Investigating the role of spatial spillovers as determinants of land conversion in urbanizing Canada

Feng Qiu[1*], Qingmeng Tong[2] and Junbiao Zhang[3,4]

[1]Department of Resource Economics and Environmental Sociology, University of Alberta, Edmonton, Alberta, Canada, [2]School of Economics and Business Administration, Central China Normal University, Wuhan, Hubei, China, [3]College of Economics and Management, Huazhong Agricultural University, Wuhan, Hubei, China and [4]International Joint Laboratory of Climate Change Response and Sustainable Agriculture, Huazhong Agricultural University, Wuhan, Hubei, China

[*]Corresponding author. Email: feng.qiu@ualberta.ca

ONLINE APPENDIX

A1. Additional information on the study area and background

In last decades, the province of Alberta has seen rapid economic and population growth but lost substantial open space due to developed land expansion. Preserving valuable natural land that generates abundant environmental, ecological, and recreational benefits is becoming an inevitable challenge for Albertans. However, an increasing amount of natural landscape in the suburban/peri-urban areas, especially on the privatized land where the provincial-level legislative framework has not been established, faces great risks and pressure of being converted. The Edmonton Metropolitan Region (EMR) and Calgary Regional Partnership (CRP) are among the prominent regions worth urgent attention to avoid severe environmental amenity degradation.

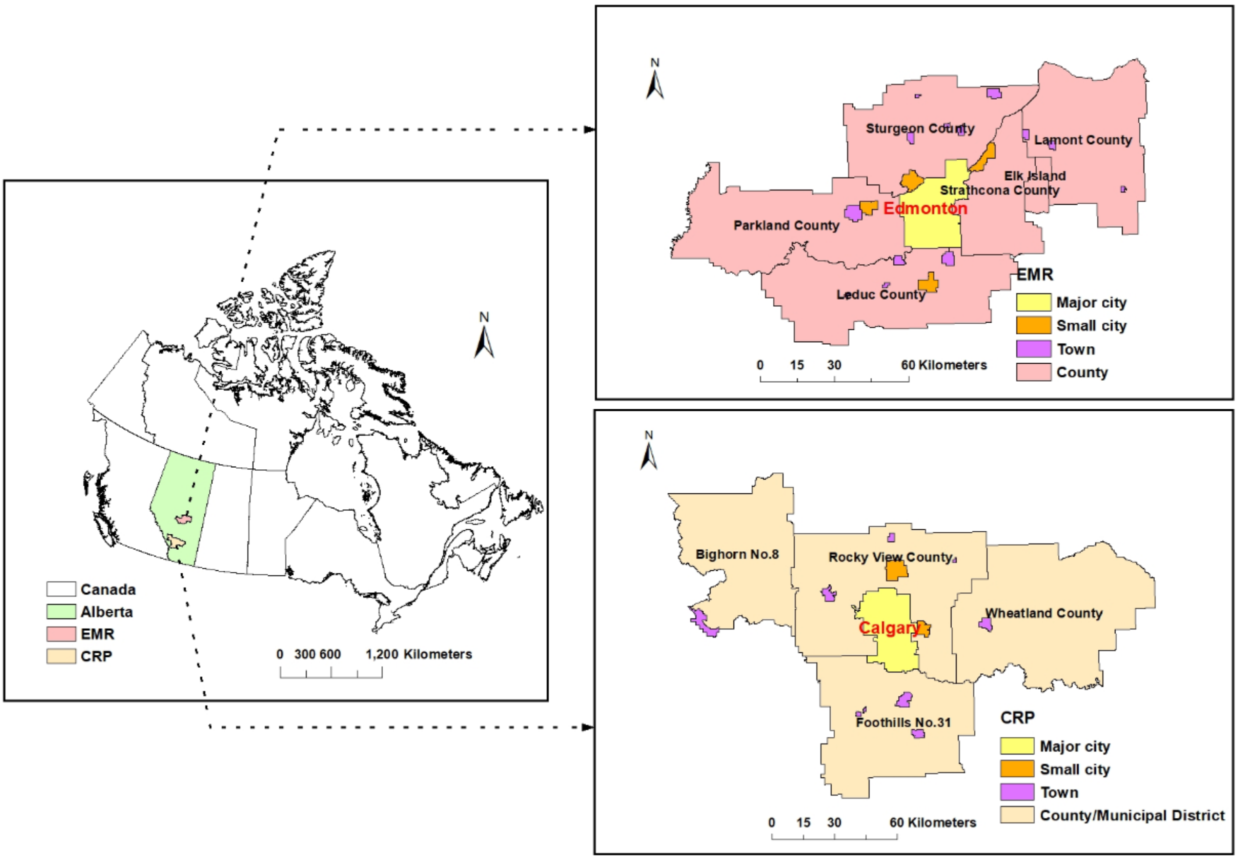

Figure A1. Geographic locations of the EMR and CRP.

