2013

Scenarios of bioenergy development impacts on regional groundwater withdrawals

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doi:10.2489/jswc.68.5.124A

FEATURE

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IRRIGATION AND AGRICULTURAL PRODUCTION

Irrigation increases agricultural productivity, but it also stresses water resources (Huffaker and Hamilton 2007). Drought and the potential for drier conditions resulting from climate change could strain water supplies in landscapes where human populations rely on finite groundwater resources for drinking, agriculture, energy, and industry (IPCC 2007). For instance, in the North American Great Plains, rowcrops are utilized for livestock feed, food, and bioenergy production (Cassman and Liska 2007), and a large portion is irrigated with groundwater from the High Plains aquifer system (McGuire 2011). Under projected future climatic conditions, greater crop water use requirements and diminished groundwater recharge rates could make rowcrop irrigation less feasible in some areas (Rosenberg et al. 1999; Sophocleous 2005). The Rainwater Basin region of south central Nebraska, United States, is an intensively farmed and irrigated Great Plains landscape dominated by corn (*Zea mays* L.) and soybean (*Glycine max* L.) production (Bishop and Vrtiska 2008). Ten starch-based ethanol plants currently service the region, producing ethanol from corn grain (figure 1). In this study, we explore the potential of switchgrass (*Panicum virgatum* L.), a drought-tolerant alternative bioenergy feedstock, to impact regional annual groundwater withdrawals for irrigation under warmer and drier future conditions. Although our research context is specific to the Rainwater Basin and surrounding North American Great Plains, we believe the broader research question is internationally pertinent and hope that this study stimulates similar research in other areas.

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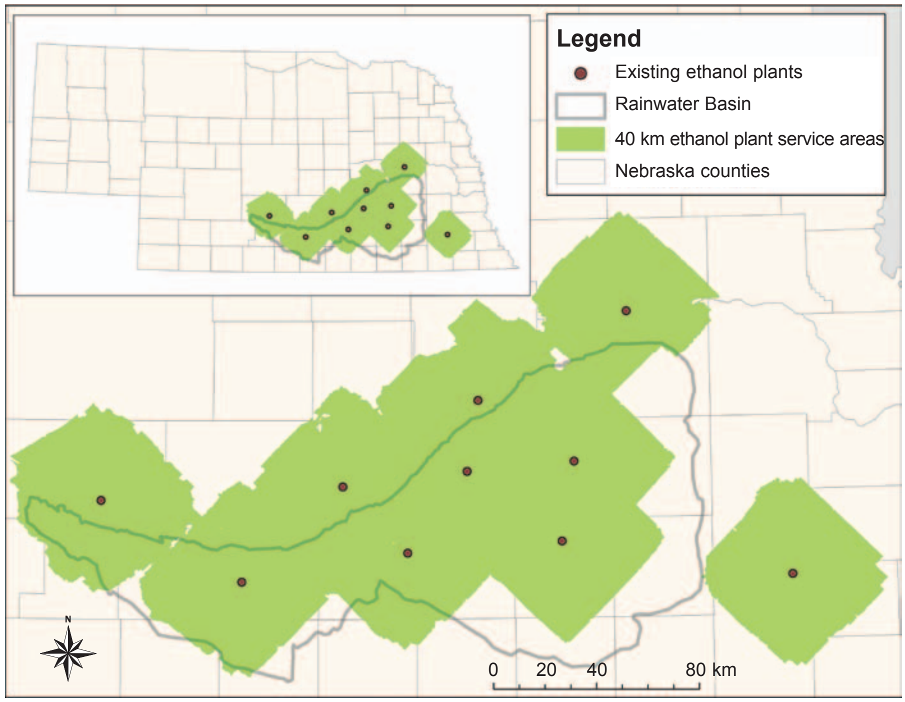
Figure 1

Locations and 40 km network service areas of ten starch-based ethanol plants currently servicing the Rainwater Basin.



