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Vulnerability of crops and croplands in the US Northern Plains to predicted climate change

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Abstract The states of Colorado, Montana, Nebraska, North Dakota, South Dakota, and Wyoming comprise the Northern Great Plains region of the USA. The soil and water resources contained in this region have historically supported highly diverse and productive agriculture enterprises that provide a significant proportion of the food, feed, and oilseed for the nation. The region also provides ecological services that influence air, water, and soil quality along with biological diversity. Combined with livestock production and a biofuel industry, crop production forms an integrated system that can offer producers flexibility in management decisions. Projected climatic changes for this region include increasing atmospheric CO_2, a longer, warmer growing season, and increased precipitation, likely received in more frequent extreme events. These changes will impact soil and water resources in the region and create opportunities and challenges for land managers. The objectives of this paper are to describe anticipated impacts of projected mid-(2050) and late-(2085) climatic changes on crop

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production systems in the Northern Great Plains and provide adaptation strategies that should be developed to take advantage of positive and mitigate negative changes. Projected climatic changes will influence agricultural productivity directly as well as indirectly due to changes in weed pressure, insect populations, and diseases. A warmer, longer growing season will change the crops and distribution of those crops grown within the region. An increase in the number of extreme temperature events (high daytime highs or nighttime lows) will decrease crop yields due to increased plant stress during critical pollination and grain fill periods. Adaptation strategies to reduce vulnerability of soil and water resources to projected climatic changes include increasing cropping intensity, reducing tillage intensity, and use of cover crops to provide surface cover to reduce erosion potential and improve nutrient and water use efficiency. Increased use of perennial forages, crop residue, and failed crops in integrated crop-livestock systems will add biological diversity and provide options for converting vegetation biomass into animal protein. Socio-economic changes will need to be incorporated into adaptation strategies planning to insure that sustaining ecosystem services and meeting desired production and conservation goals is accomplished. Education and extension services will be needed to transfer adaptive knowledge in a timely manner to producers in the field.

1 Introduction

The Northern Great Plains comprises the states of Colorado, Montana, Nebraska, North Dakota, South Dakota, and Wyoming. This region has a continental climate characterized by cold winters, hot summers, and highly variable precipitation. Much of the region was glaciated and soils across the region are relatively young and highly fertile. Within the region there are strong gradients in average annual precipitation and temperature with average annual temperature decreasing from south to north and average annual precipitation decreasing from east to west (Lauenroth et al. 1999). These climatic and edaphic conditions result in the region being well suited to grow a number of different crops.

The Northern Great Plains has significant surface and ground water resources. Major rivers include the Missouri and Platte. The Missouri River originates in Montana and flows through North Dakota and South Dakota. The Platte River originates in Wyoming and Colorado and flows through Nebraska. Both of these rivers are dependent on meltwater from mountain snowpack for a portion or most of their flow. There are also a number of smaller locally important rivers throughout the region. Many of the rivers in the region have reservoirs constructed to retain water for irrigation, municipal use, recreation, erosion control, and storage as well as to manage downstream flow seasonality and amount. The southern portion of the region overlies the High Plains Aquifer with other smaller ground water resources within the region. These water resources support irrigation in many areas allowing production of crops with water demands greater than that provided by precipitation and sustain production during below normal precipitation periods. As an example, Nebraska has more irrigated acres than any other state in the USA (USDA-NASS 2013). Irrigation development varies greatly throughout the region and is dependent on proximity to water resources, water quality (salinity and sodicity), and suitability of soils to support irrigation (depth to water table, internal drainage capacity) (Springer et al. 1999).

In 2015, this region represented 24.6% of the cropland area planted in the USA and produced 90% of the canola (*Brassica napus* L.), 84% of the sunflower (*Helianthus annuus* L.), 60% of the barley (*Hordeum vulgare* L.), 48% of the dry edible bean (*Phaseolus vulgaris*

L.), 38% of the wheat (*Triticum aestivum* L.), 30% of the sugarbeet (*Beta vulgaris* L.), 22% of the corn (*Zea mays* L.), 22% of the hay, and 18% of the soybean (*Glycine max* (L.) Merr.) (USDA-NASS 2016a). The region also produces smaller amounts of a number of other crops (e.g. oats (*Avena sativa* L.), flax (*Linum usitatissimum* L), safflower (*Carthamus tinctorius* L.), potato (*Solamum tuberosum* L.), and sorghum (*Sorghum bicolor* (L.) Moench)). Crops harvested in 2015 had a value of $27.1 billion (USDA-NASS 2016b). Sustaining production in this region is essential to meeting future food, feed, fiber, and fuel demands.

