailed to meet this timeline. First, it is important to highlight the role of Agriculture in society.

- Agriculture has and continues to change the diets, migration patterns, lifestyles, culture, social hierarchy, and conflict of people all over the world.

- Agriculture is and will always be a significant economic sector to mid-western American states.
- Investing in agro-technology helps to solve social issues (i.e., poverty, wages, employment)

Higher yielding crops like wheat have historically been important in compensating for small planting areas via the high seeding density (Harari, 2014). Therefore, it is not surprising that modern human diets are based on cereal crops. Cereal crops are a driver of our population growth over the past 1,000 years. An increase that will continue as humanity reaches the predicted global population of ~11 billion individuals by 2100 (UN Department of Economic and Social Affairs, 2017).

Land Use: Agriculture, Oil, and Conservation

The common accepted scientific consensus is “clear that the dominant cause of the rapid change in the climate of the past half century is human-induced increases in a number of atmospheric greenhouse gases, including carbon dioxide (CO2), chlorofluorocarbons, methane, and nitrous oxide." (2012). Recognizing this crisis, 197 nations signed, and 147 ratified the Paris Climate Accords to reduce carbon emissions and mitigate CC (Jayaraman, 2016). The Paris Climate Accords were designed to politically commit the powerful nations of the world in the common goal of reversing global climate trends by enacting new climate mitigation policies. In the US, these policies include broad legislation to protect large bodies of animals or ecosystems like those available through the USDA Farm Service Agency (FSA) (table 15). Or these could be focused legislation to reduce emissions or protect a specific watershed. These policies will have a positive impact on mitigating CC and enforcing environmental protections. American climate mitigation strategies and measures may have diminished in 2017, but as of the previous year, several programs have enhanced the production of agricultural commodities. These programs improve the lives of those who farm the land with the added benefit of mitigating CC and helping people's lives.

Table 7: Programs offered by local and federal governments to aid in mitigating CC and improve agricultural operations.

Program	Services Provided
Conservation Reserve Program	Pays a yearly rental payment in exchange for the removal of environmentally sensitive land from agricultural production and planting species that will improve environmental quality.
Emergency Conservation Program	Provides funding and technical assistance for farmers and ranchers to restore damaged farmland from natural disasters. Also, provide emergency water conservation measures during severe droughts.
Farmable Wetlands Program	Designed to restore wetlands and wetland buffer zones to farmland, FWP provides farmers and ranchers with annual rental payments in return for restoring wetlands and establishing plant cover.
Grassland Reserve Program	Prevents grazing and pasture land from being converted into cropland or used for urban development, in exchange for voluntarily limiting the future development of their land, farmers receive a rental payment.
Source Water Protection Program	Designed to protect surface and groundwater as drinking water for rural residents. The program targets areas for aid based on their water quality and population.

(Source: USDA-FSA)

As of July 2014, North Dakota, Kansas, and Colorado lead in the creation of "Permanent Wildlife Habitat" under the CRP program enrolling a combined 2,126,750 acres (Stubbs, 2014). However, the number of acres enrolled will likely shrink due to diversions of funding for agriculture to other environmental sectors (i.e., grass/wetland restoration). Balancing these two land-use sectors is only made more complex when the petroleum-based natural resources in the Bakken Oil Field and the Dakota access pipeline are considered (Volcovici, 2017).

Global Durum Production

Durum Wheat is produced in several parts of the world, the highest producing areas being the climatic regions where pasta is commonly a consumed foodstuff consumed. Most of the Durum production occurs in the Mediterranean, North Africa, and SW Asia, all areas where wild wheat species were first cultivated in ancient times (Sicignano, 2015). The US was the 5th largest producer of Durum worldwide from 2011 to 2014 behind the EU, Syria & Turkey, Canada, and North Africa (Fig. 33). The only single nation that produces more than the US is Canada which makes it a more accurate to combine the US and Canada into one region (Fig. 33).

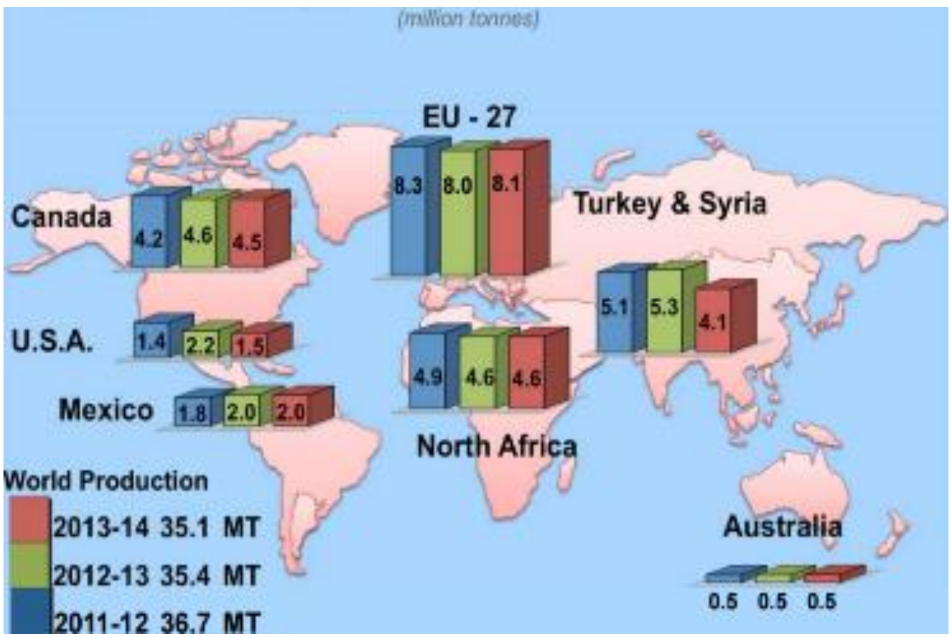


Fig. 32: Production of Durum Wheat worldwide, measured in million tons (Source IGC, CWB)

It's simple preparation requirements, versatility as a key carbohydrate, and easy storage and transportation aid in feeding millions annually (Sicignano, 2015). Many of the populations in these regions depend on Durum to produce flatbreads or couscous, a primary source of energy and carbohydrates for many people in the near east and in Africa. Meanwhile, the best quality Durum grain is milled into a fine flour called semolina. Semolina is made from the best quality of grain and is used with water to create a sticky dough that can be processed via machines into multiple forms of pasta.

Much of the grain produced in North American is of superior quality and is used to create the semolina for pasta. Other nations with inferior quality Durum will import end-use pasta products or raw grain from North American Durum growers. Durum produced in North America is often exported internationally, creating possible issues related to the transportation of these goods. Transportation (i.e., import and exports) is impacted by changes in political landscapes (i.e., Brexit, the Syrian conflict, and conflicts in North Africa).

As discussed previously, many of these geopolitical issues are driven by changes in spatial distributions of climate, weather, and geopolitical variables (i.e., temp, precip, revolution, war, famine, plague). Any effort to decipher such massive global events and the fallout is riddled with complications. Even domestic production is a complex system of cooperation between farmers, regulating agencies, political influences (i.e., Unions and lobbies), and consumers. It is not unreasonable to draw conclusions based on current events, but these conclusions are often seemingly unconnected. For example, changes that are driven by changes in spatial distributions of climate, weather, and geopolitical variables (i.e., temp, precip, revolution, war, famine, plague). Many of which are difficult to predict or understand until post hoc analysis is applied.

North Dakota Durum Production

ND currently represents ~60% of the US domestic Durum production (BU) and ~67% of total planted/harvested Durum acres. The remaining ~40% of production occurs in Arizona, California, Minnesota, Montana, and South Dakota. North Dakotas status as the largest domestic producing state remained relatively unchanged given the statistically significant decreases in domestic production (BU) and planted/harvested acres (Fig. 34 and 35). Cultivars released from

North Dakota's breeding program are grown on over 93% of Durum hectares in North Dakota and surrounding regions. The remaining 7% of hectares are planted with cultivars released by breeding programs in Canada and private companies.

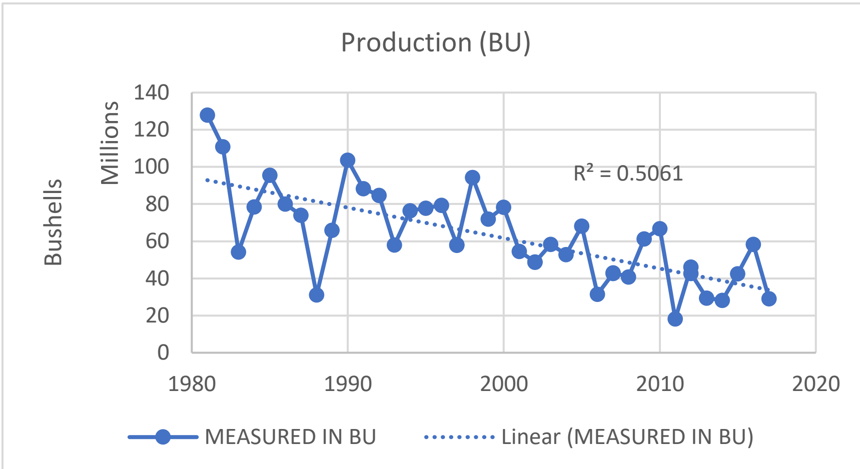


Fig. 34: Total domestic production measured in BU.

Durum has one key use, pasta production. This means the Durum market is inherently smaller than that of other wheat markets and that any shortage will likely result in significant price increases for the consumer.

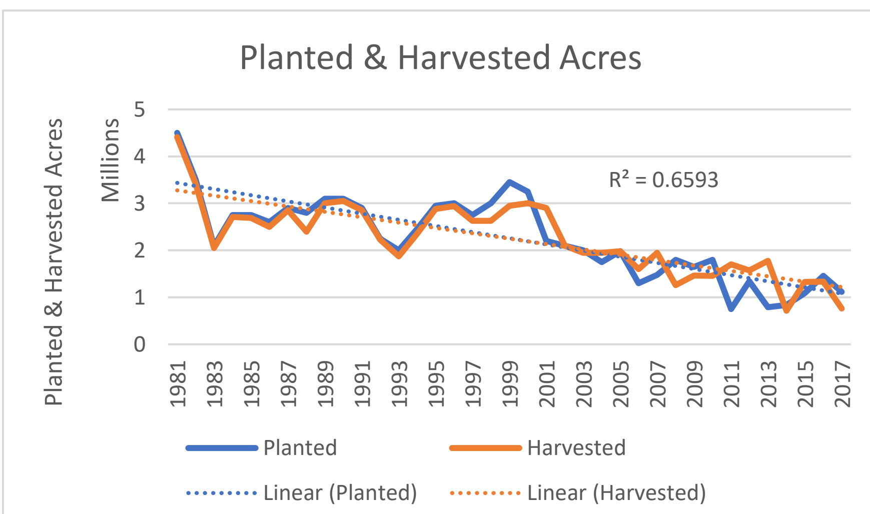


Fig. 33: Total domestic production measured in BU.

Durum produced in North Dakota has a reputation for superior quality, especially for semolina color and gluten strength. Pasta manufacturers want cultivars with strong gluten to ensure the desired quality of the finished product. This creates strong demand from domestic and foreign pasta producers for excellent ND Durum. In 2017 producers from North Africa visited the state to learn more about producing superior quality Durum grain and products.

Impacts on Durum Quality, Price, and Markets

Durum is in competition with Hard Red varieties for planting acres. Often a poor previous year coupled with poor forecasts will incentivize farmers to produce Hard Red varieties rather than Durum. To remain economically competitive, new durum cultivars must produce higher yields or at least equal to Hard Red cultivars while maintaining high protein and quality to be considered for planting.

To understand the economic costs associated with producing Durum wheat under future CC, an estimation of the production impact of changes in precip and temp must be evaluated.