BIOENERGY SWITCHGRASS

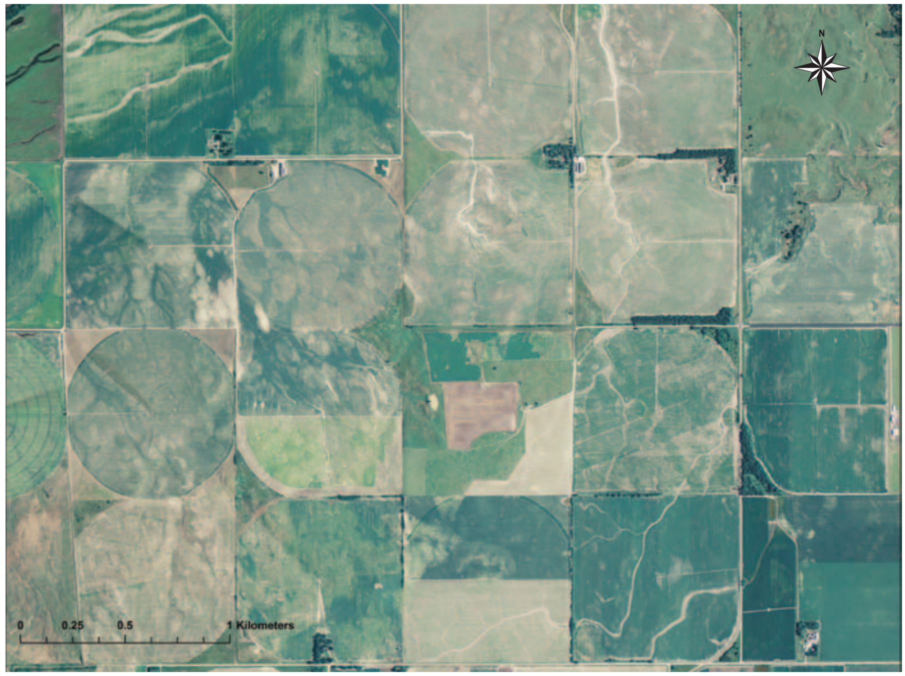
Switchgrass is a perennial, C4 grass species, native to the Great Plains (Kaul et al. 2006). It has been proposed as an alternative biofuel feedstock that could be produced with economic and environmental benefits, one of which is reduced dependence on irrigation (Mitchell et al. 2012). Switchgrass thrives in rain-fed systems east of the 100th meridian (Vogel 2004) where nonirrigated (dryland) farming can be conducted in most years (Mitchell et al. 2010). Simple sugars from switchgrass cell walls can be fermented to produce cellulosic ethanol (Dein et al. 2006), and although cellulosic ethanol production has not yet been implemented on a commercial scale in the United States, government mandates aimed at increasing second generation biofuel production (USEPA 2011) could spur development. Economically, switchgrass is a relatively drought-tolerant crop (Vogel 2004), produces large quantities of biomass on marginally productive lands (Schmer et al. 2008), requires less water and chemical inputs than annual rowcrops, requires less intensive management than annual rowcrops, can be managed and harvested using traditional farm machinery (Mitchell et al. 2010), and could help diversify farmer income (Sanderson et al. 2004). Switchgrass is also net energy positive, with an estimated net energy yield of 60 gigajoules ha^{-1} yr^{-1} on marginally productive cropland in the Northern Great Plains (Schmer et al. 2008). Environmentally, switchgrass is a near carbon-neutral fuel source (Fargione et al. 2008) that releases less carbon into the atmosphere than rowcrop cultivation (Adler et al. 2007) and sequesters carbon in prairie soils (McLaughlin et al. 2002).

Beyond its economic value, switchgrass is a common component of Conservation Reserve Program plantings and has been promoted for reducing soil erosion and protecting water resources (McLaughlin and Kszos 2005). There also could be substantial ecological benefits associated with reestablishing native perennial vegetation in rowcrop-dominated agricultural landscapes (Robertson et al. 2010). Thus, increased switchgrass establishment could improve ecosystem service provisioning to Great Plains societies in the future, both in economic and ecological terms.

