Reg Environ Change (2013) 13:311–328
DOI 10.1007/s10113-012-0339-9

ORIGINAL ARTICLE

# Possible future trade-offs between agriculture, energy production, and biodiversity conservation in North Dakota

**Michael J. Hill · Rhonda Olson**

Received: 20 March 2012 / Accepted: 27 July 2012 / Published online: 9 August 2012


**Abstract** In this study, we describe a spatially explicit scenario analysis of global change effects on the potential future trade-offs and conflicts between agriculture, energy generation, and grassland and wetland conservation in North Dakota (ND), USA. Integrated scenarios combining global policy, oil security, and climate change were applied to North Dakota using a spatial multi-criteria analysis shell. Spatial data describing climate changes and grassland, wetland, cropland, and energy distributions were used to characterize the geographical environment. The final multi-criteria framework examined the potential trade-offs between climate change, agricultural expansion, and energy generation resulting from global change scenarios on one hand, and the current footprint of wetlands and grasslands for six regions of ND that capture the major climate gradients and differences in land use. The results suggest that the tension between regional climate changes that may limit agricultural expansion, and global changes in food and energy security and commodity prices that favor agricultural expansion, may focus a zone of potential pressure on grasslands and wetland conversion in central ND and the Prairie Pothole Region. The balance between conservation programs, commodity prices, and land parcel productivity may determine grassland conversion, while wetland outcomes may almost totally depend upon regional climate change.

**Keywords** Multi-criteria · Trade-off · Land use · Ecosystem function · Climate change

## Introduction

North Dakota (ND) sits in the middle of one of the great granaries of the world. It is a significant producer of wheat, corn, soybeans, canola, sugar beet, potatoes, and sunflowers. In addition, it is the center of a major oil and gas boom made possible by rising oil prices and advances in technology that enable deep shales containing oil and gas to be fractured and mined, with multiple shafts emanating from one drill site (Sorenson 2008). It also has significant potential for the development of renewable energy (Boyer et al. 2008; Knoll and Klink 2009; Aravindhakshan and Koo 2011). However, it contains one of the largest areas of National Grasslands in the USA (Hurt 1985), and the Prairie Pothole Region (PPR) contains wetlands that are the breeding grounds for millions of ducks and other water birds (Niemuth et al. 2010). As such, ND represents a microcosm of the trade-offs faced globally in many of the major grassland biomes-turned-granaries between resource exploitation and food production on one hand, and maintenance of ecosystem function and services on the other (e.g., Euliss et al. 2010; Aravindhakshan and Koo 2011; Gascoigne et al. 2011). This confluence of attributes and pressures provides an opportunity to explore trade-offs under a plausible set of future global change scenarios.

The IPCC Fourth Assessment Report (AR4) indicates that the Northern Great Plains region of the USA (contained within the Central North America (CNA) land region) is likely to experience annual warming that exceeds the global mean, with warming from as low as between 2 and 5 °C under the B1 scenario to warming as high as 3–8 °C under the A2 scenario (Christensen et al. 2007). It is likely that precipitation will

M. J. Hill (✉)
Department of Earth System Science and Policy,
University of North Dakota, Grand Forks, ND 58202, USA
e-mail: hillmj@aero.und.edu

R. Olson
Department of Geography, University of North Dakota,
Grand Forks, ND 58202, USA

increase in winter and spring, but decline in summer, although uncertainties are higher for precipitation than for warming. The line of zero change moves north from winter to summer. These changes may be critically important for wetlands, in particular, since more spring rain will increase storage in Prairie Potholes, but drier summers may reduce wetland area and water volume (e.g., Johnson et al. 2005, 2010) and encourage drainage and conversion to agriculture.

Scenarios are a useful approach to exploration of potential futures for complex systems such as the global coupled human–environment system subject to changes in climate and land use. The exploration of global change scenarios has expanded from the landmark Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES; Nakićenović et al. 2000) to include global development scenarios (UNEP/RIVM 2003; Rosen et al. 2010), environmental impact scenarios (Carpenter et al. 2005), and oil security scenarios (Johnston 2010). Future land use in Europe has been a focus for some of the most comprehensive analysis (Abildtrup et al. 2006; Audsley et al. 2006; Berry et al. 2006; Rounsevell et al. 2005, 2006). Significant attention has also been paid to the effects of climate change on global food production and food security (Parry et al. 2004a, b; Schade and Pimental 2010; Scherr et al. 2010; Godfray et al. 2010).

Downscaling is a significant issue for regional assessment of global scenarios (Carpenter et al. 2005). For a State like ND, or smaller regional entity, the economic and natural resource status is easier to define than for larger more diverse regions or entities, and it can largely be directly linked to national and international markets and regulations. For example, a recent analysis of the economics of grassland conversion to cropland (Rashford et al. 2010) found that agricultural commodity prices were a major potential driver of conversion, but that probability of conversion was spatially heterogeneous depending upon the soil quality and yield potential of parcels. In addition, it seems likely that only a global revolution in terms of energy preference, which reduced oil consumption to a degree that resulted in a major fall in prices, could have a major negative effect on the ND oil exploration given the current reserve estimates of 3.0–4.3 billion barrels (Pollastro et al. 2008)—now considered to be a very conservative estimate. On a national scale, federal programs provide cash incentives for grassland and wetland conservation through land retirement mechanisms that are highly significant in ND. These fall under several headings including the Conservation Reserve Program (CRP), the Conservation Security Program (CSP), the Farm and Ranch Land Protection Program (FPP), the Grasslands Reserve Program (GRP), the Wildlife Habitat Incentives Program (WHIP), and the Environmental Quality Incentives Program (EQIP) (Wiebe and Gollehon 2006).

In this study, we undertake a spatially explicit assessment of the potential effects of a range of scenarios derived from combining global scenario frameworks emphasizing development, climate change, environmental conservation, and oil security, on the trade-offs between agriculture and energy on one hand, and grassland and wetland conservation on the other in the US state of North Dakota. The study aims to identify the geographical areas of greatest tension between energy and agricultural enterprises, and key natural ecosystems.

## Methods

### Grasslands and wetlands in North Dakota

North Dakota is dominated by three major land cover types: agricultural lands, grasslands under grazing and in CRP, and wetlands in the Prairie Pothole Region. North Dakota has a very substantial east–west precipitation gradient, a corresponding change in ecoregion type from largely converted tall grass prairie in the east to largely intact but grazed short mixed prairie west of the Missouri River, and a strong north–south temperature gradient. The area under grazing and hay production in ND is about 5.24 m ha or about 28.3 % of the land area (Table 1). The most recent census data from 2007 (Table 1) show as much as 1.39 M ha of land enrolled in Federal conservation programs. As of January 2012, ND had about 1.01 M ha remaining in CRP; however, potentially 0.32 M ha could come out of CRP by September 2012 (US Farm Service Agency 2012). Publicly conserved native prairie in ND is managed by a combination of 11 state and national agencies, with national agencies controlling about 0.36 M ha and state agencies controlling about 0.2 M ha. With the exception of the North Dakota Land Department, which manages land for sustainable use as rangeland, the remaining state agencies collectively manage 1.3 % of the remaining native prairie on public lands. About 90 % of the total conserved native prairie lands are managed by the U.S. Forest Service (USFS), North Dakota Land Department (NDLD) and the U.S. Fish and Wildlife Service (USFWS). Wetlands now cover about 1.09 M ha of North Dakota, which is a substantial reduction from the original 1.98 N ha due to drainage and agricultural conversion (http://nd.water.usgs.gov/wetlands/index.html). The PPR is essentially made up of wetlands in depressions in the landscape with a shallow water table, dependent upon ground water, precipitation, and overland snowmelt for recharge. The sensitivity of these wetlands to variations in climate depends upon precipitation or ground water or both, and connectivity to ground water flows and discharges from other wetland units (Winter 2000).

**Table 1** Area and percentage of North Dakota occupied by grassland of various types (Nickerson et al. 2011)

| Category | Hectares | Percent | Context |
|---|---|---|---|
| North Dakota total area | 17,871,663 | 100.0 % | NA |
| Cropland used only for pasture or grazing (acres) | 328,829 | 1.8 % | This category represents dynamic grassland acres that may switch in tenure depending on market forces |
| Forage—land used for all hay and all haylage, grass silage, and greenchop | 1,021,919 | 5.7 % | This category shows the total amount of harvested land that is in a "grassland"-type tenure. These acres are also dynamic and may switch tenure depending on market forces |
| Permanent pasture and rangeland, other than cropland and woodland pastured | 4,216,380 | 23.6 % | This category represents land that is qualified as permanent grassland but varies in level of productivity/quality/condition |
| Land enrolled in conservation reserve, wetlands reserve, farmable wetlands, or conservation reserve enhancement programs | 1,389,707 | 7.8 % | The category represents cropland that is currently enrolled in a Federal Conservation Program. These acres are susceptible to reversion back to cropping |

## Overview of the approach

The approach is based on an integration of the story lines from four major global scenario frameworks. The frameworks each use a response space with two orthogonal axes. The scenarios prepared by Rosen et al. (2010), which are very similar to the GEO-3 (Group on Earth Observations) framework defined by UNEP/RIVM (United Nations Environment Program 2003) for Europe, were chosen as the baseline global development framework (Fig. 1a). The next scenario framework examines the potential future world states based on oil security (Johnston 2010). This