The most substantial threat to Durum production is the increased propagation of disease like the outbreaks that occurred from 1993 to 1998 (Nganje, 2004). Fusarium is caused by wet field conditions. Making it likely that changes in the frequency or distributions precip and temp will only increase the damage from FHB on yield and quality. From 1998 to 2000 North Dakota incurred 41% of all direct impacts from FHB outbreaks. The total damage to the Durum crop from FHB was ~$70 million USD (Nganje, 2004). The Fusarium impact from 1998 to 2000 is a reasonable case study of widespread impacts of disease on Durum production in North Dakota. A deep analysis of economic impacts of disease during these years said,

"In North Dakota, FHB losses in wheat from 1998 through 2000 averaged more than 10% of the value of the wheat crop while barley losses averaged almost 26% of the total crop value over the same period." (Nganje, 2004)

It was also estimated that every dollar lost to FHB creates more than double the economic loss in secondary economic sectors of Durum production. Nganje 2004 provides an upper measure of FHB economic losses related to yield decreases and abandoned acres (Nganje, 2004). However, secondary economic impacts are likely a more crucial factor in the production of Durum in ND.

Should changes in temp and precip increase the rates of FHB infection, then the overall costs for cleaning will increase with the demand for machine rental and cleaning services.

Farmers will be required to clean harvested grain more and more in the future to meet quality standards. Since the trends of decreasing planted and harvested acres are likely to continue, those that continue to plant Durum will need to produce superior quality grain.

For example, a TriQ machine is commonly used to clean grain like Durum, Spring, and other Wheat species which require cleaning services. These services and machines can sort approximately 25,000 kernels per second or ~100 BU/hour. NDSU calculated that the statewide average cost of cleaning infected grain with chemical treatment is $2.87/BU and an average of $0.73/BU w/o chemical treatment.

Other costs that may be required to deal with CC and FHB include economic investments into irrigation tech to combat with drought or waterlogged fields. These future costs remain potential unknowns since North Dakota Durum is currently rainfed and may require these services in the future.

Table 16: Trends in production (BU) from 1981-2005.

#	County	Trend	R2
1	Bottineau	D	0.61
2	Bowman	I	0.38
3	Burke	I	0.11
4	Cavalier	D	0.63
5	Divide	I	0.16
6	Hettinger	I	0.25
7	McHenry	D	0.43
8	McKenzie	I	0.50
9	McLean	D	0.06
10	Morton	I	0.28
11	Mountrail	N	0.00
12	Pembina	D	0.28
13	Stark	I	0.52
14	Towner	D	0.70
15	Williams	I	0.73

It is unlikely that a change in the production of Durum to a different crop such as corn or soybean will occur. Overall state production acreage has been decreasing from 1981 – 2016 (table 16). However, individual county production has decreased in 40% of study area counties and increased by 53% with the remainder being Mountrail with no production trend. This is consistent with the overall trend in decreasing production (BU) statewide. It is more likely that farmers will diversify the crop profile as needed but will keep Durum in the rotation hoping the international market will be promising. In the wake of current decreases in Durum production, there are no new counties "filling in" and planting Durum.

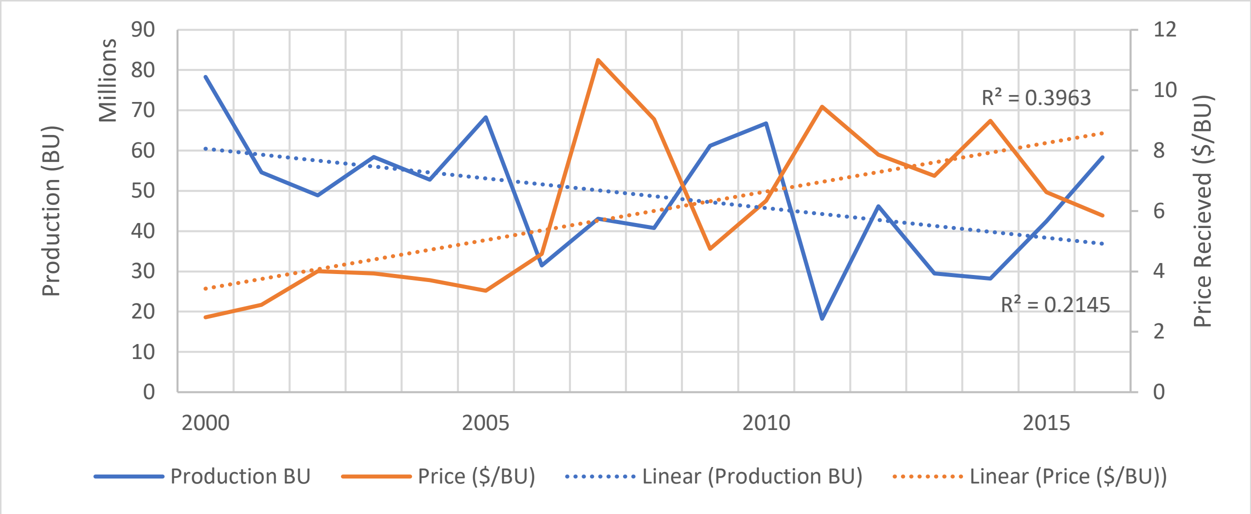


Fig. 36: North Dakota Production (BU) and Price received ($/BU) (NASS, 2017).

The USDA estimated domestic Durum production at 104 million BU in 2016, up 20 million, or 24%, from 2015 (84 million BU) (Fig. 36) (NASS, 2017). The r^2 between total production (BU) and price ($/BU) is 0.44 from 2000 to 2015 indicating that as production (BU) decreased, price ($/BU) increased. This price reaction to changes in production (BU) is statistically significant. No other combination of the three variables, yield (BU/acre), production (BU), and price ($/BU), had statistical significance.

The impacts of CC on North Dakota Durum production have not been extensively researched. However, evidence agrees that the impacts on ND will follow the global trend with spatially specific changes of increasing temp and varied changes in precip.

The 2016 Durum harvest had an average statewide yield of 3.15 t/ha which is 0.30 t/ha lower than the ten-year average of 2.85 t/ha (2005 – 2015) (NASS, 2017). This information would normally be optimistic if 2017 news and reports didn't estimate that the Durum planted area will be 17% lower than the 2015 – 2016 average which was hit heavily by vomitoxin.

Solutions

Should Durum production continue to decrease, an alternate strategy or crop commodity will be required. For example, North Dakota has a production permit to grow industrial hemp classified as a form of "Grain" production. The North Dakota Farmers Union has strongly recommended for congressional authorization to produce industrial hemp on a larger scale in North Dakota (Johnson, 2014). Within the study area, Cavalier, Hettinger, and the Langdon region encompassing NE counties have been identified as suitable locations for industrial hemp production (Hanson et al. 2017). Industrial hemp is a new grain commodity used on a trial basis for planting by North Dakota farmers and grows during months that would directly compete with a Durum growing season (Johnson, 2014). The planting dates would be between March and May with harvest between September and November, the same as Durum. The addition of this crop would open the state's economy to a wealth of industrial commodities including food from grains and oils, building materials, paper, textiles, personal hygiene products, and alternative fluids or biofuels (Johnson, 2014). In North Dakota, one of the few trial states in the nation, five producers with 70 acres cultivate industrial hemp for grain (Johnson, 2014). Industrial hemp would be a crop in direct competition with certain producers of Durum and Hard Red Wheat especially in NE counties where trials have been successful.

The Cost of Change

When discussing the limitations of crop models, it is important not to forget the significant benefits they provide. Analyzing historical patterns in yield and production provide perspective into the future production of Durum in ND. When discussing Durum modeling, the results represent:

> "drought stress, nutrient stress, and cold temperature and hot temperature stresses, but [if] the main causes of yield variability are something else, then the correlations

> [between Y_o and Y_s] will be low. I have seen it often." – Jim Kinery (Personal Communication)

The model results vary based on forecasted climate data including trends in daily weather parameters (Tmax, Tmin, and precip). Decreasing trends in Durum yields across all RCP's by ~0.07 – 0.10 t/ha in the least and most extreme scenarios (2.6 and 8.5 respectively), indicating a negative crop response to CC. This decrease continued in the 2050's and may be the first sign of diminishing Durum production in ND. Y_S decreased in the 2050's an additional 0.07 – 0.27 t/ha from the 2020's yields.

Climate impacts are visible in Bowman and Divide Counties which have a historical average yield of 1.77 and 1.80 t/ha respectively. In the 2020's and 2050's these yields could drop as low as 1.56 t/ha in Divide and 1.46 t/ha in Bowman. These decreases in production (BU) are already observable in 2017. As of May 14, North Dakota planted acres were down from this time last year but still above the 5-year average. ND production conditions were dry statewide except for the extreme north. The state did get some rain with recent Spring showers, but much of ND's Durum growing counties were affected by the infrequent rains this year.

Internationally, Durum crops in competing nations such as Algeria and Morocco are not suffering major setbacks. This has led some experts to believe that there will be little international demand for US Durum unless there is an interest in expensive, high-quality Durum from the other Durum producing nations.

To summarize:

Changes in climate will impact every sector of society. Those who will be most affected include those that rely on the delicate balance of human stewardship, nature, and the energy sources held therein (i.e., agriculture, coal, natural gas, and oil). To extract these resources, conflict over land use may arise as they have in the Bakken Oil Fields of McKenzie County, ND or struggles over land management like those seen regarding the Dakota Access Pipeline from 2016 – 2017 (Whyte, 2017). The complicated interactions between fossil fuels, humans, and the environment will only worsen under future CC. It is evident that the combative demand for land between the agricultural and energy sector will come to a headway that can only be resolved via legislation.

Independent of these land use issues, agriculture, and plant growth requires a delicate balance of the basic climate parameters responsible for growth, Tmax, Tmin, and precip (Mall, 2006). Therefore, any change in the distribution, quantity or quality of sunlight, nutrients, and water which plants require will influence growth. For example, Durum yields (t/ha) in North Dakota are anticipated to decrease under every scenario/simulation of CC in this study. While these decreases will not destroy the Durum industry, they may be indicators of a greater change. Many changes in production are driven by increased drought and disease and will worsen under various CC scenarios. To make up for this decrease in planted acres, scientists and researchers have been increasing Durum yields (t/ha) via facilities like North Dakota State University's Durum Breeding program (NDSU-DWBP). The goal of the program is to, "develop improved Durum germplasm for characteristics such as grain yield, maturity, pest resistance, and quality." All of these genetic enhancements will be needed to combat the negative effects of CC on Durum production and maximize yields.

These modifications have reduced the impact of crop diseases and increased crop yields beyond natural capabilities. It is the advancement of crop genetic structures that compensated for decreases in produced acres thus far. Genetic yield modifications play a significant role in enhancing the nutrition and increasing quantities of food. The average Durum yield of new varieties being produced by NDSU-DWBP increased from 1.60 (the 1950's) to 3.11 t/ha (2007) (Gunderson, 2007). The natural progression of crop genetics, as well as the efforts of the NDSU-DWBP, have undeniably benefited Durum grain production. One study showed that Durum genetic enhancement increased harvested yield more markedly than increases in bread wheat (Marti, 2014). It is likely that these advances will not outpace decreases in planted or harvested acres. Lastly, these decreases will be compounded by decreases in the percent of the land area classified as arable in the US which has decreased from 1961 (48.9%) to 2014 (44.6%) and is anticipated to continue decreasing (Rozenberg, 2015). This raises the question, what are the future relationship between agriculture, land use, and climate going to look like in North Dakota? Climate, topography, and continental geography are key to determining the vegetation of a specific location. A common rule to determine a vegetative change is to look 100 miles to the south, and the climate/vegetation of that region will likely be the future vegetation under CC. This would mean a hotter and drier climate for North Dakota. Based on this, the agricultural economy of North Dakota would be heavily based on corn as it is in the corn belt of the US (Kansas, Oklahoma, Nebraska) and as we have seen in SE North Dakota in recent years. Should a change from Durum production be necessitated, corn may be a viable alternative. Even if Durum remains viable in upcoming decades, an increase in crop diversity will promote security for those who farm as a means of primary income. Allowing small operations to withstand the altered climatic.

