

The effects of environmental and socioeconomic factors on land-use changes: a study of Alberta, Canada

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Abstract Various environmental and socioeconomic issues have been attributed to land-use changes, and therefore, the underlying mechanisms merit investigation and quantification. This study assesses a comprehensive series of land-use conversions that were implemented over a recent 12-year period in the province of Alberta, Canada, where rapid economic and population growth has occurred. Spatial autocorrelation models are applied to identify the comprehensive effects of environmental and socioeconomic factors in each conversion case. The empirical results show that the impacts of key environmental and socioeconomic factors varied in intensity depending on the type of land-use conversion involved. Overall, land suitability for agricultural uses, road density, elevation, and population growth were found to be significant predictors of land-use changes. High land suitability, low elevation, and moderate road density were associated with land conversion for agricultural purposes.

Keywords Land-use conversion · Spatial regression model · Land suitability · Road density · Population growth

Introduction

Land-use changes may have significant environmental effects by increasing greenhouse gas emissions (Fearnside 2000; Miles and Kapos 2008), causing losses of biodiversity and productivity (Reidsma et al. 2006; Robson and Berkes 2011) and degrading land and water quality (Tilman 1999; Schneider and Pontius 2001). Hence, the identification of major drivers that shape land-use patterns and cause land-use changes has been an important but challenging task for scholars, policy makers, landowners, and other stakeholders (Li et al. 2013; Schweizer and Matlack 2014).

Previous studies have reported that topographical, climatic, and soil/land quality are the major environmental characteristics that affect vegetation-cover changes (Matlack 1997; Deng et al. 2002; Hall et al. 2002; Duram et al. 2004; Van Doorn and Bakker 2007; Chakir and Parent 2009; Begue et al. 2011). At the forefront of socioeconomic activities, urban expansion and road construction associated with population and economic growth are the main contributors to agricultural and forested land degradation (Heilig 1997; Jaeger et al. 2007; Baumann et al. 2011; Deng et al. 2011; Jiang et al. 2012; Upton et al. 2014; Xie et al. 2014; Sen et al. 2015). However, the potential causes of land losses are complex and vary over time and space. Hence,

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researchers have been motivated to quantify the changes in land-use decisions and explore the causes of these changes worldwide (Chowdhury 2006; Bawa et al. 2007; Qasim et al. 2013).

There are numerous empirical models available in the literature to study the land-use changes. Early acreage response models directly related the acreage of a parcel of land to its resource endowment, weather, and other factors (Houck and Ryan 1972; Lidman and Bawden 1974; Moore and Negri 1992; Miranda et al. 1994). Land-use share models were developed based on the decision-making processes of growers, who will allocate land to the use that provides the greatest value of profits (Maddala 1983; McMillen 1989; Wu and Brorsen 1995; Plantinga et al. 1999; Wu and Adams 2001; Wu et al. 2004). However, the above models neglect spatial autocorrelation, which is a prevalent phenomenon in both natural and artificial landscapes (Tobler 1970; Legendre 1993; Wang et al. 2002; Liang 2012). In this analysis, the agricultural clustering pattern may be caused by the shared technology between neighboring farms, reduced management or transportation costs, and/or particular social norms (Li et al. 2013). To account for neighborhood externalities, researchers included neighboring-level explanatory variables in cellular automata (Wu and Webster 1998) and parcel-level models (Carrion-Flores and Irwin 2004). Additionally, many new empirical models have been invented to explicitly account for spatial autocorrelation, such as geographically weighted regression (GWR) (Luo and Wei 2009; Su et al. 2012), spatial autocorrelation models (SAC) (Anselin 1988), and spatial logit/probit models (McMillen 1992; Anselin 2002; Klier and McMillen 2008). Given the extensive study area and regular lattice systems in this analysis, we adopted SAC models to investigate the effects of these environmental and socioeconomic factors on land-use changes. These spatial models can explicitly take spatial autocorrelation and heterogeneity into consideration in identifying various drivers of land-use conversions.

Our study area is Alberta, Canada. As the third largest producer and exporter of agri-food products in Canada, the province is currently experiencing rapid economic and population growth (Government of Alberta 2014a, b). These socioeconomic changes, along with shifting environmental factors (e.g., climate and water quality and availability) and potentially heightened market profitability and volatility, place unprecedented pressure on the province's private agricultural and forested

land areas, which are increasingly being converted into residential, recreational, and industrial uses (Carew et al. 2013; Haarsma and Qiu 2015). Although several notable studies were conducted in Calgary (the largest city in the province), a relatively small zone near the capital city of Edmonton, and the pothole region in the southwest of the province (Young et al. 2006; Sun et al. 2007; Rashford et al. 2011) and in the Edmonton Calgary corridor area (Qiu et al. 2015; Wang et al. 2016), the knowledge of the land-use changes across the entire province and the potential causes remain unclear. Therefore, to build a healthy future for Albertans, there is a pressing need to understand the province's changes in land use and the underlying mechanisms.

The objective of this paper is to quantify the effects of major environmental and socioeconomic factors on land-use change for each conversion type. To achieve this goal, we compile a comprehensive geographic information system (GIS) database that documents land-use changes and major environmental and socioeconomic factors that may affect land conversions on a fine lattice system in Alberta. Because policy makers, landowners, and other stakeholders often are interested in different conversion cases, we comprehensively assess all 12 types of land-use changes in the province. In addition to common factors, such as precipitation and temperature, we consider unique but important drivers for the current study area, such as snowpack levels and irrigation conditions, to investigate the underlying mechanisms that cause land-use changes in Alberta.

Study area and methods

Study area and period

Alberta is the fourth largest province in terms of land area in western Canada. The province is bordered by British Columbia to the west, Saskatchewan to the east, the Northwest Territories to the north, and the US state of Montana to the south. The capital city of Edmonton is located near the geographic center of the province, with an estimated population of approximately 812,200 according to the 2011 census. Another metropolitan city, Calgary, is situated approximately 280 km south of Edmonton and 80 km east of the Rocky Mountains, with an estimated population of 1,214,000 in 2011.

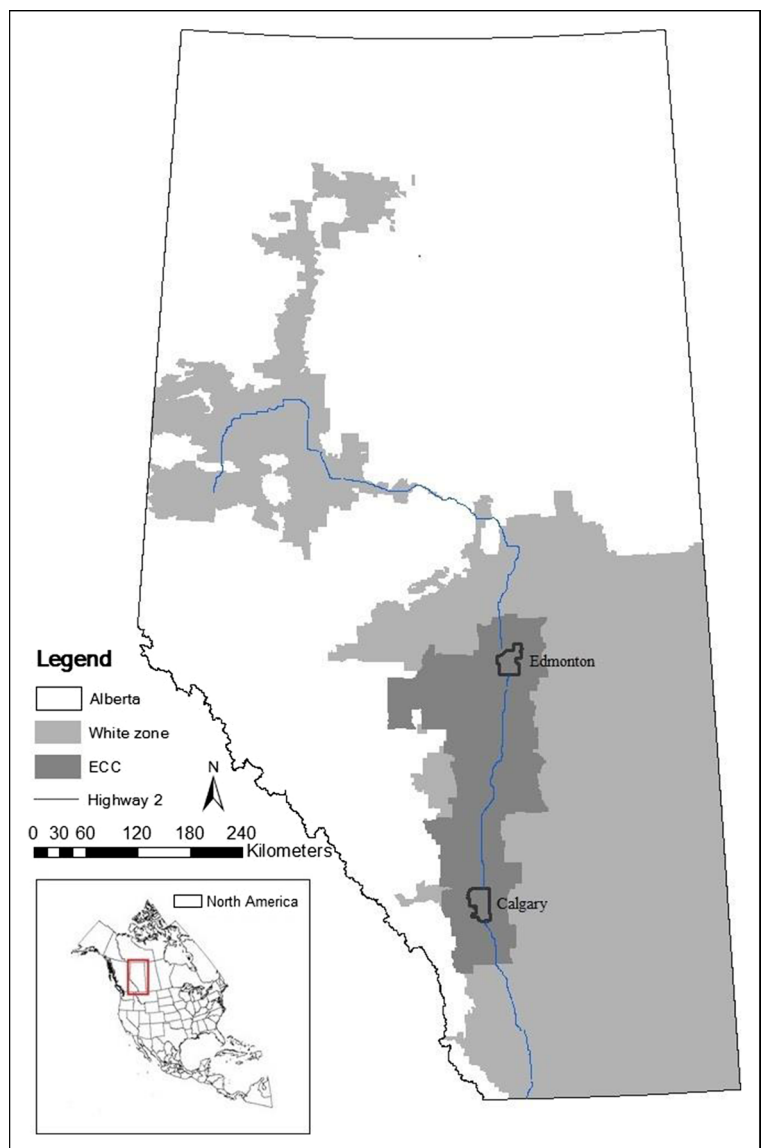
Over the past 20 years, the province of Alberta has been the national leader in economic growth, with an

average growth of 3.5 % per year (Government of Alberta 2014b). Additionally, the province’s population is expected to be six million by 2041, which is an increase of approximately 2.2 million from 2013 (Government of Alberta 2014c). To accommodate economic, environmental, and social considerations, the government of Alberta proposed the Land-Use Framework (LUF) in 2008 after consulting a wide range of stakeholders (Government of Alberta 2008). The LUF complements the province’s current policies, such as Water for Life and the Clean Air Strategy for Alberta. Its subplan also proposes a variety of strategies and policies for land use, including preservation of watersheds and

maintaining the contiguous blocks of agricultural land as well as smaller parcels of agricultural land (Government of Alberta 2014d). But as previously mentioned, the land-use changes across the whole province and the potential reason have not been explored yet.

This study focuses on Alberta’s white zone, which has a total area of 25.8 million ha (Government of Alberta 2011). The white zone contains all of the province’s privately owned land, and the majority of the province’s agricultural activities are conducted within this area (Fig. 1). Our study area also covers the Edmonton-Calgary corridor, which is the most developed area in the province and is one of the country’s top

Fig. 1 Map of the white zone in Alberta, Canada



four urbanized regions. The Queen Elizabeth II Highway (also called Highway 2) runs through the corridor as the central spine. Most urban encroachment occurs within the corridor and along Highway 2 (Fig. 1; Figs. 8, 11, and 14 in the Appendix).

Data and variables

We compiled a GIS database of land-use data and multiple environmental and socioeconomic factors at the Alberta Township System (ATS) level. The ATS is a lattice network that divides the white zone into equal-sized land parcels that are approximately 9.7×9.7 km. The boundaries of a parcel (referred to as a “township”) are defined by the range line (running north-south) and by the township line (running east-west). Because many environmental and agricultural studies and government research reports have been conducted at the township level, we apply this level of analysis to determine policy recommendations and to conduct comparisons with different studies. All land-use data and environmental and socioeconomic variables used for this study have been adapted to the township scale. The detailed computation of each variable is given in the subsequent subsection.

Thirty-meter resolution land-use raster images for the years 2000 and 2012 were provided by Agriculture and Agri-Food Canada (AAFC). The 2000 raster dataset has 11 land-use classes: annual crops, hay and pasture, developed (or built-up), water, barren, shrubland, wetland, grassland, coniferous trees, deciduous trees, and mixed trees. The 2012 raster dataset contains the last 10 classes, as well as detailed crop type classifications (e.g., wheat, corn, and sugar beet) that are included as annual crops in the 2000 dataset. The overall accuracies of the 2000 and 2012 maps are 87.1 and 88 %, respectively (AAFC 2015a, b). We reclassified all of the land-use types into four categories: cropland, pasture, natural land, and developed land. Definitions of each land-use type are presented in Table 1. Figure 2 depicts the total area for each land-use class in 2000 and 2012. Using the *Combination* tool in ArcGIS 10.1, we determined the locations and areas (in hectares) of the initial land use (2000) that were converted into any of the other three land-use types (2012) for each township. A total of 12 cases of land-use conversions were obtained. The total hectares of each land-use conversion case are summarized in Table 2. We then studied the effects of environmental and socioeconomic factors for each of the 12 conversion cases separately.