Switchgrass stands are not likely to replace productive rowcrop fields due to the profitability of raising rowcrops under favorable conditions; however, marginally productive lands could be converted to switchgrass (Varvel et al. 2008). Marginally productive cropland can include small, complexly shaped, nonirrigated portions of agricultural fields located on less productive soils (Mitchell et al. 2012). Under novel climatic conditions, average annual precipitation and irrigation limitations also could be important for identifying marginally productive cropland because groundwater withdrawals on some presently irrigated fields could be restricted.

Figure 2

Aerial photograph of a typical Nebraska agricultural landscape (Nebraska DNR 2010). Within square fields, circular patterns are center-pivot irrigation systems, and the remaining four segments are nonirrigated pivot corners (Mitchell et al. 2012). Other fields of various sizes and shapes are irrigated with gravity irrigation systems or are not irrigated at all (dryland).



IDENTIFICATION OF MARGINALLY PRODUCTIVE ROWCROP FIELDS

Six characteristics of marginally productive cropland that make rowcrop fields better suited to raising switchgrass are (1) proximity to existing ethanol plants, (2) lack of irrigation infrastructure, (3) reduced soil productivity, (4) small size and complex shape of fields, (5) reduced average annual precipitation, and (6) history of irrigation limitations (Uden et al. 2013). We used each of these characteristics to identify marginally productive rowcrop fields in the Rainwater Basin, with fields possessing more of these characteristics being considered relatively more marginal and suitable for conversion to switchgrass than fields possessing fewer.

Proximity to Existing Ethanol Plants. Agricultural fields in close proximity to existing starch-based ethanol plants could be suitable for growing alternative bioenergy feedstocks because of the availability of infrastructure that could be modified for cellulosic ethanol production (Mitchell et al. 2012). We considered 40 km (25 mi) to be the maximum distance farmers are willing to transport grain or other feedstock to ethanol plants for processing (Khanna et al. 2008) and identified all agricultural fields within the 40 km service areas of 10 starch-based ethanol plants currently servicing the Rainwater Basin (figure 1).

Irrigation Availability. We grouped rowcrop fields according to four irrigation types: (1) center-pivot irrigated, (2) pivot corners, (3) gravity irrigated, and (4) dryland fields (figure 2). Crops on center-pivot and gravity irrigated fields are provided water throughout the growing season, but dryland fields and pivot corners are not. Consequently, we considered dryland fields and pivot corners more suitable for conversion to switchgrass than irrigated rowcrop fields due to the increased drought tolerance of switchgrass over rowcrops (Kiniry et al. 2008; Uden et al. 2013).

Soil Productivity. Soils in USDA Natural Resource Conservation Service land capability classes 3 through 6 are marginally productive for agriculture and may be better suited to less intensive forms of landuse, such as seeding with perennial grasses. Switchgrass remains productive on marginal soils, with ethanol yields comparable to or greater than that of combined maize grain and stover on similar soils (Varvel et al. 2008); therefore, we considered fields containing soils in classes 3 through 6 more suitable for conversion than those with more productive soils.

Field Size and Shape. A typical rowcrop field in the Rainwater Basin is situated on a quarter section and covers approximately 64 ha (160 ac) (Mitchell et al. 2012); however, smaller fields resulting from streams, roadways, and agricultural development are also common. Raising rowcrops on small, complexly shaped fields with increasingly large, modern farm equipment can be inconvenient and time consuming, and these fields may be better suited to raising less management intensive crops. We considered all pivot corners and small, complexly shaped dryland fields more suitable for conversion than larger, compactly shaped dryland fields.

Average Annual Precipitation. Because of the rain shadow effect of the Rocky Mountains, precipitation increases from west to east across the Rainwater Basin, with drier areas located in the western half (Ricketts et al. 1999). Rowcrop fields

in areas with average annual precipitation of 63.5 cm (25 in) or less are more suitable for conversion than fields in areas with greater average annual precipitation (Kiniry et al. 2008).

