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ABSTRACT

Land use and land cover changes have complex linkages to climate variability and change, biophysical resources, and socioeconomic driving forces. To assess these land change dynamics and their causes in the Great Plains, we compare and contrast contemporary changes across 16 ecoregions using Landsat satellite data and statistical analysis. Large-area change analysis of agricultural regions is often hampered by change detection error and the tendency for land conversions to occur at the local-scale. To facilitate a regional-scale analysis, a statistical sampling design of randomly selected 10 km × 10 km blocks is used to efficiently identify the types and rates of land conversions for four time intervals between 1973 and 2000, stratified by relatively homogenous ecoregions. Nearly 8% of the overall Great Plains region underwent land-use and land-cover change during the study period, with a substantial amount of ecoregion variability that ranged from less than 2% to greater than 13%. Agricultural land cover declined by more than 2% overall, with variability contingent on the differential characteristics of regional human–environment systems. A large part of the Great Plains is in relatively stable land cover. However, other land systems with significant biophysical and climate limitations for agriculture have high rates of land change when pushed by economic, policy, technology, or climate forcing factors. The results indicate the regionally based potential for land cover to persist or fluctuate as land uses are adapted to spatially and temporally variable forcing factors.

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Introduction

The dynamics of land-use and land-cover change are increasingly recognized as operating within a linked human–environment system that is shaped by the complex interactions of social, economic, climate, and biophysical factors (Rindfuss et al., 2004; Global Land Project, 2005; Turner et al., 2007). In practice, the organization, function, and causes of land use activities are often not adequately considered in environmental change studies. As a result, the spatial and temporal complexity of human–environmental processes and feedbacks that operate at regional to global scales are not fully understood (Liu et al., 2007). Regardless, regional analyses of the extent, types, and processes of land change are critical for further assessment of the prospects for ecological and socioeconomic sustainability (Loveland et al., 2002; Turner et al., 2007), as well as for issues of climate (Pielke et al., 2007), hydrology (Scanlon et al., 2005), carbon exchange (Burke et al., 1991; Post and Kwon, 2000; Guo and Gifford, 2002), and biodiversity (DeFries et al., 2004).

Over the past two centuries, the United States Great Plains has undergone significant land surface change as it was transformed from extensive grassland to a modern mosaic of rangeland, dryland farming, and intensive irrigated and industrial agriculture. Perceptions of the Great Plains, which have ranged from desert to agricultural oasis, have also evolved over time, in part as advances in technology and agricultural practices aided adaptation to climate variability and drought (Lawson and Stockton, 1981; White, 1994). Recent scientific thought emphasizes the longevity and sustainability of agricultural pursuits, while also recognizing the risks and vulnerability of the region to socioeconomic and environmental change and the opportunities to enable resilience (Cunfer, 2005; Parton et al., 2007). Many areas of the Great Plains may remain relatively stable producers of food, fiber, and fuel well into the future. However, other areas in the region are significantly affected or may be affected in the near future by climate change, land use policies, increased demand for biofuels, globalization, national economic conditions, declining water availability, population change,

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and other factors. Indeed, regional land use practices have been adapting to climate and resource variability, new technology, regulatory policy, and new global economic opportunities for decades (Easterling et al., 1993). In light of the contemporary pressures and driving forces shaping the Plains, how dynamic and diverse are the land changes in the region?

Across the Great Plains, where extensive areas of land are dedicated to livestock and cropping activities, land use patterns inevitably rely on the environmental capacity for agricultural production, as well as the human capacity to utilize available resources. However, the timing and extent of land changes are modulated by numerous socioeconomic forces. Essentially, different locations have geographic advantages or limitations for intensive crop production, rangeland grazing, or other agricultural uses that are contingent on the prevailing climate and land quality (e.g., soils, topography, and water availability). Human interactions further strengthen or diminish the characteristics of local and regional-scale change through land use policies and economic opportunities (Drummond, 2007), technological advances and agricultural inputs (Parton et al., 2007), population and demographic shifts (Gutmann et al., 2005), industrialization of agriculture (Hart and Mayda, 1998), and surface and groundwater irrigation (Kromm and White, 1992). The human–environmental land system not only enables the management of the landscape for the production of food, fiber, feed grains, and fuel but also causes feedbacks and consequences that ultimately affect the vulnerability and sustainability of the system. Because of these interacting forces, the rates, causes, and implications of land change may vary substantially across the region.

To examine land change dynamics, we analyzed the geographic and temporal variability of land use and land cover for five dates between 1973 and 2000 stratified across 16 nested ecoregions that comprise the greater Great Plains ecoregion (Fig. 1) (Omernik, 1987; Commission for Environmental Cooperation [CEC], 1997; US Environmental Protection Agency [USEPA], 1999). The hierarchical ecoregion framework provides a set of relatively homogenous land units (EPA Level III ecoregions) to compare, contrast, and generalize the characteristics of land conversion across the diverse conditions of a large region such as the Great Plains (EPA Level I ecoregion), which has considerable potential for regional transformation. The individual ecoregions of the Great Plains may show differential characteristics of change that ultimately relate to many of the pressing issues of land use that include providing food and fuel for a growing world population, carbon sequestration, groundwater mining, strategic habitat conservation, and climate change.

Land change research

Several contemporary research issues help to frame the regional-scale land-cover changes affecting the Great Plains, including a significant historical redistribution of human population and demographics. Population has declined and aged in many rural areas since the 1930s, although there may not be a close relationship between modern rural population loss and land-cover change across most of the Great Plains (Gutmann et al., 2005). Population has stabilized or increased in a few locations of expanding agricultural industry, including Finney County, Kansas where confined feeding operations and meat packing plants provide employment opportunities (Broadway, 1990; Harrington and Lu, 2002). Large cities and their surrounding areas have gained population, which can have a detrimental effect on the local extent of agricultural land as urban areas, exurban settlements, and industry gain water rights and expand onto cropland and pasture (Parton et al., 2003). Total population in the region increased by about 50% between 1970 and 2000; however many rural counties had net population loss, while there were substantial gains in urban and peri-urban areas (Wilson, 2009). This is linked to decreases in farm numbers, larger farm sizes, and decreased labor needs of modern agricultural production (Hart, 2003).

Public policies and subsidies that incentivize or delimit access to natural resources have a variable impact over time and space. This includes policies that promote or mitigate the use of energy sources, water resources, and environmentally sensitive land. The Conservation Reserve Program (CRP) established by the Food Security Act of 1985, which has encouraged landowners to retire millions of hectares of highly erodible and environmentally sensitive cropland from production using 10–15 year contracts, has had a substantial effect on land use patterns while also improving wildlife habitat, water quality, and soil carbon and nitrogen storage (Riebsame, 1990; Gebhart et al., 1994). Retired land is planted to native and cultivated grasses, windbreaks, and other cover types allowed by the initial program and subsequent Farm Bills. Although some rangeland and native grasslands may be newly tilled even as potentially less-diverse CRP grassland is established, the more than 7 million hectares of Great Plains CRP land benefits numerous birds and other wildlife species (Higgins et al., 2002). If the economic and social incentives to keep farmland in CRP weaken, then a significant amount of land could be put back into production and perhaps have a detrimental effect on local ecosystem services.

Efforts to establish biofuels as a substitute energy source could influence a trend away from land retirement (Searchinger et al., 2008). For example, the expanded use of various cultivated grasses in the drier western plains that are useful for biofuel production could cause large areas of land to be dedicated to biomass crops, although questions remain about the ramifications of such changes (Rosenberg and Smith, 2009). The amount of corn used for ethanol production in the United States tripled between 2003 and 2008, while the worldwide demand for food and livestock feed accounted for a much higher (greater than 90%) amount of the global increase in wheat, corn and other grains (Trostle, 2008). This suggests that global demand for food and feed as population and demographic factors evolve will continue to be a significant factor for future land change, and suggests a need to explore biomass sources that do not impact food production.

Climate variability and change pose risks to farmers, biota, and human well-being. Future variability of summer temperature, evaporation, and precipitation may stress the wetland and riparian ecosystems and other habitat, as well as put additional pressure on land use and a limited water supply (USGCRP, 2009). Access to water, including the High Plains Aquifer, has enabled agricultural intensification and expansion, although declining water availability and drought takes a toll on land use. Water-levels of the aquifer declined by a geographically weighted average of more than 11 ft. (200 million acre-ft.) between predevelopment and 2001 and had a greater than 50% loss of saturated thickness in the southwestern part of the Texas Panhandle due to land use (McGuire, 2003). Saturated thickness is highly variable across the aquifer, and recharge rates are generally low compared to pumping rates (Dennehy et al., 2002). Limits to the water supply have reportedly caused farm abandonment in areas of the semi-arid High Plains (Walsh, 1980; Nellis et al., 1996; Wu et al., 1999; Kettle et al., 2007). This has occurred even as industrial agriculture, crop irrigation, and confined feeding operations expanded and integrated around readily available, but declining, water supplies (Kromm and White, 1992; Harrington and Lu, 2002).