Adequate climate conditions and genetic improvements have driven a shift in agriculture from wheat varieties to corn and soybeans (Aguilar, 2015). Anecdotally, it was stated that corn was not grown north of Bismarck and now it is produced across a greater area of the state. A shift accelerated by FHB which devastated wheat yields in the 1990's (Aguilar, 2015). In just over a century, growing season length has extended by nearly 12 days favoring corn production (Weise 2013). NDSU climatologist, Adnan Akyüz, told USA today that in Fargo, ND nearly 16% of the total thermal energy needed to grow a corn plant to maturity comes from CC effects on temp (Weise, 2013). Future climate will only exacerbate this trend creating favorable conditions for soybean or corn production in the E half of the state (Aguilar, 2015).

If yields decrease into the 2020's as was shown in the simulations of this thesis, then the added impacts of disease and drought will drive farmers to switch to a different crop. Making a switch is a possible option to access the ethanol and food markets for corn harvests, likely incentivizing farmers to either alternate corn and wheat varieties (Spring, Hard Red, or Durum) or switch to other crops entirely. No matter what, changes in climate will eventually be costly if not anticipated and given adequate preparation. It is important to remember that the soils in the W, where Durum is produced, are substandard and may be hostile to many different crops, even corn. Therefore, as the state and national populations increase, the efficiency of the land we cultivate and the Durum cultivars we plant will need to be improved to provide higher yield and meet growing demand.

The conclusion of this study is that the impact of CC is unilaterally a negative force in the production of North Dakota Durum. The simulation results showed decreased yields in the 2020's and 2050's from historical values (1981 – 2005). Even the scenario with the most climate mitigation (RCP 2.6) is still likely to result in decreased crop yields, increased disease, and decreased grain quality (Triccolli, 2000). These negative impacts will intensify under the 4.5, 6.0 and 8.5 scenario.

Given the possible negative impacts of CC, it would be prudent for ND to re-evaluate and re-design aspects of the agricultural sector (i.e., introducing increased irrigation, enhanced monitoring strategies, disease mitigation measures, etc.) to ensure resilience. However, there are opportunities posed by CC. Areas that become unfavorable to wheat production may become suitable for alternative crops such as corn or industrial hemp. While the impacts from increased temps may not occur for several years, others such as crop disease and pestilence may affect harvests soon. Effective technologies and management may aid in overcoming these difficulties.

Conclusions

The amount of core literature explaining the relevance of the four IPCC scenarios in the 21st century is overwhelmingly in support of anthropogenic activities as the source of CC (Riahi, 2011; van Vuuren, 2011; Rogelj, 2012; Hirabayashi, 2013). In 2017, some of the scenarios (i.e., RCP 2.6) created to understand future climate are unlikely to remain viable in the presence of certain political decisions which will enhance CC. It is undeniable that global changes will impact regional and local climates causing temp increases in many locations.

The agricultural districts with the highest Durum production are located in the W, SW, and C regions of the state. Durum is extremely sensitive to changes in precip and temp. Durum producing counties in the W and SW have a higher number of harvested acres even though the yield in those counties may be lower than in the E with the lowest planted and harvested acres but the highest yields. Rainstorms are already more frequent, with increased intensity and increased annual rainfall increasing the concerns of flooding and wet farmland during the pre-planting period.

It is expected that increased CO_2 will increase yields via the carbon fertilization effect under future CC. The CO_2 fertilization effect, coupled with a longer growing season, will increase the yields and production of many crops in North Dakota. However, increases in temps and precip may lead to melting snow and wet fields in the spring. Rising temps may offset the benefits from the carbon fertilization effect. However, one of the biggest concerns is the increased temps in the early spring which affect water resource distribution throughout the growing season. These conditions will hamper production or reduce yield.

Summary of Future Climate and Yield Changes

The four RCP scenarios (2.6, 4.5, 6.0, and 8.5) portray a hotter and drier North Dakota climate in the 2020's and 2050's. The changes in Durum yield in ND reflect these anticipated effects of CC including decreases in Precip and increases in Tmax and Tmin. The average yield decreased in response to changes in climate and plant growth (i.e., stomatal opening and closing, increased temp stress). In the 2020's the Avg. annual yield decreased from historical values (1981 – 2005) between 0.10 and 0.22 t/ha. Average yields dropped from a historical value of ~2.00 t/ha to 1.91 t/ha, 1.88 t/ha, 1.89 t/ha, and 1.79 t/ha for RCP's 2.6, 4.5, 6.0, 8.5, and 2020's values respectively. Meanwhile, yields in the 2050's continued to decrease with average yields ranging from 1.87 t/ha at the highest (RCP 2.6) to a minimum of 1.66 t/ha (RCP 8.5).

What we observe in the 2020's and 2050's is continued decreases in Avg. Y_s from historical values (1981 - 2005) likely caused by increased temps and decreased precip.

- Yields are likely to continue decreasing as Tmax and Tmin increase and precip decreases.
- North Dakota's climate is predicted to experience increases in Tmax and Tmin and changes in the distribution and frequency of precip.
- Precip events are becoming more intense, and annual rainfall is increasing statewide.
- Changes to local climates will influence the production of Durum since the crop thrives under cool, dry conditions.
- The differences in yield from the scenario of lower climate impact (RCP 2.6) towards scenarios of greater impacts (RCP 8.5), indicates that increases in Tmin and Tmax and decreases in precip negatively affect Durum yields in North Dakota.

Certain regions do experience different climatic change with the SW experiencing decreased precip and higher temps in the later part of the century, causing decreased yield. This change will likely make several counties unsuitable for producing Durum such as Hettinger and Stark counties. Meanwhile, those counties bordering the Missouri River will benefit from more positive features of CC such as the increased drainage of the river ensuring dry fields come planting and the increased annual precip in the region. These differences in regional climate within North Dakota will alter the distribution of production acres.

An important feature of the 2050's is the frequency of counties with Avg. Y_s below 2.00 (t/ha). In the 2020's only 8 counties experienced frequent yields below 2.00 t/ha and in the 2050's this increased to 10 counties.

Appendix A: Climate Forecasts 2020's

RCP 2.6

Under RCP 2.6 the increase in CO_2 will likely increase global temp between 0.40 and 1.60ºC by 2050 (Bjørnæs, 2013; Van Vuuren, 2011). A global change in temp will influence the distributions of Tmax, Tmin, and precip at a regional scale and across North Dakota. In the 2020's, Precip increased in the NE and decreased in the SW (Table 17). The central region of the state has increased precip compared to historical distributions. Precip in the 2020's increased in all but Pembina county, (Table 17).

Table 17: Average values for Tmax, Tmin, and Precip under RCP 2.6.

RCP 2.6 - 2020's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	11.97	-0.94	1.16
NC	20	12.32	-0.93	1.22
NE	30	11.09	-0.74	1.29
WC	40	13.55	-0.08	1.02
SW	70	14.36	0.46	1.13
SC	80	14.33	1.48	1.22

The statewide trend in Tmin increased from -3 °C (1981-2005) to just over -1.0 °C in the 2020's. Increases in Tmin were similar. Meanwhile, changes in the 2020's Tmax (°C) values increased in the N border counties.

RCP 4.5

The 4.5 scenario sets an ambitious goal of 4.5 W/m^2 which would increase GMST by ~1.40 and 2.00 °C. RCP 4.5 emissions related to land use and productivity are measured as a total contribution from agricultural activities not necessarily specific point sources. Meanwhile, the positive changes under RCP 4.5 include reforestation programs and decreased demand for cropland conversion.

Table 18: Average values for Tmax, Tmin, and Precip under RCP 4.5.

RCP 4.5 - 2020's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	12.08	-0.83	1.11
NC	20	12.36	-0.94	1.14
NE	30	10.98	-0.81	1.3
WC	40	13.7	0.29	1.03
SW	70	14.46	0.58	1.11
SC	80	14.07	1.24	1.25

As far as emissions are concerned, under the 4.5 CH_4 emissions stabilize and CO_2 slightly increases through 2020 which then decline after 2020 (Thomson, 2011). Trends in pCO_2 require new monitoring methods and CC policies. Precip in the 2020's changed in many counties between -0.82 and + 1.28 meters. The historic Tmax (1981-2005) in North Dakota was spatially specific with values of 9.16 °C (NE), 10.42 °C (NW) and 12.74 °C (SW) and increased to 11.05°C (NE), 12.31°C (NW), and 13.91°C (SW) in the 2020's (Table 17 & 18).

The last climate parameter, Tmin, increased in the 2020's to -0.26 °C from the historic Tmin of -1.98 °C (Table 7 & 8). The Tmin increases were greatest along the N border of the state (1.90°C) with smaller increases in the S and W (1.50°C) (Table 17 & 18).

RCP 6.0

The second intermediate scenario, RCP 6.0, aims for a net radiative forcing of 6.0 W/m^2 by 2100 (Van Vuuren, 2011). This radiative forcing is equivalent to 850 ppm pCO_2 by 2100. This change is likely driven by a continued heavy reliance on fossil fuels and increased use of cropland (Van Vuuren, 2011). This continued fossil fuel use creates peaks in pCO_2 by 2050 followed by decreases closer to 2100. In this scenario, the effect on the 2050's North Dakota climate is an increase in Tmin and Tmax of 1.21 and 1.12 °C respectively (Table 19). The climate will experience increases in Tmin and Tmax together with a decrease in precip. However, not every county will experience decreases in precip with 5 counties increasing by an average of 6.00 mm (Table 19).

Table 19: Average values for Tmax, Tmin, and Precip under RCP 6.0.

RCP 6.0 - 2050's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	12.67	-0.21	1.11
NC	20	13.1	-0.17	1.17
NE	30	12.35	0.53	1.32
WC	40	14.54	1.22	0.99
SW	70	15.22	1.23	1.09
SC	80	15.49	2.68	1.33

RCP 8.5

RCP 8.5 is a scenario with the greatest increase in radiative forcing, 8.5 W/m^2 by 2100. This change will likely increase GMST anywhere from 2.0 to 2.6°C. In North Dakota, the distribution of Tmin is colder along the NE and N border with warmer temps in the SW. Historic Tmin values (1981 – 2005) were 1.65°C cooler in the NE than in the SW. The Tmin values expand the differences between the colder NE and hotter SW to 2.90°C (table 20).

Table 20: Average values for Tmax, Tmin, and Precip under RCP 8.5.

RCP 8.5 - 2020's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	12.16	-0.83	1.13
NC	20	12.49	-0.88	1.04
NE	30	11.34	-0.56	1.28
WC	40	13.65	0.13	1.07
SW	70	14.53	0.62	1.12
SC	80	14.22	1.44	1.28

Meanwhile, the statewide Tmax increased from 11.08 to 12.76°C. The Statewide Tmin also increased from -2.05 to -0.25°C (Table 20). The precip distribution remained unchanged from 1981 – 2005 with higher precip in the E and lower precip in the W (Table 20). Lastly, the statewide the precip increased by 0.62 cm.

Appendix B: Climate Forecasts 2050's

RCP 2.6

In the 2050's the RCP 2.6 scenario has passed the peak of emissions (490 ppm) and begun declining to the pCO_2 of 400 ppm nearing 2100. A level is less than the 406 ppm as of 2017. This is the only scenario that leads to a net decrease in pCO_2 by 2100 (Bjørnæs, 2013; Van Vuuren, 2011). To achieve a radiative forcing of 2.6 W/m^2, the cumulative emissions of GHG would need to be 70% lower than baseline (Van Vuuren, 2011). The 2.6 W/m^2 goal would increase GMST approximately 2.0°C from baseline values.