Table 1 The detailed information of land use types in Alberta

Land-use classes in this paper	Land covers in the satellite maps	Description
Cropland	Annual crops	Annually cultivated cropland and woody perennial crops
Pasture	Hay and pasture	Tame grasses and other perennial crops such as alfalfa and clover grown alone or as mixtures for hay, pasture, or seed
Developed land	Developed	Land built-up or developed, including road surfaces, buildings and pave surfaces, urban areas, industrial sites, mine structures, and farmsteads
Natural land	Water	Water bodies: lakes, reservoirs, rivers, streams, salt water, etc.
	Barren	Land nonvegetated and nondeveloped, including exposed land, bare soil, rock, burned area, rubble, etc.
	Shrubland	Woody vegetation of relatively low height
	Wetland	Land with a water table near/at/above soil surface to promote aquatic processes, including fens, bogs, swamps, etc.
	Grassland	Native grasses and other herbaceous vegetation
	Coniferous trees	Coniferous forests
	Deciduous trees	Broadleaf/deciduous forests
	Mixed trees	Mixed coniferous and broadleaf/deciduous forest

The construction of key environmental and socioeconomic variables

A summary of the environmental and socioeconomic explanatory variables is presented in Table 3 and described in detail in this section.

Land-use decisions are often made based on predicted weather conditions (e.g., the upcoming crop year for agricultural use). To ameliorate the impact of extreme weather events, the weather variables in 2000 and 2012 were generated based on mean values from 1997 through 2000 and 2009 through 2012, respectively. We then computed the changes in weather variables

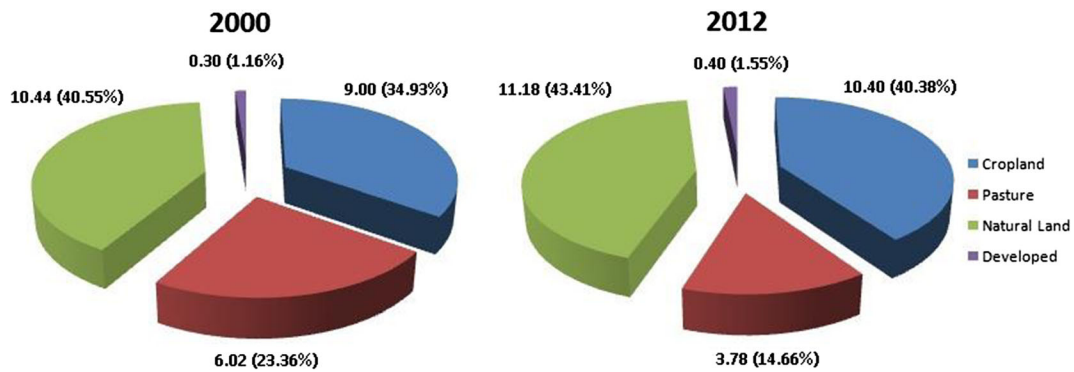


Fig. 2 Summary of land-use classes in 2000 and 2012 (unit: Mha)

between 2000 and 2012 to represent weather changes for the 12-year period. Historical weather data at the township level were provided by Alberta Agriculture and Rural Development (AARD). The original daily variables included precipitation, maximum temperature, minimum temperature, evapotranspiration, soil moisture, and snowpack water equivalent values. We generated a number of phenological indices, such as the change in the number of frost-free days between 2000 and 2012 (Δ FFD) and the change in growing-degree days over 5 °C (Δ GDD5) to investigate the effects of weather conditions on agriculturally relevant land uses. Given the multicollinearity concern and insignificance of the coefficients, we only used five weather variables in the final model specification. Four of these variables describe changes in the growing season (April through September) weather conditions between 2000 and 2012. These four variables are cumulative precipitation (Δ PREC), frost-free days (Δ FFD), growing-degree days over 5 °C (Δ GDD5), and daily mean soil moisture (Δ SMOIS). We also computed the change in the water equivalence of the daily mean snowpack for the month of April (Δ SNOW4) because snowpack levels at the start of the growing season may significantly affect soil

temperature and soil moisture at the time of seeding and thus impact farmers’ land-use decisions.

A 1-km resolution elevation raster dataset was obtained from the Commission for Environmental Cooperation (CEC). We aggregated the elevation to the township level using the area-weighted mean. Land suitability for agricultural uses (LANDS23) was computed by using the Land Suitability Rating System (LSRS) released by AARD. The LSRS is a national, 7-class rating system that evaluates the suitability of land for agricultural uses based on measureable soil, landscape, and climate characteristics. Land that is considered suitable for sustained production of the crop is within the range of class 1 to class 3. Given the province’s relatively arid climate compared with agricultural areas in Ontario and Quebec, class 2 (similar to class 1 but with climate limitations) is the highest suitability classification found in Alberta. Thus, the highest quality agricultural land in Alberta is classified under the class 2 and class 3 categories (no significant limitations other than climate), and this land is best suited for the production of high-value annual crops. Class 4 and class 5 land is characterized by soil texture (very coarse or stony) or topographic (steep slopes) limitations and is best suited for rangeland or perennial forage production. We computed the proportion of land with suitability rates of 2 or 3 for each township. A larger proportion indicates that land is more suitable for agricultural use.

In addition to the seven environmental variables, we generated four socioeconomic variables to account for the impact of human activities on land-use changes. Road density (DROAD) values were used to represent transportation costs and market accessibility levels. Road network data for Alberta in 2012 were obtained

Table 2 Land-use conversion for 2000–2012 (unit: ha)

	To cropland	To pasture	To natural land	To developed
Cropland	–	1,018,968	457,373	56,760
Pasture	2,397,098	–	1,129,855	49,401
Natural land	522,763	310,680	–	26,553
Developed	17,004	6083	11,462	–

Note: The entries denote the number of hectares of the initial land use in 2000 (listed in rows) that were converted into subsequent land uses in 2012 (listed in columns)

Table 3 Detailed description of explanatory variables at the township level

Explanatory variables	Description	Range	Mean	Standard deviation
Environmental variables				
ΔPREC	Change in growing season prec. (mm)	−236.81–194.80	−15.20	58.69
ΔFFD	Change in growing season frost-free days	−6.00–5.50	−0.70	1.24
ΔGDD5	Change in growing-degree days over 5 °C	−247.65–427.55	−25.29	89.34
ΔSMOIS	Change in growing season daily mean soil moisture in the upper 120-cm soil layer (mm)	−89.68–74.04	−14.60	24.75
ΔSNOW4	Change in daily mean snowpack water equivalent in April (mm)	−126.30–188.65	−10.51	21.51
ELEV	Elevation (m)	37.3–1777.7	764.27	216.52
LAND23	Proportion of land with suitability ratings of 2 or 3	0–1	0.54	0.36
Socioeconomic variables				
ΔDPOP	Population density (ind./ha)	−6.62–8.31	0.02	0.33
DROAD	Road density (m/ha)	0–115.9	7.16	6.96
IRRIG	Irrigated or nonirrigated	0, 1	–	–
LVAL	Agricultural land value (CAD\$/ha)	0–170,296.4	6526.3	9019.5

Note: The weather and population variables were computed based on differences between 2000 and 2012. The weather variables for 2000 were calculated from the average values from 1997 to 2000, and the weather variables for 2012 were computed from the average values from 2009 to 2012

from AltaLIS Ltd. The lengths of all the road types in each township, including both public and private roads, were summed and then divided by the township area.

The boundary shapefile for the southern Alberta irrigation districts was obtained from AARD. Note that not all the land within the irrigation districts is currently under irrigation. Because we do not have detailed irrigated-acres data at the township level, we made the following simple assumption to generate the irrigation variable: if more than 50 % of the township area was located within irrigation districts, then we assigned an irrigation (IRRIG) value of 1 to the township; otherwise, we assigned an IRRIG value of 0.

The agricultural-land value was provided by Statistic Canada for each county. The county-level values are projected to the township level by the weight of the percentage of high-quality agricultural land (classes 2 to 4 in LSRS rating) in the township versus the percentage in the county. Thus, a township with a higher percentage of good-quality agricultural land will have relatively higher agricultural land value.

Because no population data are available for 2000 and 2012, we used 2001 and 2011 census subdivision (CSD)-level population density data provided by Statistics Canada to approximate the populations in 2000 and 2012. We derived township-level population densities based on road-density weights. This practice closely

mimicked the actual conditions because residential areas often exhibit higher road densities than nonresidential areas.

Empirical models

To explicitly account for the effect of the spatial dependence, three related but distinct spatial models were applied and compared: the spatial autoregressive (SAR) model, the spatial error model (SEM), and the SAC. In practice, the SAR model is applied when the dependent variable is spatially correlated, the SEM model is adopted when unobserved factors affect the dependent variable and correlate over space, and the SAC model captures the spatial correlations of both the dependent variable and the unobserved factors.

Spatial autocorrelation has been found to be prevalent in both natural and artificial landscapes (Tobler 1970; Legendre 1993; Wang et al. 2002; Liang 2012; Li et al. 2013). The agricultural clustering pattern may have resulted from the technology sharing between neighboring farms, declining management or transportation costs, or particular social norms (Li et al. 2013). However, land-use decisions may be strongly affected by unobserved factors, such as variances in crop prices and, during this period in Alberta, an episode of bovine spongiform encephalopathy (BSE) in 2007. Therefore,

we based the regression on the SAC model, and the results of the model comparison confirm the SAC model’s superiority (see the final paragraph of the section “Empirical models”). A SAC model can be expressed as follows:

$$\begin{aligned} Y &= \rho W_1 Y + \beta X + \mu \\ \mu &= \lambda W_2 \mu + \varepsilon \end{aligned} \tag{1}$$

where ρ and λ are scalar parameters, β is a vector of parameters, Y is a vector of the number of hectares of an initial land-use class in 2000 converted into a corresponding land-use class in 2012 at the township level, X is a matrix of explanatory variables, μ is a vector of disturbance terms that contain unobserved factors (e.g., crop prices), ε is a vector of standard disturbances following $N(0, \sigma_\varepsilon I)$, and W_1 and W_2 are $n \times n$ spatial weight matrices, where n is the number of observations. $W_1 Y$ is a spatial lag that describes the spatial correlation between Y and Y ’s neighboring observations, while $W_2 \mu$ denotes the spatial correlations of the unobserved factors. In practice, W_1 and W_2 are typically set as equal due to difficulties in detecting unobserved factors (LeSage and Pace 2009). If $W_1 = 0$, then Eq. 1 becomes a SEM:

$$\begin{aligned} Y &= \beta X + \mu \\ \mu &= \lambda W_2 \mu + \varepsilon. \end{aligned} \tag{2}$$

If $W_2 = 0$, then Eq. 1 becomes a SAR:

$$Y = \rho W_1 Y + \beta X + \varepsilon. \tag{3}$$

If both W_1 and W_2 equal 0, then Eq. 1 becomes a simple linear regression model:

$$Y = \beta X + \varepsilon. \tag{4}$$

Several methods can be used to create spatial weight matrices, e.g., spatially contiguous neighbors, ranked distance, and n nearest neighbors (Anselin 1988). In this study, we assigned values to the spatial weight matrices using an inverse-distance approach. Townships within a particular radius were defined as the neighbors of the township under consideration. We assigned a value to each neighboring township within this radius based on its inverse distance to the respective central township, whereas we assigned a value of 0 to townships positioned outside of this radius. Using the *Incremental Analysis* tool in ArcGIS 10.1, we identified the radius at which the highest degree of spatial clustering occurs for each conversion case. Most of the radii were approximately 30 km. To eliminate the possible effect of

unequal-sized neighbors on the model performance, we set the radius to 30 km for all 12 cases.