Woody plant encroachment onto grasslands and savannas, such as in the southern plains, may significantly alter carbon sequestration dynamics and contribute to a carbon sink (Hibbard et al., 2003; Wessman et al., 2004), as well as affect soil moisture and other biota. Climate and land use factors contribute to the expansion. Encroaching brush and trees are sometimes cleared by landowners as part of rangeland management and habitat enhancement. The regional extent of woody encroachment in the southern plains

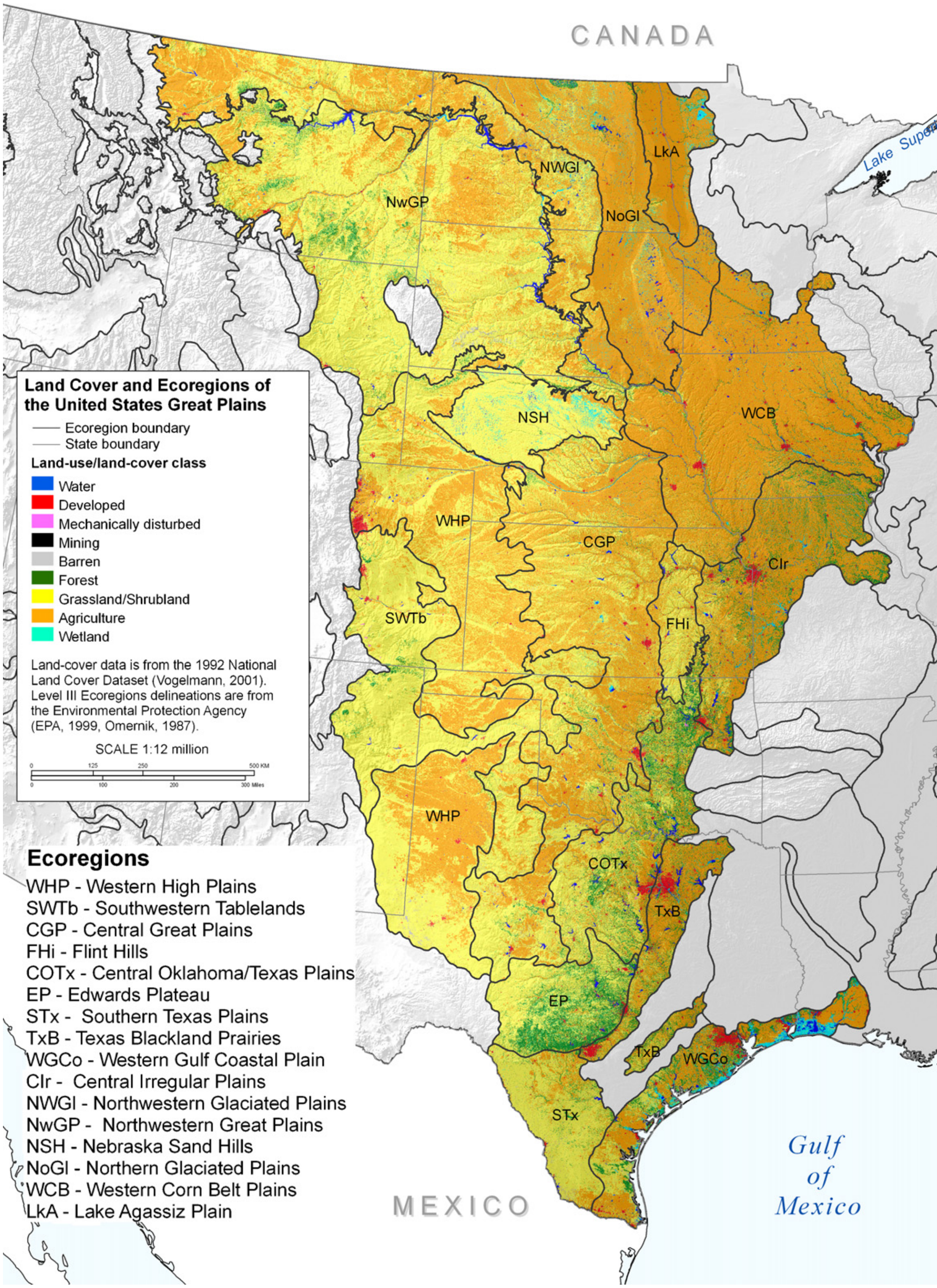

Fig. 1. The greater Great Plains region (EPA Level I ecoregion) includes 16 Level III ecoregions that extend north to south from the borders with Canada and Mexico and west to east from the Rocky Mountains to the Midwestern woodlands (Omernik, 1987; CEC, 1997; USEPA, 1999).

may be extensive (Mitchell, 2000); however, the amount of subsequent clearance is unclear. The dynamics of woody growth and clearance affects land use patterns, biodiversity, soil carbon and other environmental factors. Global carbon management depends, in part, on land and soil conditions in the grassland and agricultural regions. The storage of soil carbon differs spatially and temporally across the Plains depending on environmental characteristics such as drought but also on land-use change and the intensity, type, and time-span of cultivation (Parton et al., 2005).

Regional agricultural land use changes occur within a global context of an increasing human population and changing demographics that affects the demand and preferences for agricultural products. A projected 34% increase in global population and a more affluent and urban society may necessitate a 70% increase

in food production by 2050 (Food and Agriculture Organization of the United Nations [FAO], 2009). Part of the equation for meeting that demand is to ensure that food production has the capacity to adapt to changes in climate and to other pressures such as increased biofuel production (FAO, 2009). Global population growth coupled with the effects of regional climate variability and drought on food supplies could increase the demand for agricultural land in the Great Plains. Given these pressures, regions must balance land-use change and the provision of ecosystem goods with the unintended consequences to climate, carbon, water, biodiversity and other ecosystem services (DeFries et al., 2004; Ramankutty et al., 2008).

In many regards, the theoretical underpinnings of land use and land-cover change are still being developed beyond the broad interpretations of the von Thünen model of declining bid-rent as the distance to market increases (Walker and Solecki, 2004), although Lambin et al. (2000) discuss several theoretical concepts useful in agricultural land use models. Central to the von Thünen model is the assumption that land, for a given location and its environmental attributes, will be allocated to the use that earns the highest profit or surplus with variability of agricultural rent dependent on climate, land quality, and socioeconomic factors (Polsky and Easterling, 2001). The land rent concept provides a basic framework to help characterize successive land changes and their relationship to potential economic forces and proximate causes.

Material and methods

Study region

The Level I Great Plains ecoregion of the U.S. includes all or part of 14 states, covering an area of 2,187,091 km^2. It is characterized by relatively flat grassland and shrubland plains and prairies with few trees and a semi-arid to semi-humid climate (CEC, 1997). A strong west to east gradient of increasing precipitation (approximately 25–125 cm) and a north to south gradient of increasing temperature largely define the distribution of ecosystems and agricultural management (Gutmann et al., 2005). Precipitation can be highly variable, with periods of drought as well as deluge. Grass and shrubland cover-types transition from drier, shortgrass steppe in the west to tallgrass in the east. Although most of the land cover is characterized as cropland, grassland, and shrubland, there are woodlands in the southeast, sand dunes in the west-central plains, and prairie pothole and playa wetlands in the northern and southern plains. The numerous pothole depressions left by glaciation and the shallow playa lake depressions caused by wind erosion and other processes of deflation provide wetland habitat and other ecosystem services (Smith et al., 2011).

Land cover approach

Because of the potential for a variety of land-use changes across such a large region, an appropriate geographic framework is needed for generalizing the characteristics of land change and identifying the diversity of interactions with environmental and socioeconomic factors (Gallant et al., 2004). An ecoregion framework, with homogenous characteristics for land use within each of the strata relative to the surrounding ecoregions, is used here to capture a range of land-cover conversion types in a region sometimes perceived as agriculturally uniform. The spatially variable biotic and abiotic characteristics of the individual ecoregions, including vegetation, soil characteristics, water availability, topography, and climate directly influence the land use patterns (Gallant et al., 2004). The integration of the Land Capability Classification into a conceptual model of land system change, as a surrogate for land quality, provides additional characterization of agricultural conditions. The classification provides a generalized measure of the suitability of land for crop production using eight land quality groups (USDA, 1973).