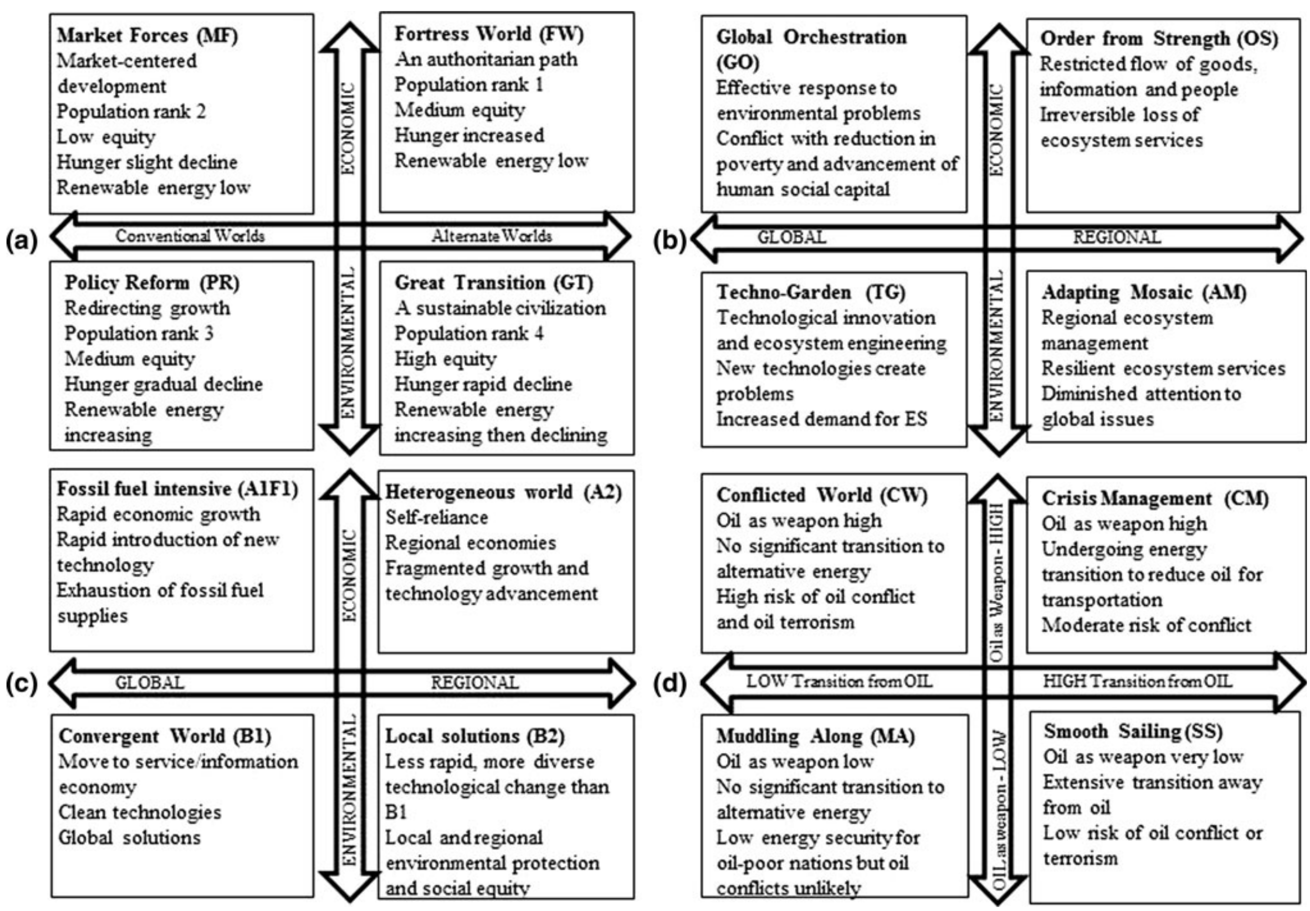


**Fig. 1** Comparison of scenario frameworks from four sources. **a** Global (Rosen et al. 2010); **b** millenium ecosystem assessment (Carpenter et al. 2005); **c** IPCC SRES (Nakićenović et al. 2000); and **d** security impact of oil nationalization (Johnston 2010). The simple two-dimensional matrix is derived from Höök et al. (2010)

framework places the future world states in a two-dimensional space with propensity to use oil as a weapon on the vertical axis and rate of transition from an oil-based economy on the horizontal axis (Fig. 1b).

The final two scenario frameworks, IPCC SRES (Nakićenović et al. 2000) and Millenium Ecosystem Assessment (Carpenter et al. 2005), are well known and are mapped on the same two-dimensional space where the vertical axis represents the range from more environmental to economically oriented futures and the horizontal axis represents the range from more global to more regional outcomes (Fig. 1c, d). While the first three scenario frameworks are heavily mediated by global effects that influence regional USA, the MEA scenarios are very substantially mediated through national regulation and conservation incentive programs, and through the land structure and private land management administration and culture within the State of North Dakota.

## Development of integrated story lines

Global integrated scenarios are constructed based on a logical combination of these four frameworks. A logical alignment of these scenarios is shown in Fig. 2. The alignment of scenario frameworks varies according to whether some can be nested alternatives with others. Remembering that the top level is provided by Rosen et al. (2010); Fig. 1a), the next by Johnston 2010; Fig. 1b), the third by the IPCC SRES, and the fourth by the Carpenter et al. (2005); the following logical integrated scenario combination can be constructed.

1. The Great Transition can only occur with the Smooth Sailing oil scenario and leads to the Convergent World climate change scenario and the Techno-Garden MEA scenario.
2. Market Forces can align with either Muddling Along or Crisis Management oil scenarios. Depending upon the extent of transition away from oil, this aligns with the A1 family of SRES scenarios with A1F1 for more fossil intensive and A1B for a more balanced energy development. Depending upon whether fossil fuel use and environmental conservation are closely coupled or de-coupled and follow separate paths, this story line could align with Global Orchestration of response to environmental problems or development of a Techno-garden approach while still having significant fossil fuel use.

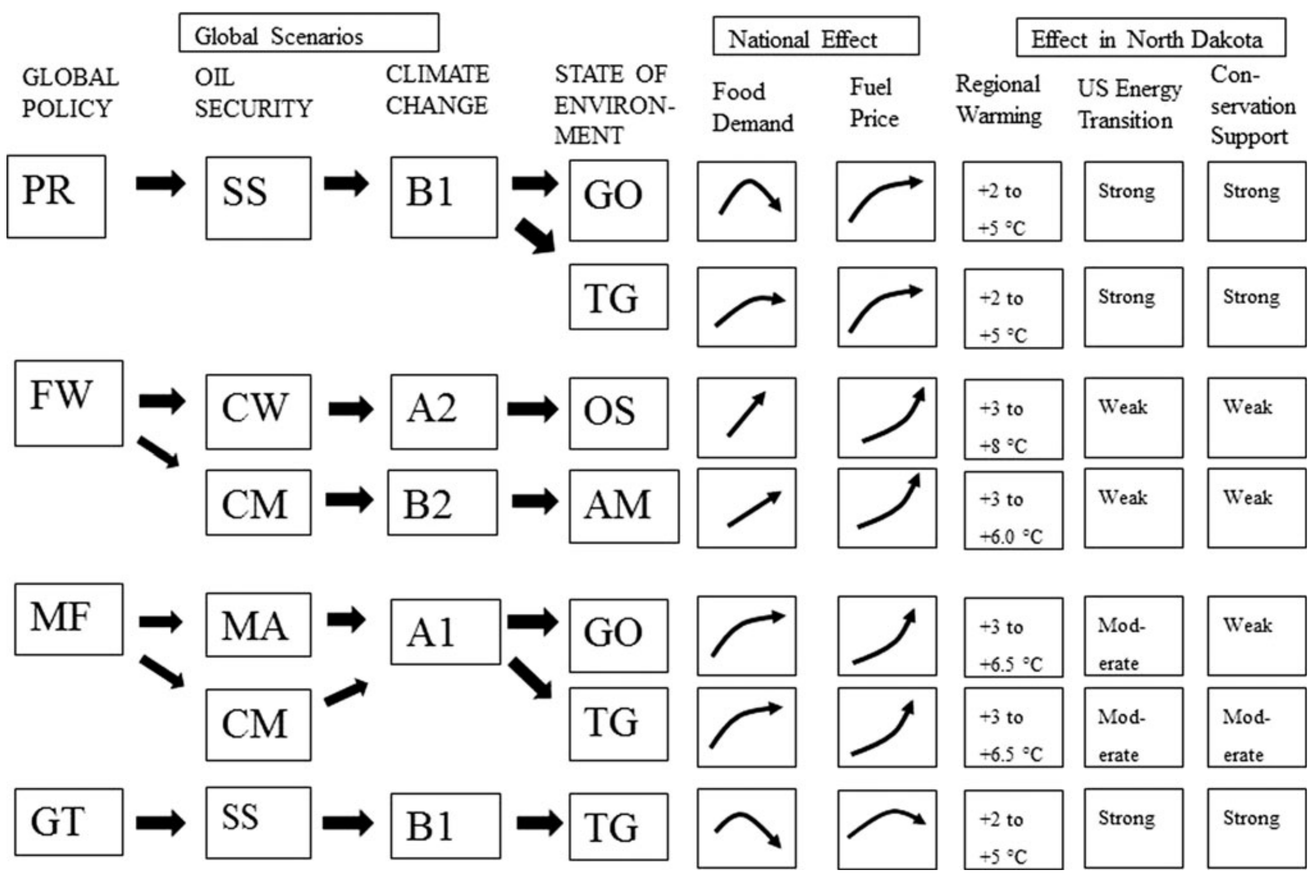


**Fig. 2** Linked global scenarios for development, soil security, climate change, and state of the environment together with proposed effects manifested in North Dakota. Details of each global scenario framework described in Fig. 1

3. Fortress World could provide both the Conflicted World and Crisis Management oil scenarios. This could then lead to either of the SRES regional options with A2 resulting in an Order from Strength environmental scenario, and B2 resulting more in an Adapting Mosaic environmental outcome.
4. Policy Reform can only really occur with a Smooth Sailing oil scenario. This combination then tends to lead to the B1 SRES option, which could be aligned with either Global Orchestration or Techno-Garden environmental frameworks.

These seven scenario combinations that cover development, oil security, climate change, and environmental condition then provide some drivers that would affect directly, or indirectly, the agricultural and energy sectors of North Dakota.

## Downscaling drivers to North Dakota

North Dakota has a very strong commodity-based economy and a very strong primacy philosophy for private land management rights. In other words, there is a strong philosophical belief and consequential legislative enforcement of maintenance of private land in the private domain, and within some limits, the right of private land holders to do what they want with their land. This makes land management across North Dakota highly responsive to market forces. The links from the global scenarios can be summarized by a discrete set of drivers: global population increase and resulting food demand, global oil price, availability and national oil security, climate change impact on food supply, demand for biofuel, global policy on energy transition, national policy on energy transition, and national conservation policy (federal incentives). The national energy environment will be driven by national security imperatives resulting from US dependence on foreign oil. However, rising oil prices will make more difficult reserves economic and hence may extend the life of the oil and gas reserves. The nature of the federal conservation measures will be driven in the medium term by the political balance between budget constraints and the senatorial power of rural states like North Dakota. However, these programs are persistent and have been in existence in one form or another for 80 years (Claassen et al. 2011).

## Multi-criteria analysis shell for spatial decision support (MCAS-S)

The construction of spatial data composites to characterize climate changes, agriculture, grasslands, and wetlands and energy resources, and carry out analysis of trade-offs occurring as a result of different scenarios was carried out in the Multi-Criteria Analysis Shell for Spatial decision support (MCAS-S; Hill et al. 2005; Lesslie et al. 2008). MCAS-S is a visualization and integration shell exploring complex assessment and decision issues with spatial data. It has previously been used to examine trade-offs among competing land uses in city greenbelts (Hill et al. 2009; FitzSimons et al. 2012) and to assess salinity mitigation and biodiversity enhancement (Lesslie et al. 2008). The shell utilizes ArcGIS grids directly provided these have the same projection, extent, and spatial resolution. The shell allows the user to import, select, and display spatial data in a dynamic workspace window, see multiple datasets simultaneously, group data sets under specific topics, interactively modify and combine these data sets, and carry out two-way and multi-way comparisons to form meaningful map-based flow diagrams.

## Spatial data

The spatial analysis was undertaken at 300-m pixel resolution and in a Universal Transverse Mercator Zone 14 N projection with a WGS 84 spheroid. Baseline data layers were generated by three main methods depending upon their original type and the need to retain fine scale variation at the project scale. Line data were converted to grid format by a proximity operation to create a 300-m pixel grid of distance from a feature. Polygon data were converted to grid format by direct rasterization and by the distance operation. Fine resolution image or grid data, such as crop type or land cover classifications, were aggregated to project resolution by the conversion of each class to a single binary 1/0 layer and summing to give a percentage of pixel occupied by that class.