The four models were separately estimated and compared for the 12 conversion cases using the R software package (version 2.15.0). With respect to the general goodness of fit, the lowest Akaike information criterion (AIC) and highest R -squared values indicated that the SAC model was the superior model for most of the conversion cases (see an example in Table 4), although the SAR model was preferable for the pasture-to-developed land conversion.

Marginal effects

Once the parameters (ρ , β , and λ) are estimated, the marginal effects of explanatory variables can be calculated by Eq. 5:

$$\frac{\partial Y}{\partial X} = n^{-1} l_n' (I_n - \rho W_1)^{-1} \beta l_n \tag{5}$$

where n is the number of observations, l_n is an $n \times 1$ vector with all entries equaling 1, I_n is the identical matrix, and l_n' is the transpose of l_n . Let $G(\rho, \beta) = \frac{\partial Y}{\partial X}$. Then, the standard errors of marginal effects are computed by using the delta method as follows:

$$\left(\frac{\partial G(\rho, \beta)}{\partial \rho}, \frac{\partial G(\rho, \beta)}{\partial \beta} \right) \text{cov}(\rho, \beta) \left(\frac{\partial G(\rho, \beta)}{\partial \rho}, \frac{\partial G(\rho, \beta)}{\partial \beta} \right) \tag{6}$$

In this study, the marginal effects describe the acreage change for the response variables associated with a one-unit increase in the explanatory variables.

Table 4 Model comparison for the pasture-to-cropland conversion

	Δ AIC value	R -squared
Simple linear regression (OLS)	1595	0.2810
Spatial autoregressive model (SAR)	118	0.6140
Spatial error model (SEM)	18	0.6298
Spatial autocorrelation model (SAC)	0	0.6326

Results

Descriptive summary of land-use conversions

Over the 12-year period, the cropland area increased by 14.9 %, while the pasture area decreased by 37.5 %; a 6.1 % net loss occurred in the province's agricultural land base (Fig. 2). Detailed data on the area changes for each land-use class are summarized in Table 2. The entries listed in Table 2 denote the number of hectares of the original land use in 2000 (rows) converted into the resulting land use in 2012 (columns). The analysis shows that 2,397,098 ha of pasture were converted into cropland between 2000 and 2012, encompassing 39.8 % of the total pasture area in 2000. Note that many of these changes may not be permanent. We examined land-use data for only two discrete time periods, and agricultural rotations may account for the large loss of pasture area that was likely converted into annual crops but remains reversible if cattle prices rise in the future. Moreover, the increased rate of land-use conversion to developed land was substantial (33.2 %); however, the overall proportion of developed land was comparatively lower (only 1.6 % in 2012, Fig. 1).

Due to space limitation, we presented only two cases of land-use conversion at the township level (Figs. 3 and 4) and compared these with the land suitability (Fig. 5). The maps of all the 12 cases of land-use conversion can be found in the Appendix. As shown in Fig. 5, most of the high-quality land is located in the Edmonton-Calgary corridor area (Figs. 1 and 5), while low-quality land is clustered in the east-southern part of the white zone (blue area in Fig. 5). Figure 3 shows that cropland outside the corridor was more likely to be converted into natural land, while Fig. 4 indicates that pasture in the mid-southern part of the white zone was inclined into natural land. Clearly, the conversion of cropland and pastureland to natural land (Figs. 3 and 4) was most prevalent in the area that indicated relatively low suitability for agriculture, with the exception of the northwestern area in the white zone. The abandonment of agricultural land in this region (the Peace River area) may be attributable to the occurrence of intermittent flooding and drought. We excluded the northwestern area of the white zone (the Peace River area) from the regression analysis for the following reasons: (1) the isolation and irregular shape of particular areas in this region may skew the results because townships within

this region possess significantly fewer neighbors than other townships in the south, and (2) agricultural land losses in this region are temporary (caused by extreme weather events), and they do not reflect typical rational land-use decisions that can be explained by land-use models.

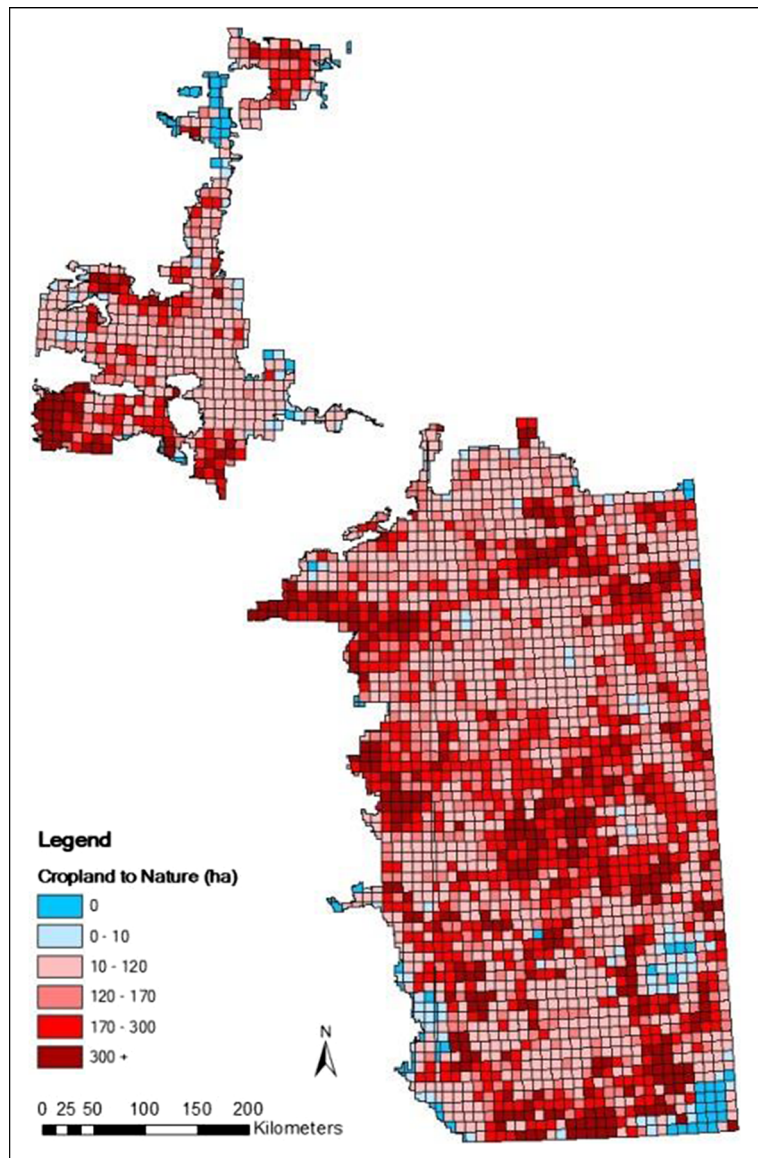
Drivers of land-use conversion

Because performing comparisons among the 12 conversion cases in separate tables tends to be difficult, we list the marginal effects of the six most influential drivers in Tables 5, 6, 7, 8, and 9. The complete results for the 12 conversion cases are presented in the Appendix.

Land suitability for agricultural uses (LAND23) was the most influential factor among all of the explanatory variables. Table 5 illustrates the marginal effects of LAND23 for the 12 conversion cases. Positive marginal effects shown in the first column indicate that pasture, natural land, and developed land with higher agricultural land suitability (i.e., classes 2 and 3) were more likely to be converted into cropland. This finding is consistent with those of Matlack (1997), Duram et al. (2004), and Rashford et al. (2011), who found that an increase in agricultural land acreage is associated with high-quality land.

The effect of road density (DROAD) on land-use decisions is controversial in the existing literature. Although numerous researchers have argued that higher DROAD levels increase the probability that farmland and natural land will be converted into developed land (Matlack 1997; Hall et al. 2002; Baumann et al. 2011), Deng et al. (2011) found that DROAD had no impact on forest loss in Jiangxi Province, China. In the present study, we found that DROAD did have a significant relationship with land-use conversion in Alberta. In particular, agricultural land and natural land with relatively higher DROAD levels were more likely to be converted into developed land (Table 6), whereas the acreage of natural land increased in areas with lower DROAD levels. These results should signal to policy makers that road construction can result in both positive and negative outcomes. Although high DROAD areas increase market accessibility and reduce transportation fees, they may also attract more migrants and increase the possibility that agricultural land will be converted into residential and recreational uses. Notably, DROAD had a positive effect on the conversion of developed

Fig. 3 Cropland hectares converted into natural land at the township level

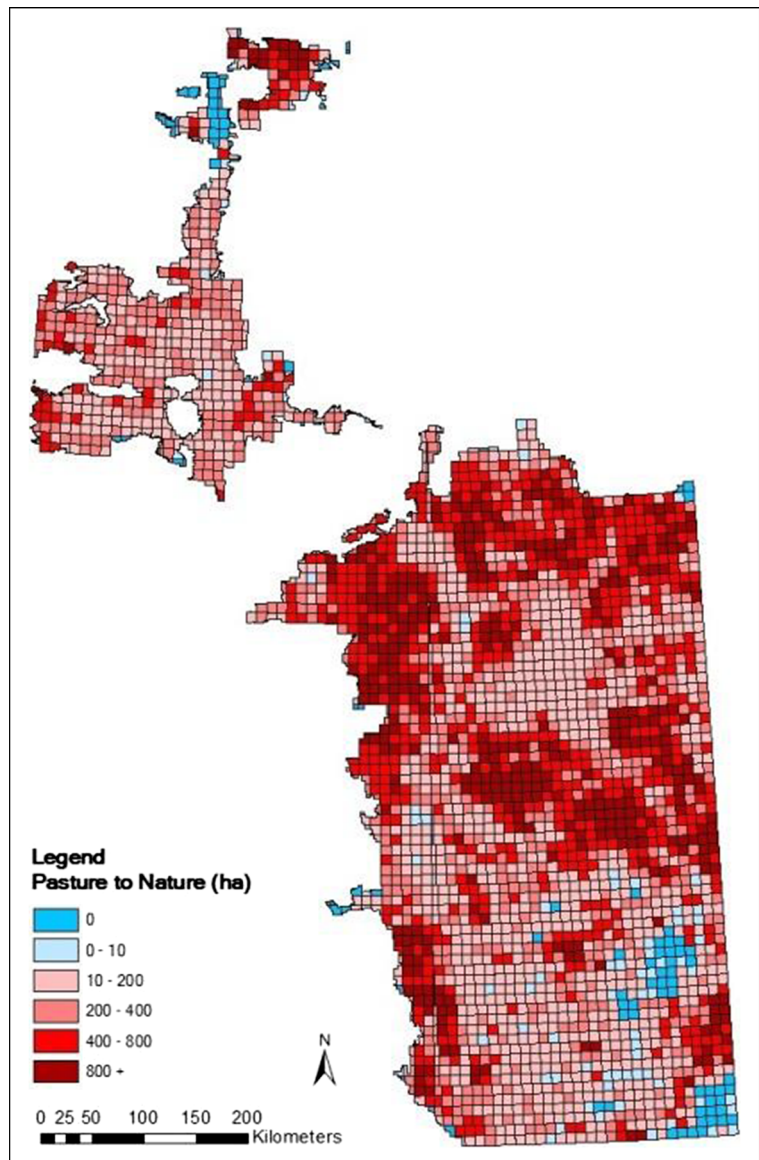


land into agricultural and natural land (see the last row of Table 6). Land reclamation may have played an important role in these conversion cases. Unused trails, roads, and oil-well leases may have been reclaimed and reincorporated into the agricultural land base. In particular, developed land-to-cropland conversion was most evident along the Edmonton-to-Calgary corridor due to the ease of accessibility and high land suitability.