Figure A1 shows the study area. Located within central Alberta and considered the major gateway to the Canadian north, the EMR is a conglomeration of municipalities centered on the provincial capital, the city of Edmonton. To the south of EMR is the CRP, a cooperative between 14 municipalities surrounding the city of Calgary and sharing a regional-effort of sustainable growth. The EMR and CRP make up more than 60 per cent of the provincial population, and they are also the most active regions for economic development and human activities in Alberta.

The two metropolitan areas share some key similarities like population growth rates and median income levels, but there are also distinct disparities. The EMR has a population density of 140 persons/km^2, compared to 273 persons/km^2 for the CRP (Statistics Canada, 2021). Furthermore, the differences in resource endowments are apparent. Benefiting from the proximity to national parks and natural reserves, the CRP has more natural land with higher amenity and ecological values compared with the EMR case. In addition, most natural landscapes in the CRP have high soil quality (for example, forests bordering Banff National Park). In contrast, a large amount of natural land in the EMR is marginal land converted from abandoned farmland. The development/growth strategies adopted by the two metropolitan areas are noticeably different. The CRP has implemented a high-intensity developing strategy, especially in its matured communities (CRPB, 2014). However, the EMR has adopted a low-density outward diffusion strategy because it is located almost entirely on the plains and has a large amount of land available for conversion (EMRB, 2017).

A2. Additional information on model specification

The spatial Durbin model (SDM) model can be expressed in the following form:

$$y = \alpha\iota_n + \rho Wy + X\beta + WX\theta + \gamma Z + \varepsilon,$$

where y is an $n \times 1$ vector of the dependent variable, and X is an $n \times k$ matrix carrying key explanatory variables. The term ε stands for a vector of *i.i.d.* disturbances, ι_n is an $n \times 1$ vector of ones with the associated scalar parameter α, and Z is a vector of other controls. Parameters ρ, β, θ and γ are coefficients to be estimated, and W is an $n \times n$ weights matrix representing the spatial relationship between observations. Specifically, $W_{ij} > 0$ if j is a defined neighbor to i, and $W_{ij} = 0$ otherwise.

Applying the model to the current study, the total area of natural land converted to developed land from 2000 to 2016 is defined as the dependent variable y. X carries a series of associated explanatory variables that explain the natural land conversion or conservation. The selection of explanatory variables is based on a review of previous theoretical and empirical works. For factors related to economic development, we consider the per capita income and the change of population density (Uusivuori *et al*., 2002; Seto *et al*., 2011). Road density is included because the road networks not only provide convenience for natural land (e.g., forest) being converted (Pfaff, 1999), but significantly drive urban sprawl (Aljoufie *et al*., 2013). Road density is also highly related to individuals' traveling decisions, which have spillovers (e.g., spillovers related to the congestion issue).

Additionally, areas of (developable) natural land in 2000 is considered. Because an area with abundant endowments is more likely to satisfy the land demand for development or construction uses (Kivell, 1993) on the one hand. On the other hand, large endowments of natural landscapes also mean high conservation values. Thus, it would be interesting to see the actual impact using real data. Additionally, we include land suitability for agriculture (i.e., soil quality) in the covariates. For natural landscape, high land suitability represents the opportunity for conservation as people tend to have higher WTP for preserving fertile land for potential production uses in the future (Busch and Ferretti-Gallon, 2017). The land suitability and natural land endowment variables are also expected to have spatial spillovers due to the previously discussed ecological-physical links. The elevation is included to represent the geographical characteristic following previous studies (e.g., Deng *et al*., 2010). For variables in Z, we consider the Central Business District (CBD) effect by controlling the distance to the city cores of Edmonton or Calgary, as suggested by the literature (Liu *et al*., 2011; Addae and Oppelt, 2019). The distances are measured using the road network data. The variable of reciprocal distance is adopted to reflect the nonlinear distance-decay effect. Besides, regional dummies based on counties or municipal districts are also included to control the fixed locational effects.