Also under RCP 2.6, land use will continue to change with a ~20% increase in cropland conversion for food production. This is coupled with the estimated stabilization of the human population at ~9 million individuals by 2100 (Van Vuuren, 2011). Alternatively, the bioenergy industry is expected to be a burgeoning industry creating an increased demand for cropland. This means that the issue of feeding the population may be subverted by the needs of these other industries.

Pastureland remains relatively stable throughout the rest of the century with any change likely tied to increased food demand and population. A shift to a less meat-intensive diet would help in reducing the demand on pastureland and in turn, maintain population estimates under the ~9 billion individual's thresholds (Bjørnæs, 2013).

Table 21: Average values for Tmax, Tmin, and Precip under RCP 2.6.

RCP 2.6 - 2050's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	12.55	-0.34	1.11
NC	20	13.05	-0.13	1.17
NE	30	12.12	0.18	1.29
WC	40	14.09	0.74	1.06
SW	70	14.8	0.84	1.08
SC	80	15.13	2.2	1.22

Tmin increased 2.43°C from historical values (1981 – 2005). With a Tmin in the SW of 0.93°C which is higher than in the NW 0.10°C and higher in the NE -0.02°C. Precip in most counties decreased with an average decrease of 40mm. The highest precip being in the NE and the lower in the S and SW. Meanwhile, Tmax and Tmin increased in the NE between 2.50 and 3.00 °C while in the NW, and SW Tmax increased by 1.75 and 1.54°C respectively. Lastly, Tmax and Tmin increased by 0.74 and 0.68°C respectively.

RCP 4.5

In the 2050's, the increased pCO_2 peaks and then stabilizes at 650 ppm maintaining the trend in net radiative forcing of 4.5 W/m^2 leading to 2100 (Van Vuuren, 2011). This scenario is consistent with several methods of reducing emissions from 2040 – 2100 including decreases in cropland conversion (Van Vuuren, 2011). These changes in land use would be critical to reducing N_2O emissions from agricultural operations. Emissions under RCP 4.5 are strictly regulated, and CH_4 emissions will decrease and stabilize by 2100 (Van Vuuren, 2011).

In North Dakota, the statewide precip decreased by 40 mm between the 2020's and 2050's. The Tmax and Tmin increased by 0.52 and 0.65°C respectively. The Tmax and Tmin increases were in Stark County (0.80 °C) and Bottineau County (0.81). While the greatest increases in Tmax were in Stark (0.72°C), Burke (0.73°C), McKenzie (0.71°C), and Mountrail (0.71°C) (Table 20).

Table 22: Average values for Tmax, Tmin, and Precip under RCP 4.5.

RCP 4.5 - 2050's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	13.37	0.43	1.12
NC	20	13.92	0.54	1.16
NE	30	12.73	0.99	1.43
WC	40	15.07	1.9	1.01
SW	70	15.68	1.65	1.11
SC	80	15.78	2.97	1.31

RCP 6.0

This radiative forcing is equivalent to 850 ppm pCO_2 by 2100. This change likely is driven by a continued heavy reliance on fossil fuels and increased use of cropland (Van Vuuren, 2011). This continued fossil fuel use creates peaks in pCO_2 by 2050 followed by decreases closer to 2100. In this scenario, the effect on the 2050's North Dakota climate is an increase in Tmin and Tmax of 1.21 and 1.12 °C respectively (Table 23). The climate will experience increases in Tmin and Tmax together with a decrease in precip. However, not every county will experience decreases in precip with 5 counties increasing by an average of 6.00 mm (Table 23).

Table 23: Average values for Tmax, Tmin, and Precip under RCP 6.0.

RCP 6.0 - 2050's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	12.67	-0.21	1.11
NC	20	13.1	-0.17	1.17
NE	30	12.35	0.53	1.32
WC	40	14.54	1.22	0.99
SW	70	15.22	1.23	1.09
SC	80	15.49	2.68	1.33

RCP 8.5

RCP 8.5 provides some disturbing realities for global climate. The most troubling is a possible net radiative forcing of 8.5 W/m^2 and a corresponding pCO_2 of ~1370 ppm by 2100 (Van Vuuren, 2011). This pCO_2 will increase GMST between 3.70°C and 4.80°C (Van Vuuren, 2011).

This increase is the result of changing policies (i.e. adoption of policies that reduce emissions) and societal change (i.e., increases in population and demand for land and food). For example, the emissions of CH_4 under the RCP 8.5 increase rapidly by 2100 adding to the CO_2 emissions which are already the highest of all four RCP's. Inaction and ineffective policies will create this less than ideal net radiative forcing of 8.5 W/m^2.

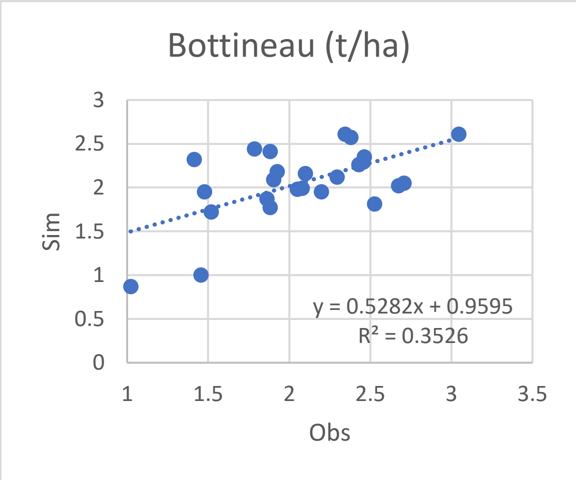
The effect of these changes is not only global; there are several changes that will impact individuals personally. Including an estimated population of 12 billion individuals by 2100, or the significant increase in agricultural production and land conversion. In turn, N_2O emissions will increase as agricultural activity and land conversion increases. The 2050's will follow the trend created by the effects observed in the 2020's and the anticipated impacts in 2100. In North Dakota, the RCP 8.5 impacts are intensifications of observed changes in previous scenarios. Under the RCP 8.5 precip increases in the SW and decreases in the rest of the state reducing the statewide average by 0.02 m. Meanwhile, Tmax and Tmin increased 2.10°C and 1.95°C respectively, and Tmax increases ranging from 1.85°C and 2.06 °C. The increases in the Tmin range from 1.92°C and 2.22°C.

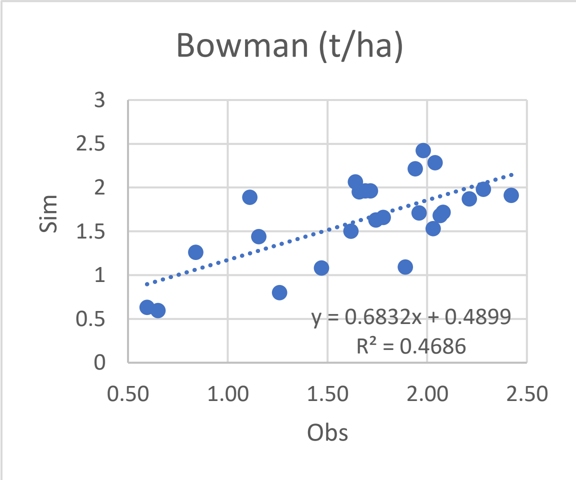
Table 24: Average values for Tmax, Tmin, and Precip under RCP 8.5.

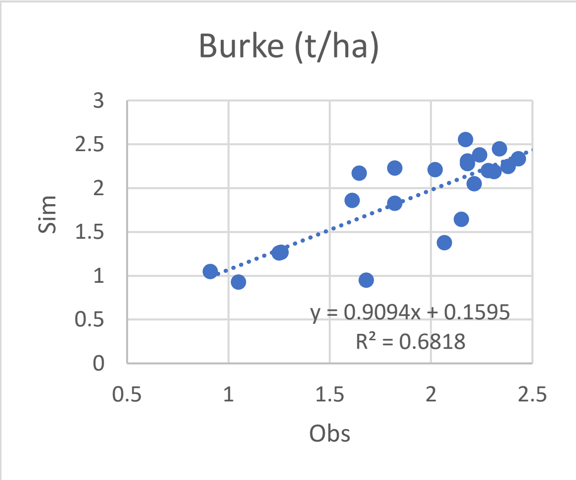
RCP 8.5 - 2050's				
Region	Ag. District	Tmax	Tmin	PRECIP
NW	10	13.85	1.04	1.17
NC	20	14.45	1.28	1.17
NE	30	14.21	2.22	1.31
WC	40	16.05	2.75	1.02
SW	70	16.3	2.3	1.09
SC	80	16.97	4.15	1.36

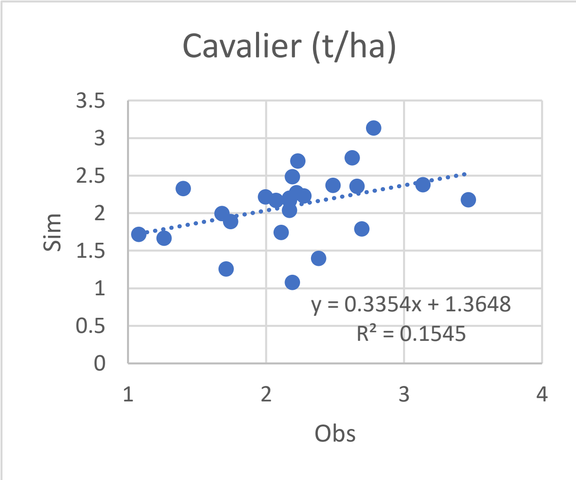
Appendix C: Residuals

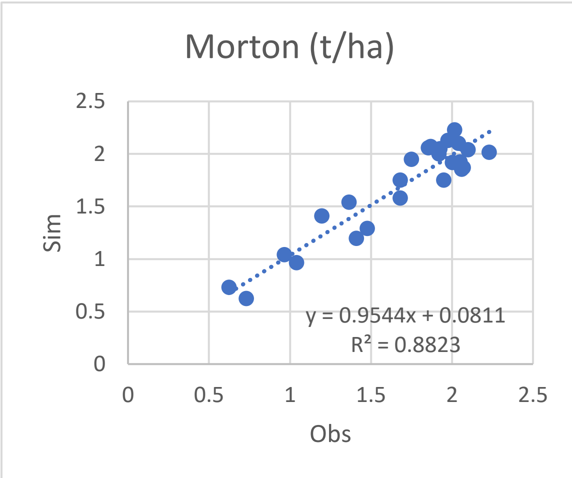
These graphs represent the comparison between simulated and observed yield. Included in the graphs are the statistics and equations for the linear regression of each set.