A diverse range of spatial data was used to construct spatial data composites for scenario realization and impact assessment (Table 2). The basic composites developed were growth benefit (GB), heat drought (HD), thermal environment (TE), overall warming (OA), agricultural intensity (AI), grassland strength (GS), energy intensity (EI), energy potential (EP), and wetlands strength (WS) These composites were constructed using data for climate, land cover, infrastructure, production, soil, topography, water, energy, and public land areas (Table 1).

Climate data were acquired for North America from the WORLDCLIM database (Hijams et al. 2005). Data were acquired for the four SRES emissions scenarios, A1FI, A2, B1, and B2 from three global circulation models representing a wide range of perspectives: the Canadian model (McFarlane et al. 1992), the Hadley Centre model (Martin et al. 2006), and the Australian CSIRO model (Phipps et al. 2011). These models provide predictions from a North American, European, and Southern Hemisphere perspective. The

**Table 2** GIS data layers for North Dakota showing allocation to construction of spatial data composites used for scenario development

| Type | Layers | GB | HD | TE | OA | AI | GS | EI | EP | WS |
|---|---|---|---|---|---|---|---|---|---|---|
| Biofuel potential | Biomass from crops, forests, landfill, manure, paper mills, sawmills, urban | | | | | | | | X | |
| Current and future (A1FI, A2, B1, B2) climate | Annual and seasonal precipitation (3 month seasons, frost-free period, warm 6 months), annual maximum and minimum temperature, maximum and minimum temperature in January and July, precipitation in January and July, annual and seasonal (3 month) potential evaporation | | X | | X | | | | | |
| Current and future (A1FI, A2, B1, B2) growing season | Date of first and last frost and thaw (based on maximum and minimum temperature), frost-free period (based on mean and minimum-based temperature), growing degree days for temperature of 1 and 10 °C | X | | | | | | | | |
| Current and future thermal regimes | Heating and cooling degree days—30 year mean, maximum, and minimum (base temperature 18 °C) | | | X | | | | | | |
| Current energy generation | Coal mines, coal-fired power plants, electricity transmission lines, oil refineries, wind turbine farms, oil wells and active oil wells, current wind farms | | | | | | | X | X | |
| Human demographics | Farm, rural, city and total population, population density | | | | | | | | | |
| Land cover—NASS crop type (1997–2010) | Percent cropland, grassland and wetland (97–10), percent individual crops (alfalfa, wheat, spring, winter, durum), barley, oats, sunflower, safflower, corn, soybean, sugar beet, potatoes, flax, beans, canola) | | | | | X | X | | | |
| Land cover—ND GAP | Distance from and percentage of tree cover, grass, lakes, wetlands, rivers, shrubs | | | | | | | | | |
| Value of agricultural production | Annual price of crop commodities per standard yield unit assigned to crops and aggregated to 300 m pixels for 1997–2009 | | | | | X | | | | |
| Protected and government lands | Distance from military bases, ND Forest Service land, ND Game and Fish land, ND Land Department lands, ND Parks and Recreation Lands, tribal lands, Bureau of Land Management, Bureau of Reclamation, US Fish and Wildlife Service, US National Park Service | | | | | X | X | | | |
| Soil—USGS STATSGO | Available soil water (25, 50, 100, and 150 cm), drainage class, flooding frequency, hydrologic class, irrigated and non-irrigated land capability class, water depth (annual and April–June); soil yield potential (alfalfa, barley, sugar beet, corn, flax, oats, potatoes, rye, sunflower, sorghum, soybeans, spring, and winter wheat) | | | | | X | | | | |
| Renewable energy sources | Monthly and annual solar energy potential, wind energy potential, hydrogen potential | X | X | | | | | | X | |
| Water | Distance to intermittent lakes and streams, permanent lakes, streams, rivers and dams, surface aquifers, area of watersheds | | | | | | | | | X |

Layer types are values, classes, distance to features, and percentage cover of features. Basic spatial data composites: *GB* growth benefit, *HD* heat drought, *TE* thermal environment, *OA* overall warming, *AI* agricultural intensity, *GS* grassland strength, *EI* energy intensity, *EP* energy potential, and *WS* wetlands strength

climate data consisted of the following direct and derived measures: seasonal and annual maximum and minimum temperatures, seasonal and annual precipitation, seasonal evapotranspiration, annual growing degree days for 1 and 10 °C base temperatures (corresponding to growth thresholds for C3 and C4 plants), annual heating and cooling days (based on 18 °C), and annual freeze/thaw dates and frost-free periods. All data were converted to a difference basis by subtraction of values for the current climate. Since the effects of climate change are quite specific and related to the seasonal magnitude of changes and the concurrency or opposition of effects, attention was focused on the overall warming, the changes to the length of the growing season, and the changes in precipitation and the ratio of precipitation to evapotranspiration in particular seasons.

The baseline land cover was defined by the North Dakota GAP Analysis data set (Strong et al. 2005), which represented land cover for 1997. The land cover map provides the most detailed representation of native prairie grasslands available. The GAP land cover also provided a base line mapping of wetland areas. The National Agricultural Statistical Service (NASS) has completed annual remote sensing-based mapping of crop types for North Dakota from 1997 to 2010. These data map crop type at high spatial resolution (30 m 1997–2005 with Landsat TM and 56 m from 2005 to 2010 with AWIFS data) and with explicit accuracy assessments. These data form an annual land cover assessment from 1997, tuned to be most sensitive to cropping, but also providing some valuable data on wetlands and grassland (from 2005, grassland is "hard-wired" into these maps using the 1992 National Land Cover Data (Vogelmann et al. 2001)).

Construction of spatial data composites

In order to establish the scenario analysis, it was necessary to construct spatial data composites (layers that combine a range of spatial products that describe components of an overall feature of the system) to represent the "strength" of land cover by grassland and wetlands, and the intensity of land use for agriculture and energy generation at 300-m pixel spatial resolution (Fig. 3). The intensity of land use for agriculture (Fig. 3a) was constructed from five data layers: cropland likelihood, crop diversity, soil yield potential, agricultural dollar value, and protected lands. Cropland Likelihood was created by combining percentage cropland data layers for all years from 1997 to 2010. Crop diversity was constructed in two stages. First, data for 2007–2010 (4 years) were combined using equal weights and real values to give spatial data composites that describe distribution in terms of average percentage of pixel occupied by that crop. Then, these composite layers for the 12 most important crops were combined with equal weights, but standardized data values to form a single composite describing the distribution of crop diversity. Soil yield potential data were acquired from the national database at http://soildatamart.nrcs.usda.gov/Templates.aspx. The data for "Yields, non-irrigated" were formatted to yield per hectare, average values were computed, and values for each crop type were added to the STATSGO soil attribute table for North Dakota. These data were then converted to grids. Yield potential layers for the 12 major crop types were combined to form a single composite layer describing soil yield potential. Agricultural dollar value was

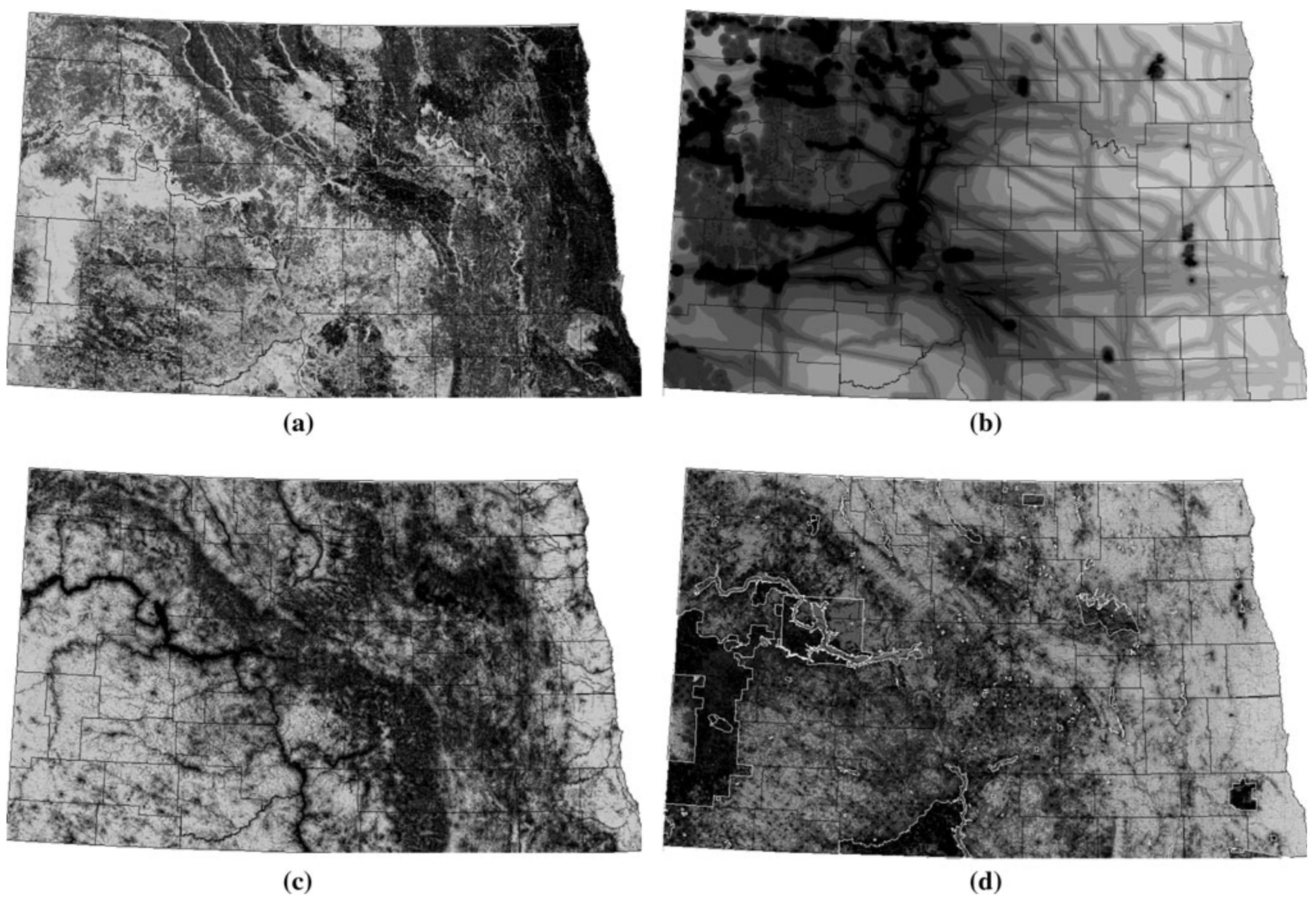


**Fig. 3** Maps of key land and resource characteristics of North Dakota. **a** Agricultural potential, current energy exploitation, wetland "strength," and **d** grassland "strength." All maps have county boundaries overlaid. Grassland strength has federal lands overlaid in white

constructed by aggregating cropland data layers for each year up to 300 m using the most common crop type, then assigning the average price of commodity unit per year to the annual average yield per area per year. The individual year layers were then combined with equal weights and actual dollar values to produce a single composite crop value layer. The protected lands data layer was constructed from data defining federal and state lands that could not be used or converted for cropping (Table 1).