The marginal effect of the increasing population density (Δ DPOP) reveals that the expansion of developed land into agricultural and natural land was associated

with population growth (Table 7). In Alberta, the booming oil and gas industries resulted in an increasing demand for labor and other services, which caused rapid population growth. The province is expected to comprise a population of 6.2 million by 2041, which is an increase of approximately 2.2 million from 2013. This rapid population growth will likely accelerate the future encroachment of residential land into agricultural areas. This finding is consistent with that identified in China and India. Both countries have experienced explosive population growth and rapid urban expansion over the last 20 years (Heilig 1997; Sudhira et al. 2004; Deng et al.

Fig. 4 Pasture hectares converted into natural land at the township level



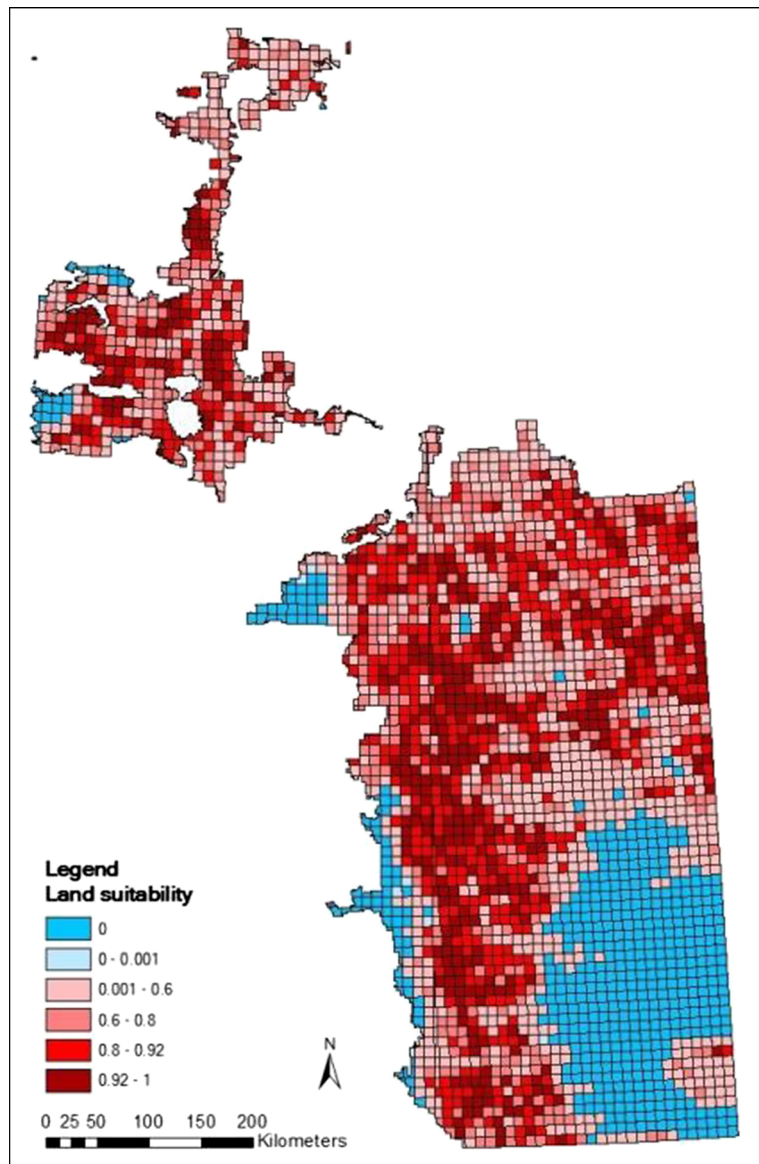
2008). Our results also suggest that the relation between the conversion rate and population growth may vary across conversion cases. For example, population sizes increased dramatically in cases of natural-to-developed land conversion, while comparatively smaller population increases occurred when pasture was converted into developed land.

The marginal effect of elevation (ELEV) demonstrates that both agricultural and developed land acreages primarily increased in comparatively low-elevation regions, whereas natural land acreage primarily increased in high-elevation regions (Table 8). This finding

is consistent with that of Li et al. (2013), who comprehensively examined the conversions of six land-use classes in China. These transitions occur because settlers prefer low-elevation regions for residing and farming because these regions are easily accessible. Additionally, given the glacial origin of the Albertan landscape, higher elevations are also associated with complex, rolling or hummocky topography, land types that are less suitable for agriculture and more difficult to cultivate.

Not surprisingly, pasture and developed land located within irrigation districts (IRRIG) was more

Fig. 5 Proportion of land suitability equal to class 2 or 3 at the township level



likely to be converted into cropland (Table 9). Samarawickrema and Kulshreshtha (2008) described the benefits of irrigated farming relative to dryland

farming. The additional water supply provided through irrigation not only offsets the adverse effects of drought to a great extent but also improves

Table 5 The marginal effects of land suitability for agricultural uses (LAND23) on land conversion for the 12 cases

	To cropland	To pasture	To natural land	To developed
Cropland	–	208.73*** (62.861)	28.010 (27.598)	–17.481 (14.497)
Pasture	1179.8*** (240.38)	–	–292.82** (116.71)	–18.675 (11.747)
Natural land	114.70* (72.377)	–14.963 (31.056)	–	–11.159*** (2.9970)
Developed	11.067*** (1.6992)	1.3453* (0.5669)	–3.5526*** (1.2123)	–

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

Table 6 The marginal effects of road density (DROAD) on land conversion for the 12 cases

	To cropland	To pasture	To natural land	To developed
Cropland	–	2.5070 (1.7202)	–1.0726 (1.0939)	7.2292*** (0.9492)
Pasture	2.4350 (4.2574)	–	–6.5318* (3.3849)	8.6605*** (0.9423)
Natural land	–0.8022 (1.8240)	–1.5342 (1.2048)	–	3.0190*** (0.2578)
Developed	0.2451*** (0.0516)	0.1095*** (0.0396)	0.6270*** (0.1333)	–

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

productivity because high summer temperatures increase evapotranspiration rates, leading to greater crop growth when moisture is not constrained. Additionally, irrigation reduces production uncertainties/risks associated with precipitation shortages, which are otherwise a major concern for crop farmers. Irrigation also enables farmers to grow more profitable commodities for value-added processing, such as potatoes, sugar beets, and beans. Finally, both high-cost irrigation facilities and water rights raise the price of agricultural land. Based on the agricultural land values shown in the “[Study area and methods](#)” section, we found agricultural land values in these areas to be approximately 1.5 times higher than the average value for the entire province. With the aim of maximizing their returns from the land, farmers and landowners should be willing to preserve agricultural land in irrigation districts.

Our results show that agricultural land values (LVAL) only have significant effects in the conversion cases when the developed land is involved (Tables 10, 11, and 13 in the [Appendix](#)). Furthermore, it seems counterintuitive that high agricultural land value may cause the conversion of agricultural land to developed uses. The logic behind this phenomenon is that the land close to the urban center may have comparatively higher value and have a greater chance of being converted into residential, recreational, or/and commercial uses. Similar results can be found in previous research. In a relevant case

study concerning 10 coastal provinces in China, Lichtenberg and Ding (2009) found that urban development first occurred in the most productive areas with comparatively high LVAL. Li et al. (2013) also concluded that the impact of LVAL has varied over time but that it tends to be significant during urban expansion.

The effects of weather conditions on land-use changes and patterns have been widely documented by researchers worldwide (Deng et al. 2002; Hall et al. 2002; Ureta et al. 2013). Our results show that cropland was more likely to be converted into natural land with decreasing growing-degree days (Δ GDD5) and soil-water deficit levels (Δ SMOIS) because heat accumulation and soil moisture are positively correlated to crop growth (Table 10 in the [Appendix](#)). Pasture was more likely to be converted into natural land as precipitation levels decreased (Table 11 in the [Appendix](#)). These results are consistent with those of Deng et al. (2002), Hall et al. (2002), and Ureta et al. (2013), who demonstrated the significant effects of weather conditions on land-use decisions. We are also particularly interested in the role of snowpack water equivalent levels in the early growing season (Δ SNOW4). This factor may be a major concern in the Canadian Prairie Provinces because it can delay spring agricultural activities (i.e., seeding and land preparation) while also contributing significantly to soil moisture. The negative marginal Δ SNOW4 value for the

Table 7 The marginal effects of changing population density (Δ DPOP) on land conversion for the 12 cases

	To cropland	To pasture	To natural land	To developed
Cropland	–	–25.068 (26.056)	–3.3968 (15.221)	178.18*** (28.203)
Pasture	–139.93* (72.935)	–	–52.303 (44.794)	121.06*** (19.107)
Natural land	–11.647 (28.693)	–13.66 (17.493)	–	13.690*** (2.3008)
Developed	–1.1174* (0.6343)	–0.1127 (0.3031)	–1.7141* (0.8459)	–

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

Table 8 The marginal effects of elevation (ELEV) on land conversion for the 12 cases

	To cropland	To pasture	To natural land	To developed
Cropland	–	0.0219 (0.1560)	0.0290 (0.0667)	–0.0752*** (0.0291)
Pasture	0.6301 (0.3955)	–	0.4092* (0.2564)	–0.0644*** (0.0208)
Natural land	0.2803 (0.1591)	–0.1557 (0.1004)	–	0.0012 (0.0062)
Developed	0.0003 (0.0027)	–0.0022* (0.0013)	–0.0006 (0.0023)	–

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

pasture-to-crop conversion indicates that less snow-pack on the ground in April may motivate farmers to shift from pastures to cropland. The shift from natural land to pastures with decreasing precipitation (Δ PREC) and increasing frost-free days (Δ FFD) (Table 12 in the Appendix) is counterintuitive and difficult to interpret. This conversion may be caused by the abandonment of pasture for reasons other than weather conditions early in the year or by the association between low-elevation land and greater market access, which is considered vital to the expansion of agricultural activities.

Discussion

Implications

This study provides farmers, landowners, policy makers, and other stakeholders with detailed information on land-use conversions in Alberta and the major land-use drivers from 2000 to 2012. The study also serves as a benchmark for future studies on the impacts of changing weather conditions, road construction, population growth, and irrigation expansion on current land-use patterns.

The empirical results indicate that socioeconomic factors are the dominant forces behind land-use changes in Alberta. Decision makers may be

particularly interested in the construction of roads and in the potential expansion of irrigation. The role of road density (DROAD) is complex and varies across land-conversion cases. A higher DROAD value denotes ease of market access and low transportation fees. Consequently, a higher value promotes the conversion of natural land to agricultural land (Table 6). However, in suburban regions, higher DROAD values may attract more migrants and cause agricultural land to be converted into residential and recreational land.