There is a potential concern that population growth might be endogenous in determining natural land conversion due to possible bi-directional interactions (Tong and Qiu, 2020). We therefore test the endogeneity before proceeding to the SDM estimation. Following Irwin *et al*. (2014) and many others, we use the past population growth as the instrumental variable to test for the endogeneity of the population growth. The Durbin-Wu-Hausman test cannot reject the null hypothesis that population growth is exogenous for either the EMR or CRP case. The maximum likelihood estimation (MLE) method is adopted to estimate the SDMs for the EMR and CRP.

A3. The results of local autocorrelations

The local Moran's I can be interpreted as the spatial autocorrelation for each unit with its neighbors. The local Moran's I can be useful in identifying local clusters. Figure A2 presents the spatial distribution of hot and cold spots (clusters of high and low values) with a significance level of 0.05. Hot spots are clustered within and around the major cities for both regions, while cold spots are gathered far away from the major cities.

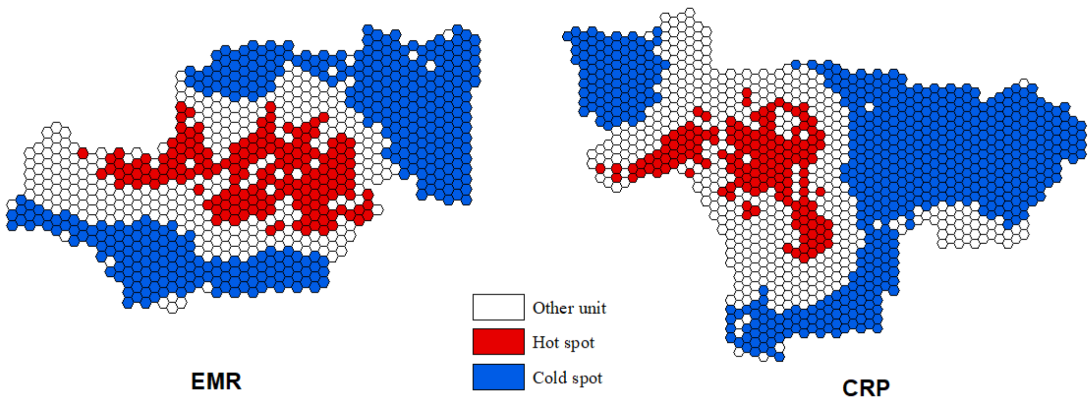

Figure A2. Cluster map for local Moran's I.

A4. Detailed information of the model estimation results

Table A1 shows the regression results from the general linear model (GLM) estimated by the OLS method and the SDM by the MLE method for two metro areas. The two spatially-lagged dependent variables' coefficients ρ are both significant and positive, indicating that the natural land conversion in neighboring areas is positively associated with a focal area. This is in accordance with conventional evidence that co-directional spatial externalities exist in the urban land development process (Deng *et al.,* 2010). Since the estimated parameters of β in spatial regressions cannot be interpreted directly, in the manuscript, we discuss the marginal effects and spillovers summarized in table 3. As a robustness check, we also calculate the marginal effects for estimates using different spatial weights matrices. The results are presented tables A6 and A7. Overall, the results are robust and consistent with our mechanism discussion in section 2 in the main text. Own and spillover effects of income increase are in opposite directions. The strength and significance of local vs. global spillover effects are different. Other key determinants also exhibit spatial spillover effects, the impact of which varies by local and global scales, too.

Table A1. Regression results of natural land conversion for the EMR and CRP

	EMR		CRP	
	GLM (OLS)	SDM (MLE)	GLM (OLS)	SDM (MLE)
Key drivers				
Income	41.086***	28.137***	15.578***	14.763***
	(4.821)	(5.669)	(4.034)	(5.065)
PopulationGrowth	0.005	0.003	0.095***	0.084***
	(0.006)	(0.006)	(0.009)	(0.008)
RoadDensity	0.353***	0.289***	1.006***	0.875***
	(0.070)	(0.067)	(0.109)	(0.095)
NaturalLand2000	0.026***	0.035***	0.023***	0.033***
	(0.003)	(0.003)	(0.003)	(0.004)
LandSuitability	−0.018	−0.004	−0.081*	0.017
	(0.028)	(0.026)	(0.045)	(0.050)
Elevation	−1.564	4.999	−0.735	−2.446**
	(1.871)	(3.379)	(0.665)	(1.207)
Distance_Inverse	49.704	−113.152**	−218.245**	−737.141***
	(53.010)	(53.336)	(91.570)	(94.058)