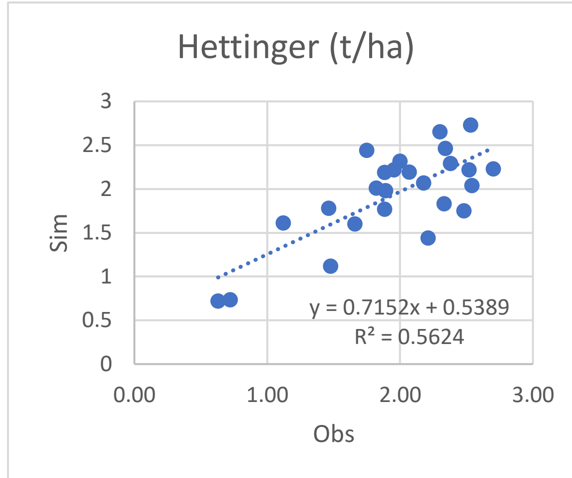


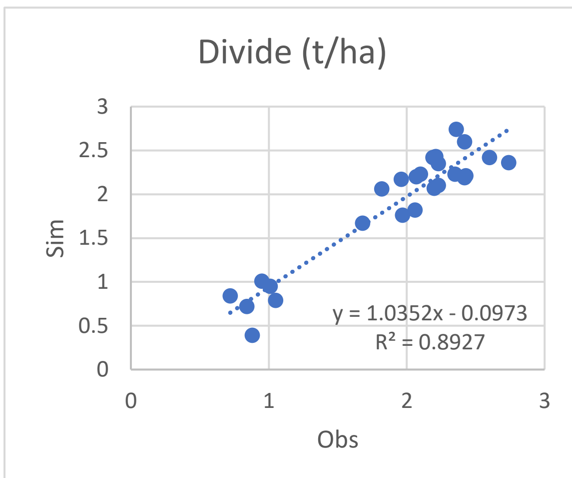


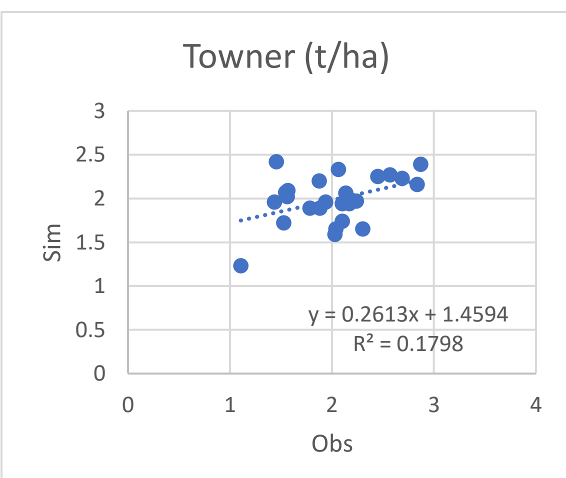


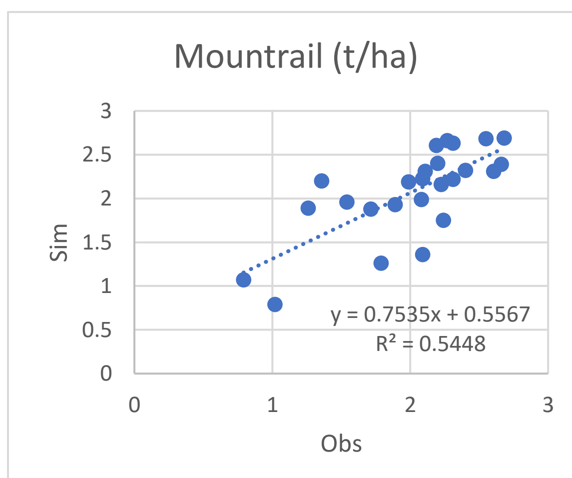


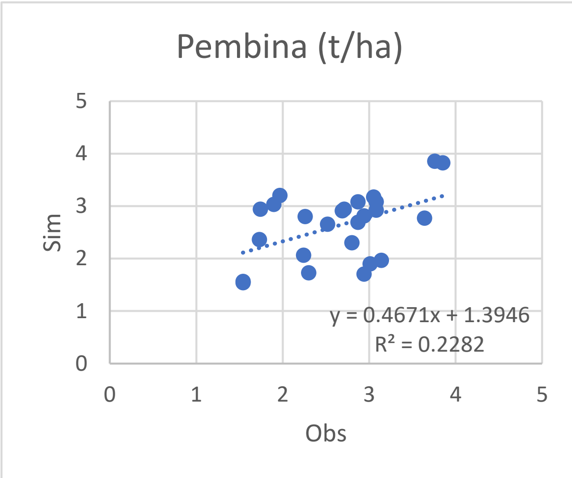

Morton (t/ha)
Sim
Obs
y = 0.9544x + 0.0811
R² = 0.8823

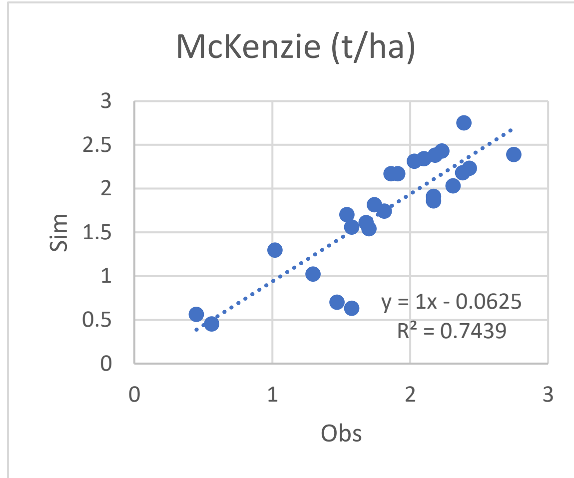

Hettinger (t/ha)
Sim
Obs
y = 0.7152x + 0.5389
R² = 0.5624

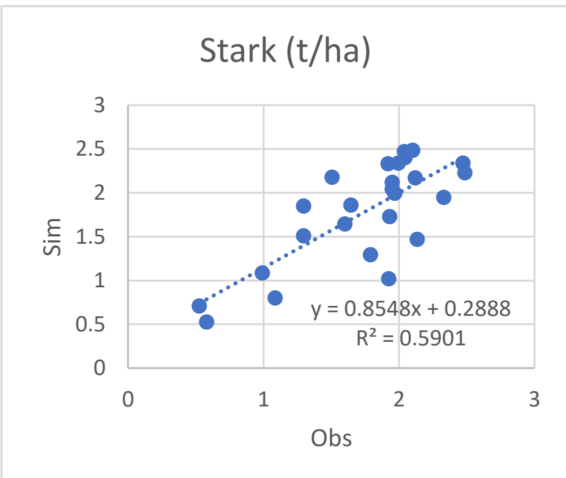

Divide (t/ha)
Sim
Obs
y = 1.0352x - 0.0973
R² = 0.8927

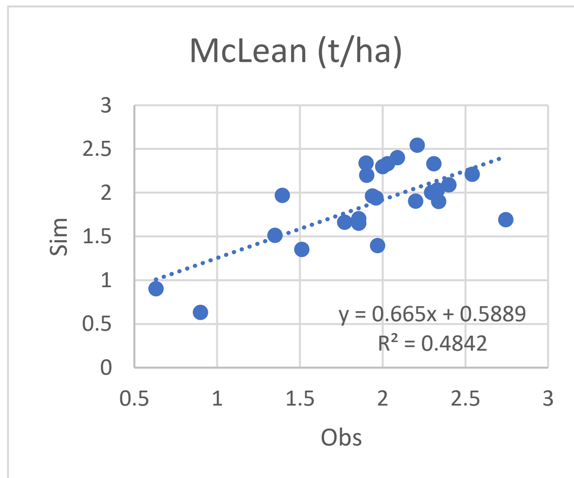

Towner (t/ha)
Sim
Obs
y = 0.2613x + 1.4594
R² = 0.1798


Mountrail (t/ha)
Sim
Obs
y = 0.7535x + 0.5567
R² = 0.5448

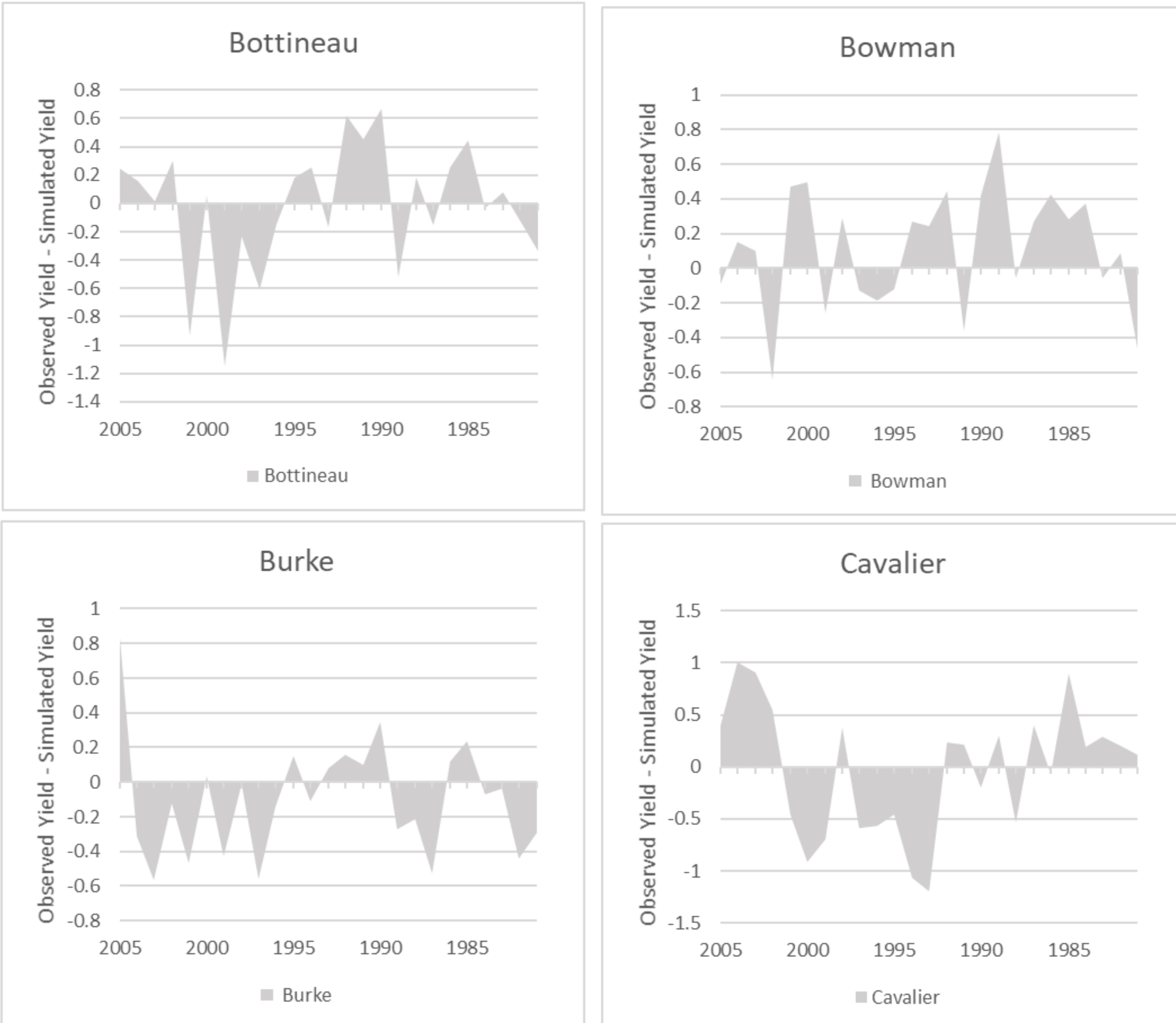

Pembina (t/ha)
Sim
Obs
y = 0.4671x + 1.3946
R² = 0.2282


McKenzie (t/ha)
Sim
Obs
y = 1x - 0.0625
R² = 0.7439

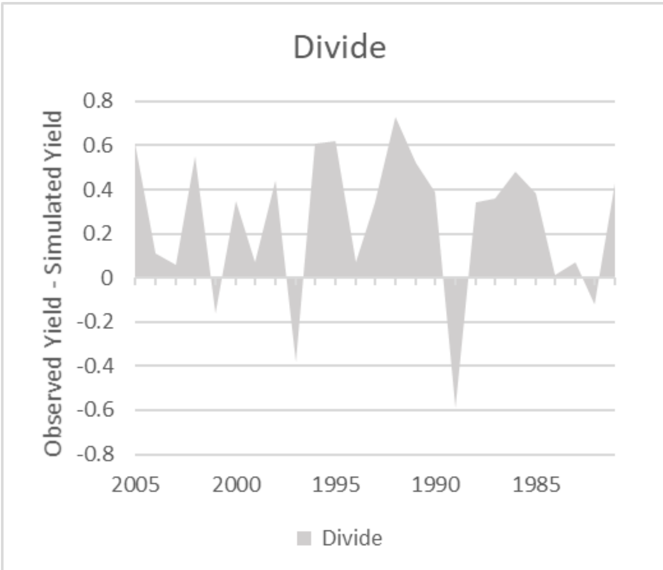

Stark (t/ha)
Sim
Obs
y = 0.8548x + 0.2888
R² = 0.5901

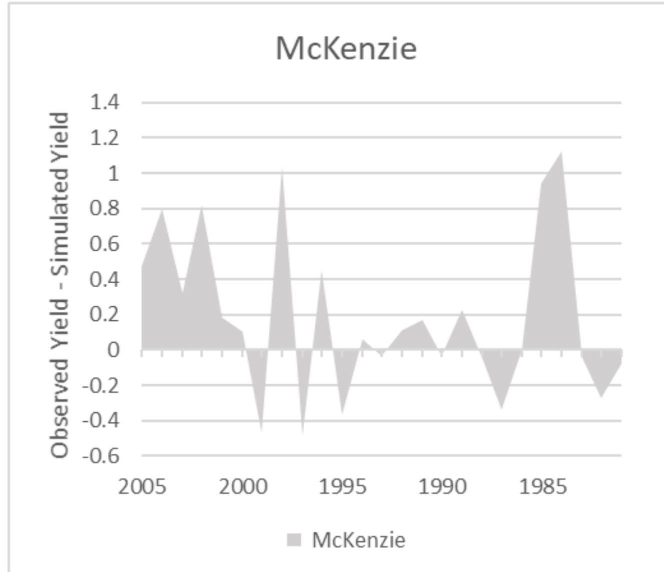

McLean (t/ha)
Sim
Obs
y = 0.665x + 0.5889
R² = 0.4842

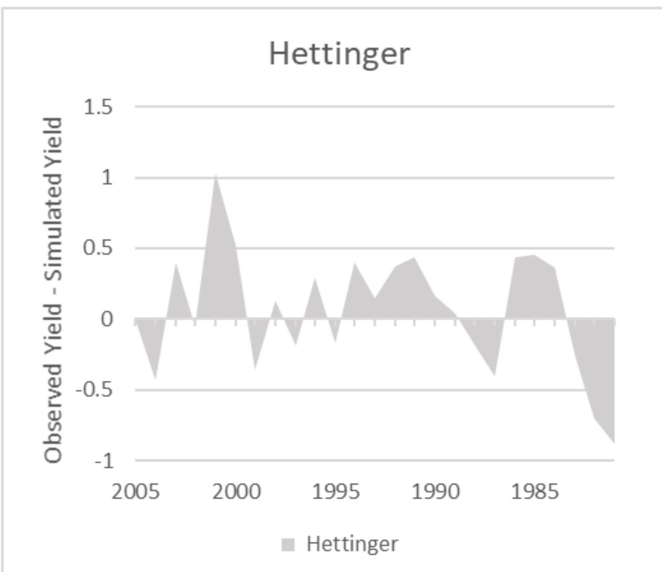
Residuals

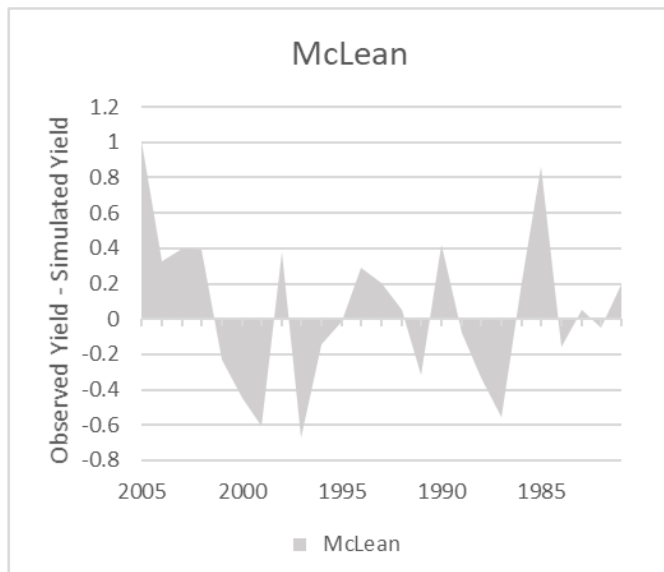


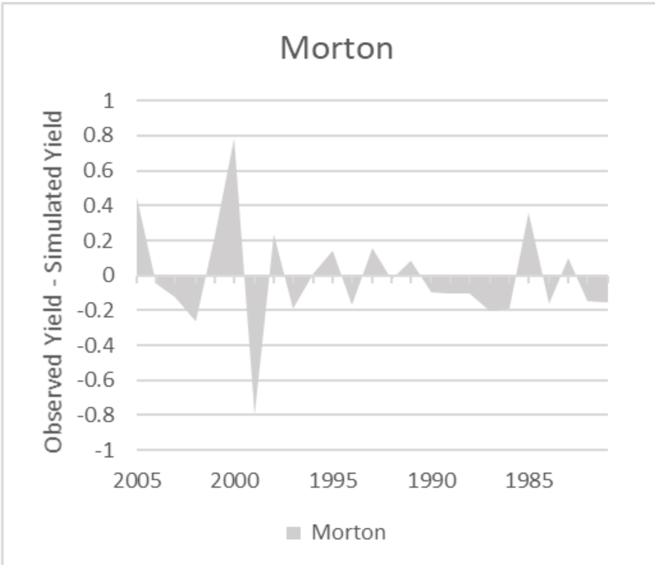
These plots are called residual plots, and they show the over and underestimation of the ALMANAC model in each county for the calibration and validation period (1981-2005). Residual plots show the difference between simulated and observed yields for the historical period representing (1981-2005). A value below 0 represents the simulated yield is lower than the observed value for that year. For example, Bottineau has values above 0.00 for the last 3 years of the simulation (2002 – 2005) indicating that the modeled yields were lower than the observed yields. Residual values above 0 indicate that the simulated yield was greater than the observed yield.