Intensity of land use for energy (Fig. 3b) was based on combining of data layers mapping the extent of the potential Bakken formation coal, oil, and gas reserves, current point coverages of oil and gas well locations, locations of coal mines and power stations, current locations for wind turbine farms, and rasterized county-scale polygon data from NREL indicating potential for solar, biomass, hydrogen, and future wind in North Dakota. Strength of wetland land cover was defined by combining three data layers: buffered distance to GAP wetland classes; buffered distance to line and polygon data defining permanent and intermittent streams, lakes, and wetlands; and likelihood of wetland derived from the combination of wetland classes from 14 years of the NASS crop-type mapping (Fig. 3c). The distance classes were defined on a modified geometric scale (0, 25, 50, 100, 200, 400, 800, 1,600, 3,200, and 6,400 m) in order to emphasize the localness of pothole wetlands. When the 300-m pixel resolution is taken into account, there is a strong distinction between the pixel containing the wetland and the surrounding pixels, since these will fall into the class corresponding to the 400 m distance category. The NASS crop-type maps provide an annual snapshot of wetland extent since classifications are undertaken on mosaicked Landsat and AWIFS (Indian satellite) data and the mix of image dates varies within and between years. Finally, strength of grassland land cover was defined by combining three data layers: percentage of grassland in a 300-m pixel based on GAP land cover classes; likelihood of grassland based on combining 14 years of percentage grassland in a 300-m pixel from NASS cropland maps; and protected lands based on tightly buffered distance to federal and state lands including Native American lands (Fig. 3d).

The State was divided into 6 subregions based on county boundaries (Fig. 4a) in order to facilitate reporting of subregional impacts and interactions. These subregions capture the northern (NE) and southern (SE) parts of the Red River Valley and adjacent lands east of the Prairie Pothole Region (PPR); the northern (NC) and southern central (SC) areas containing a significant component of wetlands; and the western region with an area north of the Missouri (NW) and an area south and west of the Missouri (SW). A measure of the relative intensity of the land footprint for cropping, energy generation, wetlands, and grassland by subregion can be obtained from histograms of the proportion of pixels in each subregion against intensity score from the composite layers representing grassland, wetland, agriculture, and energy (Fig. 4b). These histograms show the strength of cropping in the eastern regions, the strength of grassland cover in the western regions, the increased footprint of energy generation in the western regions, and the intermingling of wetlands, grasslands, and croplands in the central regions of the State.

## Results and discussion

### Scenario story lines

The local characteristics are used to assign impacts from the global scenarios down to North Dakota (Table 3; Fig. 2). This results in seven scenarios with the following simple story lines.

1. PRSSB1GO—Under this combined story line, emphasis on global policy solutions leads to transition away from oil, moderating greenhouse gas emissions, moderate warming with lower risk of regional food shortages, and moderating food demand. Demand for agricultural commodities is strong but this is balanced by support for balanced land management and conservation measures in the US Farm Bill. Global pressure leads to a significant transition away from oil, but substitution of natural gas and hydrogen for transport maintains pressure on land use in the Bakken region of North Dakota.
2. PRSSB1TG—Under this combined story line, the path is similar to 1. However, there is increased emphasis on technological solutions resulting in more development of alternative energy such as wind, solar, and biofuel. Biofuels compete with food uses from soybeans and corn. In addition, more marginal land is returned to tall grass prairie in eastern ND for cellulosic biomass production.
3. FWCWA2OS—Under this combined story line, there is no transition away from oil; there are wars over energy resources, oil and gas exploration, and power from coal are maximized; global warming is very high; global climate changes are large with highly unpredictable consequences. Global food shortages and famine lead to huge spikes in food prices and encourage farmers to crop every possible arable land area; however, export markets are disrupted and more food is required for national purposes. The United States is forced to transition from imported oil to local stocks of natural gas, oil from coal and hydrogen systems for transportation. Coal dominates power generation and there is local mining and

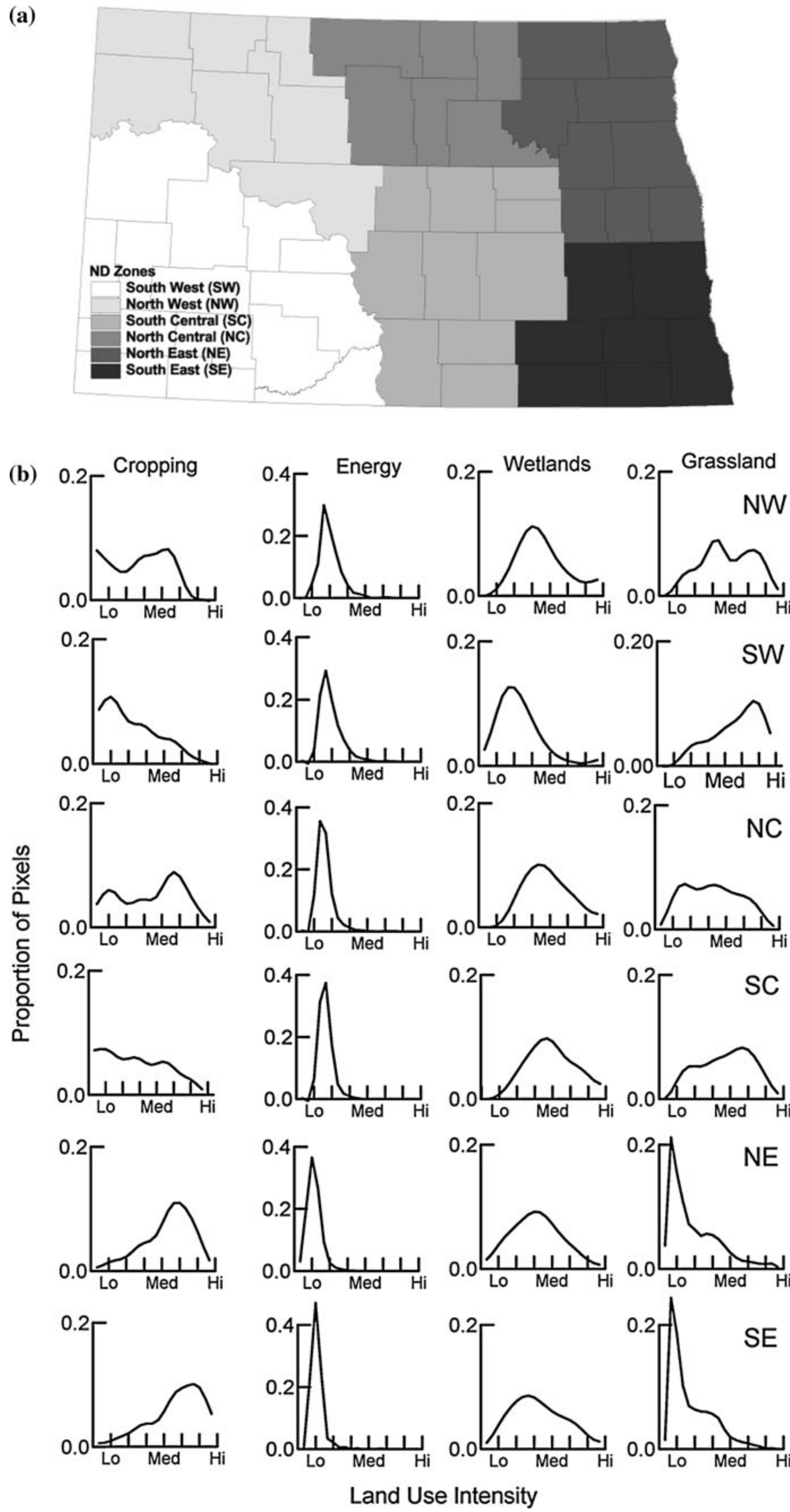


**Fig. 4** **a** Map showing six subregions for North Dakota. **b** Zone profiles for land use intensity for the six subregions

**Table 3** Factors arising from scenarios operating at the regional scale in North Dakota

| Trade-off | Positive factors | Negative factors |
|---|---|---|
| Climate and agricultural land use—relative ranking of SRES scenarios A2 > A1 > B2 > B1 in benefits and detriments (see Fig. 6) | Increase in frost-free period<br>Increase in growing degree days<br>Increase in spring precipitation—soil moisture for sowing (except eastern ND) | Increase in spring precipitation—delay of sowing (eastern ND)<br>Decrease in summer precipitation and increase in summer evaporation—greater moisture deficit and drought risk<br>Overall warming with higher extreme temperatures—damage to flowering and seed set |
| Climate and wetlands | Increase in spring precipitation—wetland saturation<br>Increase in fall precipitation—some wetland recharge | Decrease in summer precipitation and increase in summer evaporation—drying of wetlands with potential loss of intermittent wetlands to agriculture<br>Greater increase in fall evaporation than in fall precipitation—further drying of wetlands prior to winter |
| Agricultural land use and grassland | Viability of cropping is reduced by increased moisture deficits and drought risk in western ND<br>Demand for meat increases economic viability of livestock grazing relative to cropping<br>CRP or equivalent programs continue | Global food demand encourages more cropping in regions where climate change impacts are not detrimental<br>Reduction in CRP or equivalent grassland conservation activities<br>Subsidies for energy crops driven by energy security imperatives |
| Energy land use and grassland | New technology for multi-hole drilling from single surface points limits aboveground drilling footprint<br>More coherent and integrated conservation policies between State and Federal jurisdictions protect grasslands | National security imperative for maximum energy development from all resources<br>State need for energy revenue |
| Agricultural land use and wetlands | Federal monetary incentives for farmers to maintain wetlands continue<br>More coherent and integrated conservation policies between State and Federal jurisdictions protect wetlands | Increased economic returns from cropping on drained or dried-up wetlands<br>Federal conservation measures are reduced and removed due to financial constraints |

refining of uranium for new nuclear power stations. Renewable energy develops slowly as a minor but important component in a national energy system based on self-reliance.