Spatially lagged variables				
*W*Income*	—	−34.661***	—	−14.253
		(13.173)		(9.743)
*W*PopulationGrowth*	—	−0.137**	—	0.102
		(0.065)		(0.077)
*W*RoadDensity*	—	1.235***	—	0.203
		(0.396)		(0.458)
*W*NaturalLand2000*	—	−0.041***	—	−0.056***
		(0.010)		(0.010)
*W*LandSuitability*	—	−0.349**	—	−0.431***
		(0.144)		(0.138)
*W*Elevation*	—	−2.854	—	1.911
		(5.504)		(1.813)
County/district dummies				
Parkland	8.858*	17.096***	—	—
	(5.341)	(5.200)		
Sturgeon	1.240	8.027	—	—
	(5.210)	(5.143)		
Leduc	1.203	10.279*	—	—
	(5.421)	(5.461)		
Elk	−18.870**	−8.260	—	—
	(8.168)	(7.725)		
Strathcona	11.313**	21.645***	—	—
	(5.358)	(5.074)		
Lamont	−0.681	9.624*	—	—
	(5.574)	(5.627)		
Bighorn	—	—	12.495	47.571***
			(10.090)	(9.807)
Rocky	—	—	30.753***	38.459***
			(8.799)	(8.078)
Wheatland	—	—	19.226***	42.926***
			(9.535)	(9.319)
Foothills	—	—	19.353***	42.144***
			(9.163)	(8.564)
Constant	−428.715***	55.640	−181.255***	−8.860

	(54.330)	(131.000)	(44.730)	(85.968)
ρ	—	0.5231***	—	0.8169***
		(0.121)		(0.050)
Wald test for ρ	—	18.58***	—	262.12***
LR test for ρ	—	15.02***	—	109.54***
LR test against SAR	—	94.83***	—	70.78***
LR test against SEM	—	65.99***	—	58.13***
R^2	0.338	—	0.331	—
Pseudo R^2	—	0.442	—	0.495
Log-likelihood	—	−3768.1	—	−5825.9
AIC	—	7580.2	—	11692

Notes: The weight matrix is based on a threshold distance of 24 km and 20 km for EMR and CRP, respectively. ***, ** and * indicate the coefficient is significant at the 1%, 5% and 10% level, respectively. Standard errors in parentheses. The regional dummies are included by taking the major city as the base group.

A5. Extra tables/results

For deciding W in this study, we have tried several spatial weights with different threshold distances (i.e., 20 km, 22 km, 24 km, 25 km, 26 km and 28 km). The thresholds of 24 km and 20 km are adopted in the final investigation for the EMR and CRP, respectively, based on AIC values and Efron's pseudo R^2 (Efron, 1978). Regression results using other thresholds are provided below for interested readers (tables A2 and A3).

Table A2. Spatial Durbin regression results for EMR with different spatial weights

	W=20 km	*W*=22 km	*W*=24 km	*W*=25 km	*W*=26 km	*W*=28 km
Key non-spatial variables						
Income	31.161***	30.919***	28.137***	26.447***	25.736***	22.109***
	(5.761)	(5.767)	(5.669)	(5.664)	(5.660)	(5.618)
PopulationGrowth	0.001	0.003	0.003	0.002	0.002	0.002
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.001)
RoadDensity	0.270***	0.274***	0.289***	0.289***	0.293***	0.298***
	(0.066)	(0.067)	(0.067)	(0.067)	(0.067)	(0.067)
NaturalLand2000	0.035***	0.034***	0.035***	0.035***	0.034***	0.034***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
LandSuitability	0.003	0.001	−0.004	−0.013	−0.019	−0.033
	(0.027)	(0.027)	(0.026)	(0.026)	(0.026)	(0.026)
Elevation	4.728	4.963	4.999	5.781*	5.905*	5.776*
	(3.581)	(3.530)	(3.379)	(3.304)	(3.272)	(3.103)
Distance_Inverse	−113.470**	−113.663**	−113.152**	−115.418**	−114.334**	−116.540**
	(54.243)	(53.908)	(53.336)	(53.271)	(53.304)	(53.082)
Spatially lagged variables						
*W*Income*	−33.888***	−37.099***	−34.661***	−35.057**	−35.974**	−34.522**
	(12.291)	(12.528)	(13.173)	(13.729)	(14.008)	(15.092)
*W*PopulationGrowth*	−0.069	−0.076	−0.137**	−0.106	−0.096	−0.099
	(0.055)	(0.058)	(0.065)	(0.070)	(0.072)	(0.079)
*W*RoadDensity*	0.822**	0.945***	1.235***	1.185***	1.228***	1.333***
	(0.339)	(0.354)	(0.396)	(0.420)	(0.432)	(0.476)
*W*NaturalLand2000*	−0.037***	−0.036***	−0.041***	−0.041***	−0.039***	−0.044***
	(0.008)	(0.009)	(0.010)	(0.010)	(0.011)	(0.012)
*W*LandSuitability*	−0.187	−0.186	−0.349**	−0.383**	−0.361**	−0.444**
	(0.126)	(0.130)	(0.144)	(0.152)	(0.156)	(0.176)
*W*Elevation*	−3.653	−4.185	−2.854	−3.876	−4.216	−2.454
	(5.380)	(5.421)	(5.504)	(5.589)	(5.650)	(5.748)
County/district dummies						