Our results also show that irrigation (IRRIG) is beneficial to agricultural preservation but that it favors annual crops over pastures. Irrigation districts typically exhibit a higher degree of productivity because irrigation can, to a large extent, offset the adverse effects of extreme weather events, such as droughts and high temperatures (Tao et al. 2008; Samarawickrema and Kulshreshtha 2008; Wang et al. 2009; You et al. 2009). This factor may further encourage the expansion of irrigation throughout the province. In 2012, irrigated farms across the 13 irrigation districts in southern Alberta covered approximately 1,380,000 acres. During 1993–2002 and 2003–2012, the total irrigated farm acreage increased by approximately 0.7 and 0.4 % per year, respectively. Applying the Farm Financial Impact and Risk Model (FFIRM), Bennett et al. (2013) found that water supply deficits have had no effect

Table 9 The marginal effects of irrigation (IRRIG) on land conversion for the 12 cases

	To cropland	To pasture	To natural land	To developed
Cropland	–	–6.7756 (55.418)	–57.963 (40.817)	–20.088 (18.800)
Pasture	1277.7*** (282.71)	–	63.911 (90.795)	–15.486 (15.486)
Natural land	–42.257 (61.730)	–49.283 (40.189)	–	–6.1038* (3.6180)
Developed	9.4087*** (1.7958)	–0.1249 (0.5930)	–2.4399* (1.3851)	–

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

on net farm-income (NFI) levels in a current irrigation expansion scenario (1991–2009), and the deficits would cause a small reduction in the NFI according to a projected expansion scenario. However, with the continuous expansion of irrigation resulting in increasing water demands, we expect that water supply deficits will be the main obstacle to irrigation development.

This study also shows that potential drivers and their magnitudes vary across conversion cases. For example, while road density (DROAD) plays an important role in the conversion of pastures into natural land, no statistically significant relationship exists between DROAD and the pasture-to-cropland conversion (Table 6). Therefore, policy makers, farmers, landowners, and other stakeholders may identify different drivers based on specific cases of concern.

Finally, we found that an increase in cropland was associated with a decrease in snowpack water equivalent levels that occurred in April (Δ SNOW4). This result indicates that weather conditions early in the growing season may have a significant effect on land-use decisions in Alberta. This issue has not yet been considered explicitly in the literature. Agricultural industries should thus consider this factor when deciding whether to expand agricultural activities in the province. The effects of climate change on early growing-season weather may also have significant impacts on future land-use in the province.

Perspectives

Application of spatial regression models in land use and land-use change analysis is still young and deserves further investigation and improvement. The primary advantage of the SAC model is that spatial autocorrelation is explicitly considered in identifying various drivers of land-use conversions, and thus eliminates the estimation biases resulting from ignoring the spatial dependence. However, the prediction of the SAC model may exceed the total area of a township or even become negative under extreme circumstances, which is impractical and may lead to inappropriate policy recommendations. To overcome this shortcoming, spatial multinomial logit or probit models, which are new developments in this field, may be utilized in the further research though they may also bring the heavy computational

requirement issue especially when one is working with large remote sensing data.

As noted above, the drivers of land-use changes vary over time and space. The results of this study reveal the effects of these factors on land-use changes over a recent 12-year period in Alberta. Because agricultural activities have been conducted in the province for over 100 years, numerous factors, particularly climate changes, may have already forced farmers and landowners to make land-use decisions that shaped the current land-use patterns. Future studies may investigate the effects of varying factors, particularly climatic influences, on land-use conversions over longer time scales.

Conclusions

The main objectives of this paper were to assess land-use changes and to quantify the effects of potential drivers of these changes in the province of Alberta. We compiled a comprehensive GIS database of land-use information and multiple environmental and socioeconomic variables at the township level for the entire province. The SAC empirical results showed that cropland areas expanded by 14.9 %, while pasture areas decreased by 37.5 %. A 6.1 % net decline in the province's agricultural land base occurred over the 12-year period. Nearly 40 % of pasture was converted into cropland within the agricultural class. The expansion of developed land was substantial, reaching 33.16 %, although the proportion of developed land remained relatively small (1.55 % in 2012). The marginal effect outcomes showed that the specific impact of environmental and socioeconomic drivers varied, depending on the type of land-use change involved. Land suitability for agricultural uses (LAND23), road density (DROAD), elevation (ELEV), and population growth (Δ DPOP) were generally found to be central drivers of the province's land-use choices. Our results also imply that weather conditions early in the growing season may significantly guide land-use choices.

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Appendix

Table 10 The marginal effects on the cropland conversion in the SAC model

Explanatory variables	To pasture	To natural land	To developed area
Environmental variables			
ΔPREC	0.1102 (0.7306)	0.2325 (0.3527)	0.3596* (0.1880)
ΔFFD	24.886 (18.967)	16.550 (10.796)	-2.4078 (4.5544)
ΔGDD5	-0.8930** (0.4500)	-0.5155** (0.2596)	-0.1624 (0.1045)
ΔSMOIS	-2.1581 (1.4274)	-1.2220* (0.7616)	-0.2351 (0.3598)
ΔSNOW4	-0.9475 (1.0047)	-0.4144 (0.5579)	-0.4886 (0.3362)
ELEV	0.0219 (0.1560)	0.0290 (0.0667)	-0.0752*** (0.0291)
LAND23	208.73*** (62.861)	28.010 (27.598)	-17.481 (14.497)
Socioeconomic variables			
ΔDPOP	-25.068 (26.056)	-3.3968 (15.221)	178.18*** (28.203)
DROAD	2.5070 (1.7202)	-1.0726 (1.0939)	7.2292*** (0.9492)
IRRIG	-6.7756 (55.418)	-57.963 (40.817)	-20.088 (18.800)
LVAL	0.0003 (0.0012)	0.0003 (0.0007)	0.0047*** (0.0008)
Rho	0.3891*** (0.1489)	0.5021* (0.3026)	0.6452*** (0.0532)
Lambda	0.8027*** (0.0739)	0.5962** (0.2675)	0.2097** (0.1042)
R-squared	0.4818	0.3006	0.4799

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

Table 11 The marginal effects on the pasture conversion in the SAC model

Explanatory variables	To cropland	To natural land	To developed area
Environmental variables			
ΔPREC	-2.0481 (1.8474)	-2.3147* (1.3354)	0.2806 (0.2403)
ΔFFD	62.252 (47.971)	8.7706 (28.647)	2.0206 (3.5342)
ΔGDD5	-3.3413*** (1.1845)	-0.8157 (0.7090)	-0.1135 (0.0772)
ΔSMOIS	0.0663 (3.5314)	3.5266 (2.4163)	-0.3805 (0.2779)
ΔSNOW4	-8.0095*** (2.8910)	-2.3990 (1.8193)	-0.1587 (0.2750)
ELEV	0.6301 (0.3955)	0.4092* (0.2564)	-0.0644*** (0.0208)
LAND23	1179.8*** (240.38)	-292.82** (116.71)	-18.675 (11.747)
Socioeconomic variables			
ΔDPOP	-139.93* (72.935)	-52.303 (44.794)	121.06*** (19.107)
DROAD	2.4350 (4.2574)	-6.5318* (3.3849)	8.6605*** (0.9423)
IRRIG	1277.7*** (282.71)	63.911 (90.795)	-15.486 (15.754)
LVAL	0.0022 (0.0032)	0.0053 (0.0057)	0.0025*** (0.0005)
Rho	0.5786*** (0.0903)	0.5637*** (0.1584)	0.7123*** (0.0257)
Lambda	0.7679*** (0.0670)	0.7929*** (0.1002)	NA
R-squared	0.6326	0.5147	0.4685

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively. Pasture-to-developed conversion is fitted by the SAR model

Table 12 The marginal effects on the natural land conversion in the SAC model

Explanatory variables	To cropland	To pasture	To developed area
Environmental variables			
ΔPREC	-0.6613 (0.7117)	-0.9820* (0.5506)	0.0207 (0.0378)
ΔFFD	-6.9846 (16.688)	24.449* (13.710)	0.5277 (0.9424)
ΔGDD5	-0.6713 (0.5039)	-0.4079 (0.2896)	0.0290 (0.0208)
ΔSMOIS	1.2306 (1.4567)	0.5005 (0.9187)	0.1092 (0.0745)
ΔSNOW4	-0.6742 (1.0490)	-0.0359 (0.6454)	-0.0072 (0.0630)
ELEV	0.2803 (0.1591)	-0.1557 (0.1004)	0.0012 (0.0062)
LAND23	114.70* (72.377)	-14.963 (31.056)	-11.159*** (2.9770)
Socioeconomic variables			
ΔDPOP	-11.647 (28.693)	-13.660 (17.493)	13.690*** (2.3008)
DROAD	-0.8022 (1.8240)	-1.5342 (1.2048)	3.0190*** (0.2578)
IRRIG	-42.257 (61.730)	-49.283 (40.189)	-6.1038* (3.6180)
LVAL	0.000001 (0.0013)	0.0003 (0.0008)	-0.0001 (0.0001)
Rho	0.6191** (0.2502)	0.5601*** (0.1760)	0.1418* (0.0855)
Lambda	0.6497*** (0.2399)	0.7820*** (0.1140)	0.4156*** (0.0831)
R-squared	0.4676	0.5557	0.3898

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

Table 13 The marginal effects on the developed area conversion in the SAC model

Explanatory variables	To cropland	To pasture	To natural land
Environmental variables			
ΔPREC	-0.0128 (0.0145)	-0.0103 (0.0069)	0.0073 (0.0139)
ΔFFD	0.1012 (0.3657)	-0.0687 (0.1705)	0.0603 (0.3416)
ΔGDD5	-0.0082 (0.0083)	-0.0016 (0.0040)	0.0082 (0.0075)
ΔSMOIS	0.0499* (0.0291)	-0.0187 (0.0142)	0.0210 (0.0270)
ΔSNOW4	-0.0122 (0.0217)	-0.0019 (0.0105)	0.0116 (0.0225)
ELEV	0.0003 (0.0027)	-0.0022* (0.0013)	-0.0006 (0.0023)
LAND23	11.067*** (1.6992)	1.3453** (0.5669)	-3.5526*** (1.2123)
Socioeconomic variables			
ΔDPOP	-1.1174* (0.6343)	-0.1127 (0.3031)	-1.7141** (0.8459)
DROAD	0.2451*** (0.0512)	0.1095*** (0.0396)	0.6270*** (0.1333)
IRRIG	9.4087*** (1.7958)	-0.1249 (0.5930)	-2.4399* (1.3851)
LVAL	-0.0001*** (0.00003)	-0.00002 (0.00002)	-0.0001** (0.00004)
Rho	0.4518*** (0.0946)	0.4610** (0.2045)	0.5326*** (0.1108)
Lambda	0.6474*** (0.0795)	0.6001*** (0.1732)	0.4498*** (0.1314)
R-squared	0.5130	0.3499	0.3740

Note: *, **, and *** denote statistical significance at the 10, 5, and 1 % levels, respectively