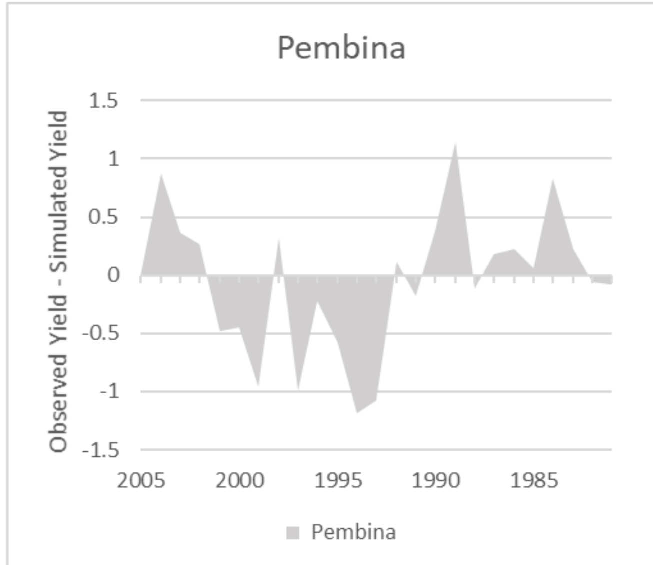

Divide
Observed Yield - Simulated Yield
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
2005
2000
1995
1990
1985
Divide

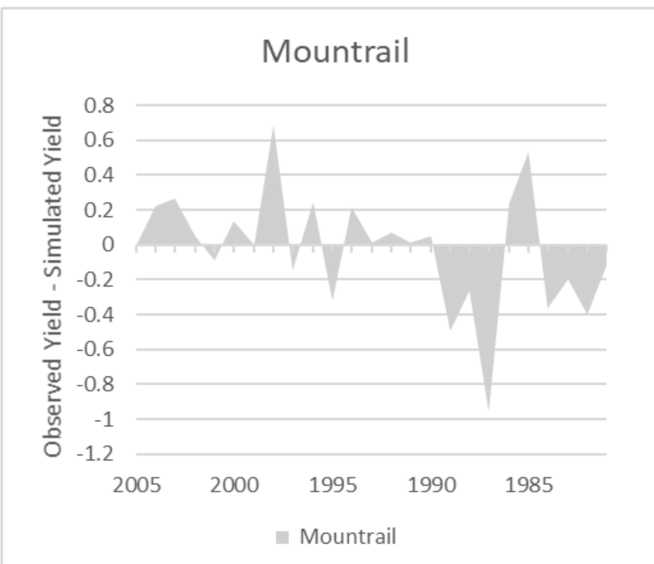

McKenzie
Observed Yield - Simulated Yield
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
2005
2000
1995
1990
1985
McKenzie

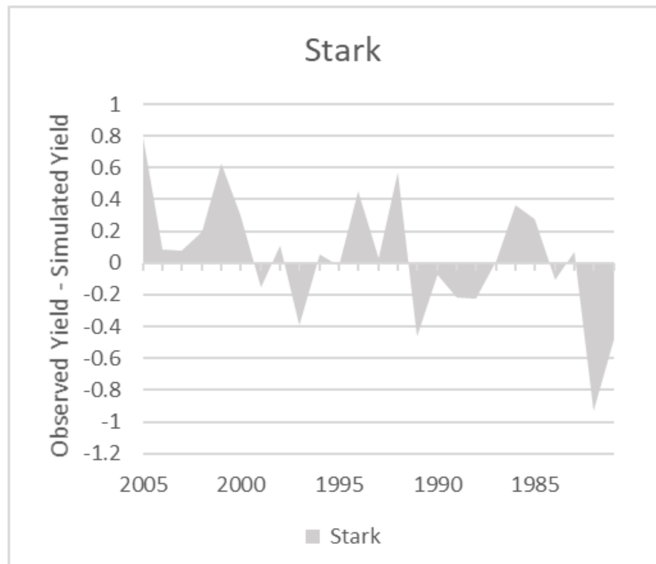

Hettinger
Observed Yield - Simulated Yield
1.5
1
0.5
0
-0.5
-1
2005
2000
1995
1990
1985
Hettinger

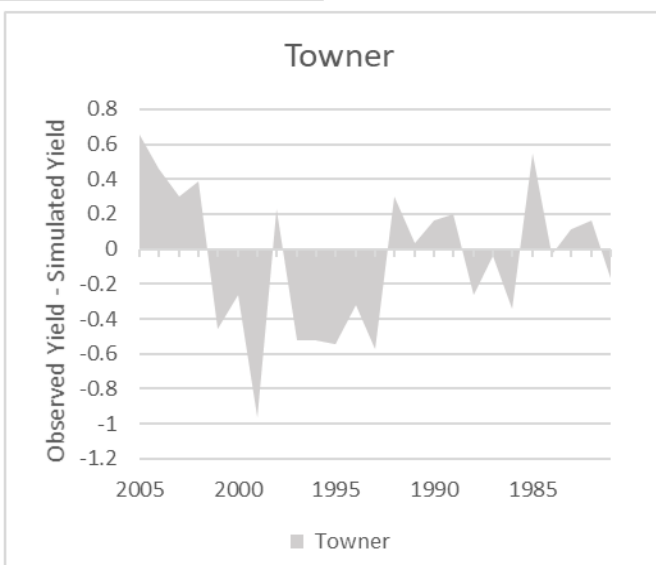

McLean
Observed Yield - Simulated Yield
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
2005
2000
1995
1990
1985
McLean


Morton
Observed Yield - Simulated Yield
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
2005
2000
1995
1990
1985
Morton


Pembina
Observed Yield - Simulated Yield
1.5
1
0.5
0
-0.5
-1
-1.5
2005
2000
1995
1990
1985
Pembina


Mountrail
Observed Yield - Simulated Yield
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
2005
2000
1995
1990
1985
Mountrail


Stark
Observed Yield - Simulated Yield
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
2005
2000
1995
1990
1985
Stark


Towner
Observed Yield - Simulated Yield
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
2005
2000
1995
1990
1985
Towner

References

Abadie, L. M., Sainz de Murieta, E., & Galarraga, I. (2016). Climate risk assessment under uncertainty: An application to main european coastal cities. *Frontiers in Marine Science, 3*, 1,2,6,12.