Parkland	16.160***	16.787***	17.096***	16.881***	16.993***	15.633***
	(5.220)	(5.222)	(5.200)	(5.194)	(5.209)	(5.155)
Sturgeon	8.819*	9.261*	8.027	7.545	7.536	5.596
	(5.185)	(5.174)	(5.143)	(5.125)	(5.121)	(5.087)
Leduc	9.247*	9.660*	10.279*	9.737*	9.298*	7.162
	(5.3485)	(5.502)	(5.461)	(5.479)	(5.508)	(5.430)
Elk	−8.390	−8.121	−8.260	−8.838	−9.235	−10.969
	(7.744)	(7.751)	(7.725)	(7.755)	(7.779)	(7.777)
Strathcona	20.162***	20.782***	21.645***	21.915***	21.901***	21.129***
	(5.119)	(5.112)	(5.074)	(5.081)	(5.090)	(5.084)
Lamont	9.510*	9.616*	9.624*	8.944**	8.627	7.713
	(5.628)	(5.632)	(5.627)	(5.641)	(5.664)	(5.668)
Constant	14.774	51.112	55.640	84.539	101.351	122.080
	(118.404)	(121.547)	(131.000)	(138.479)	(142.475)	(156.522)
ρ	0.5884***	0.5601***	0.5231***	0.4505***	0.4029***	0.3512**
	(0.101)	(0.108)	(0.121)	(0.138)	(0.147)	(0.165)
Wald test for ρ	33.81***	26.91***	18.58***	10.70***	7.48***	4.51**
LR test for ρ	25.80***	21.47***	15.02***	9.61***	7.12***	4.29**
Pseudo R^2	0.440	0.439	**0.442**	0.439	0.436	0.436
Log likelihood	−3770.9	−3771.0	**−3768.1**	−3769.9	−3771.6	−3771.7
AIC	7585.7	7586.1	**7580.2**	7583.8	7587.1	7587.5

Notes: *W* represents the threshold distance for the spatial weights matrix. ***, ** and * indicate the coefficient is significant at the 1%, 5% and 10% level, respectively. Standard errors in parentheses.

Table A3. Spatial Durbin regression results for CRP with different spatial weights