The Great Plains study is part of the Land Cover Trends project that is examining the rates and causes of land-use and land-cover change across 84 conterminous U.S. ecoregions between 1973 and 2000 (Loveland et al., 2002). Additional analyses of recent trends are planned as part of a national land change assessment that expands on the original study design. Omernik's 1999 Level III Ecoregions of the Continental United States (Omernik, 1987; EPA, 1999), provide the basic strata for analyzing regional-scale patterns of land cover and land use change. A probability sampling approach of randomly selected grid locations was used to derive estimates of change (Loveland et al., 2002; Stehman et al., 2003). Each of the 16 ecoregion assessments used stratified random samples of 10 km × 10 km blocks of multi-temporal data. For the Great Plains synthesis, a total of 554 sample blocks were analyzed. Land cover estimates are based on the interpretation of five time steps (nominally 1973, 1980, 1986, 1992, and 2000) of Landsat Multispectral Scanner, Thematic Mapper, and Enhanced Thematic Mapper Plus satellite data. Multiple dates of satellite imagery were used that spanned the growing season in order to distinguish between temporary states, such as a recently plowed field, and an actual conversion from one land cover to another.

Land-use and land-cover interpretations were manually digitized at a 60 m minimum mapping unit, which allows for delineation of objects that are at least 60 m in width. To develop the change database, a baseline reference date was interpreted and then used as a spatial template to manually digitize and recode changes that occurred in the next time step. This technique was chosen in order to eliminate errors that occur when two or more time steps of independently created interpretations are used, which can cause a significant amount of difference between the temporal landscape patterns where none occurs. The National Land Cover Database (Homer et al., 2004) and historical aerial photography, maps, and documents aided with the interpretations. High resolution aerial photography from the National High Altitude Photography (NHAP) program and the National Aerial Photography Program (NAPP), which provide nearly complete national coverage beginning in 1980, aided in the identification of the historical patterns of land use and land cover. Ancillary data was not consistently available prior to 1980.

The manual method used in conjunction with a sampling approach allows detailed localized interpretations of land conversion over a smaller total area, which reduces some of the measurement errors that often occur with large-scale change detection (Loveland et al., 2002; Stehman et al., 2003). Quantities of land cover and land-cover change derived from the sample data were scaled-up to develop estimates of total change in each ecoregion. Mean change was computed from the sample blocks for each Level III ecoregion and was multiplied by the total population of blocks to develop the estimates of change. A limitation of this approach is the inability to target rare land cover types or specific sites such as isolated agricultural valleys or specific urban areas, which could affect the representation of some land-cover types. The estimation criteria for gross change aims for a margin of error between ±1% at an 85% or greater level of confidence, and reflects the practical considerations of generating precise ecoregion estimates using a sample based approach (Stehman et al., 2003). Based on this targeted precision level, prior change detection case studies, and the expected level of variation of change within Level III ecoregions, we determined that between 25 and 48 sample units were likely sufficient to identify change in each ecoregion.

The land cover classes used in the study are described in Table 1. The agriculture class encompasses cropland, intensive cultivated

Table 1
Land cover classifications and descriptions used in the study.

Land cover class	Description
Open water	Persistently covered with water, including streams, canals, lakes, reservoirs, bays, and ocean.
Developed (urban and built-up)	Intensive use where much of the land is covered by structures or anthropogenic impervious surfaces (residential, commercial, industrial, roads, etc.); and less-intensive use where the land-cover matrix includes both vegetation and structures (low-density residential, recreational facilities, cemeteries, utility corridors, etc.); and including any land functionally related to urban or built-up environments (parks, golf courses, etc.).
Agriculture (cropland and pasture)	Land in either a vegetated or unvegetated state used for the production of food and fiber, including cultivated and uncultivated croplands, hay lands, pasture, orchards, vineyards, and confined livestock operations. Forest plantations are considered forests regardless of their use for wood products.
Forest and woodland	Non-developed land where the tree-cover density is >10%. Note cleared forest land (i.e. clear-cuts) is mapped according to current cover (e.g. mechanically disturbed or grassland/shrubland).
Grassland/shrubland (including rangeland)	Non-developed land where cover by grasses, forbs, or shrubs is >10%.
Wetland	Land where water saturation is the determining factor in soil characteristics, vegetation types, and animal communities. Wetlands can contain both water and vegetated cover.
Mines and quarries	Extractive mining activities with surface expression, including mining buildings, quarry pits, overburden, leach, evaporative features, and tailings.
Barren	Land comprised of soils, sand, or rocks where <10% of the area is vegetated. Does not include land in transition recently cleared by disturbance.
Mechanically disturbed	Land in an altered, often unvegetated transitional state caused by disturbance from mechanical means, including forest clear-cutting, earthmoving, scraping, chaining, reservoir drawdown, and other human-induced clearance.
Non-mechanically disturbed	Land in an altered, often unvegetated transitional state caused by disturbance from non-mechanical means, including fire, wind, flood, and animals.

pasture, and associated uses including confined feeding operations and structures. Rangelands, which are extensively managed as predominately natural ecosystems though they may be used for livestock grazing, are included in the grassland/shrubland class. Forest is defined as areas with at least 10% tree cover, with trees at least 2 m in height. Developed lands include built-up areas, roads, and maintained corridors that meet the minimum mapping unit of 60 m. Fieldwork was also conducted to document contemporary land use types in each of the 16 Great Plains ecoregions and provides an extensive library of geo-referenced field photographs.

Summary statistics of land cover change rates, types, and extent were calculated for each of the four time intervals. A temporal interval of 6–8 years captures a wide variety of change including successive land conversions such as land clearance followed by abandonment, cyclic brush clearance and regrowth, as well as unidirectional land cover transitions such as the conversion of cropland to urban uses. This approach provides clear evidence of the geographic variability of land conversion processes.

Results

Great plains land-cover change

Overall, an estimated 7.8% (±1.5) of the greater Level I Great Plains ecoregion changed between 1973 and 2000, including 1.6% that changed multiple times. Most of the multiple changes involved at least two exchanges between crop agriculture and grassland at the same location. This occurred, for example, when cropland was converted to grassland cover after enrollment in the CRP and was subsequently converted back to cropland when the contract expired, but it also occurred as a grassland-to cropland-to grassland sequence. Wetland fluctuations, including exchanges between wetland and water, also contributed to the amount of multiple changes.

The rate of land-cover change increased substantially during the latter two time intervals (1986–1992; 1992–2000), more than doubling from a low of 1.6% during the 1980–1986 interval to a high of 3.6% during the following 1986–1992 interval (Table 2). The transition occurred as an economic slowdown during the late-1970s and early-1980s met the change in federal farm policy beginning in 1985 that set a goal for substantial conversion of erodible croplands to permanent grassland cover through the CRP.

Grassland and agriculture are the most extensive land cover types and together account for approximately 89% of the land cover, although the extent of each differs through time (Table 3). Agriculture expanded between 1973 and 1980 with smaller increases between 1980 and 1986, but declined thereafter as grassland became the dominant land cover. There were also small gains in developed land and open water. Grassland became the most extensive land cover by 1992, which continued through 2000. Grassland increases affected 1.8% of the region, but caused a 4.0% expansion of the grassland sector, which is the extent of increase in grassland cover between 1973 and 2000. Agricultural declines affected 2.2% of the ecoregion, which was a 4.7% decline in that sector. In contrast to a large extent of gross exchanges between grassland and agriculture that led to the substantial net changes in land cover, developed lands had small relatively steady increases at each time step. The expansion of urban areas and other development affected 0.4% of the region and was a 37.2% sector increase. Other cover types, which individually are a small part of the total land cover but are important to biodiversity and ecosystem services, comprise nearly 10% of the region when combined. However, the overall changes between 1973 and 2000 obscure the differential characteristics of land change that occur in the individual ecoregions.

Rates and types of change within ecoregions

The total extent of land-cover change between 1973 and 2000 varies widely among the ecoregions (Table 4). For example, Lake Agassiz (1.4%) and the Western Corn Belt (3.2%), two areas of intensive agriculture, have a relatively low overall extent of change. The Flint Hills (2.2%) and the Nebraska Sand Hills (4.2%), both with large amounts of productive rangeland and geologic and soil conditions not conducive to crop agriculture due to rocky soils and stabilized dunes, respectively, also have relatively low amounts of change. The lower rates of change suggest a state of equilibrium and are one indication that the highest and best agricultural uses are likely sustained as persistent land cover in these ecoregions. This contrasts with relatively unstable and fluctuating patterns of change in the southern and western plains. The Northwestern Glaciated Plains (13.6%), an ecoregion in a transitional location between the relatively flat cropland to the east and the broken semi-arid Northwestern Great Plains to the southwest, has the highest amount of overall change. As a transitional ecoregion, it may have less chance to reach a state of land-use and land-cover persistence, as it may

Table 2
Estimated rate of change for four time intervals and associated error at an 85% confidence interval (CI) for the greater Level I Great Plains ecoregion. Average annual rate of land change is included for the four time intervals.