4. FWCMB2AM—Under this combined story line, there is a transition away from oil for transportation, but the other global patterns are the same as for 3. Although substantial oil is still available, the security situation still forces the USA to transition to natural gas, oil from coal and hydrogen systems for transport. However, renewable energy development is more rapid. Global warming is significant but the US Congress maintains federal conservation mechanisms and these provide some mitigation of wholesale conversion of land to agriculture in order to provide biofuel and supply both domestic and international food demand.
5. MFMAA1GO/TG—Under this combined story line, the world continues in the current economic and cultural state with development strongly driven by market forces. In North Dakota, oil and gas exploration and energy generation from coal and alternatives expand to meet national needs in the face of international supply shortages. Agriculture expands onto marginal lands and most of the CRP land is returned to cropping in order to meet international demand for food from expanded markets and climate change-induced famine.
6. MFCMA1GO/TG—This story line varies from number 5 above in the manifestation of major oil security crises, which divert financial resources to the military, and disrupt markets reducing growth, and diverting intellectual and political energy from a necessary focus on productivity and dealing with environmental issues. This results in reduced financial resources for the federal programs and limited conservation mechanisms.
7. GTSSB1TG—Under this combined story line, the global development model is transformed to focus on

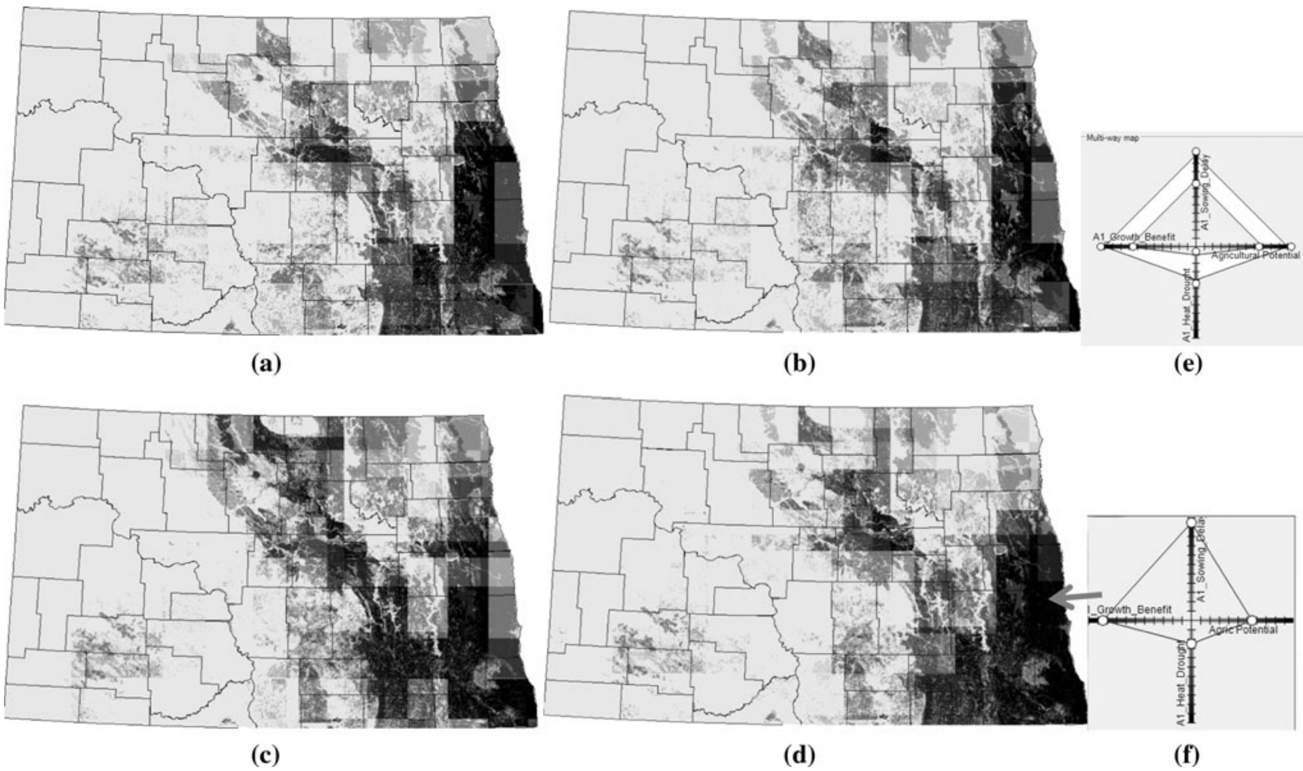


**Fig. 5** Climate versus agriculture. Areas with high agricultural potential, high climate change growth benefit, smallest increase in heat and drought risk, but potential delays in sowing due to wet springs. **a** A1FI. **b** A2; **c** *B1*; **d** *B2*; **e** the mapping envelope; and **f** example location in eastern ND showing the correspondence with the mapping envelope. The *grayscale* from *light* to *dark* indicates low to high match to the envelope

sustainability. There is a rapid transition away from oil and a rapid development of alternative energy generation. In North Dakota, fossil fuel supplies are conserved and energy and transportation are supported by a mix of fossil and alternative energy sources including wind, biofuel, hydrogen, and solar. Land use maintains a mix of cropping, and conservation of grassland and wetland that enhances overall ecosystem function and helps to mitigate flooding.

## Climate versus agriculture

Based on an integration of the major issues for agriculture in North Dakota (wet spring reducing planting, short growing season, requirement for sufficient GDD to reach maturity, and drought) with the current assessment of climate changes expected in ND (Christensen et al. 2007), the major positive effects could be captured through the increases in growing degree days (GDD) and in the length of the frost-free period (FFP). The major negative effects could be captured through the increase in overall warming, the increase in summer moisture deficit due to decreased precipitation and increased evapotranspiration, and the potential effect of wetter springs on access to planting (Table 3). When these data are examined for an envelope of lowest negative effect, highest positive effect, and high agricultural potential, southeastern ND is highlighted, along with some central areas just to the north and east of the main PPR (Fig. 5). Since the positive effects are primarily in terms of growing season and increased rainfall, but the negative effects are in terms of moisture deficit and potential drought, the practical, realizable benefits can only be quantified through detailed process modeling with multiple realizations of plausible future daily weather regimes.

## Climate versus wetlands

The examination of the impact of climate change on wetlands involved construction of composite layers that represent threat to wetlands and benefit to wetlands. Benefit is provided by increases in spring precipitation, spring P/E ratio, and fall precipitation. These all potentially lead to more water for wetlands after the snowmelt. The threat to wetlands is provided by change in spring, summer, and fall evapotranspiration, which increases, and change in summer and fall P/E ratio, which decreases. These all potentially contribute to more rapid drying of wetlands. The impacts can be summarized by deriving maps for each scenario that

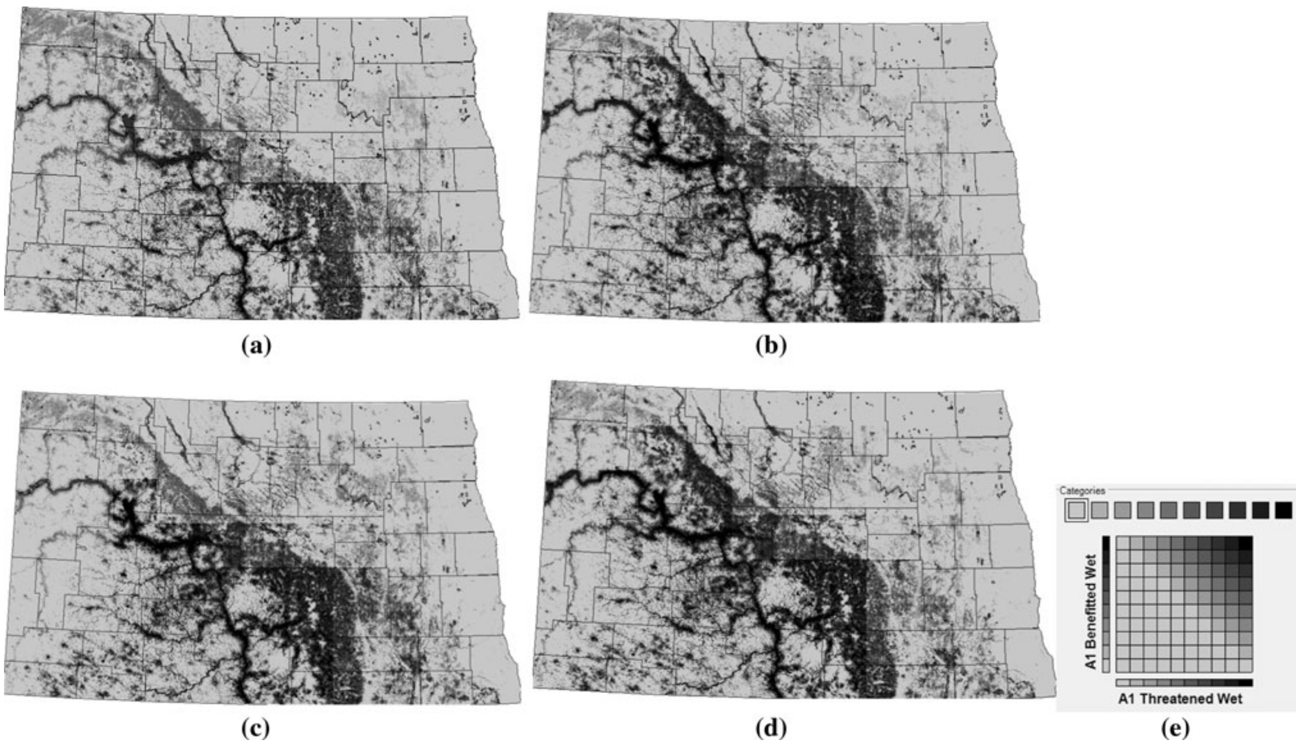


**Fig. 6** Climate versus wetlands. Areas where the benefits in terms of more spring precipitation and threat in terms of more evapotranspiration and less summer precipitation are highest. **a** A1FI; **b** A2; **c** *B1*; **d** *B2*; **e** *grayscale* legend from lowest to highest conflict

highlights wetlands with a high threat and maximum possible benefit (Fig. 6). Across the whole of ND, there is a significant increase in threat to wetlands due to increased summer drying. However, if an envelope based on high risk and low benefit is examined, then the highest risk is focused on the NW of ND under the A1 scenario.

## Agricultural and energy development likelihood

The likelihood of agricultural development in North Dakota is derived from combining spatially explicit assessment of climate change impact from the scenario trajectories in Fig. 2, with an inferred effect of food demand and biofuel demand arising from those scenarios. The climate change scenarios all constrain agricultural development to the eastern half of ND since they all predict increasing moisture deficit and hence increased drought potential in the west. However, the magnitude of the effects—the growing season and rainfall benefits and the moisture deficits—can be ranked A2 > A1 > B2 > B1. The potential pressure for agricultural and biofuel crop expansion can also be ranked A2 > A1 > B2 > B1 since climate outcomes are the result of corresponding population and oil security drivers. These can be represented in a qualitative way by identifying the regions under each scenario that satisfies the criteria of lowest negative effect of climate change, highest positive effect of climate change, and greatest potential diversity of cropping options (Fig. 7).

All of the scenarios result in potential increased agricultural activity in eastern North Dakota, but the greatest potential for increased intrusion of agriculture into central ND arises under the most favorable global development and climate change scenario, B1. The severity of potential constraints on agriculture arising from the least favorable scenarios, A1 and A2, results in less potential from agricultural development in central North Dakota. These patterns could be modified to some degree by high demand for liquid biofuels to substitute for scarce oil, but this would increase crop substitution between corn and other crops within the SE region that is highly agriculturalized already. Provided yields were economic, cellulosic ethanol could be produced from switch grass or mixed tall grass stands in central ND since warming would make these regions more suitable for warm season tall grasses. However, summer moisture deficits could restrict yields. This analysis highlights a zone of potential pressure on the edge of the PPR in central ND.