Abbad, H., El Jaafari, S., Bort, J., & Araus, J. (2004). Comparison of flag leaf and ear photosynthesis with biomass and grain yield of durum wheat under various water conditions and genotypes. *Agronomie*, *24*(1), 20-21, 22.

AbdElgawad, H., Zinta, G., Beemster, G. T., Janssens, I. A., & Asard, H. (2016). Future climate CO2 levels mitigate stress impact on plants: Increased defense or decreased challenge? *Frontiers in Plant Science, 7*, 2-3, 5. doi:10.3389/fpls.2016.00556 [doi]

Acevedo, E., Silva, P., & Silva, H. (2002). Wheat growth and physiology. *CURTIS, BC et al. Bread wheat. Rome, Italy: FAO Plant Production and Protection Series (FAO)*, (30).

Acevedo, E., Silva, P., & Silva, H. (2006). Growth and wheat physiology, development. *Laboratory of Soil-Plant-Water Relations.Faculty of Agronomy and Forestry Sciences.The University of Chile.Casilla, 1004*, 1-17, 18, 19.

Adhya, T., Sharma, P., & Gogoi, A. (2009). Mitigating greenhouse gas emission from agriculture. In S. Singh (Ed.), *Climate change and crops* (pp. 329-330, 331-333, 340) Springer Science & Business Media.

Aguilar, J., Gramig, G. G., Hendrickson, J. R., Archer, D. W., Forcella, F., & Liebig, M. A. (2015). Crop species diversity changes in the United States: 1978–2012. *PloS one*, *10*(8), e0136580.

Akram, M. (2011). Growth and yield components of wheat under water stress of different growth stages. *Bangladesh Journal of Agricultural Research, 36*(3), 462-463.

Almansouri, M., Kinet, J., & Lutts, S. (2001). Effect of salt and osmotic stresses on germination in durum wheat (Triticum durum desf.). *Plant and Soil, 231*(2), 243-244, 245, 246, 247.

Altenbach, S., DuPont, F., Kothari, K., Chan, R., Johnson, E., & Lieu, D. (2003). Temperature, water and fertilizer influence the timing of key events during grain development in a US spring wheat. *Journal of Cereal Science, 37*(1), 10-11,12, 13, 17.

Arnell, N., Livermore, M. J., Kovats, S., Levy, P. E., Nicholls, R., Parry, M. L., & Gaffin, S. R. (2004). Climate and socio-economic scenarios for global-scale climate change impacts assessments: Characterising the SRES storylines. *Global Environmental Change*, *14*(1), 3-20.

Atkinson, D., & Porter, J. R. (1996). Temperature, plant development and crop yields. *Trends in Plant Science, 1*(4), 119-120-123.

Baez-Gonzalez, A., Kiniry, J. R., Padilla Ramirez, J. S., Medina Garcia, G., Ramos Gonzalez, J. L., & Osuna Ceja, E. S. (2015). Parameterization of almanac crop simulation model for non-irrigated dry bean in semi-arid temperate areas in mexico. *Interciencia, 40*(3), 185-186,187,188.

Barrow, E., Hulme, M., Semenov, M., & Brooks, R. (2000). *Climate Change Scenarios,* (2), 2-3,20,25,26,31.

Bjørnæs, C. (2013). A guide to representative concentration pathways. *CICERO.Center for International Climate and Environmental Research,* , 351-357, 361, 369.

Bond, J., & Liefert, O. (2017). Wheat outlook., 7.

Brown, R. A., & Rosenberg, N. J. (1997). The sensitivity of crop yield and water use to change in a range of climatic factors and CO2 concentrations: A simulation study applying EPIC to the central united states. *Agricultural and Forest Meteorology, 83*(3-4), 171-172-185.

Calvin, M., & Massini, P. (1952). The path of carbon in photosynthesis. *Cellular and Molecular Life Sciences, 8*(12), 445-446.

Deryng, D., Conway, D., Ramankutty, N., Price, J., & Warren, R. (2014). Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters, 9*(3), 1-2, 7, 9, 11.

Ehleringer, J. R., & Cerling, T. E. (2002). C3 and C4 photosynthesis. *Encyclopedia of Global Environmental Change, 2*, 186-187, 188.

Elias, E., Manthey, F., Stack, R., & Kianian, S. (2005). Breeding efforts to develop Fusarium head blight resistant durum wheat in North Dakota [Abstract]. 25-26.

Enz, J. W. (2003). North Dakota topographic, climate, and agricultural overview. *North Dakota State University. [Available Online at www.Ndsu.edu/ndsco/publication/ndsco/ndclimate.Pdf]*

Ewert, F., Porter, J. R., & Rounsevell, M. D. (2007). Crop models, CO2, and climate change. *Science (New York, N.Y.), 315*(5811), 459-459-460. doi:315/5811/459c [pii]

Faramarzi, M., Abbaspour, K. C., Vaghefi, S. A., Farzaneh, M. R., Zehnder, A. J., Srinivasan, R., & Yang, H. (2013). Modeling impacts of climate change on freshwater availability in Africa. *Journal of Hydrology, 480*, 85-101.

Feng, S., Oppenheimer, M., & Schlenker, W. (2012). Climate change, crop yields, and internal migration in the united states. *National Bureau of Economic Research*, 1-2-7, 11, 12.

Fitzgerald, D. (1991). Beyond tractors: The history of technology in American agriculture. *Technology and Culture, 32*(1), 114-126. doi:10.2307/3106015

Flenet, F., Kiniry, J. R., Board, J. E., Westgate, M. E., & Reicosky, D. C. (1996). Row spacing effects on light extinction coefficients of corn, sorghum, soybean, and sunflower. *Agronomy Journal, 88*(2), 185-186.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., . . . Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. *Climate change 2007: The physical science basis. the contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change* (pp. 135-137, 210). United Kingdom: Cambridge University Press.

Friend, D., Trenholm, H., Elliot, J., Hartin, K., & Thompson, B. (1982). Effect of feeding vomitoxin-contaminated wheat to pigs. *Canadian Journal of Animal Science, 62*(4), 1211-1222.

Friskop, A., & Ransom, J. (July 2017). *Deoxynivalenol (DON) in small grains.* (). Fargo, North Dakota: North Dakota State University.

Ghini, R., Hamada, E., & Bettiol, W. (2008). Climate change and plant diseases. *Scientia Agricola*, 65(SPE), 98-107.

Gonzalez, M. (2003). Continental Divides in North Dakota and North America. *NDGS Newsletter [vol. 30], No. 1, 1-7*

Gowik, U., & Westhoff, P. (2011). The path from C3 to C4 photosynthesis. *Plant Physiology, 155*(1), 56-57, 58, 59. doi:10.1104/pp.110.165308 [doi]

Gunderson, J. J., Carr, P. M., & Martin, G. B. (2007). *Variety Trial Yields: A Look at the Past 65 Years*. Technical Report, Dickinson Research Extension Center, North Dakota State University. Available at http://www. ag. ndsu. edu/archive/dickinso/research/2007/pdf/agron07a. pdf.

Haefner, J. W., (2012). Chapter 1: Models of systems. *Modeling biological systems: Principles and applications* (pp. 3-4, 5, 14) Springer Science & Business Media.

Hanson et al., (2017) *Industrial Hemp Performance in North Dakota* (pg. 1-4) NDSU Langdon Research Extension Center. Avaliable at: www.ag.ndsu.edu/langdonrec/documents/crop-production-management/industrial-hemp-variety-trial-langdon-2017

Harari, Y. N. (2014). The agricultural revolution. *Sapiens: A brief history of humankind* (pp. 77-79) Random House.

Hartmann, D., Tank, A., & Rusticucci, M. (2013). IPCC fifth assessment report, climate change 2013: The physical science basis. *IPCC AR5*, , 31-39.

Hartmann, D. (1994). History and Evolution of Earth's Climate. In Global Physical Climatology (pp. 204 – 228)

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., ... & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*(9), 816-821.

Hoornweg, D., & Pope, K. (2013). Socioeconomic pathways and regional distribution of the world's 101 largest cities., 1-4.

Haagsma, J. A., Graetz, N., Bolliger, I., Naghavi, M., Higashi, H., Mullany, E. C., ... & Ameh, E. A. (2016). The global burden of injury: incidence, mortality, disability-adjusted life years and time trends from the Global Burden of Disease study 2013. *Injury prevention*, *22*(1), 3-18.

Jayaraman, T., & Kanitkar, T. (2016). The Paris Agreement. *Economic and Political Weekly*, 51 (3).

Jensen, R. E. (1998). Climate of North Dakota., 1-2-19.

Johnson, R. (2014). Hemp as an agricultural commodity. Library of Congress Washington DC Congressional Research Service. Avaliable at: https://fas.org/sgp/crs/misc/RL32725.pdf

Johnson, M. V., MacDonald, J. D., Kiniry, J. R., Arnold, J., & Gassman, P. (2009). ALMANAC: A potential tool for simulating agroforestry yields and improving SWAT simulations of agroforestry watersheds. *International Agricultural Engineering Journal, 18*(1), 51-52-54.

Johnson, R. G., & Ali, M. B. (1982). Economies of wheat-fallow cropping systems in western North Dakota. *Western Journal of Agricultural Economics,* 67-68, 69, 76.

Jones, P. G. (2013). MarkSim standaloneV2 for DSSAT users. [last accessed February 17, 2017]

Jones, P., Thornton, P. K., & Heinke, J. (2009). Generating characteristic daily weather data using downscaled climate model data from the IPCC's fourth assessment., 4 - 5.

Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R., & Kushnir, Y. (2015). Climate change in the fertile crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences of the United States of America, 112*(11), 3241-3246. doi:10.1073/pnas.1421533112 [doi]

Kennedy, M. (2017,). Cash market moves: Spring wheat, durum losing ground. *The Progressive Farmer*

Kiniry, J. R., Williams, J., Gassman, P. W., & Debaeke, P. (1992). A general, process-oriented model for two competing plant species. *Transactions of the ASAE, 35*(3), 801-802.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the köppen-Geiger climate classification updated. *Meteorologische Zeitschrift, 15*(3), 259-260-262.

Kunkel, K. E. (2003). North American trends in extreme precipitation. *Natural Hazards, 29*(2), 296-297, 298, 301, 302, 303.

Laird, K. R., Fritz, S. C., Maasch, K. A., & Cumming, B. F. (1996). Greater drought intensity and frequency before AD 1200 in the northern great plains, USA. *Nature, 384*(6609), 552-554.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., . . . Houghton, R. A. (2016). Global carbon budget 2016. *Earth System Science Data, 8*(2), 605.

Maccaferri, M., Sanguinetti, M. C., Corneti, S., Ortega, J. L., Salem, M. B., Bort, J., . . . Tuberosa, R. (2008). Quantitative trait loci for grain yield and adaptation of durum wheat (Triticum durum desf.) across a wide range of water availability. *Genetics, 178*(1), 489-491, 493, 494. doi:10.1534/genetics.107.077297 [doi]

Mall, R. K., et al. (2006), Impact of climate change on Indian agriculture: A review, *Clim. Change*, 78, 445 – 478

Mann, M. E. (2014). False Hope: The Rate of Global Temperature Rise May Have Hit a Plateau, but a Climate Crisis Still Looms in the Near Future, *Scientific American, 301,* 78-81.