	Rate of change (%)	Total area (km^2)	85% CI (±)	Standard error	Relative error	Average annual (%)
Estimated rate of land cover change in the Great Plains, 1973–2000						
1973–1980	1.9	41,420	0.2	0.1	6.2	0.3
1980–1986	1.6	35,780	0.2	0.1	6.8	0.3
1986–1992	3.6	77,890	0.3	0.2	6.6	0.6
1992–2000	3.1	67,400	0.3	0.2	5.8	0.4

Table 3
Estimates of total area of each land cover type for the five dates of the study and summaries of change between 1973 and 2000. Ecoregion area change is the percentage of the total area of the Level I Great Plains ecoregion affected by land cover change. Sector change is the extent of change between 1973 and 2000 for each land cover type.

Land cover	Estimated area (%) and 85% confidence interval										1973–2000 change totals		
	1973		1980		1986		1992		2000		Ecoregion area change	Sector change	Area change (km^2)
	Area	85% CI	Area	85% CI	Area	85% CI	Area	85% CI	Area	85% CI			
Estimated area of land cover types and total change, 1973–2000													
Water	1.8	0.5	1.8	0.5	1.8	0.5	1.8	0.5	2.0	0.5	0.2	13.6	5315
Developed	1.1	0.2	1.2	0.2	1.3	0.2	1.4	0.2	1.5	0.2	0.4	37.2	8970
Mechanically disturbed	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	122.5	785
Mining	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	116.7	1340
Barren	0.6	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.0	−0.3	−35
Forest	5.4	0.4	5.3	0.4	5.3	0.4	5.3	0.4	5.3	0.4	−0.1	−2.5	−2925
Grassland/shrubland	43.3	1.7	42.8	1.7	42.7	1.7	44.8	1.6	45.0	1.6	1.8	4.0	38,260
Agriculture	45.9	1.7	46.3	1.7	46.4	1.7	44.2	1.7	43.7	1.6	−2.2	−4.7	−47,540
Wetland	1.8	0.2	1.8	0.2	1.8	0.2	1.8	0.2	1.7	0.2	−0.1	−7.9	−3120
Nonmechanically disturbed	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−75.5	−1050

be more affected by climate variability, shifts in farm policy, and technology. The semi-arid, heavily irrigated Western High Plains (11.6%), which also has a substantial amount of dryland agriculture, and the wetter, fertile, and densely populated Texas Blackland Prairies (11.1%) also have relatively high amounts of change.

Multiple changes that occur in the same location during more than one time interval indicate land systems with environmental or socioeconomic conditions that cause land use and cover to fluctuate. Multiple changes in the Southern Texas Plains (4.7% of the ecoregion) are caused primarily by cyclic brush clearance. Land uses, including livestock grazing, may have persisted while ranchers periodically cleared the overgrown land cover to improve forage. Whereas the relatively high rate of multiple changes in several western ecoregions (Northwestern Glaciated Plains, Northwestern Great Plains, Western High Plains) results from expansion and contraction of cropland that is influenced by economic conditions, drought, and federal set-aside programs.

Rates of change for the individual ecoregions during the four time intervals varied considerably (Fig. 2A). The rates were lower and more spatially uniform during the earlier intervals (1973–1980; 1980–1986) when most ecoregions had rates below 0.5%, except in the south. The range of rates was greater during each of the latter two intervals, and was generally at or near its highest rate for individual ecoregions during the 1986–1992 interval. Some of the highest rates of change during the latter two intervals were in the drier western plains.

The most extensive type of land conversion also varied during the study period, although there is a cohesive spatial pattern during each interval (Fig. 2B). Many different conversions ultimately determine the direction of change for the individual land cover

Table 4
The total footprint of change from 1973 to 2000 for the individual Level III ecoregions, including the extent of each ecoregion that underwent two or more changes. The footprint of change is a measure of the total area of ecoregion conversion during the study period regardless of the number of times that the land cover at a given location may have changed.

Level III ecoregion	Total change		85% CI (±)	Area of multiple change (%)
	%	km^2		
Total footprint of change in Great Plains ecoregions, 1973–2000				
Lake Agassiz Plain	1.4	580	0.4	0.2
Flint Hills	2.2	600	0.5	0.3
Western Corn Belt Plains	3.2	6985	0.8	0.6
Nebraska Sand Hills	4.2	2520	1.5	0.8
Edwards Plateau	5.5	3230	1.2	0.8
Central OK/TX Plains	6.5	6690	1.2	0.9
Central Irregular Plains	7.2	8870	2.0	0.7
Northwestern Great Plains	7.4	25,720	2.0	2.2
Northern Glaciated Plains	7.5	10,565	1.4	1.5
Central Great Plains	8.2	22,480	1.4	1.1
Southwestern Tablelands	8.8	14,010	2.3	1.4
Western Gulf Coastal Plain	10.4	8450	2.3	2.5
TX Blackland Prairies	11.1	5620	2.6	1.1
Western High Plains	11.6	33,410	2.4	2.1
Southern Texas Plains	11.9	6520	2.5	4.7
Northwestern Glaciated Plains	13.6	21,800	2.2	3.4

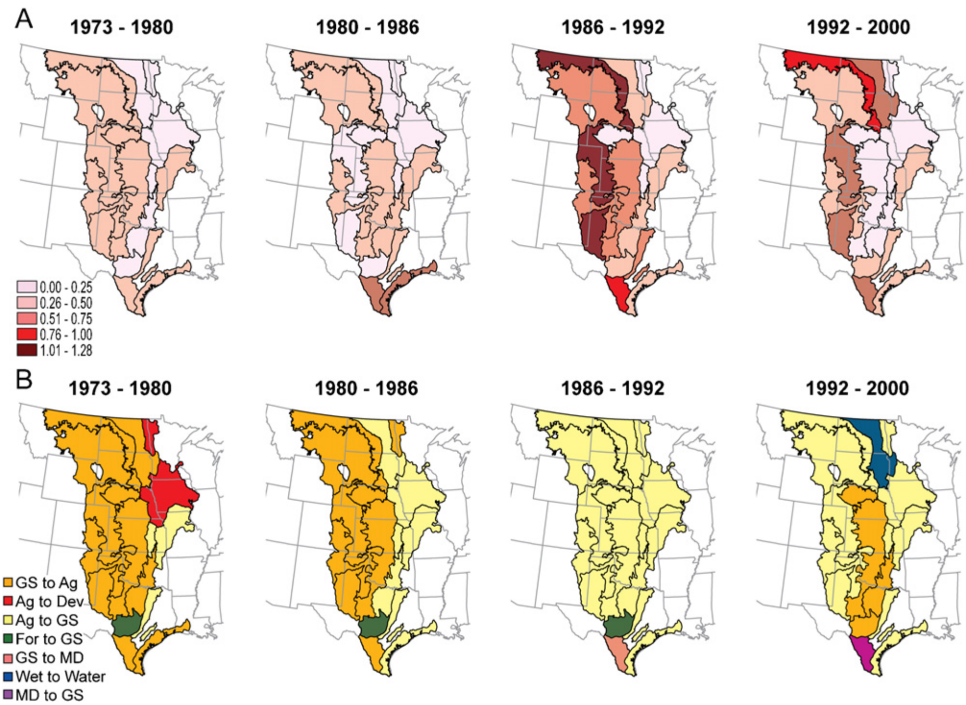

Fig. 2. (A) The annual rate of change for each time interval, in %. (B) The leading type of gross land cover conversion during each time interval. GS = grassland/shrubland; Ag = agriculture; For = forest; MD = mechanically disturbed; Wet = wetland; Dev = developed.

types; however, the leading type of change in each ecoregion indicates the most extensive type of gross conversion occurring during each time interval. Between 1973 and 1980, grassland/shrubland to agriculture was the leading conversion for much of the Great Plains, indicating the effects of favorable economic conditions, policies, and increasing use of center-pivot irrigation technologies that effectively expanded the area of highest and best use. Land change in the eastern flank of the region varied. Here, urbanization occurred on agricultural land, as well as the conversion of agriculture and forest to grassland farther south. In the Western Corn Belt, an estimated 300 km^2 of agriculture was urbanized between 1973 and 1980, and another 730 km^2 was added by 2000. The development of land cover in the Lake Agassiz Plain, which is the other ecoregion that had agriculture to developed as its leading type of change, a relatively stable ecoregion overall, was actually quite small at less than 25 km^2. The number of ecoregions with agriculture to grassland conversion as the leading change increased during each time interval until nearly dominating the entire Plains region during the 1986–1992 CRP period. The conversion to grassland relaxed between 1992 and 2000, and reversed in several of the central plains ecoregions. The Northern Glaciated Plains ecoregion continued to see conversions to grassland; however, wetland inundation and the expansion of lakes were more prevalent.