The likelihood of energy resource development is strongly influenced in different directions by the scenario paths in Fig. 2. The pattern of outcome is determined by the relative emphasis on current fossil fuel-based resources versus transition to a more balanced mix of fossil fuel and renewable wind, solar, and biomass resources. These alternatives can be represented by changes in the relative

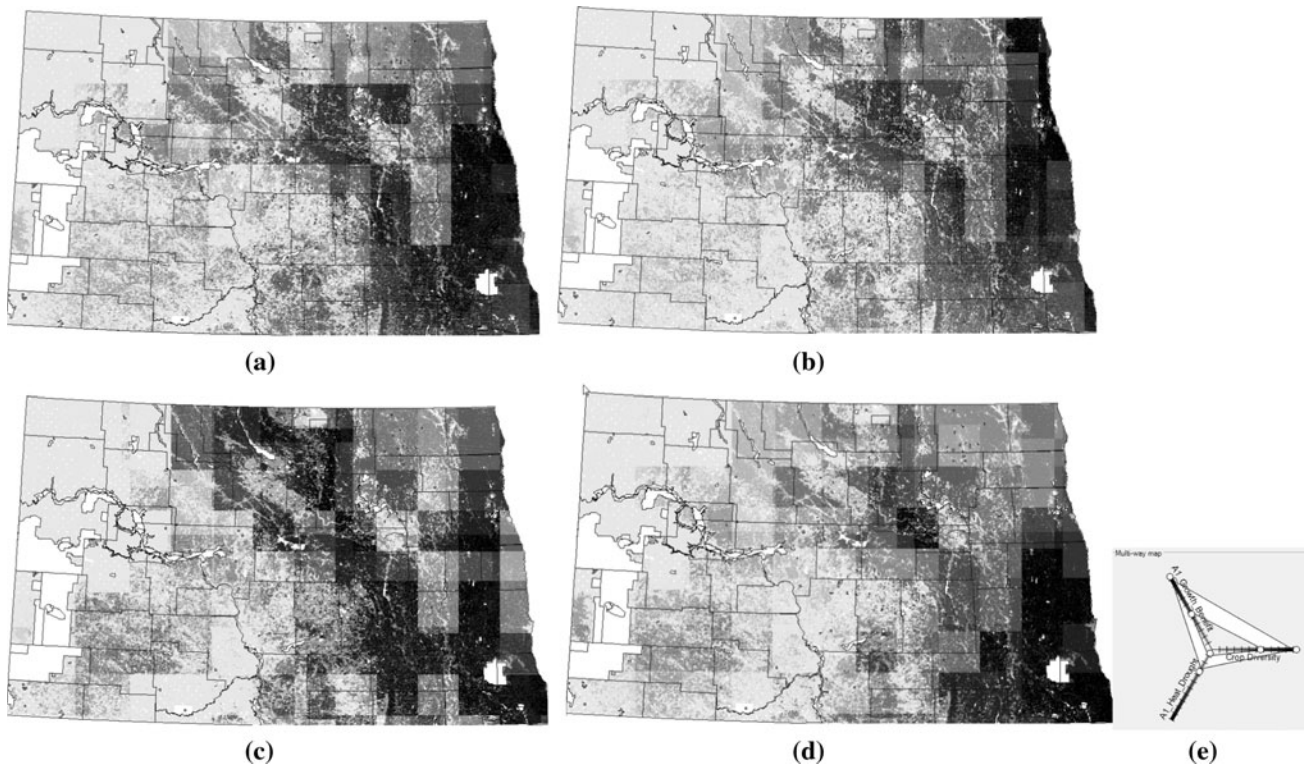


**Fig. 7** Likelihood of agricultural development. **a** *A1FI*; **b** *A2*; **c** *B1*; **d** *B2*; and **e**. Response envelope representing lowest drought and heat effects and highest crop diversity (i.e., potential adaptability and flexibility) and highest growth benefit. The *grayscale* from *light* to *dark* indicates low to high likelihood

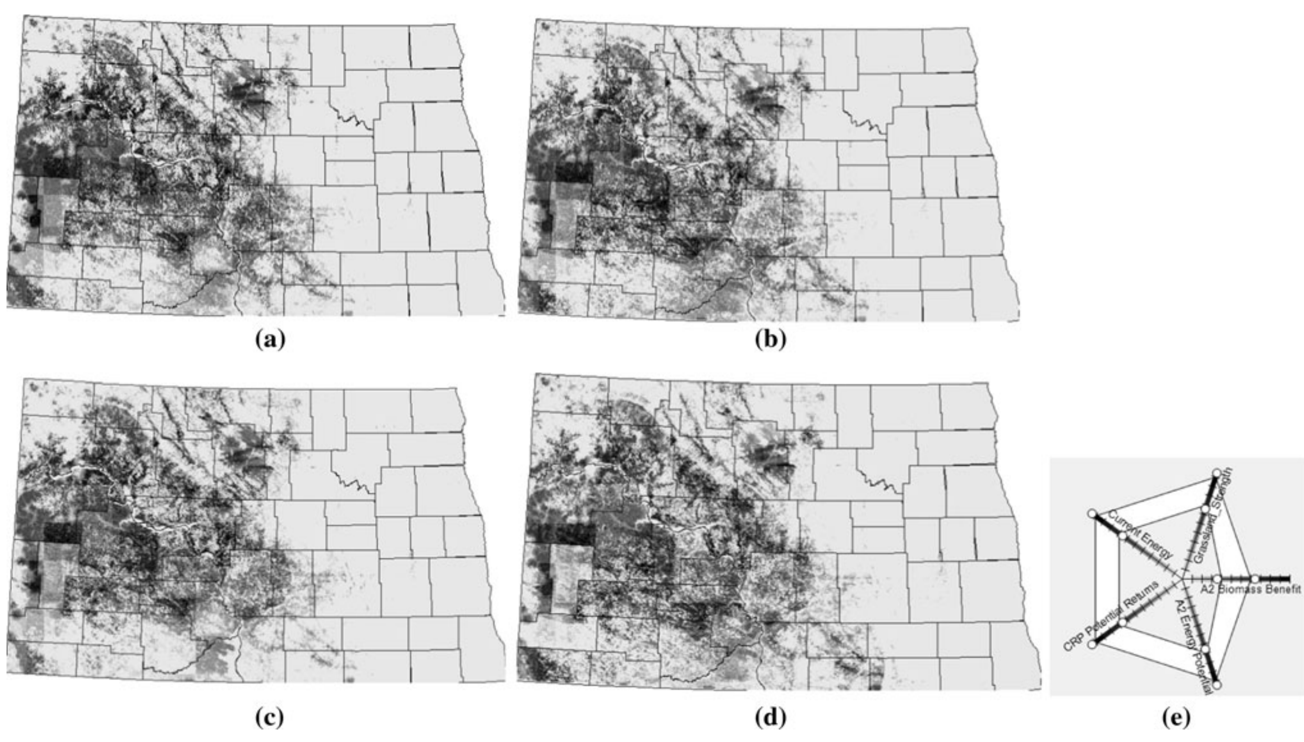


**Fig. 8** Energy versus grassland for all SRES scenarios. Multi-way composites showing areas of high conflict between energy resources and grasslands. **a** *A2*; **b** *A1*; **c** *B2*; **d** *B1*; and **e**. The response envelope corresponding to high current and future energy generation potential, moderate biomass benefits, and high grassland strength and potential CRP value. The *grayscale* from *light* to *dark* indicates low to high conflict

contribution of spatial data layers describing current energy and future energy resources. For the Fortress World/Conflicted World global path leading to A2 warming outcomes, energy potential is based on ranking on a 10:5:1:1:1:1 ratio for coal/oil:current energy:biomass:solar:hydrogen:wind. When this is contrasted with grassland, the outcome is as shown in Fig. 8a. For a Market Forces/Muddling Along global path, energy potential is based on a ranking of 6:1:1:2:1:4 ratio for the above alternatives, resulting in the grassland impact in Fig. 8b. Under a Fortress World/Crisis Management global scenario leading to regionalized responses and a B2 warming outcome, energy potential is based on a ranking of 5:1:3:1:1:2 for the alternatives, resulting in the grassland impact in Fig. 8c. Finally, under either a Policy Review or Great Transition/Smooth Sailing global scenario path, energy potential is more evenly balanced among fossil and renewable resources, and based on a ranking of 2:1:2:2:2;2 for the alternatives, resulting in the grassland impact in Fig. 8d. It is striking that the resulting maps still concentrate most of the pressure in the western half of North Dakota, since this is where the grassland land cover is high, the fossil fuel reserves are concentrated, and the potential for wind and solar energy is highest.

## Impacts of scenarios in North Dakota

The regional impacts on ND from the different scenarios can be compared by examining the distributions of values

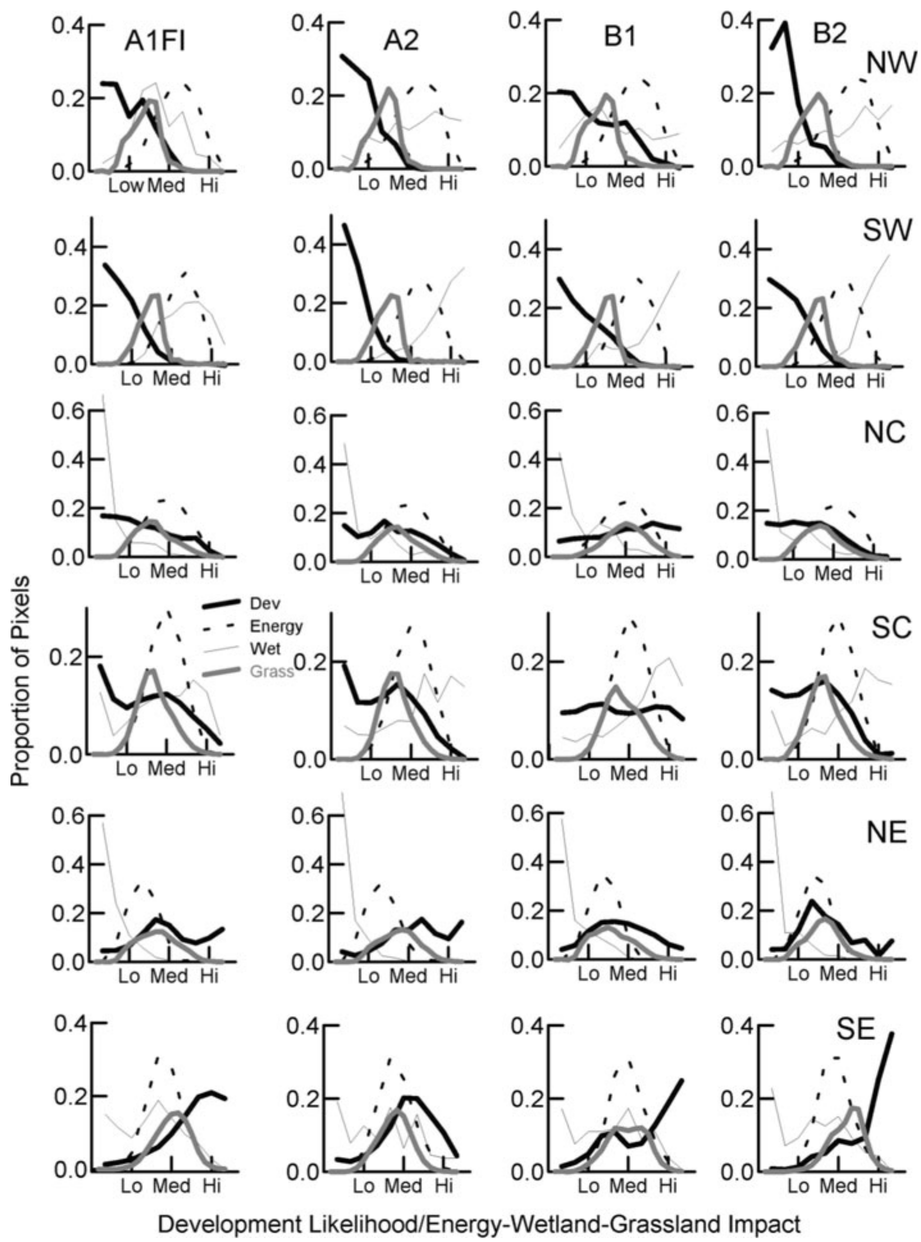


**Fig. 9** Regional impacts of scenarios on North Dakota. *Columns* represent SRES scenarios. *Rows* represent regions as shown in Fig. 4. *Lines plot* the proportion of pixels associated with low to high agricultural development potential, impact of agricultural development on grassland, impact of energy development on grassland, and impact of climate change on wetlands