Fig. 6 Cropland hectares converted into pasture at the township level

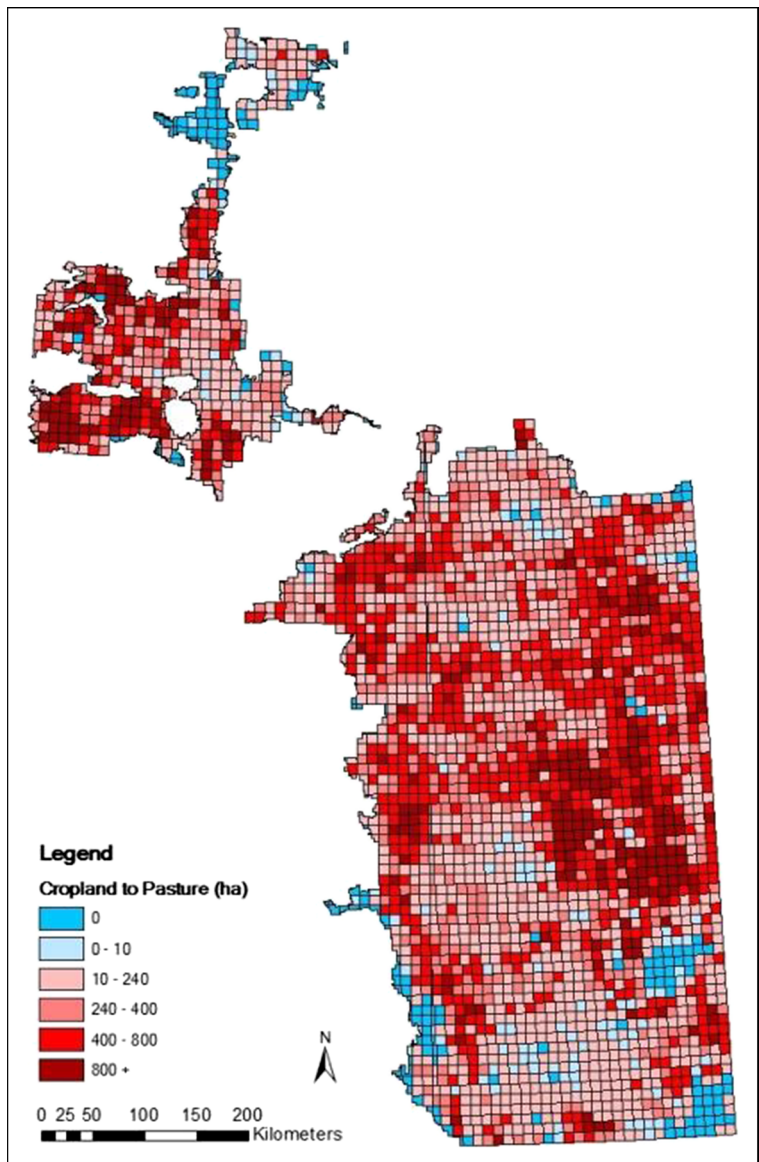


Fig. 7 Cropland hectares converted into natural land at the township level

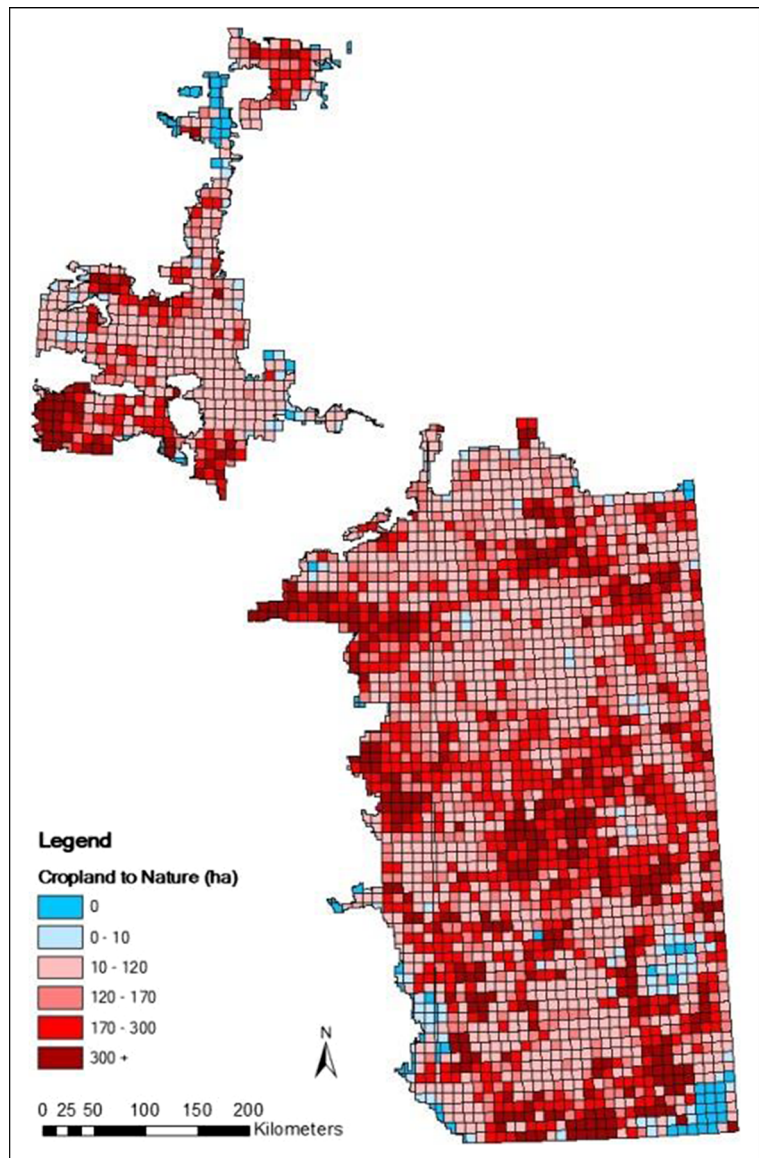


Fig. 8 Cropland hectares converted into developed land at the township level

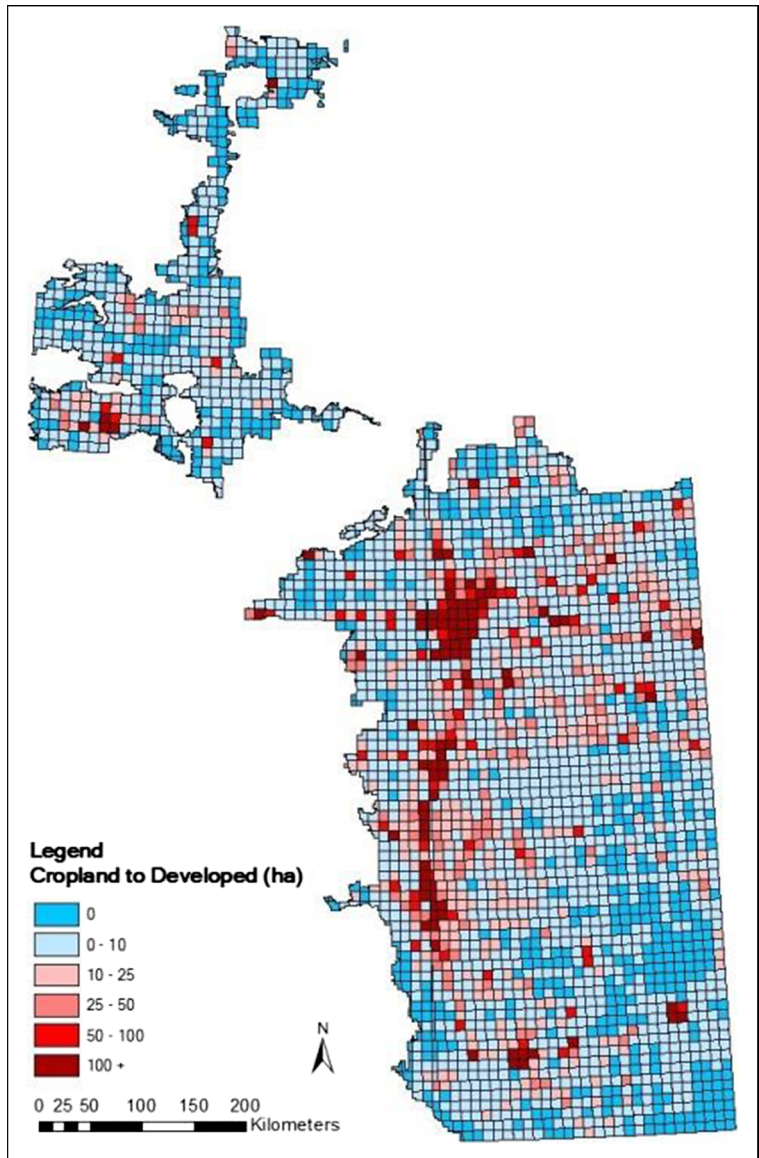


Fig. 9 Pasture hectares converted into cropland at the township level

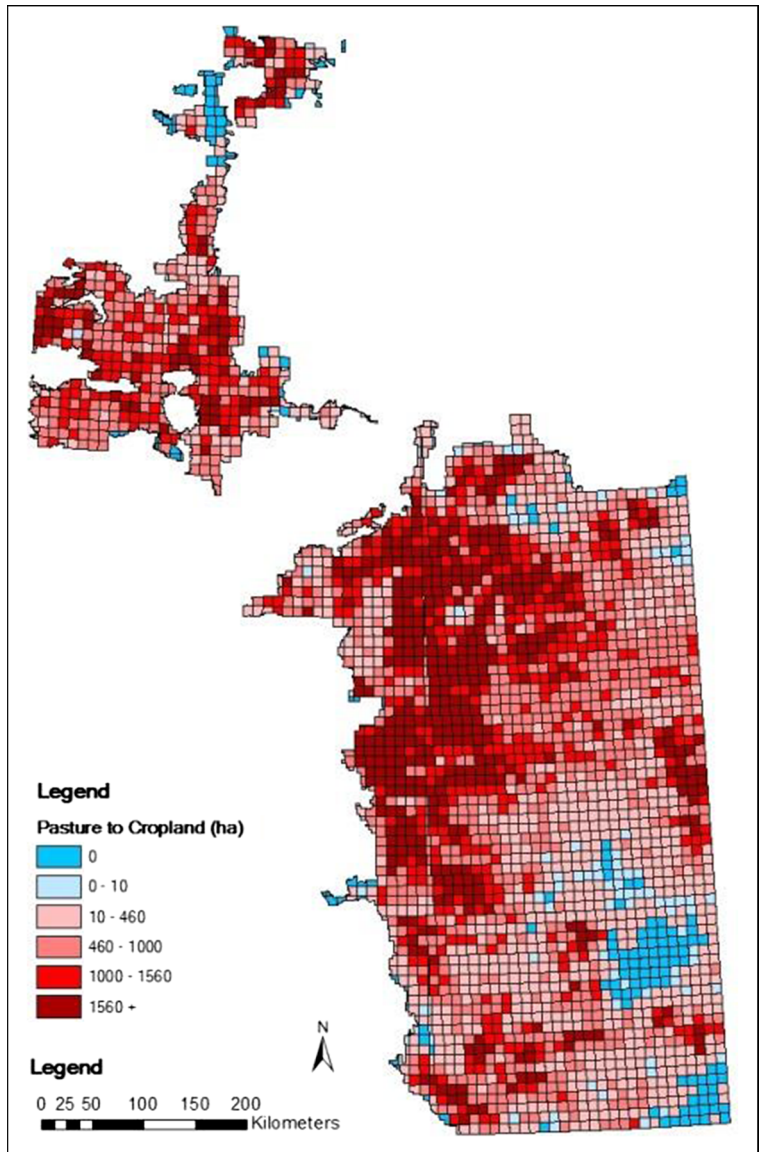