Irrigation Limitations. In Nebraska, surface and groundwater withdrawal limitations are established by Natural Resources District(s) (NRD), according to the appropriation status of water resources (Dunnigan et al. 2011). In the event that water resources are determined to be fully or overappropriated, the affected NRD is required to develop integrated management plans in conjunction with the Nebraska Department of Natural Resources for decreasing water use, which can include incentives to reduce groundwater withdrawals for farmers (Nebraska DNR 2007). Seven NRDs currently service the Rainwater Basin, and water resources in portions of three of them are classified as fully appropriated and hydrologically connected to surface water resources (Dunnigan et al. 2011). If climate changes result in increased crop water use and irrigation withdrawals and decreased groundwater recharge, these NRDs may impose greater limitations on irrigation than those where water resources have not been fully appropriated. Therefore, irrigated rowcrop fields within the three NRDs where water resources are classified as fully appropriated are considered more suitable for conversion than fields in the other four not fully appropriated NRDs.

PROPOSED SCENARIOS

We developed three biofuel-based agricultural landuse change scenarios for the Rainwater Basin, each driven by potential future climate changes, irrigation limitations, commodity prices, and ethanol demand. Interactions between these drivers could influence the future enrollment of marginally productive irrigated fields in rowcrops or switchgrass, which in turn could affect groundwater withdrawals. The more marginal characteristics a rowcrop field possesses, the more suitable it is for conversion to switchgrass. Greater temperature increases and precipitation decreases are assumed between Scenarios 1 and 2 and between Scenarios 2 and 3.

Scenario 1: Limited Change. This scenario assumes minimal climate changes without any additional irrigation limitations and an increased cellulosic ethanol demand. This scenario establishes a baseline for rowcrop conversion to switchgrass and annual groundwater withdrawals in the study area.

Scenario 2: Modest Change. Under this scenario, we assume warmer and drier climatic conditions for the Great Plains in the mid-21st century (IPCC 2007), additional irrigation limitations in the three NRDs with water resources previously determined to be fully appropriated, and greater cellulosic ethanol demand than in Scenario 1. These changes decrease the profitability of raising rowcrops under Scenario 1.

Scenario 3: Extreme Change. This scenario projects warmer and drier climatic conditions for the Great Plains in the late 21st century (IPCC 2007), widespread irrigation limitations in the three NRDs with water resources currently fully appropriated, some limitations in the remaining four NRDs, and greater cellulosic ethanol demand than in Scenarios 1 and 2. These changes further decrease the profitability of raising rowcrops under Scenarios 1 and 2.

POTENTIAL CHANGES IN ANNUAL GROUNDWATER WITHDRAWALS

For each scenario, we generated spatially explicit landcover maps identifying all registered groundwater wells on marginally productive, irrigated rowcrop fields converted from rowcrops to switchgrass. Mean annual groundwater withdrawals were calculated by multiplying individual well-pumping capacities (liters/hour) by 774 hours—the average annual well-pumping time for the State of Nebraska (Kranz 2010)—and then summing these across the region. Withdrawals from all wells located on switchgrass-converted fields are assumed to stop following conversion.

Current Withdrawals. There are currently 14,632 registered groundwater wells located on gravity or pivot irrigated rowcrop fields within the study area. Assuming each well pumps at the mean Nebraska well-pumping time of 774 hr yr-1 (Kranz 2010), the annual withdrawal rate will be more than 250,254 ha-m (2.03 x 10^6 ac-ft) of groundwater.

Scenario 1 Withdrawals. Under the Limited Change Scenario, converted fields consist exclusively of marginally productive nonirrigated pivot corners and dryland fields and cover a total of 53,672 ha (132,626 ac) (~5% of total landcover within the study area). Because no irrigated fields are converted, all groundwater wells continue to be utilized for rowcrop irrigation, and no reduction in groundwater withdrawals occurs (table 1).

Scenario 2 Withdrawals. In the Modest Change Scenario, there are 121,141 ha (299,346 ac) of marginally productive rowcrop (~12% of total landcover) converted to switchgrass. Groundwater pumping ceases on 350 groundwater wells, or ~2% of the total wells in the study area (figure 3). This cessation reduces annual groundwater withdrawals by more than 6,422 ha-m (52,064 ac-ft), or ~ 3% of current estimated annual withdrawals in the study area (table 1).