Temporal land change

Land-use and land-cover changes progressed at an uneven pace, with temporal pulses of change that relate to several key driving forces. Between 1973 and 1980, agriculture expanded at the expense of grassland (Fig. 3) when economic opportunities for overseas exports increased and public policies and price supports encouraged farmers to expand. A substantial amount of the increase occurred as center pivot irrigation and grain production expanded to take advantage of relatively inexpensive groundwater from the High Plains Aquifer. Concentrations of large confined feeding operations and intensive feed corn production, and in some areas meat-packing plants, created centers of intensive agricultural production that transformed the semi-arid Western High Plains (Harrington et al., 2003, 2009). Expansion of agriculture also occurred in several other ecoregions (Table 5), although at a lower rate. The increase is related to the economic and political climate of the early 1970s that encouraged farmers to expand production in an effort to benefit from strong export opportunities, commodity prices, farm income, and farmland values (Stam and Dixon, 2004). Millions of acres of cropland were added in the northern Great Plains in the 1970s as farmers were encouraged to plant from fence row to fence row following a period of declining farmland acreage

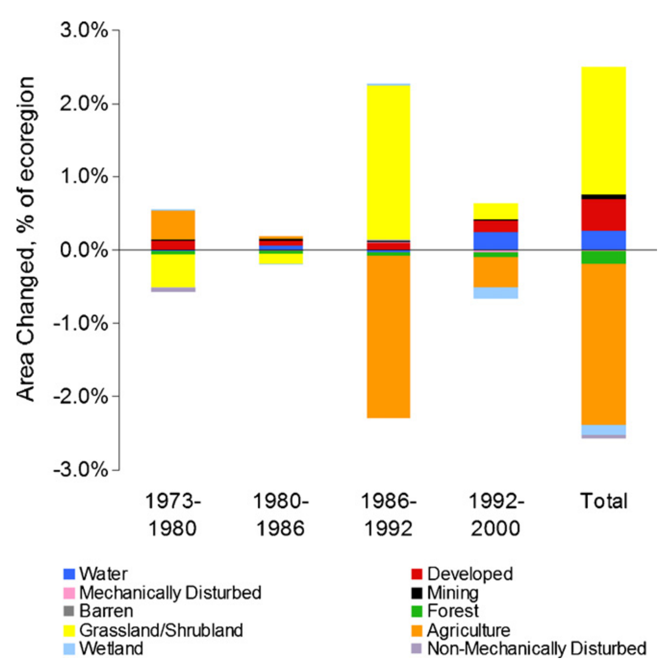

Fig. 3. Estimated net land cover change by time interval for the greater Great Plains region.

Table 5
Total ecoregion area affected by expansion (gray) and decline (white) of agriculture across the four time intervals of the study.

Level III ecoregion	1973–1980	1980–1986	1986–1992	1992–2000	Total
Agricultural land cover change by ecoregion, 1973–2000					
TX Blackland Prairies	−1.1	−1.3	−1.7	−1.4	−5.6
Central Irregular Plains	−0.3	−0.6	−1.2	−1.0	−3.0
Western Corn Belt Plains	−0.2	−0.2	−1.2	−0.5	−2.1
Flint Hills	−0.1	0.0	−0.3	−0.3	−0.7
Lake Agassiz Plain	0.0	0.1	−0.4	−0.2	−0.6
Central OK/TX Plains	0.0	−0.3	−0.4	−0.0	−0.7
Western Gulf Coastal Plain	0.1	−0.4	−0.4	−0.4	−1.0
Northern Glaciated Plains	0.1	−0.2	−0.8	−1.1	−2.0
Southwestern Tablelands	0.2	−0.1	−1.5	−0.4	−1.8
Northwestern Great Plains	0.3	0.6	−1.9	−0.8	−1.8
Edwards Plateau	0.3	0.1	−0.1	0.3	0.6
Southern Texas Plains	0.7	0.5	−0.4	0.3	1.0
Central Great Plains	0.8	0.1	−1.5	0.0	−0.6
Northwestern Glaciated Plains	0.9	0.3	−4.5	−0.3	−3.7
Western High Plains	1.4	0.4	−7.3	−0.3	−5.8
Nebraska Sand Hills	1.6	0.3	−0.4	0.1	1.5

that began in the 1930s (Hargreaves, 1993). The large 1972 grain purchase by the former Soviet Union facilitated the higher commodity prices and the resulting expansion of cropland (Conklin, 2008). The few ecoregions with significant declines during this time were primarily caused by the countervailing forces of urban growth and development, particularly in the Texas Blackland Prairies, as well as a few pockets of abandonment of farming activities.

Although the real price of farmland had the fastest decadal rate of increase on record during the 1970s, the years between 1981 and 1986 had the steepest declines on record as farmland values dropped by nearly 10% annually (Lindert, 1988). Export markets also contracted and domestic farm input prices and interest rates rose, leaving many farmers in financial distress (Stam and Dixon, 2004). Between 1980 and 1986, the overall amount of net land change was at a near standstill. A few ecoregions continued to expand the agriculture base, while trends of urbanization on agricultural land, as well as abandonment of farming activities, caused the overall regional rate of expansion to slow considerably. There was also a small increase in the extent of surface water that caused local declines in agriculture, caused by the pace of water impoundment and by a climate-driven lake expansion in the Northern Glaciated Plains (Todhunter and Rundquist, 2004).

Overall, 1986–1992 had the most change, caused when a substantial amount of cropland on marginal land was converted to grassland cover. All ecoregions had a net loss of agricultural land cover during this interval. Much of the conversion to grass was driven by the economic incentives of the CRP that also aided with the problems of overproduction spurred by the export opportunities and agricultural productivity increases of the 1970s (Riebsame, 1990). Indeed, the eventual complications caused by too much grain and the related price declines that are linked to the earlier fence row to fence row cropland expansion was likely a significant driving factor behind the size and scope of the CRP (Hargreaves, 1993). The CRP had its largest effect on land-cover conversion in the Western High Plains and Northwestern Glaciated Plains, although it was spread among many ecoregions. Some cultivated lands may have been abandoned due to economic hardships as difficult financial times continued for many farmers. The implementation of the CRP, post-1985, along with other forms of abandonment between 1986 and 1992, had the greatest single net effect on land-cover change in the Great Plains during the entire study period.

Between 1992 and 2000, the conversion to grassland continued at a much slower pace as the CRP matured. Agriculture declined overall in the Great Plains region and the extent of grassland cover increased. Some ecoregions maintained high gross rates of change as spatial changes in the location of cropland and CRP occurred, but resulted in relatively low net rates of agricultural decline. Also referred to as swap, this is an underused measure of land change (Pontius et al., 2004). Spatial exchanges between agriculture and grassland occurred as CRP contracts expired and the fields were returned to crop production while other cropland was newly enrolled in the program. For example, approximately 63% of land that left the program by 1997 was returned to crop production and another 31% was used for livestock grazing (Sullivan et al., 2004). In some areas, slippage, an unintended consequence of land use policy, may have occurred as farmers opened up new areas for cultivation to replace other lands that were enrolled in the CRP; although, slippage may have primarily occurred at the start of the CRP program rather than with later enrollment or renewals (Leathers and Harrington, 2000). A few ecoregions had small net increases in agriculture, although it had little effect on the overall direction of land-cover change in the Plains. Water impoundment and lake expansion (Northern Glaciated Plains) caused an even larger spike in the extent of surface water than earlier periods. Urbanization continued to be a factor in a few ecoregions.