In addition to crop production, the region is a major livestock producer (beef, mutton, pork, and poultry) and supports a large biofuels industry. Crop, livestock, and biofuel production have developed into an integrated system within the region. Large areas not suited for cropping remain in native vegetation or improved forages and are used for grazing. In North and South Dakota, grazing land increases as precipitation decreases but this is not necessarily true in Nebraska and Kansas (Hendrickson et al. 2008b) potentially because of the impact of irrigation. Animals produced in the region and brought in from other regions are finished in confined feeding operations that utilize locally grown grain and forage. A byproduct of grain ethanol production is distiller's grain which is commonly included as part of the feed ration in confined feeding operations and as a diet supplement for energy, fat, and protein for cows and developing yearlings (stocker steers and replacement heifers). This integrated crop—livestock—biofuel system can provide significant flexibility for producers. The objectives of this paper are to describe anticipated impacts of projected climatic changes in precipitation and temperature during the remainder of the twenty-first century on crop production systems in the Northern Great Plains and provide adaptation strategies that should be developed to take advantage of positive and mitigate negative changes.

2 Northern Great Plains climate change projections

2.1 Temperature

Projected changes in average annual temperature by the end of the century are an increase of 5.6 °C in the southern part of the region and 6.7 °C in the northern part of the region (Pierce et al. 2014, 2015). Projected warming will be greater during winter and spring than during summer and fall and there will be greater warming for nighttime lows than for daytime highs. Evidence for these changes is already emerging. Long-term weather records show an increase in the frost free period of 7 to 10 days when comparing temperatures in 1991–2012 to those from 1901 to 1960. The frost free period is projected to increase by 30 to 40 days by the end of the century. Projections include an increase of 22 to 25 high temperature stress days (daytime temperatures >37 °C) and 25 to 40 warm nights (nighttime temperatures >15 °C) which will have significant impacts on crop and animal production.

2.2 Precipitation

Average annual precipitation is projected to increase in the northern part of the region with little or no change in the southern part of the region (Pierce et al. 2014, 2015). Precipitation intensity is also expected to change with an increase in the number of heavy rainfall events. Precipitation received during heavy rainfall often exceeds the infiltration rate of the soil and this precipitation can be lost as runoff. An increase in runoff raises the potential for soil erosion

(Zhang et al. 2012) and flooding of receiving rivers and streams. Another consequence of heavy rainfall events is precipitation lost due to runoff is not available for crop production (SWCS 2003). Precipitation received during heavy rainfall events from 1991 to 2012 increased 16% when compared to 1901–1960 (Walsh et al. 2014). Observed trends in amount and intensity of precipitation are projected to become more pronounced.

3 Cropping system opportunities and vulnerabilities

3.1 Soils

In the southern portion of the region where temperatures are projected to increase with little change in precipitation, it is expected that soil moisture will decrease by 5 to 10% resulting in an increase in crop water stress. These changes will place additional stress on water resources where irrigation is practiced. In the northern portions of the region where temperature and precipitation are projected to increase, soil moisture will increase. An increase in soil moisture will increase N_2O emissions (Doran et al. 1990). A longer frost free period and warmer soil temperatures will increase biological activity affecting nutrient cycling and carbon sequestration. Under current management practices, decomposition and mineralization rates will increase resulting in increased nutrient availability and reduced potential for C sequestration (Cheng et al. 2011; Wienhold et al. 2015). Increases in the amount of precipitation received during high intensity events will increase the potential for leaching and erosion losses of nutrients. Leaching of solutes, lateral flow, and seepage can result in development of saline seeps (Halvorson and Black 1974). Increases in precipitation are resulting in an increase in salinity issues in the northern portion of the region (Lobell et al. 2009). Increased precipitation is also resulting in an increase in installation of tile drainage in eastern North and South Dakota to remove excess soil water to facilitate field operations such as planting in the spring (North Dakota State Water Commission 2015).