	W=20 km	*W*=22 km	*W*=24 km	*W*=25 km	*W*=26 km	*W*=28 km
Key non-spatial variables						
Income	14.763***	14.904***	15.607***	16.328***	16.766***	17.526***
	(5.065)	(5.017)	(4.870)	(4.780)	(4.739)	(4.607)
PopulationGrowth	0.084***	0.083***	0.084***	0.084***	0.082***	0.083***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.009)
RoadDensity	0.875***	0.885***	0.900***	0.922***	0.947***	0.962***
	(0.095)	(0.096)	(0.098)	(0.099)	(0.100)	(0.102)
NaturalLand2000	0.033***	0.032***	0.032***	0.031***	0.032***	0.030***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
LandSuitability	0.017	0.021	0.002	−0.002	−0.004	−0.029
	(0.050)	(0.050)	(0.050)	(0.050)	(0.050)	(0.050)
Elevation	−2.446**	−2.419**	−2.366**	−2.459**	−2.388**	−2.889**
	(1.207)	(1.203)	(1.191)	(1.182)	(1.176)	(1.172)
Distance_Inverse	−737.141***	−733.720***	−710.190***	−702.60***	−685.062***	−649.796***
	(94.058)	(94.419)	(94.227)	(94.554)	(95.124)	(95.059)
Spatially lagged variables						
*W*Income*	−14.253	−14.409	−18.636*	−21.128**	−20.658*	−27.728**
	(9.743)	(9.936)	(10.445)	(10.760)	(10.944)	(11.700)
*W*PopulationGrowth*	0.102	0.073	0.103	0.053	−0.065	−0.042
	(0.077)	(0.082)	(0.096)	(0.106)	(0.109)	(0.124)
*W*RoadDensity*	0.203	0.387	0.207	0.542	1.178*	1.119
	(0.458)	(0.483)	(0.547)	(0.596)	(0.613)	(0.686)
*W*NaturalLand2000*	−0.056***	−0.057***	−0.063***	−0.065***	−0.064***	−0.065***
	(0.010)	(0.010)	(0.011)	(0.012)	(0.012)	(0.013)
*W*LandSuitability*	−0.431***	−0.460***	−0.522***	−0.561***	−0.551***	−0.558***
	(0.138)	(0.144)	(0.157)	(0.168)	(0.173)	(0.189)
*W*Elevation*	1.911	2.007	1.658	2.111	2.803	3.689*

	(1.813)	(1.831)	(1.887)	(1.923)	(1.941)	(2.019)
County/district dummies						
Bighorn	47.571***	47.463***	46.796***	46.136***	45.078***	41.110***
	(9.807)	(9.867)	(10.012)	(10.113)	(10.128)	(10.349)
Rocky	38.459***	37.882***	34.767***	33.933***	33.823***	30.778***
	(8.078)	(8.094)	(8.084)	(8.115)	(8.139)	(8.185)
Wheatland	42.926***	42.972***	40.146***	40.135***	40.784***	38.275***
	(9.319)	(9.355)	(9.369)	(9.418)	(9.448)	(9.502)
Foothills	42.144***	41.775***	39.140***	38.356***	37.862***	34.479***
	(8.564)	(8.579)	(8.573)	(8.600)	(8.626)	(8.657)
Constant	−8.860	−9.742	42.649	57.911	31.905	101.014
	(85.968)	(89.120)	(97.304)	(102.853)	(105.546)	(116.284)
ρ	0.8169***	0.8032***	0.7910***	0.7517***	0.7225***	0.6728***
	(0.050)	(0.054)	(0.061)	(0.070)	(0.076)	(0.092)
Wald test for ρ	262.12***	219.26***	169.71***	114.40***	89.42***	53.95***
LR test for ρ	109.54***	97.33***	70.28***	60.27***	51.28***	35.06***
Pseudo R^2	**0.495**	0.488	0.472	0.461	0.455	0.439
Log likelihood	**−5825.9**	−5834.0	−5850.7	−5860.6	−5866.2	−5882.5
AIC	**11692**	11708	11741	11761	11772	11805

Notes: *W* represents the threshold distance for the spatial weights matrix. ***, ** and * indicate the coefficient is significant at the 1%, 5% and 10% level, respectively. Standard errors in parentheses.

Table A4. Results of other spatial models for EMR

	SAR	SEM	SLX
Key non-spatial variables			
Income	30.906***	35.360***	26.903***
	(4.910)	(5.619)	(5.796)
PopulationGrowth	0.003	0.002	0.003
	(0.006)	(0.006)	(0.006)
RoadDensity	0.341***	0.316***	0.288***
	(0.068)	(0.067)	(0.068)
NaturalLand2000	0.025***	0.033***	0.034***
	(0.003)	(0.003)	(0.003)
LandSuitability	−0.016	−0.007	−0.009
	(0.027)	(0.027)	(0.027)
Elevation	−1.185	0.330	5.233
	(1.810)	(2.899)	(3.455)
Distance_Inverse	−40.691	−76.112	−104.694*
	(51.890)	(53.472)	(54.520)
Spatially lagged variables			
*W*Income*	—	—	−18.488
			(12.880)
*W*PopulationGrowth*	—	—	−0.157**
			(0.066)
*W*RoadDensity*	—	—	1.750***
			(0.393)
*W*NaturalLand2000*	—	—	−0.028***
			(0.009)
*W*LandSuitability*	—	—	−0.340**
			(0.147)
*W*Elevation*	—	—	−3.031
			(5.626)
County/district dummies			
Parkland	9.063*	10.299*	20.465***
	(5.167)	(5.950)	(5.285)
Sturgeon	6.050	5.035	8.354
	(5.077)	(5.533)	(5.259)
Leduc	6.887	0.944	10.423*
	(5.320)	(5.889)	(5.585)
Elk	−16.541**	−11.704	−7.652
	(7.907)	(8.563)	(7.900)
Strathcona	9.907*	14.432***	23.894***
	(5.188)	(5.380)	(5.183)
Lamont	8.280*	11.518	8.653
	(5.502)	(7.273)	(5.753)
Constant	−334.864***	−386.331***	−100.264
	(54.684)	(62.517)	(126.400)
ρ	0.6414***	—	—
	(0.082)		
λ	—	0.9189***	—
		(0.038)	
Wald test for ρ	61.51***	—	—
Wald test for λ	—	593.95***	—