for agricultural development likelihood, impact of agriculture on grassland, impact of energy potential on grassland, and impact of climate on wetlands for the six regions of ND (Fig. 9). These graphs show marked regional differences in potential for agricultural expansion and energy impacts on grassland and significant regional differences between scenarios. In most regions, the majority of the area has a low-to-moderate impact of agricultural expansion on grasslands except in the SE where grasslands are very low in "strength" in any case. The main area of potential pressure falls in the NC and SC regions, which correspond to the zones of most likely agricultural expansion (Fig. 9). Regional climate impacts on wetlands are calculated from only those pixels with high wetland strength, since wetlands are highly dispersed in the landscape. The SC and SW regions have high proportion of wetland pixels with high climate change impacts. The highest impacts of energy on grassland occur in the NW and SW regions; however, patterns do not vary much between scenarios due to the highly regionalized spatial patterns of fossil and renewable energy potential.

The overall impact of the combined effects of climate change, agricultural expansion, and energy development on grassland and wetlands results in concentrated pressure on central areas of ND in an arc running from SE to NW that aligns very well with the PPR. Histograms of overall impact show that around 50 % of the land in the SW, NW, and SC faces medium-to-high impacts from global changes under all scenarios (Fig. 10). The potential impacts are lower in the NE and SE since there is less grassland, much less energy potential, more beneficial climate change, and less wetland.

## State of ND environment: MEA scenarios

The final stage of the analysis involves "conceptual overlay" of the results of the combined global development, oil security, and climate change scenarios with the local conservation framework as driven by the scenario story lines. The global MEA scenarios (Figs. 1, 2) provide an overall orientation and sentiment that may affect local outcomes in terms of global environmental awareness and ecosystem management. However, with North Dakota, the primacy of private land management rights and the economic imperatives for land conversion driven by commodity price rises will dominate. If the 1.8 % of land in dynamic pastures is ignored, there are about 28 % of lands under grazing or hay production, and just over 5 % in CRP and other conservation programs (Table 1). The fate of CRP lands lies in the hands of the US Congress and in the relative returns from CRP and other conservation programs compared to commodity prices. The scenarios would most likely be ranked in order to commodity price rise, in order GTSSB1TG < PRSSB1GO

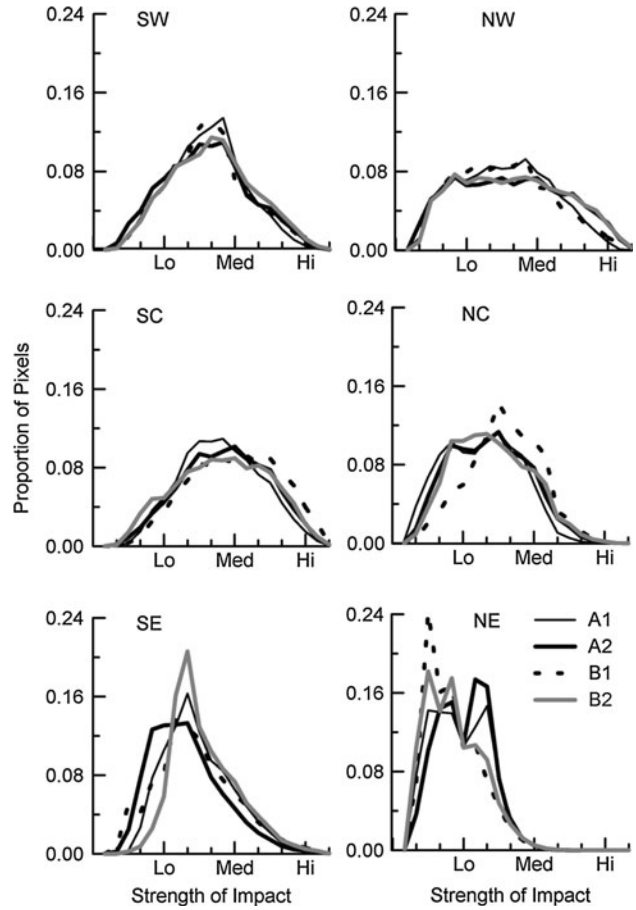


**Fig. 10** Strength of impact of global change scenarios on regions of North Dakota as measured by the proportion of pixels associated with low to high impact values for the four SRES scenarios

< PRSSB1TG = MFCMA1TG− = MFMAA1TG < MFMAA1GO < FWCMB2AM < FWCWA2OS. Economic analysis suggests that rates of conversion will increase with increased commodity prices (Rashford et al. 2010). The fate of hay fields and grazing land will be strongly controlled by the balance between limits on potential crop production due to negative climate changes and the relative economic returns from livestock and field crops. Given that the analysis shows that the highest likelihood of conversion to agriculture falls in central ND and in the PPR, the likelihood of conversion on a land parcel basis may be highly variable depending upon land capability, soil type, yield potential, and prices for suited crops (Rashford et al. 2010).

The fate of wetlands is almost entirely in the hands of realized climate impacts with severity of effect being A2 > A1 > B2 > B1 conforming to the detailed analysis of Johnson et al. (2005, 2010). Within these outcomes, the strength of incentives and/or regulations protecting remaining wetlands on private lands from conversion may be manifested as shown in Fig. 2, where in GTSSB1TG > PRSSB1GO = PRSSB1TG > MFCMA1TG > MFMAA1GO > FWCWA2OS = FWCMB2AM.

The fate of western grasslands impacted by oil and gas exploration depends upon the extent to which fragmentation and indirect effects from transport and invasive species impact endangered species habitats or hydrology. There is likely to be a constant tension, but an uneasy coexistence between oil and gas drilling and grassland habitats for as long as extraction is economically viable and in the national interest. Therefore, global change scenarios that lead to energy regimes more balanced between fossil and renewable fuels may lead to reduced tension between grassland and drilling. Hence, the scenarios in Fig. 2 are ranked in terms of most to least favorable for grasslands as GTSSB1TG > PRSSB1GO = PRSSB1TG > FWCWA2OS = FWCMB2AM = MFMAA1GO = MFCMA1TG.

## Conclusion

All future global change scenarios focus more potential pressure on central ND and the PPR, since all current SRES climate change outcomes predict a tension between better thermal and poorer moisture growing conditions, with a tipping point for benefits lying around central ND and the middle of the PPR. The scenarios with the greatest climate change, population increase, and oil consumption will magnify food and bioenergy demand, and hence may result in commodity price rises that substantially drive conversion of grassland to cropland (Rashford et al. 2010). However, these scenarios also result in the greatest reductions in precipitation during summer and hence the greatest restriction on the westward expansion of cropping. As a result, food and energy imperatives might demand that grassland with moderate or even relatively low crop yield potential currently in CRP or under grazing be converted for food or biofuel production in the humanitarian and national security interests. Such conversion may be facilitated by shrinking of PPR wetlands due to dryer summers (Johnson et al. 2005, 2010), removal of "conservation" limits (reduced federal programs), and increased resumption of private wetland for cropping. The land area rendered idle has historically shown a tendency to vary inversely with net farm income (Wiebe and Gollehon 2006). The primacy of private land management rights in ND means that Federal incentives for conservation such as CRP, WRP, and other Farm Bill programs would be very important factors in retaining residual perennial wetland, and remnant native grassland on private land and maintaining biodiversity and ecosystem function (e.g., Gleason et al. 2011). Conservation programs in the Dakotas are estimated to provide a net benefit to society of $1 billion over a 20-year time period with largest benefits from carbon sequestration and waterfowl production (Gascoigne et al. 2011).

Projection of federal conservation programs out to the 2070–2100 period in a scenario context could be regarded as highly problematic; however, land retirement programs have been in existence since the 1930s (Claassen et al. 2011), so it is not unreasonable to suggest that similar mechanisms may be active or even more prominent in 60 years from now. Assessments of some of these programs (CRP, CSP, and EQIP) indicate variable levels of success, concerns with effectiveness, and some reservations about CRP as a default means of conserving/maintaining grassland in the landscape (SWCS/EDF 2008). Recent assessment of ecosystem services in the PPR that focused on native prairie grasslands, CRP/WRP, and cropland found that CRP/WRP does not compensate for loss of native prairie grassland (Gascoigne et al. 2011).

Analysis of long-term oil and gas leases in grasslands of Saskatchewan indicates that impacts extend beyond the direct footprint of the physical infrastructure, with litter and herbaceous cover increasing and bare soil and compaction decreasing with distance from the well head (Nasen et al. 2011). In addition, range health and desirable species diversity was lower, and abundance and diversity of undesirable species were higher on lease sites. Given that energy demand and security issues likely mean that western ND will have a high intensity of oil and gas extraction for as long as reserves hold out, similar impacts to those described for Saskatchewan may be expected on native prairie grasslands associated with oil and gas leases in ND. Recent discoveries and advances in extraction technology, and a full appreciation of the potential diversity of fuel resources from shale oil, gas, coal conversion, and electrification may have cast doubt on the peak oil hypothesis (Helm 2011). "Peak oil" assumes that limited supply and expanding demand result in increased prices and shortages (e.g., Sorrell et al. 2010). However, the oil security scenarios used here still represent an appropriate framework for this analysis, since United States consumption is so much greater than current national stocks, and gas substitution for oil does not change potential impacts in western North Dakota.

The outcome of this analysis is highly dependent upon the regional climate change projections associated with the SRES scenarios. North Dakota is at a critical location in relation to the line of zero change in summer precipitation for North America: the line lies further to the north for SRES scenarios with greater greenhouse gas emissions (IPCC 2007). However, the uncertainty around precipitation projections is high and a shift in this line further to the south could reduce negative climate effects on agriculture, and agricultural expansion in response to food demand and commodity prices, and longer growing seasons, could be more intensive and extensive in central and western ND. In addition, the SRES scenarios are somewhat confining due to the linear consequential framework. A more flexible framework (Moss et al. 2010) that operates in parallel and facilitates information flow between physical, biological, and social sciences could provide more variety in outcomes.