3.2 Water resources

Warmer winters will result in a greater percentage of precipitation falling as rain instead of snow (Bathke et al. 2014). A major implication is reduced snowpack in mountainous areas that supply runoff for streamflow in rivers that run through the Northern Great Plains. Meeting competing demands for water (recreation, wildlife, municipal, and industrial) in these river systems will likely result in reduced water availability for irrigation of crops. Reduced surface water availability will increase pressure on ground water resources (Burbach et al. 2014). Currently, irrigation for growing crops uses 95% of the water extracted from the High Plains Aquifer. In Nebraska this portion of the aquifer is closely monitored and managed by Natural Resource Districts and water levels have been maintained (Schneider 2014). The region also benefits from the extensive Sandhills region of north-central Nebraska that serves as a major recharge zone for the aquifer. However, the aquifer in the southwest corner of Nebraska extending into Kansas has seen significant depletion and current extraction rates are not sustainable (Burbach et al. 2014). Increased precipitation in northern part of the region will present opportunities for increased crop production and a geographic shift in the growing of crops with higher water demands. The increase in precipitation is projected to occur during winter and spring with little change during summer and fall. These projected changes may create challenges for field operations such as planting, fertilizing and pest control. The northern part of this region has a relatively short growing season and delays in field work may result in some cropland not being planted in some years. Also, much of the northern part of the region has a relatively young landscape with closed topography. An increase in precipitation will result in increasing salinity and waterlogging in some areas. High intensity precipitation will increase the potential for localized flooding.

3.3 Crop responses

Crop responses to projected climatic changes will depend on individual crop response to direct effects (higher temperatures, altered precipitation patterns and greater frequency of extreme events, and increasing atmospheric CO_2 concentration) and indirect effects (greater abundance and occurrence of agronomic weeds, invasive weeds, insect pests, and pathogens).

All crops have a relatively narrow range in temperature for optimum reproductive (grain) production. Crops are most susceptible to temperature effects during pollination and grain fill. The projected increase in maximum daily temperature will increase the potential for suboptimum pollination and projected increase in extreme temperature days and nights will reduce grain fill. It has been estimated that each 1 °C increase in average growing season temperature will decrease corn yield by 8.3% and soybean yield by 13% (Lobell and Field 2007). Wheat yields are reduced when the crop experiences air temperatures >31 °C which reduces pollen and ovule formation leading to fewer and smaller kernels (Ferris et al. 1998).

Reduced water availability will limit crop production. However, Zipper et al. (2016) suggests drought will have less impact on corn and soybean in the Northern Great Plains than in the Southeastern United States. Soil water availability in the southern part of this region is projected to decline and sustaining crop production will require prudent use of available water resources for irrigation (Bathke et al. 2014). Increasing precipitation in the northern part of the region may result in adequate soil water availability benefiting crop production especially in the western part of the region where wheat, dry edible beans, and corn are currently grown under water stress conditions. Precipitation projections are not as certain as temperature projections and the actual crop response will depend on year-to-year variation, the distribution of precipitation received during the growing season, and the amount of precipitation received in extreme events (Shafer et al. 2014).

Crop response to increasing atmospheric CO_2 concentration differs between C_3 and C_4 plants. In general, C_4 plants such as corn and sorghum do not exhibit an increase in yield in a higher CO_2 environment. Soybean and wheat, which are C_3 plants, do exhibit an increase in photosynthesis and a decrease in respiration as atmospheric CO_2 concentration increases (Bernacchi et al. 2006). Grain production for C_3 crops under higher atmospheric CO_2 may result in higher yields but lower quality (protein content) for human and animal nutrition (Erbs et al. 2010; Asif et al. 2016).

Agronomic weeds compete with crops for space, water, and nutrients. Many agronomic weeds have their origin in warmer regions (tropical or warm temperate) and are expected to expand northward with projected increases in air temperature (Patterson et al. 1999; Rahman and Wardle 1990). Invasive weeds are anticipated to be a greater challenge in grasslands than in crop productions areas, however.

Increasing temperatures will impact insect populations in a number of ways. Higher annual temperatures will accelerate insect life cycles and allow expansion of their geographic range (Walther 2010). There is evidence of this already occurring as corn pests are being observed farther north as corn production increases in North and South Dakota (Diffenbaugh et al. 2008). Species that are capable of producing multiple generations per year will not only be capable of producing more individuals each growing season but the presence of multiple generations each growing season increases the potential for development of resistance to control measures (e.g., insecticide resistance) (May and Dobson 1986).

The impact of pathogens on crop production under a changing climate is difficult to generalize because of the complexity of the interactions among host–pathogen–vector–environment (Coakley et al. 1999). Conditions that reduce the impact of one pathogen may greatly increase the impact of another or result in a pathogen having an impact in a region where it had not been present.