LR test for ρ	37.60***	—	—
LR test for λ	—	66.44***	—
Pseudo R^2	0.380	0.409	0.430
Log likelihood	−3815.5	−3801.1	—
AIC	7663	7634.2	—

Notes: The weight matrix is based on a threshold distance of 24 km. ***, ** and * indicate the coefficient is significant at the 1%, 5% and 10% level, respectively. Standard errors in parentheses.

Table A5. Results of other spatial models for CRP

	SAR	SEM	SLX
Key non-spatial variables			
Income	11.959***	15.190***	18.460***
	(3.625)	(4.908)	(5.388)
PopulationGrowth	0.087***	0.082***	0.088***
	(0.008)	(0.008)	(0.008)
RoadDensity	0.881***	0.837***	0.965***
	(0.097)	(0.097)	(0.101)
NaturalLand2000	0.019***	0.030***	0.033***
	(0.003)	(0.004)	(0.004)
LandSuitability	0.043	0.013	0.009
	(0.040)	(0.050)	(0.053)
Elevation	−0.730	−2.446**	−2.864**
	(0.596)	(1.133)	(1.284)
Distance_Inverse	−487.497***	−522.874***	−884.163***
	(81.737)	(91.220)	(99.930)
Spatially lagged variables			
*W*Income*	—	—	−23.242**
			(10.360)
*W*PopulationGrowth*	—	—	0.287**
			(0.081)
*W*RoadDensity*	—	—	0.645
			(0.487)
*W*NaturalLand2000*	—	—	−0.065***
			(0.011)
*W*LandSuitability*	—	—	−0.863***
			(0.143)
*W*Elevation*	—	—	0.609
			(1.924)
County/district dummies			
Bighorn	28.326***	34.651***	59.711***
	(9.000)	(12.630)	(10.410)
Rocky	29.258***	26.490***	54.856***
	(7.843)	(8.272)	(8.556)
Wheatland	31.927***	30.918***	54.447***
	(8.518)	(11.521)	(9.897)
Foothills	29.908***	32.263***	54.497***
	(8.184)	(10.347)	(9.089)
Constant	−163.999***	−170.188***	86.936
	(40.023)	(60.642)	(91.460)
ρ	0.9088***	—	—
	(0.030)		
λ	—	0.9665***	—
		(0.016)	
Wald test for ρ	928.88***	—	—
Wald test for λ	—	3616.00***	—

LR test for ρ	234.06***	—	—
LR test for λ	—	246.71***	—
Pseudo R^2	0.469	0.478	0.437
Log likelihood	−5861.3	−5855.0	—
AIC	11751	11738	—

Notes: The weight matrix is based on a threshold distance of 20 km. *** and ** indicate the coefficient is significant at the 1% and 5% level, respectively. Standard errors in parentheses.