Fig. 10 Pasture hectares converted into natural land at the township level

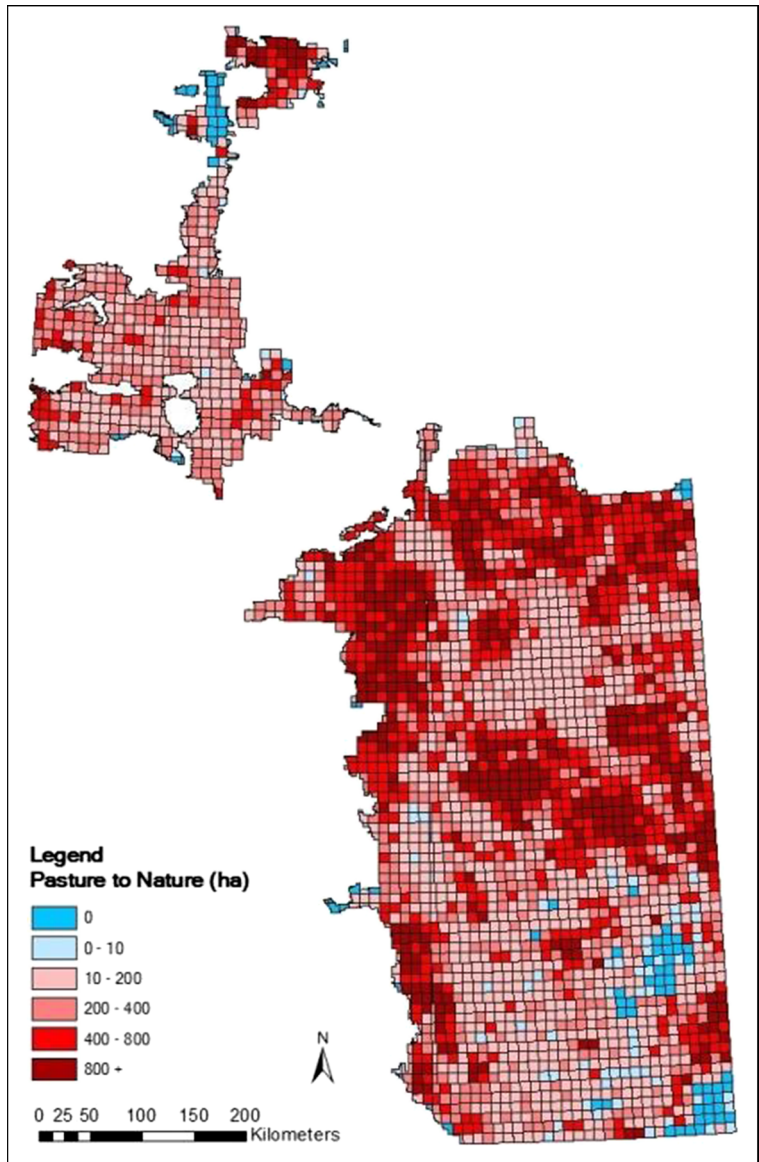


Fig. 11 Pasture hectares converted into developed land at the township level

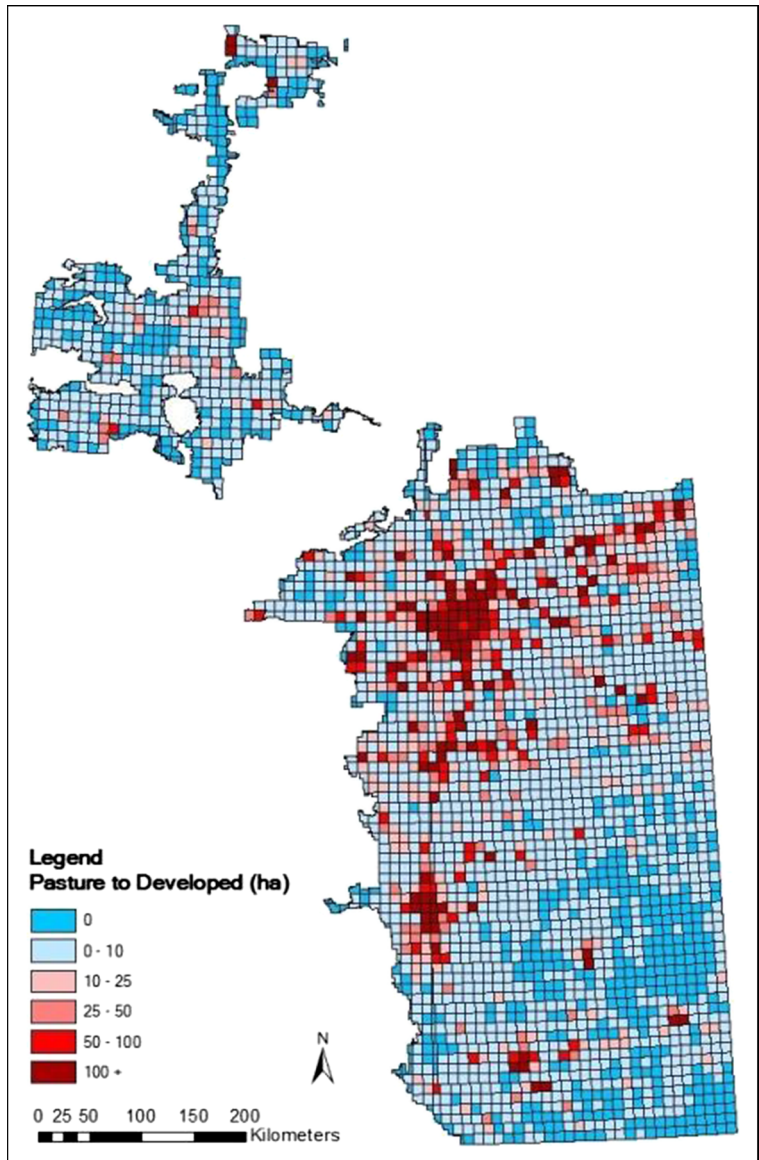


Fig. 12 Nature land hectares converted into cropland at the township level

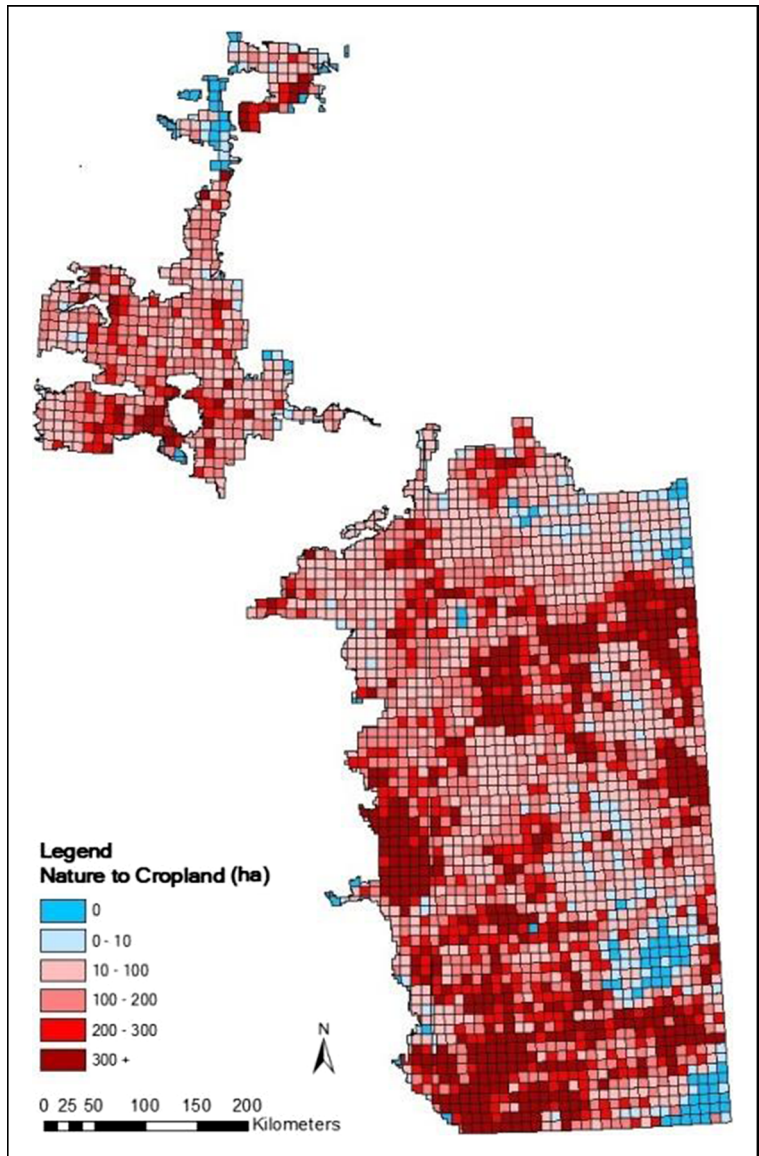


Fig. 13 Nature land hectares converted into pasture at the township level

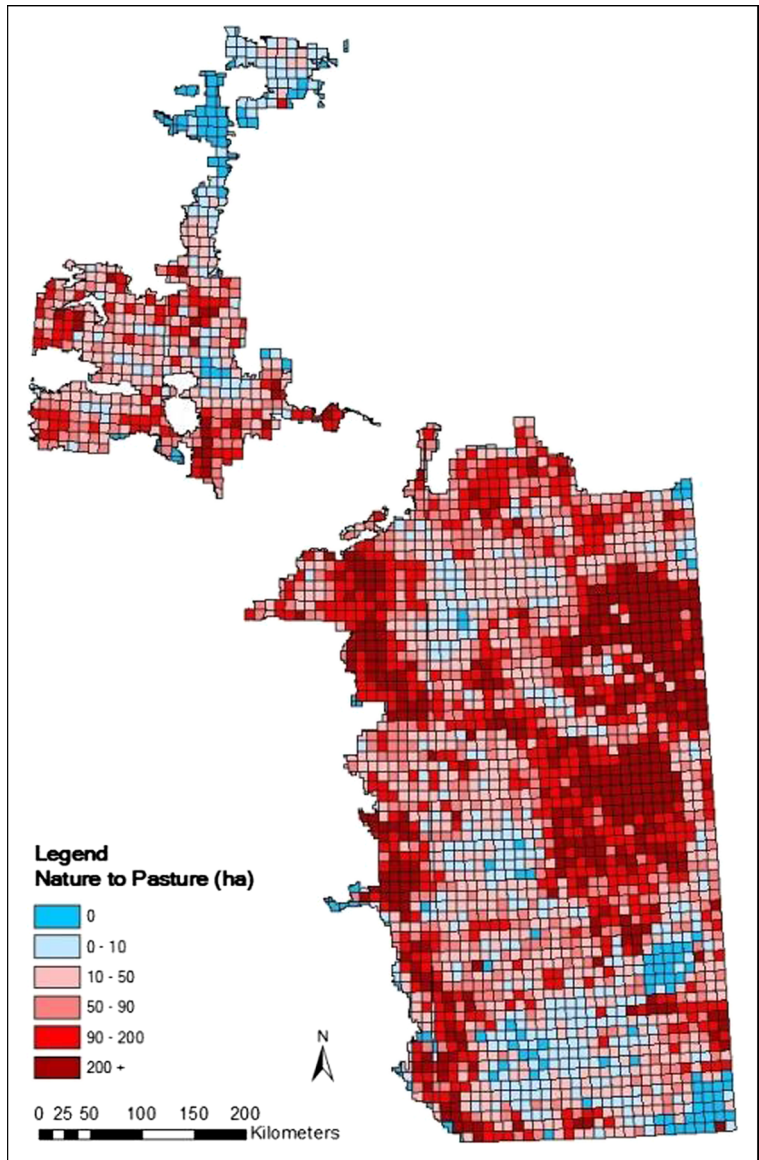


Fig. 14 Nature land hectares converted into developed land at the township level