Scenario 3 Withdrawals. Under the Extreme Change Scenario, there are 208,827 ha (516,023 ac) of marginally productive rowcrops (~21% of total landcover) converted to switchgrass. Groundwater pumping ceases on 737 groundwater wells located on irrigated fields (figure 3), reducing annual groundwater withdrawals by more than 13,917 ha-m (112,827 ac-ft), or 5.6% of current estimated annual withdrawals (table 1).

Withdrawals in Previously Fully Appropriated Natural Resources Districts. Within the study area, there are 3,843 registered groundwater irrigation wells located inside the three NRDs with water resources determined to be fully appropriated. Together, these wells have a combined annual groundwater withdrawal potential of 67,154 ha-m (544,426 ac-ft). All irrigated rowcrop fields converted to switchgrass under Scenario 2 are in these three NRDs, and if considered apart from the other four NRDs, the 6,422 ha-m (52,064 ac-ft) annual reduction in Scenario 2 translates into a 9.6% decrease in withdrawals (table 2). Under Scenario 3, selected irrigated rowcrop fields in all seven of the NRDs are converted to switchgrass; however, within the three NRDs with water resources fully appropriated, there are 679 groundwater wells that ceased pumping, which reduces annual groundwater withdrawals in these three NRDs by more than 12,846 ha-m (104,144 ac-ft), or 19.1% (table 2).

Conservation Implications. Effective groundwater conservation and sustainable water use will be critical for irrigation-dependent agricultural landscapes in the future. In addition to economic, environmental, and ecological benefits, the adoption of drought-tolerant alternative bioenergy crops creates novel opportunities for groundwater conservation in the North American Great Plains under future climate and agricultural policy changes. Replacing marginally productive irrigated rowcrops with switchgrass in areas where water resources are most limited could conserve groundwater while providing an alternative source of income for farmers, thereby making farming operations and agricultural landscapes more resilient to agricultural policy changes and variations in commodity prices. In rowcrop-dominated areas, residual maize stover and switchgrass supplies could be combined to supply adequate biomass to cellulosic ethanol plants (Uden et al. 2013).

Although the conversion to switchgrass did not drastically reduce basin-wide groundwater withdrawals under the proposed scenarios, withdrawal reductions were more substantial when inference was limited to NRDs where future irrigation limitations are most likely to be implemented, i.e., where withdrawals are currently maximized, which includes much of the Great Plains. Groundwater withdrawal reductions in the three fully-appropriated NRDs are comparable to the 20% reduction goals recently identified by several Nebraska NRDs with overappropriated water resources (Hilger 2010; Supalla 2010; Middle Republican NRD 2011).

Water Use Requirements. Reduced precipitation and elevated evapotranspiration rates associated with future climate changes could increase crop water use, and subsequently, irrigation requirements and well-pumping intensities on rowcrop fields, thereby offsetting potential reductions in groundwater withdrawals associated with conversion to drought-tolerant bioenergy feedstocks. Furthermore, even drought-tolerant, perennial crops like switchgrass may require some irrigation under warmer and drier conditions, especially as plant root systems develop during the establishment year.

Profitable returns for farmers could promote the conversion of additional marginally productive irrigated rowcrop fields to switchgrass or other alternative feedstocks, thereby conserving more groundwater. Agricultural water use competes with other uses, including domestic and fish and wildlife resources, which often mandate minimum in-stream flows for surface waters. Agricultural water uses should be considered in a resilience framework (Nemec et al. forthcoming) that accounts for tradeoffs among competing uses. Drought-tolerant bioenergy feed-

Figure 3

Registered Rainwater Basin groundwater wells located on irrigated rowcrop fields within 40 km road network service areas that ceased pumping following conversion of the field to bioenergy switchgrass under Scenarios 2 (Modest Change) and 3 (Extreme Change), which assume warmer and drier climatic conditions projected for the Great Plains in the mid- and late 21st century and additional irrigation limitations in Natural Resources Districts.