Managing pests and disease under a changing climate will be further challenged by biological, social, and economic factors that influence what practices are available (CAST 2017). Pesticide resistance will reduce the number of products available to manage pests and will modify how practices are implemented to reduce the chance of additional pests from developing resistance. Public perception of pesticides and the cost of developing new products and bringing them to market have slowed the introduction of new pesticides. Integrated pest management with practices deployed area-wide to manage pests will become more common. Advances in identifying new modes of action, biological control agents, seed treatments, and emerging genetic tools will provide new opportunities for pest management as well (CAST 2017).

4 Adaptation strategies

Vulnerability of agroecosystems in the Northern Great Plains is dependent on the magnitude and rate of change in weather parameters impacting production and the sustainable provision of other ecosystem services which have neutral to positive environmental impacts. Producer management responses to climatic change include mitigation (e.g., C sequestration and reducing greenhouse gas emissions) and adaptation strategies (e.g., land use changes and regional water management) (Bathke et al. 2014). In addition to the production of food, feed, fiber, and fuel, these agroecosystems provide additional ecosystem services desired by society such as pollinator services, hydrological and nutrient cycling, and habitat for organisms maintaining regional biodiversity (Power 2010). Currently, the impact is difficult to assess but adaptation strategies should address sustaining the multiple functionality of these systems (Hatfield 2006).

4.1 Cropping systems

Projected changes in temperature and precipitation suggest that opportunity exists for further intensification of cropping systems in this region. Increasing precipitation in the northern part of the region should result in reduced use of fallow and provide opportunities for use of cover crops. If there is sufficient soil moisture to support a cover crop without reducing yield of the subsequently planted cash crop a number of benefits result (Basche et al. 2016). The hydrologic cycle may be favorably altered by cover crops to reduce leaching and runoff nutrient losses. Cover crop water use may result in spring soil water conditions more conducive for field operations such as planting and fertilizing. Incorporating cover crops into row crop production can improve soil quality (Moore et al. 2014). Cover crop biomass protects soil from wind and water erosion and serves as a substrate to sustain soil biota, thereby increasing the potential for C sequestration. Cover crops can improve water infiltration by providing root channels and breaking up tillage pans (Kaspar and Singer 2011). Legume cover crops are a source of fixed N that subsequent crops can utilize which reduces the need for fertilizer N and improves the energy balance of the production system (Rathje et al. 2007). Non-legume cover crops utilize inorganic N remaining after harvest reducing the potential for leaching losses and N_2O emissions. Cover crop production can also play a role in management of agronomic weeds through shading and competition. Cover crops are not a panacea management strategy in all parts of the region as soil water use by cover crops can negatively impact yields of subsequently planted crops in drier (more xeric) portions of this region (Vigil and Nielsen 1997; Nielsen et al. 2015). In other systems, choice of cover crops is important as some may serve as a host for pathogens of subsequent crops (Bakker et al. 2016). Management of the cover crops is crucial to their benefits to provision of both ecosystem goods and services.

Projected changes in temperature and precipitation will change the distribution of crops grown in the region due to the longer growing season and earlier frost free period. There has already been an increase in the amount of corn and soybean produced in the northeastern portion of the region and this trend will likely increase. A recent analysis has concluded that the increase in corn and soybean is the result of replacing perennial grass and increased use of marginal land for row crop production (Wright and Wimberly 2013). These shifts in land use increase the potential for soil erosion, reduce habitat for grassland wildlife, and will constrain efforts to increase use of cellulosic feedstocks for biofuel production. To sustain multiple ecosystem services and break weed, insect pest, and disease cycles there is a need for rotations more diverse than a prevalent corn–soybean rotation or continuous corn. In general, crop diversity in the USA has declined over the past three decades as has occurred in eastern Nebraska, and eastern Dakotas (Aguilar et al. 2015). However, there are other geographic areas in this region where crop diversity has increased, such as central North Dakota which may have been a response to improvements in technology, such as no-till and disease pressure. As cropping patterns change, the migration of weeds, diseases, and insect pests that are not currently present in the region will present management challenges to producers.