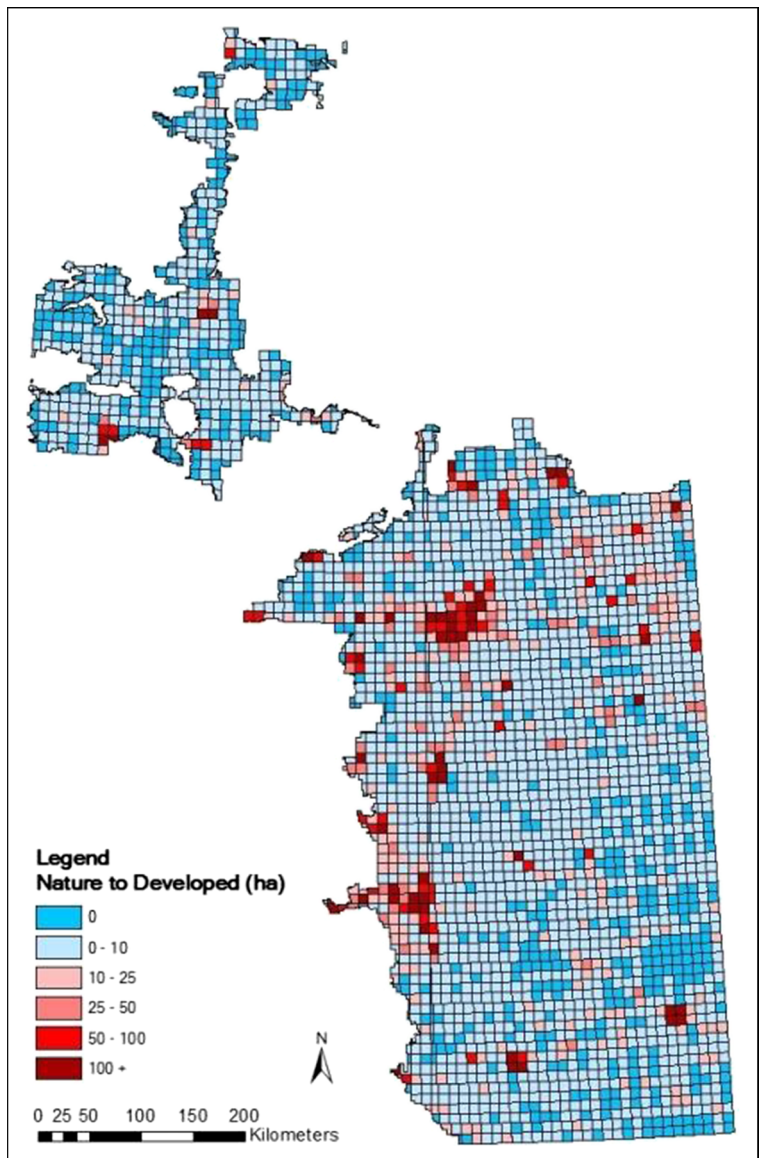


Fig. 15 Developed land hectares converted into cropland at the township level

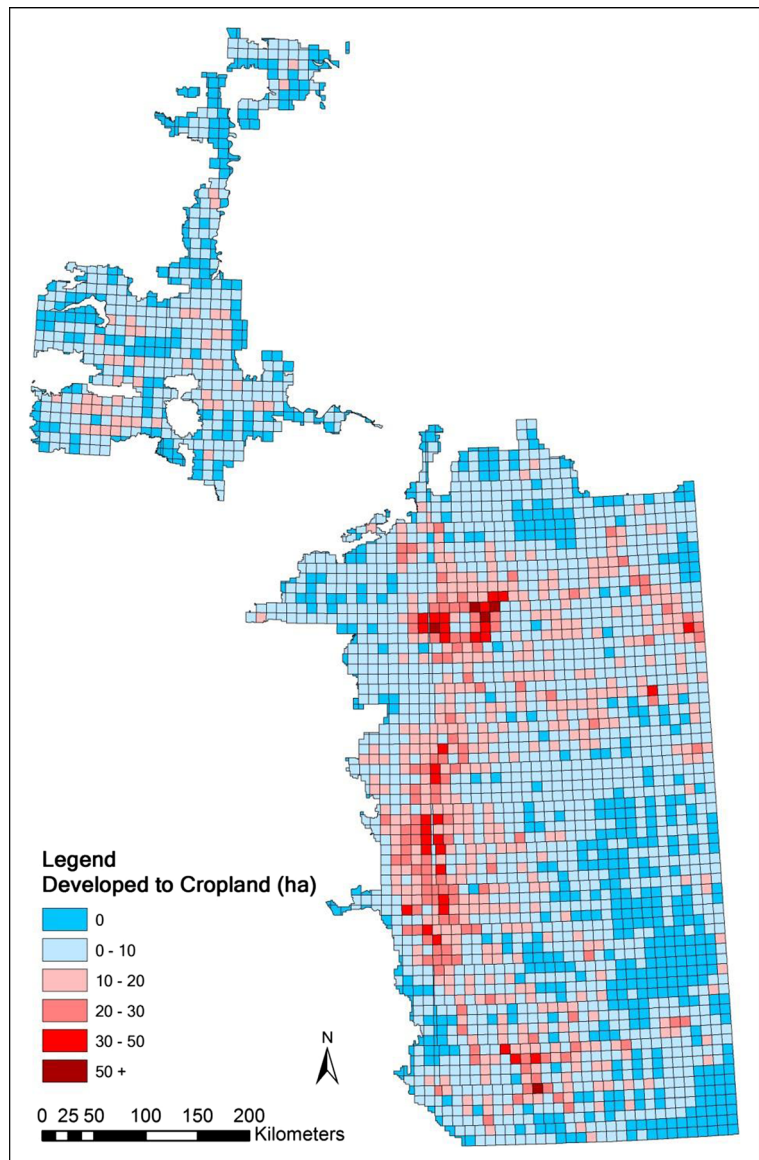


Fig. 16 Developed land hectares converted into pasture at the township level

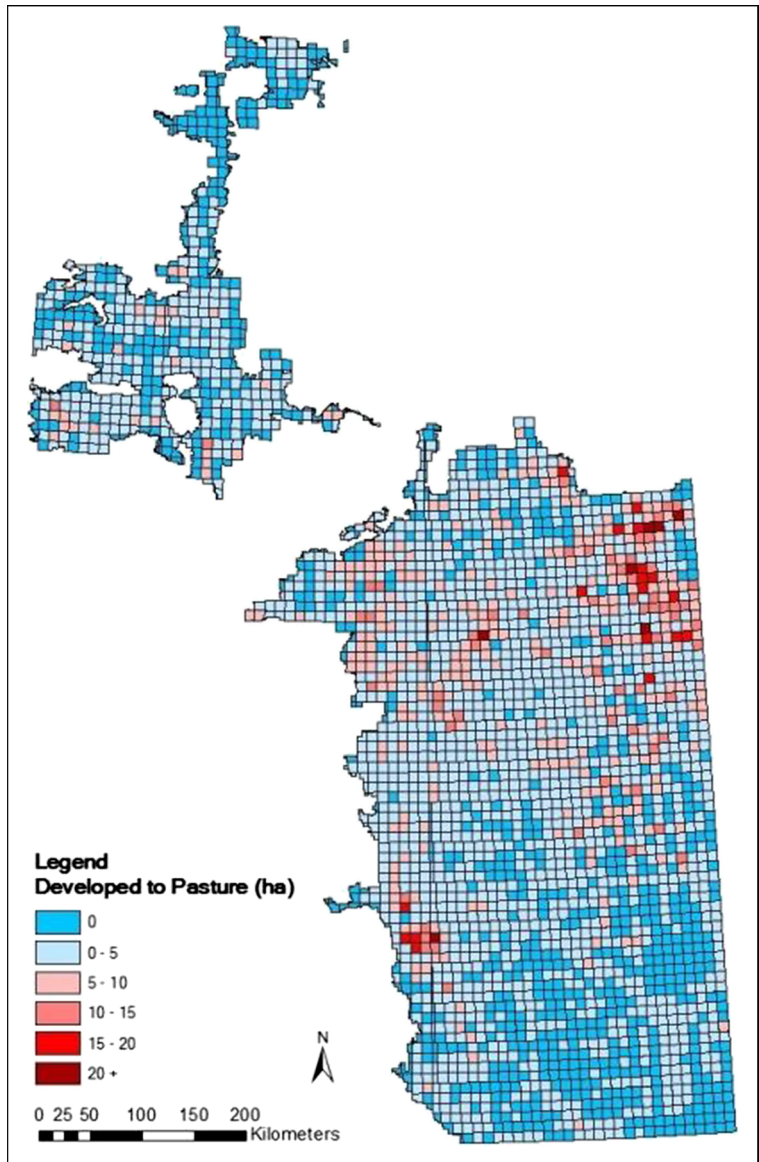
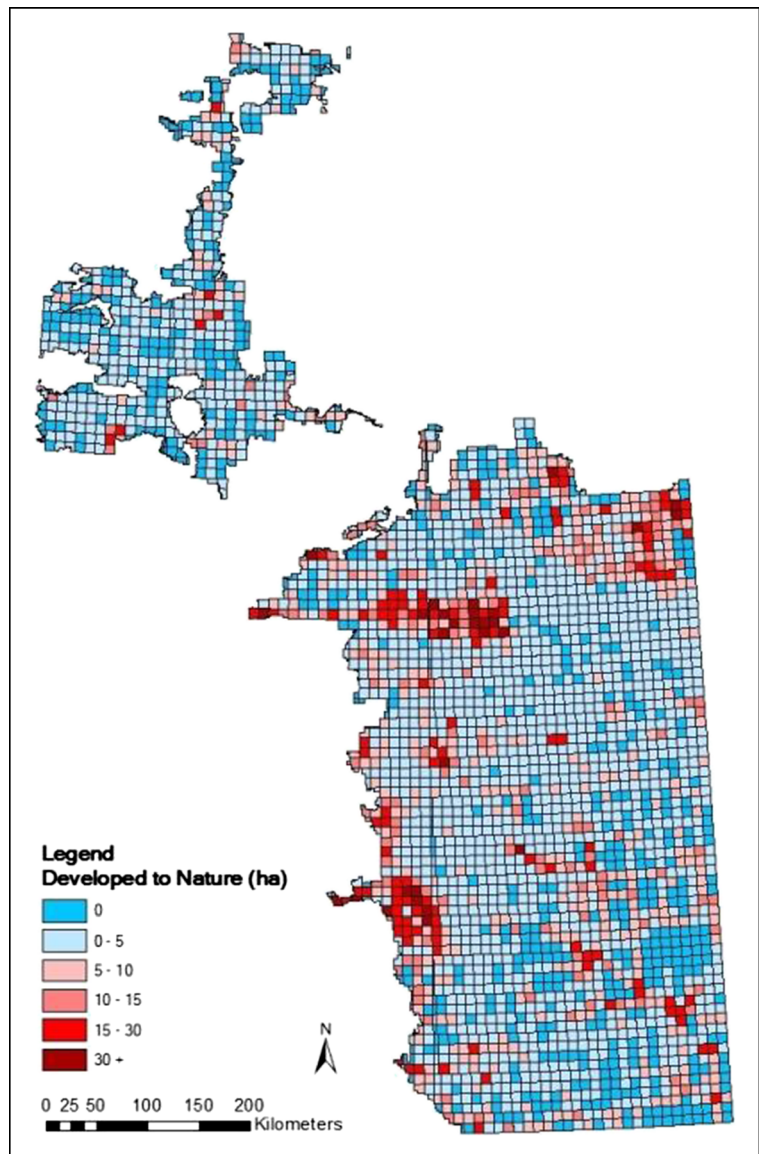


Fig. 17 Developed land hectares converted into natural land at the township level



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