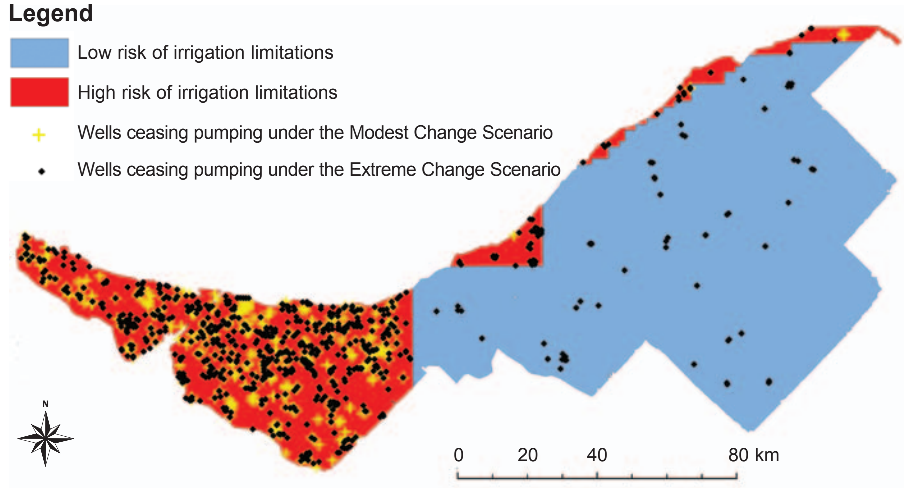


Table 1

Potential annual groundwater withdrawal reductions and percent changes in withdrawals for the Rainwater Basin region within 40 km ethanol plant service areas under Scenarios 1 (Limited Change), 2 (Modest Change), and 3 (Extreme Change). The intensity of climate change, irrigation limitations, ethanol demand, and the number of rowcrop hectares converted to switchgrass increases between Scenarios 1 and 2 and Scenarios 2 and 3.

Scenario	Withdrawal reduction (ha-m)	Percent change
1	0	0.0
2	6,422	-2.6
3	13,917	-5.6

Table 2

Potential annual groundwater withdrawal reduction and percent changes in withdrawals for Natural Resources Districts in 40 km ethanol plant service areas of the Rainwater Basin region that have previously implemented limitations on irrigation under Scenarios 1 (Limited Change), 2 (Modest Change), and 3 (Extreme Change). The intensity of climate change, irrigation limitations, ethanol demand, and the number of rowcrop hectares converted to switchgrass increases between Scenarios 1 and 2 and Scenarios 2 and 3.

Scenario	Withdrawal reduction (ha-m)	Percent change
1	0	0.0
2	6,422	-9.6
3	12,846	-19.1

stock cultivation on marginal croplands could contribute to energy production and lessen demand on stressed water resources in agricultural systems worldwide, but the conversion of native or restored habitats to bioenergy production could negatively impact wildlife and the provision of ecosystem services (Robertson et al. 2012).

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Mark Burbach from the School of Natural Resources at the University of Nebraska-Lincoln, Lincoln, Nebraska; Dr. David Angeler from the Department of Aquatic Sciences and Assessment at the Swedish University of Agricultural Sciences, Uppsala, Sweden; and Nathan Rossman from the Department of Earth and Atmospheric Sciences at the University of Nebraska-Lincoln, Lincoln, Nebraska, for their contributions to this manuscript. The authors also would like to thank the Rainwater Basin Joint Venture, Nebraska Department of Natural Resources, and the USDA for providing GIS data and the Great Plains Landscape Conservation Cooperative and US Geological Survey Climate Effects Network for financial support. The Nebraska Cooperative Fish and Wildlife Research Unit is jointly supported by a cooperative agreement between the US Geological Survey, the Nebraska Game and Parks Commission, the University of Nebraska–Lincoln, the US Fish and Wildlife Service, and the Wildlife Management Institute.

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