Manske, L. L. (2012). *Range Plant Growth Related to Climatic Factors of Western North Dakota, 1982-2011*. North Dakota State University, Dickinson Research Extension Center.

Marti, J., & Slafer, G. A. (2014). Bread and durum wheat yields under a wide range of environmental conditions. *Field Crops Research, 156*, 258-271.

Masoni, A., Ercoli, L., Mariotti, M., & Arduini, I. (2007). Post-anthesis accumulation and remobilization of dry matter, nitrogen and phosphorus in durum wheat as affected by soil type. *European Journal of Agronomy, 26*(3), 179-180, 185, 186.

Maurer, E. P., & Hidalgo, H. G. (2008). The utility of daily vs. monthly large-scale climate data: An intercomparison of two statistical downscaling methods., 51-52-53.

McCarthy, J., Canziani, O., Leary, N., Dokken, D., & White, K. (2001). Climate change 2007: Impacts, adaptation, and vulnerability. , *Intergovernmental Panel on Climate Change,* , 9-13, 32, 211, 349, 661, 813, 814.

Mesterhazy, A. (1995). Types and components of resistance to Fusarium head blight of wheat. *Plant Breeding, 114*(5), 377-378-380, 384-385.

Miller, P., Lanier, W., & Brandt, S. (2001). Using growing degree days to predict plant stages. *Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO,* 1-2, 3.

Miller, T. D. (1997). Growth stages of wheat: Identification and understanding improve crop management.texas agricultural extension service, the Texas A&M University system. *Texas Agricultural Extension Service,* 1-4.

Millett et al. (2009). Climate trends of the North American prairie pothole region 1906–2000. *Climatic Change*, *93*(1-2), 243-267.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., . . . Kram, T. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747-748,749,750,751.

Munski, D. C., O'Kelly, B. O., Robinson, E. B., (2018). North Dakota. *Encyclopedia Britannica,* Retrieved: Jan 23rd, 2018, https://www.britannica.com/place/North-Dakota

NASS, U. (2017). United States Department of Agriculture-National Agricultural Statistics Service. Quick Stats: *Top Producing Agricultural Commodities (1981 – 2005)*.

NASS, U. (2017). United States Department of Agriculture-National Agricultural Statistics Service. *Quick Stats: Top Producing Agricultural Commodities (1981 – 2005).*

NASS, U. (1997). Usual planting and harvesting dates for US field crops. *Agricultural Handbook*, *628*, 44.

Nelson, C., & Larson, K. (1984). Seedling growth. *Physiological Basis of Crop Growth and Development*, (physiological), 93-105-122,

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., . . . Running, S. W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science (New York, N.Y.)*, *300*(5625), 1560-1563. doi:10.1126/science.1082750 [doi]

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PloS one*, *10*(3), e0118571.

Newbold, T., Hudson, L. N., Hill, S. L., Contu, S., Lysenko, I., Senior, R. A., ... & Day, J. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*(7545), 45-50.

Nganje, W. E., Bangsund, D. A., Leistritz, F. L., Wilson, W. W., & Tiapo, N. M. (2004). Regional economic impacts of Fusarium head blight in wheat and barley. *Review of Agricultural Economics*, *26*(3), 332-347.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., . . . Dasgupta, P. (2014). *Climate change 2014: Synthesis report. the contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change* IPCC, viii, 4, 40, 60, 122.

Patz, J. A., Campbell-Lendrum, D., Holloway, T., & Foley, J. A. (2005). The impact of regional climate change on human health. *Nature, 438*(7066), 310-317.

Peterson, A., Koppen Climate Types of North Dakota (SVG version), (2016) CC BY-SA 4.0

Pinter Jr, P. J., Hatfield, J. L., Schepers, J. S., Barnes, E. M., Moran, M. S., Daughtry, C. S., & Upchurch, D. R. (2003). Remote sensing for crop management. *Photogrammetric Engineering & Remote Sensing, 69*(6), 647-664.

Poole, N. (2005). *Cereal growth stages.* (No. Pgs. 1-3). Lincoln, New Zealand: Grains Research & Development Corporation.

Porter, J. R., & Gawith, M. (1999). Temperatures and the growth and development of wheat: A review. *European Journal of Agronomy, 10*(1), 23-24-26, 30-34.

Porter, J. R., & Semenov, M. A. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society of London.Series B, Biological Sciences, 360*(1463), 2021-2033. doi:10.1098/rstb.2005.1752 [doi]

Prat, N., Guilbert, C., Prah, U., Wachter, E., Steiner, B., Langin, T., . . . Buerstmayr, H. (2017). QTL mapping of Fusarium head blight resistance in three related durum wheat populations. *Theoretical and Applied Genetics, 130*(1), 9-10-20.

Qaderi, M. M., & Reid, D. M. (2009). Crop responses to elevated carbon dioxide and temperature. In J. Singh (Ed.), *Climate change and crops* (pp. 1-2-12) Springer.

Rasmusson, D. C., & Gengenbach, B. G. (1984). Genetics and use of physiological variability in crop breeding. *Physiological basis of crop growth and development,* (physiological), 291-321.

Ranieri, R. (2015). Geography of the durum wheat crop. *Pastaria International,* , 1-2, 5, 6, 9.

Reyer, C. P., Leuzinger, S., Rammig, A., Wolf, A., Bartholomeus, R. P., Bonfante, A., . . . Abou Jaoudé, R. (2013). A plant's perspective of extremes: Terrestrial plant responses to changing climatic variability. *Global Change Biology, 19*(1), 2-3, 5, 7, 8, 9, 75-76-89.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., . . . Rafaj, P. (2011). RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change, 109*(1-2), 33-53.

Ritchie, J., & NeSmith, D. (1991). Temperature and crop development. *Modeling Plant and Soil Systems,* 9-10-25.

Rogelj, J., Meinshausen, M., & Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature climate change*, *2*(4), 248-253.

Rosenzweig, C., Iglesias, A., Yang, X., Epstein, P. R., & Chivian, E. (2000). Climate change and US agriculture: The impacts of warming and extreme weather events on productivity, plant diseases, and pests. *Center for Health and the Global Environment, Harvard Medical School, Boston, MA, USA*, 13-14.

Rosenzweig, C., Tubiello, F. N., Goldberg, R., Mills, E., & Bloomfield, J. (2002). Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change*, *12*(3), 197-199, 200, 201.

Rozenberg, Julie; Hallegatte, Stephane. 2015. *The impacts of climate change on poverty in 2030 and the potential from rapid, inclusive, and climate-informed development (English)*. Policy Research working paper; no. WPS 7483. Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/349001468197334987/The-impacts-of-climate-change-on-poverty-in-2030-and-the-potential-from-rapid-inclusive-and-climate-informed-development

Sanna, G., Giunta, F., Motzo, R., Mastrangelo, A. M., & De Vita, P. (2014). Genetic variation for the duration of pre-anthesis development in durum wheat and its interaction with vernalization treatment and photoperiod. *Journal of Experimental Botany*, *65*(12), 3177-3188.

Schwartz, P., & Randall, D. (2003). An abrupt climate change scenario and its implications for united states national security. *An Abrupt Climate Change Scenario and Its Implications for United States National Security,* 2-5.

Sicignano, A., Di Monaco, R., Masi, P., & Cavella, S. (2015). From raw material to dish: Pasta quality step by step. *Journal of the Science of Food and Agriculture, 95*(13), 2579-2587.

Sinclair, T. R., & Weiss, A. (2010). *Principles of ecology in plant production* (1051-1055 ed.) CABI.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., . . . Jafari, M. (2014). Agriculture, forestry and other land use (AFOLU). *Climate Change,* , 811-819, 832, 868,.

Stafford, J. V. (2000). Implementing precision agriculture in the 21st century. *Journal of Agricultural Engineering Research, 76*(3), 267-275.

Standage, T. (2009). The invention of farming. *An edible history of humanity* (pp. 3-15, 16, 27). New York, NY: Bloomsbury Publishing USA.

Stovall, B. (August 24, 2016, **North Dakota's top agricultural commodities**. *Farm Flavor,* https://www.farmflavor.com/north-dakota/north-dakota-ag-products/north-dakotas-top-agricultural-commodities/ *(Accessed, 2017)*

Stubbs, M. (2014). Conservation Reserve Program (CRP): Status and Issues. *Conservation Research Service* (pp. 4 – 6).

Tans, P. NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., ... & Edmonds, J. A. (2011). RCP4. 5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, *109*(1-2), 77.

Troccoli, A., Borrelli, G., De Vita, P., Fares, C., & Di Fonzo, N. (2000). Mini-review: Durum wheat quality: A multidisciplinary concept. *Journal of Cereal Science*, *32*(2), 1-2,3,4.

Trzaska, S., & Schnarr, E. (2014). A review of downscaling methods for climate change projections. *United States Agency for International Development by Tetra Tech ARD*, 1-42.

Tudge, C. (2000). The plow. In J. Brockman (Ed.), *The greatest inventions of the past 2,000 years* (pp. 25-27) Simon and Schuster.

U.S. Wheat Associates. (2016). *U.S. durum wheat regional quality report.* (Regional Durum Production Report).U.S. Wheat Associates.

USDA. (2017). *National agricultural statistics service QuickStats online database*. USDA – NASS, Washington, DC:

Vanaja, M., Yadav, S., Maheswari, M., & Srinivasarao, C. (2017). Increasing atmospheric carbon dioxide and Temperature—Threats and opportunities for rainfed agriculture. In V. Belavadi (Ed.), *Agriculture under climate change: Threats, strategies, and policies* (pp. 84-90) Allied Publishers.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Masui, T. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*(1-2), 6-28.

Vaughan, M., Backhouse, D., & Ponte, E. D. (2016). Climate change impacts on the ecology of Fusarium graminearum species complex and susceptibility of wheat to Fusarium head blight: A review. *World Mycotoxin Journal, 9*(5), 2-3, 4, 5, 6.

Verma, S., Yunus, M., & Sethi, S. (1998). Breeding for yield and quality in durum wheat. *Euphytica, 100*(1), 15-16,17,18.

Vocke, G., & Ali, M. B. (2013). US wheat production practices, costs, and yields: Variations across regions., 1-11.

Volcovici, V., (2017). U.S. judge orders oil-spill response plan for Dakota Access Pipeline. *Reuters*

Waller, S., & Lewis, J. (1979). The occurrence of C3 and C4 photosynthetic pathways in North American grasses. *Journal of Range Management*, 12-13, 14.

Whyte, K. (2017). The Dakota access pipeline, environmental injustice, and US colonialism., An International Journal of Indigenous Literature, Arts, & Humanities, Issue 19.1,

Wienhold, B. J., Vigil, M. F., Hendrickson, J. R., & Derner, J. D. (2017). The vulnerability of crops and croplands in the US northern plains to predicted climate change. *Climatic Change*, , 1-2,4,6,7,8.

Xie, X., Zhang, X., He, B., Liang, D., Zhang, D., & Huang, L. (2016). A system for diagnosis of wheat leaf diseases based on an Android smartphone. Paper presented at the *International Symposium on Optoelectronic Technology and Application 2016*, 200-208.

Xie, Y., Kiniry, J. R., & Williams, J. R. (2003). The ALMANAC model's sensitivity to input variables. *Agricultural Systems, 78*(1), 1-16.

Yamori, W., Hikosaka, K., & Way, D. A. (2014). Temperature response of photosynthesis in C3, C4, and CAM plants: Temperature acclimation and temperature adaptation. *Photosynthesis Research, 119*(1-2), 101-102, 103, 104, 105, 106, 107.

Zadoks, J. C., Chang, T. T., & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research, 14*(6), 415-416, 417, 418, 419, 420.

Zhu, X., Long, S. P., & Ort, D. R. (2008). What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Current Opinion in Biotechnology, 19*(2), 153-154, 155, 156.