Major processes of change

The most extensive land-cover changes between 1973 and 2000 occurred as a result of several major processes (Fig. 4). Region-wide, conversions from agriculture to grassland resulted in the largest net change of more than 41,000 km^2 of land. Much of the conversion occurred in the drier, western reaches of the region where the CRP had a substantial effect, including the Western High Plains, Northwestern Great Plains, and the Northwestern Glaciated Plains. These ecoregions averaged a combined approximately 45,000 km^2 of CRP between 1990 and 2000 (US Department of Agriculture [USDA], 2010). Similar, but less extensive, trends occurred in the more-humid northeastern ecoregions (Northern Glaciated Plains, Lake Agassiz Plain, Western Corn Belt Plains, and Central Irregular Plains). Other ecoregions, including the Central Great Plains that stretches between central Nebraska and central Texas, had a nearly even exchange between agricultural land cover expansion and conversion to grassland that resulted in a net change of near zero when observed across the entire study period. Agricultural expansion at the expense of grassland was more extensive during all periods in the Central Great Plains ecoregion except the 1986–1992 period that covers the initial CRP enrollment. Land that is marginally suited to growing crops may also sit idle or fluctuate between dryland crops and rangeland depending on commodity price supports and other subsidies, as well as on the patterns of climate variability and drought. This may have resulted in some temporary or long-term conversions away from cropland. Overall, the effect of the CRP on

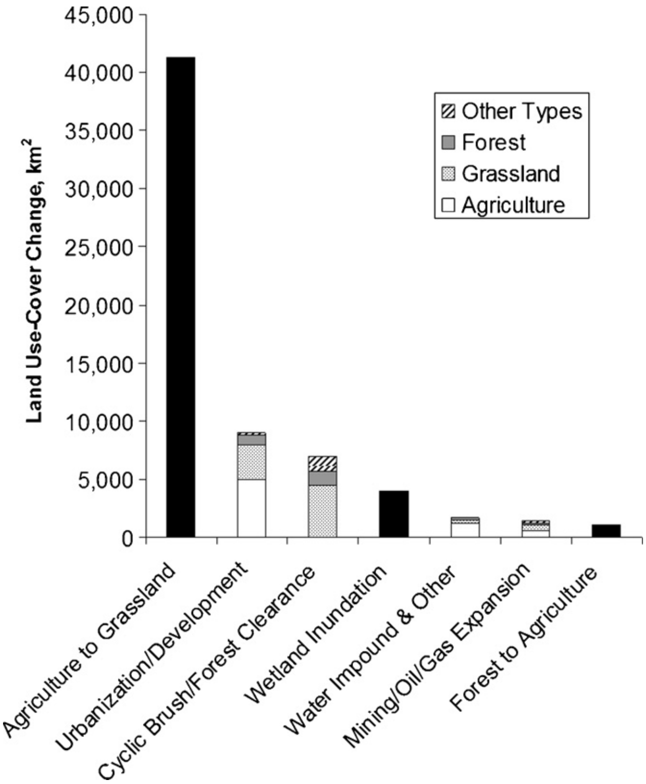

Fig. 4. The seven most extensive processes of change in land use and land cover, 1973–2000. "Other Types" of cyclic brush/forest clearance refers to land that remained in a state of clearance during two consecutive time intervals.

land conversion underscores the role that federal policy plays as a driver of change in the plains.

Urbanization and other dispersed development is a primary pathway of change in a small subset of ecoregions, although it also had a small but pervasive effect, causing a slow rate of conversion across most ecoregions. Nearly 9000 km^2, primarily of agriculture and grassland/shrubland, was estimated as converted to developed land between 1973 and 2000. While many rural areas lost population, the built-up areas of towns and settlements do not generally contract, whereas expansion of infrastructure or population growth around larger towns causes a low rate of change in the ecoregions. The leading ecoregions for increased development were located in the eastern and southern portions of the greater Level I Great Plains ecoregion and had a denser settlement pattern than the mostly rural ecoregions, which are generally sparsely populated and only occasionally punctuated with urban centers or are lacking any large cities. For example, Denver and other Colorado front range cities have urban growth trends that cause local effects within the Western High Plains and Southwestern Tablelands, but the changes affect only a small fraction of the overall area of the ecoregion. The Texas Blackland Prairies, with the Dallas-Austin-San Antonio axis of major metropolitan areas, had the highest rate of development, primarily on agricultural land (2.3% of the ecoregion) and grassland (1.2% of the ecoregion). Other leading ecoregions for conversions to development included the Central Great Plains, the Western Cornbelt, and the Central Oklahoma/Texas Plains. Urban growth and development was likely affected by several alternating economic expansions and contractions, including the early 1980s recession and the overall economic prosperity during the 1990s. Higher gains in developed land during the 1973–1980 interval may have been augmented by completion of the original Interstate highway system and the improving Texas energy economy after the 1973 Mideast oil embargo.

The cyclic clearance of brush and forest, which caused nearly 7000 km^2 of land change, generally occurs in southern areas of scrubby vegetation including areas of mesquite, juniper, and scrub oak that stretch from the Central Irregular Plains to southern Texas. While many of these areas may be in pre-settlement vegetation cover types, an unknown extent is from invasion that is facilitated by climate and land-use change (Wessman et al., 2004). Climate change and variability, increased atmospheric CO_2 concentration, nitrogen deposition, fire suppression, and livestock grazing pressures are likely the main contributors to woody expansion onto perennial grasslands (Mitchell, 2000; Briggs et al., 2005). Land is subsequently cleared to improve grazing for livestock, increase the amount of open areas for commercial game hunting, and manage for water flow objectives. Brush is often cleared with machinery and in some cases by chemical applications or burning. The practice is also encouraged and subsidized by state and other institutions (Tennesen, 2008).

Wetland changes of nearly 4000 km^2 were located in the northern plains and along the Gulf Coast. These sub-regions are well-known wetland locations; the northern plains have the continental prairie potholes and the coastal plain has various types of fresh, brackish, and saltwater wetlands. Substantial long-term increases in precipitation since 1993 led to the flooding of wetlands and the formation of larger closed-basin lakes in the northern glaciated ecoregions, such as a threefold increase in open water area for Nelson County in eastern North Dakota that caused substantial areas of agricultural land to be taken out of production (Todhunter and Rundquist, 2004). The Northern Glaciated Plains was the leading ecoregion for agriculture to wetland change. Its southerly neighbor, the Western Cornbelt, an ecoregion that historically had been part of the prairie potholes before massive wetland drainage for farming during the later 19th and early 20th centuries, still possessed some wetland landscape characteristics that influenced this type of change, although it was only a fraction of the process occurring in the less-drained Northern Glaciated Plains. These results indicate that climate variability became a direct factor of land change particularly during the 1992–2000 interval as precipitation increased and the area switched from a Palmer Hydrological Drought Index of extreme drought in 1991 to extreme wet conditions by 2001 (Todhunter and Rundquist, 2007). Climate variability and drought are often direct, as well as indirect, factors of change throughout the Great Plains, both regionally and temporally. The direct changes here, among water, wetland, and agriculture, were caused by pulses of drought and deluge.

Water impoundment and other surface water changes (approximately 1700 km ^{2}), except wetland inundation, are primarily driven by water storage needs for agriculture and drinking water, as well as for flood control, recreation, and navigation. There is concern that many western plains reservoir-levels are declining due to climate change and groundwater use (Brikowski, 2008); however, similar concern for declining water availability could cause additional reservoirs to be constructed. This is counterbalanced by efforts to promote water use efficiency and an assumed decline in suitable sites for new reservoir construction.

Mining, which includes surface mines and quarries as well as oil and gas development, had small increases (1360 km^2). However, most energy related footprints including oil and gas pads, with networks of roads, pipelines, and other associated elements, did not meet the minimum mapping unit of 60 m.

Forest clearance for agriculture (1065 km^2) tended to be found in ecoregions within or near the eastern periphery of the Great Plains, including the Central Irregular Plains, the Texas Blackland Prairies, and the Western Gulf Coastal Plain. Overall, there was a small net loss of forest cover.

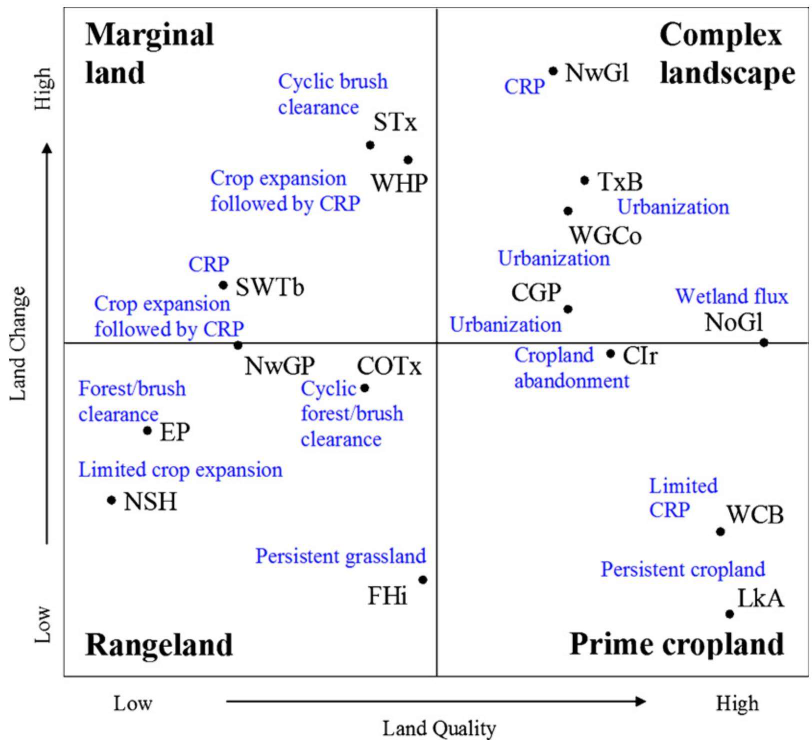

Fig. 5. The relationship between land quality for use as cropland and the total footprint of land change from 1973 to 2000. Major processes of change, or stability, are shown in blue. Land quality was averaged for each Level III ecoregion using the NRCS Land Capability Classification (NRCS, 2000). Full ecoregion names are given in Fig. 1. Conceptually, the pathways of change are expected to relate to four general land use regimes: rangeland, marginal cropland, prime cropland, and regions of greater land change complexity.