Finally, there is an element of personal judgment in any scenario analysis (Metzger et al. 2010). This is particularly so where rankings are adjusted for different energy combinations among the global scenarios in order to adjust energy pressure on grasslands. However, for the most part, the data in terms of climate change patterns and the distribution of grasslands, wetlands, and croplands form an objective, but qualitative basis for the results.

**Acknowledgments** This work was supported by USDA-ARS under cooperative agreements 58-5445-5-338 and 58-5445-0-347 (Sustainable Systems for the Northern Great Plains). WORLDCLIM surfaces and derived data were provided by Andrei Kirilenko.

## References

Abildtrup J, Audsley E, Fekete-Farkas M, Giupponi C, Gylling M, Rosato P, Rounsevell M (2006) Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pair-wise comparison approach. Environ Sci Pol 9:101–115

Aravindhakshan S, Koo WW (2011) Energy, agriculture, and GHG emissions: the role of agriculture in alternative energy production and GHG Emission Reduction in North Dakota. Center for Agricultural Policy and Trade Studies, Department of Agribusiness and Applied Economics, North Dakota State University, Agribusiness & Applied Economics Report No. 677, p 45

Audsley E, Pearn KR, Simota C, Cojocaru G, Koutsidou E, Rounsevell MDA, Trnka M, Alexandrov V (2006) What can scenario modelling tell us about future European scale agricultural land use, and what not? Env Sci Pol 9:148–162

Berry PM, Rounsevell MDA, Harrison PA, Audsley E (2006) Assessing the vulnerability of agricultural land use and species to climate change and the role of policy in facilitating adaptation. Environ Sci Pol 9:189–204

Boyer W, Gadow B, Mills N, Roberts C (2008) The North Dakota wind energy cluster: an economic analysis. PA8081(7) Community and Economic Development Capstone, Hubert Humphrey Institute of Public Affairs, University of Minnesota, p 148

Carpenter SR, Pingali PL, Bennet EM, Zuek MB (eds) (2005) Ecosystems and human well-being: scenarios, vol 2. Findings of the scenarios working group, Millennium Ecosystem Assessment, Island Press, Washington DC, p 555

Christensen JH, Hewitson B, Busuioc A, Chen X, Gao I, Held R, Jones RK, Kolli W-T, Kwon R, Laprise V, Magaña Rueda L, Mearns CG, Menéndez J, Räisänen A, Rinke A, Whetton P (2007): Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Claassen R, Carriazo F, Cooper JC, Hellerstein D, Ueda K (2011) Grassland to cropland conversion in the Northern Plains: the role of crop insurance, Commodity, and Disaster Programs Economic Research Report No. (ERR-120), p 85

Euliss NH Jr, Smith LM, Lui S, Feng M, Mushet DM, Auch RF, Loveland TR (2010) The need for simultaneous evaluation of ecosystem services and land use change. Environ Sci Tech 44:7761–7763

FitzSimons J, Pearson CJ, Lawson C, Hill MJ (2012) Development of land use planning scenarios based on intrinsic characteristics and stakeholder values. Landsc Urban Plan 106:23–34

Gascoigne WR, Hoag D, Koontz L, Tangen BA, Shaffer TL, Gleason RA (2011) Valuing ecosystem and economic services across land-use scenarios in the Prairie Pothole Region of the Dakotas, USA. Ecol Econ 70:1715–1725

Gleason RA, Euliss NH, Tangen BA, Laubhan MK, Browne BA (2011) USDA conservation program and practice effects on wetland ecosystem services in the Prairie Pothole Region. Ecol Applic 21:S65–S81

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Helm I (2011) Peak oil and energy policy: a critique. Oxf Rev Econ Policy 27:68–91

Hijams RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Clim 25:1965–1978

Hill MJ, Lesslie R, Barry A, Barry SM (2005) A simple, portable, spatial multi criteria analysis shell: MCAS-S. MODSIM 2005, international symposium on modelling and simulation, University of Melbourne, 12–15 December, 2005, CDROM

Hill MJ, FitzSimons J, Pearson CJ (2009) Creating land use scenarios for city greenbelts using a spatial multi-criteria analysis shell: two case studies. Phys Geog 30:353–382

Höök M, Sivertsson A, Aleklett K (2010) Validity of the fossil fuel production outlooks in the IPCC Emission Scenarios. Nat Res Res 19:63–81

Hurt RD (1985) The national grasslands: origin and development in the dust bowl. In: The history of soil and water conservation. Agricultural History Society, Washington DC, pp 144–157

IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Cambridge University Press, Cambridge, p 976

Johnson WC, Millett BV, Gilmanov T, Voldseth RA, Guntenspergen GR, Naugle DE (2005) Vulnerability of Northern Prairie wetlands to climate change. Bioscience 55:863–872

Johnson WC, Werner B, Guntenspergen GR, Voldseth RA, Millett B, Naugle DE, Tulbure M, Carroll RWH, Tracy J, Olawsky C (2010) Prairie wetland complexes as landscape functional units in a changing climate. Bioscience 60:128–140

Johnston P (2010) The security impact of oil nationalization: alternate futures scenarios. J Strategic Sec 3:1–26

Knoll A, Klink K (2009) Residential- and commercial- scale distributed wind energy in North Dakota, USA. Renew Energy 34:2493–2500

Lesslie RG, Hill MJ, Hill P, Cresswell HP, Dawson S (2008) The Application of a Simple Spatial Multi-Criteria Analysis Shell to Natural Resource Management Decision Making. In: Pettit C, Cartwright W, Bishop I, Lowell K, Pullar D, Duncan D (eds) Landscape analysis and visualisation: spatial models for natural resource management and planning. Springer, Berlin, pp 73–96

Martin GM, Ringer MA, Pope VD, Jones A, Dearden C, Hinton TJ (2006) The physical properties of the atmosphere in the New Hadley Centre Global Environmental Model (HadGEM1). Part I: model description and global climatology. J Clim 19:1274–1301

McFarlane NA, Boer GJ, Blanchet J-P, Lazare M (1992) The Canadian climate centre second-generation general circulation model and its equilibrium climate. J Clim 5:1013–1044

Metzger MJ, Rounsevell MDA, Van den Heiligenberg HARM, Pétez-Soba M, Hardiman PS (2010) How personal judgement influences scenario development: an example for future development in Europe. Ecol Soc 15:5 [online]. URL: http://www.ecologyandsociety.org/vol15/iss2/art5/

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakićenović N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant J, Wilbanks TJ (2010). The next generation of scenarios for climate change research and assessment. Nature 463:747–756. doi:10.1038/nature08823

Nakićenović N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, Emilio la Rovere E, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M E, Shukla P R, Smith S, Swart R J, van Rooyen S, Victor N, Dadi Z (2000) Special report on emissions scenarios. Cambridge University, Press, Cambridge

Nasen LC, Noble BF, Johnstone JF (2011) Environmental effects of oil and gas lease sites in a grassland ecosystem. J Environ Manag 92:195–204

Nickerson C, Ebel R, Borchers A, Carriazo F (2011) Major uses of land in the United States, 2007. USDA Economic Information Bulletin No. (EIB-89), p 57

Niemuth ND, Wangler B, Reynolds RE (2010) Spatial and temporal variation in wet area of wetlands in the prairie pothole region of North Dakota and South Dakota. Wetlands 30:1053–1064

Parry M, Rosensweig C, Livermor M (2004a) Climate change, global food supply and risk of hunger. Phil Trans Royal Soc B Biol Sci 360:2125–2138

Parry ML, Rosensweig C, Iglesias A, Livermor M, Fischer G (2004b) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environ Change 14:53–67

Phipps SJ, Rotstayn LD, Gordon HB, Ro JL, Hirst AC, Budd W (2011) The CSIRO Mk3L climate system model version 1.0—Part 1: description and evaluation. Geosci Model Dev Discuss 4:219–287, 2011, www.geosci-model-dev-discuss.net/4/219/2011/, doi:10.5194/gmdd-4-219-2011

Pollastro RM, Cook TA, Roberts LNR, Schenk CJ, Lewan MD, Anna LO, Gaswirth SB, Lillis PG, Klett TR, Charpentier RR (2008) Assessment of undiscovered oil resources in the Devonian-Mississippian Bakken Formation, Williston Basin Province, Montana and North Dakota, 2008: U.S. Geological Survey Fact Sheet 2008–3021, p 2

Rashford BS, Walker JA, Bastian CT (2010) Economics of grassland conversion to cropland in the Prairie Pothole Region. Cons Biol 25:276–284

Rosen RA, Electris C, Raskin PD (2010) Global scenarios for the century ahead: searching for sustainability. Tellus Institute, Boston, USA, http://www.Tellus.org, p 17

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005) Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. Agric Ecosyst Environ 107:117–135

Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaanpää S, Leemans R, Metzger MJ, Schmidt C, Smith P, Tuck G (2006) A coherent set of future land use change scenarios for Europe. Agric Ecosyst Environ 114:57–68

Schade C, Pimental D (2010) Population crash: prospects for famine in the twenty-first century. Environ Devel Sust 12:245–262

Scherr SJ, Wallace C, Buck L (2010) Agricultural innovation for food security and poverty reduction in the 21st century: issues for Africa and the World. Issues paper for State of the World 2011: innovations that nourish the planet, Ecoagriculture Partners, Washington DC, http://www.ecoagriculture.org, p 20

Sorenson JA (2008) Evaluation of key factors affecting successful oil production in the Bakken formation, North Dakota. Technology status assessment. Energy and Environmental Research Center, Grand Forks, ND. Report submitted to US Department of Energy

Sorrell S, Speirs J, Bentley R, Brandt A, Miller R (2010) Global oil depletion: a review of the evidence. Energy Pol 38:5290–5295

Strong LL, Sklebar TH, Kermes KE (2005) North Dakota Gap Analysis Project. Final Report. U.S. Geological Survey, Northern Prairie Wildlife Research Center, Jamestown, ND

SWCS/EDF (2008) Conservation Reserve program (CRP) Program Assessment. A report from the soil & water conservation society and environmental defense fund. soil & water conservation society, Ankey, IA and Environmental Defense Fund, New York, NY, p 45

UNEP/RIVM (2003) Four scenarios for Europe. Based on UNEP's third Global Environment Outlook. UNEP/DEIA&EW/TR.03-10 and RIVM 402001021

USDA Farm Service Agency (2012) Summary of active and expiring CRP cropland acres by State. https://arcticocean.sc.egov.usda.gov/CRPReport/ Accessed 01 Oct 2012

Vogelmann JE, Howard SM, Yang L, Larson CR, Wylie BK, Van Driel JN (2001) Completion of the 1990's National land cover data set for the conterminous United States Photogram. Eng Remote Sens 67:650–662

Wiebe K, Gollehon NE (2006) Agricultural Resources and Environmental Indicators, 2006 Edition. USDA Economic Information Bulletin No. (EIB-16)