4.2 Improvements in management and genetics

Numerous studies have shown that past increases in crop production can be equally attributed to improvements in management and genetics (Cassman 1999; Unger and Baumhardt 1999). Efforts to develop crop varieties with increased heat tolerance, drought resistance, and disease resistance are underway. Work is underway in livestock breeding to develop genetics that can reduce the impact of heat stress on fertility and develop heat resistance (Hayes et al. 2013). Cultivars and varieties with these improved traits will have to be utilized appropriately on landscapes by producers. Topography, spatial variation in soil properties, redistribution of water following precipitation or irrigation, aspect influences on plant exposure to wind and solar radiation interact to create significant within-field variation in edaphic conditions and microclimate that effect crop yields (Kaspar et al. 2003). Precision agriculture is a strategy to optimize within-field management (McBratney et al. 2005). Sensors to measure and monitor within field variation need to be developed and interpretation tools and services will have to be provided to improve within-field management. Implements for spatially varying inputs (cultivars or crops, fertilizer, irrigation, seeding rates) need continued development. A recent analysis reported that precision agriculture was used on 30 to 50% of corn and soybean and the impact on producer profits was positive but small (Schimmelpfennig 2016). Improved management will contribute to optimizing crop yields without diminishing other ecosystem services (e.g., water and air quality). For example, within-season fertilizer application to meet crop needs can result in a reduction in the amount of fertilizer applied (Kitchen et al. 2010) which reduces the potential for greenhouse gas emission or contamination of surface or ground water.

4.3 Integration of crops/livestock (grazing of cover crops and residues)

Diversity is one of the key elements in providing resilience in ecosystems (Elmqvist et al. 2003) and diversification is a key principle in integrated livestock-crop systems (Hendrickson et al. 2008a). However, agricultural specialization over the past several decades has decoupled crop and cattle production (Sulc and Franzluebbers 2014) and specialized crop producers have shown little interest in adopting integrated production systems for numerous reasons. The agricultural landscape in the Northern Great Plains is unique because it is often a mixture of annual crops, rangeland, and seeded pasture and hayland. This landscape diversity provides opportunities for the spatial and temporal integration of crops and livestock to occur by using rotations of grain crops and perennial pastures, short rotations of grain crops with annual or short-term pastures, and utilization of grain crop residues for livestock grazing (Sulc and Tracy 2007; Sulc and Franzluebbers 2014).

4.4 Use of perennials

Changing land use from annual crops to perennial or increasing the number of forage crops in the rotation are strategies for achieving multiple production and conservation goals (Nielsen et al. 2016). As with cover crops, perennial vegetation can alter hydrologic and nutrient cycles to make more efficient use of and reduce contamination of water resources and improve soil quality (Culman et al. 2013). Progress in developing perennial grain crops is emerging (Lubofsky 2016). Development of multiple perennial crops that could be grown in mixtures and equipment for efficiently harvesting mixtures would have a positive effect on management through reduced field work, improved water and nutrient use, multiple marketable crops, and increased system diversity. Perennial vegetation can provide a source of feed for livestock, feedstock for biofuels, and habitat to support regional biodiversity. In addition, because perennials do not need to be reseeded annually and have extensive root systems, they can provide a source of system resilience in changing climatic conditions.

4.5 Grazing of cover crops and residues

Integration of livestock and cropping enterprises can provide for greater local or farm-level flexibility to adapt to weather variability and changing climate (Lemaire et al. 2014). Integrating livestock with annual cropping systems can provide a biological insurance for producers for years when climate variability may adversely impact annual crop production. Residues from either failed annual crops or crop residue from average years can be utilized by livestock (Schiere et al. 2002). Projected increases in spring precipitation may result in some cropland not being planted to annual crops. The use of cover crops as forage would still allow production from these areas.

Integrated crop-livestock systems can also benefit livestock production. For example, Kentucky bluegrass (*Poa pratensis* L.) which has become a common component of grassland vegetation in North and South Dakota is negatively impacted by heat and drought (Liu et al. 2008) thereby reducing the resilience of grazing lands during times of moisture and heat stress and shifting the forage cycle to early spring. Integrated crop-livestock systems can adapt to this weather-mediated plant invasion by utilizing cover crops or crop residue to fill the late season forage cycle. However, these integrated crop-livestock systems may require a higher management input (Hendrickson et al. 2008a).

4.6 Socio-economic considerations

As impacts of projected climatic changes in the Northern Great Plains continue to emerge and strategies for adaptation are planned and developed, socio-ecological-economic and cultural/institutional changes to support them will have to be included. Land use changes and allocation of water resources among competing uses will have to acknowledge societal demands and need to sustain the multiple functions and ecosystem services provided. Mechanisms for sustaining the economic viability of production systems under more variable conditions are needed. The insurance industry is one of the largest businesses in the world and will be impacted greatly by a more variable and changing climate as customers look to them to recover from losses in production, property, and infrastructure (Liska and Holley 2014). Government loan, price support, and insurance programs will also be needed to overcome year-to-year fluctuations experienced by producers. Public and industry research, and development of extension/education programs will be key to wise implementation of changing management practices. There are a number of innovative producers and many are early adapters of emerging technology but their lessons will need to be translated to other producers through field-days and demonstration projects.

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