Conceptualizing land change and human–environment dynamics

There is not a single profile of land change that fits all the Great Plains ecoregions. Instead, there is significant geographic variability as land use systems are adapted to the limitations and enabling factors of climate and biophysical resources. Land change is further exaggerated by population, economic, technological, and political driving forces, and by the legacy patterns of settlement and tradition. To conceptualize the variability of land change, we discuss human–environmental systems as they relate to four generic modes of land use potential (Fig. 5). The conceptualization is dependent on regionally averaged land quality (Natural Resources Conservation Service [NRCS], 2000), as well as the rates of land-cover change that suggest differential characteristics of land systems.

A picture of Great Plains land cover includes not only gross and net changes, but also persistent agriculture (Fig. 6). Measures of persistence across time intervals help to identify regional land use systems that may be well adapted to the available natural resources or otherwise resilient to the forces of change. Overall, the extent of persistent agriculture in the greater Great Plains region declined by approximately 3%; from an estimated 45.7% between 1973 and 1980 to 42.7% between 1992 and 2000. Many of the individual ecoregions had a similar pattern of decline, although the range of change and the total area of persistence were quite variable.

Rangeland systems tend to have soil or topographic constraints that limit cultivation, and offer low potential for land change in the absence of other types of land-use pressure, such as urbanization. Particularly in the western half of the Great Plains, they tend to be on sandy, shallow soils, while croplands utilize alluvial soils (Burke et al., 1993). Low human populations, long-established agricultural traditions, and extensive grazing practices create a low-intensity land system. The Flint Hills and Nebraska Sand Hills are examples of low-changing, persistent grassland systems where large tracts of tallgrass and midgrass prairie, respectively, still remain. The Flint Hills also has a substantial amount of agricultural land in the deeper lowland soils that was relatively low changing between 1973 and 2000. Upland grazing environments are expansive enough to support controlled burning of pasture that improves forage for cattle but also maintains the grassland ecosystem. The Flint Hills is one of the most stable land systems when compared to other ecoregions. This may be due in part to distinct ownership patterns that saw early settlers choose bottomland farming sites, leaving upland bluestem prairie for later purchase by commercial cattle interests for livestock grazing (Kollmorgen and Simonett, 1965). The Sand Hills had a small amount of crop increase, mostly between 1973

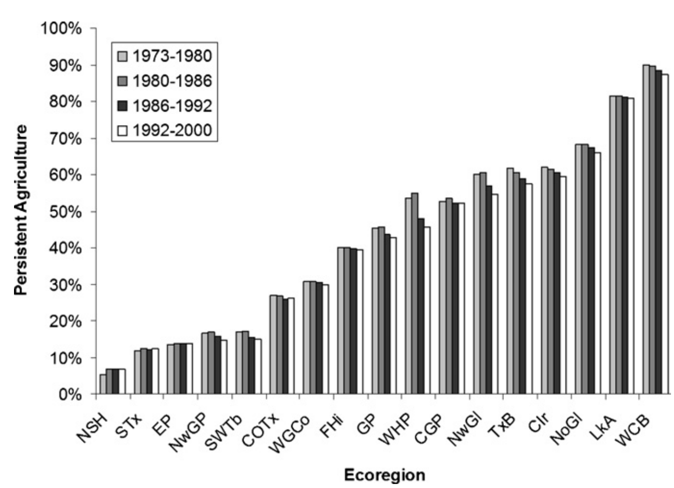

Fig. 6. Percentage of agricultural land cover (which excludes rangeland) that persisted during each of four time intervals, by ecoregion. The greater Great Plains (GP) ecoregion is included. Abbreviations refer to those used in Fig. 1.

and 1980 when agricultural expansion was more common in other ecoregions as well. Rangeland ecoregions with shrubland and forest systems, where woody vegetation is periodically cleared to create open areas for livestock grazing, have higher rates of land cover change and only a limited amount of persistent agriculture.

Marginal systems have higher rates of agricultural land use fluctuation that are enabled by the intersection of significant physical constraints to agricultural production, occasional cropland expansion driven by economic opportunities and technological advances, and targeted socioeconomic drivers of land-use change such as land retirement policies. Climate variability and drought, interacting with socioeconomic and technological factors, drives various adaptations to conditions and an increase in land change. The Western High Plains is underlain by the large High Plains Aquifer that enables intensive feed grain production and confined feeding operations. Declining water tables cause some de-intensification of land-use (Nellis et al., 1996; Wu et al., 1999; Kettle et al., 2007) and likely play a role, along with dryland agriculture fluctuations, in the cropland conversions to grassland and CRP land cover in the ecoregion. During the early years of center pivot expansion, up to the mid-1970s, natural gas prices were low, allowing for inexpensive irrigation, and facilitated some marginal cropland expansion that was perhaps followed by a more-dispersed regional pattern of abandonment. The Northwestern Great Plains and Southwestern Tablelands, with large expanses of shortgrass steppe rangeland and relatively small amounts of permanent cropland, also have substantial amounts of change as marginal croplands fluctuate. In general, these land systems are characterized by crop expansion during profitable times and land retirement when economic and climate conditions decline. The Southern Texas Plains, a rangeland-brush system, had the highest rate of change compared to other ecoregions with lower land quality. Overall, federal farm policies that include the historical and current use of the CRP are a significant factor in the declines of agricultural land cover on marginal land in the Great Plains. Local and state policies and incentives that encourage brush management may also contribute to rates of land change in the southern rangeland-brush system.

Prime cropland systems have soils and conditions that allow for persistent cultivation. In the most extreme, 80–90% of the Lake Agassiz and Western Corn Belt ecoregions are covered with intensive permanent agriculture. Lake Agassiz, with its level topography and good soil, is more stable. The Western Corn Belt has some limited pressure from urbanization and development, but this is small in total area impact. Land use systems are organized around high-quality cropland, with a historical background of substantial anthropogenic transformation of the natural ecosystems through drainage of wetlands and the nearly wall-to-wall cultivation. Contemporary land cover change is expected to be relatively low unless there are significant future non-agricultural land-use pressures to cause a higher rate of land change, although conversion of the relatively small amount of CRP land back to corn production would have an effect on ecosystem services. A moderate rate of cropland abandonment in the Central Irregular Plains, centered on northern Missouri, may be an indication of a future shift from stability to greater complexity of change, which may be partly tied to topographic irregularity that tends to increase the amount of marginal land uses.

Complex land systems are characterized by high rates of change. Land quality is generally good, however there are factors other than typical agricultural drivers that take hold and cause substantial land change. Urbanization is a competing land use that adds complexity by introducing new driving forces and different pathways of change, such as agriculture to grassland to urban transition in the Texas Blackland Prairies. Climate variability is a factor in the Northern Glaciated Plains where deluge caused lake expansion and wetland fluctuation. The Northwestern Glaciated Plains has a mix of conditions, including areas of highly erodible soil and marginal land fluctuation. Overall, urban and exurban growth and climate events had a marked effect on the land-cover change profile.

How dynamic and varied are the changes in the plains?

A large part of the Great Plains is in persistent, stable land cover. However, there is a certain amount of elasticity and resilience of agricultural land use that is an important part of the land systems. There is also a diversity of rates, processes, and causes of land change affecting the individual ecoregions.

Regional differences in the rates and types of land-use and land-cover change are the result of contrasting environmental and socioeconomic characteristics. High-value, high-quality agricultural lands have a historical legacy of enduring use, and tend towards stability. Lands with substantial biophysical constraints can undergo substantial change when pushed by socioeconomic, climate, or biophysical forcing factors. However, there is a high degree of variability, such that change is not uniform across the Plains or across time. The rates and processes of land change, and stability, vary substantially depending on the unique regional land use regime that is tied to biophysical resources and affected by the degree of climate variability and change. High change in the brush region, where cyclic clearance of woody vegetation causes substantial land change, is different from high change in the semi-arid and central plains, with marginal cropland fluctuations. Low change in the Flint Hills and Sand Hills rangelands, where livestock grazing arguably plays a significant role in either altering or maintaining those ecological systems, is different from low change in the densely cropped Western Corn Belt, except that these regions have reached some degree of land cover stability.

The regional variability of the characteristics of change suggests that the Plains should not be thought of as a uniform agricultural region, in part because this would undermine the ability to assess how differing land use systems have the potential to be either winners or losers as a result of climate change. Projections of a future rise in mean surface temperatures and a less predictable hydrologic cycle may result in more land-use and land-cover fluctuation and possible impacts to the extent of permanent agriculture in some ecoregions. The substantial amounts of fluctuation in land use, which are short-term changes, are a consequence of climate variability and change and land quality, but are exaggerated by government policies and global markets. This suggests that the Great Plains is vulnerable to change that might be exacerbated or mitigated by socioeconomic conditions, including a projected increase in the global demand for agricultural products (FAO, 2009). Parts of the Great Plains are more likely to undergo additional change than others, which was probably established a century earlier and is reflected in agricultural settlement history. Biophysical underpinnings determine the conditions for land change and resilience, and these results suggest how socioeconomic factors may amplify or dampen the characteristics of change.

Overall, Lake Agassiz and Flint Hills are the most stable ecoregions, based on low rates of cropland change and persistent land-use traditions. The Northwestern Glaciated Plains and the Southern Texas Plains have the highest rates of land cover change. Prolonged groundwater mining for intensive irrigation also presents conditions of future risk. Some of this is seen in land retirement, abandonment, and short-term land-use fluctuations in the Western High Plains where groundwater pumping exceeds natural recharge rates. In some cases, transitions may indicate a decline in land rent, including current trends in the most depleted areas of the High Plains Aquifer region that suggest farmers may switch from water-intensive corn production to less water-intensive crops in order to maximize profits under changing conditions.

Although much of the Plains agricultural production, which serves national and international markets, may be decoupled from the classic von Thünen model of a declining land rent gradient as the distance to city center increases, particularly when transportation costs are low, there are other patterns within the land system that relate to accessibility. This is seen in the co-location and integrated production of irrigated feed corn, large confined feeding operations, and meat-packing plants that overlay deep reserves of High Plains Aquifer groundwater and surround successful economic centers like Garden City, Kansas. Although the potential rent may be higher around these centers, similar to a land rent gradient, the regional pattern of groundwater availability is likely one of the more-important geographic drivers of land-use variability. However, drivers do not act solo. Increasing global demand for feed grain for animal agriculture, national policy objectives, sustainability objectives, and individual actors play important roles. Land rent may be best described as a function of land quality, the macroeconomic factors of commodity prices, and human investment into the land (Lindert, 1988).

In another example, metropolitan areas have surrounding vegetable and specialty agriculture that can be adversely affected by urbanization and spreading development, whether by transfer of water rights, loss of aesthetic value, or loss of prime local cropland. At the ecoregion scale, the pattern of urban growth, when examined alongside other land changes, does not exhibit a tight regional coupling between urban and rural systems. In decoupled regional systems, agriculture and urban expansion act independently (Walker, 2001; Walker and Solecki, 2004). Regional-scale changes suggest that the net extent of agriculture declined overall as large amounts of agricultural land transitioned to natural land cover types such as grassland. This is likely indicative of a highly productive agricultural system that can afford to shed less-productive lands, and that is subject to macro-scale economic and policy factors. However, among the gross changes that were documented, there is conversion of grassland, forest, and wetland to agriculture. Some of these changes could be indicative of peri-urban driven conversions that cause a loss of prime agricultural land and push local agriculture to cultivate new areas as urban populations expand.

Perhaps more indicative of the changes in the Plains is the sequence of agricultural expansion prior to 1986 that was followed by widespread conversion and abandonment to grassland/shrubland. The pattern and magnitude of these conversions are influenced by the contextual conditions of land quality and climate variability, as well as macro-scale economic and policy drivers. Though economic considerations, climate conditions, or cultural factors by themselves or in combination may drive some land owners to temporarily expand or abandon crop production, policy drivers often facilitate a greater extent and duration of change. Certainly, accessibility and distance from market could be a factor in a few of the larger rural regions that lost significant amounts of agriculture, although the magnitude of the effect is unclear. However, many of the ecoregions with substantial marginal cropland also saw an early expansion when land prices increased, overseas markets expanded, and policy conditions favored expansion, suggesting otherwise.

Great Plains land cover also experienced temporal pulses that affected the overall region. These pulses had drivers based primarily in changing economic situations, but also in cyclic climatic conditions. Epochs such as the 1970s Russian grain deal, rising inflation, the initiation of the CRP, economic expansions and contractions, droughts and deluges, all impacted the region's land cover over time. The temporal dynamics of change show that many land-use systems continuously adapt to climate and biophysical conditions, dependent on the socioeconomic drivers, land-use legacies, and regional land-use traditions. Great Plains agriculture has historically proven to be resilient, and has developed in response to a variable climate and resources base. The land changes discussed here likely reflect that characteristic.

A regional-scale land-cover transition occurred as grassland became the majority land cover and agriculture declined, although with substantial variability among ecoregions. The agricultural transition was driven by policy, global and national economics, technology, climate, and population and demographic movements. As the late 20th century progressed, agricultural expansion became less prevalent. As well, the earlier expansions were often dwarfed by later declines driven by government policy. Given the increases in agricultural productivity, a transition to grassland is expected. Productivity increases caused by technological and scientific advances allow for a decline in the extent of agriculture, which has generally occurred since about 1950, and a perhaps a future trending towards greater land-cover equilibrium. Future scenarios of increased biofuel production, changes in farm and energy subsidies, population growth, and changing global food demands may diminish or reverse the transition.

The persistence, fluctuation, and regional patterns of expansion and loss have many important socioeconomic and environmental consequences. In the context of climate change, if the regional weather patterns become more varied and warmer and drier in places, land cover fluctuations and declines in regions with marginal agriculture may be amplified. Land systems that depend on large amounts of water may also be significantly affected. Based on these results, climate variability, interacting with socioeconomic forces, drives a substantial amount of land change. Mitigation of the negative consequences of global environmental changes, such as the use of the CRP to restore ecosystem function, may depend on land management decisions that should benefit from ongoing assessments of land change. The CRP relates to land quality and manifests from policy and economic issues, and thus serves as a good example of how regions respond to biophysical and socioeconomic factors, illustrating the large effect that government policy has on land-cover change.

Conclusions

We have presented an analysis of Great Plains land change that highlights several modes of land use, including persistent agriculture, overall change at the ecoregion-level, and net change in agriculture. By examining regional variability, this research contributes to developing a stronger basis for understanding the vulnerability, resilience, and sustainability of land systems in the Plains. The interplay of human and environmental factors across the landscape causes a considerable variability of land change rates, types of conversion, and trajectories of change. In many regards, the story and perception of change depends on whether referring to land-use regimes of the western semi-arid rangelands, the intensively irrigated High Plains Aquifer region, the northeastern fertile glacial plains, or the more-urbanized southeastern plains. We dissect the geography of the Plains by examining regional variation of land cover progression and the relationship to differential human–environmental dynamics. An ecoregion framework provides an effective template for distinguishing generic land systems as well as for understanding the geographic variability of land change in linked human–environmental systems.

The Great Plains ecoregions capture geographic characteristics of land-use and land-cover change and persistence that help to explain the socioeconomic and environmental dynamics that drive land-change variability. A region with lower quality land or climate limitations for growing crops, such as resulting in limited water availability, has larger fluctuations, while regions of higher quality land and abundant resources are more stable. The extent and

timing of fluctuations are enabled or constrained by the underlying biophysical factors that are further amplified or dampened by socioeconomic interactions with the physical capacity of land and climate.

Agricultural regions are of major concern for understanding the linkages between land use, climate change and variability, and land management challenges. Globally, agricultural land use expansion has caused a net reduction of carbon stocks, natural habitat, and some environmental services, while also providing numerous goods. Recent declines in agriculture in some developed nations may lead to restoration of some of these services. However, linkages with climate change – and precipitation, temperature, and weather variability – and population growth and increased demand for agricultural products, including biofuels, further complicate the future of agricultural ecoregions. In the United States Great Plains, one of the world's major agricultural regions, land change variability shows distinct spatial and temporal variability, much of which is attributable to diverse ecoregion-scale interactions between climate-biophysical factors and socioeconomic processes.

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