Table A6. Marginal effects for EMR with different spatial weights

	W=20 km				*W*=22 km			
	ADE	$rb+q$	AIE	ATE	ADE	$rb+q$	AIE	ATE
Income	30.924***	−15.555***	−37.550	−6.626	30.660***	−19.780***	−44.709	−14.049
PopulationGrowth	−0.003	−0.070***	−0.169	−0.172	−0.004	−0.077***	−0.174	−0.178
RoadDensity	0.285***	0.981***	2.368**	2.653**	0.289***	1.098***	2.483**	2.772**
NaturalLand2000	0.034***	−0.017***	−0.041*	−0.007	0.034***	−0.017***	−0.038*	−0.004
LandSuitability	0.001	−0.185***	−0.447	−0.446	−0.002	−0.186***	−0.420	−0.422
Elevation	4.715	−0.871*	−2.103	2.611	4.945	−1.405***	−3.175	1.770
	W=24 km				*W*=25 km			
	ADE	$rb+q$	AIE	ATE	ADE	$rb+q$	AIE	ATE
Income	27.939***	−19.942***	−41.618	−13.679	26.281***	−23.143***	−41.949	−15.668
PopulationGrowth	−0.004	−0.139***	−0.289	−0.293	−0.003	−0.107***	−0.193	−0.196
RoadDensity	0.303***	1.386***	2.893**	3.196**	0.299***	1.315***	2.384**	2.682**
NaturalLand2000	0.034***	−0.023***	−0.047**	−0.013	0.034***	−0.025***	−0.046**	−0.011
LandSuitability	−0.008	−0.351***	−0.733*	−0.741*	−0.016	−0.389***	−0.705*	−0.721*
Elevation	4.997	−0.239	−0.498	4.498	5.772*	−1.272	−2.306	3.466
	W=26 km				*W*=28 km			
	ADE	$rb+q$	AIE	ATE	ADE	$rb+q$	AIE	ATE
Income	25.587***	−25.605***	−42.732	−17.146	21.998***	−26.757***	−41.129	−19.131
PopulationGrowth	−0.003	−0.097***	−0.161	−0.164	−0.003	−0.100***	−0.154	−0.157

RoadDensity	0.301***	1.346***	2.246 **	2.547**	0.304***	1.437***	2.209**	2.513**
NaturalLand2000	0.034***	−0.025***	−0.043**	−0.008	0.034***	−0.032***	−0.049**	−0.015
LandSuitability	−0.021	−0.368***	−0.614*	−0.635*	−0.034	−0.456***	−0.700*	−0.735**
Elevation	5.894*	−1.837**	−3.065	2.829	5.774*	−0.426	−0.654	5.120

Notes: The effects are computed using the trace created by powering sparse matrix of distance weights. The tests for the impacts are based on 5000 times of simulations from a Multivariate Normal Distribution (MND). ***, ** and * denote significance at the 1%, 5% and 10% level, respectively.

Table A7. Marginal effects for CRP with different spatial weights

	W=20 km				*W*=22 km			
	ADE	$rb+q$	AIE	ATE	ADE	$rb+q$	AIE	ATE
Income	14.690***	−2.193***	−11.913	2.777	14.833***	−2.438***	−12.318	2.515
PopulationGrowth	0.089***	0.171***	0.924*	1.013*	0.087***	0.140***	0.704	0.792
RoadDensity	0.905***	0.919***	4.974	5.879*	0.918***	1.098***	5.536*	6.454*
NaturalLand2000	0.032***	−0.029***	−0.157**	−0.126*	0.032***	−0.031***	−0.155**	−0.124**
LandSuitability	0.004	−0.416***	−2.255**	−2.252**	0.008	−0.444***	−2.238**	−2.230**
Elevation	−2.449**	−0.087	−0.468	−2.917	−2.417**	0.065	0.329	−2.088
	W=24 km				*W*=25 km			
	ADE	$rb+q$	AIE	ATE	ADE	$rb+q$	AIE	ATE
Income	15.457***	−6.290***	−29.938	−14.481	16.161***	−8.854***	−35.495	−19.333
PopulationGrowth	0.088***	0.170***	0.808	0.897	0.086***	0.113***	0.463	0.549
RoadDensity	0.922***	0.919***	4.370	5.292	0.946***	1.235***	4.952	5.898*
NaturalLand2000	0.031***	−0.038***	−0.181**	−0.150**	0.031***	−0.041***	−0.166**	−0.135**
LandSuitability	−0.010	−0.520***	−2.473***	−2.483***	−0.012	−0.562***	−2.254**	−2.266**
Elevation	−2.371**	−0.214	−1.015	−3.385	−2.454**	0.262	1.051	−1.403
	W=26 km				*W*=28 km			
	ADE	$rb+q$	AIE	ATE	ADE	$rb+q$	AIE	ATE
Income	16.628***	−8.544***	−30.650	−14.022	17.338***	−15.937***	−48.516	−31.178
PopulationGrowth	0.082***	−0.002	−0.019	0.063	0.083***	−0.014*	0.042	0.125

RoadDensity	0.977***	1.862***	6.680*	7.657**	0.983***	1.765***	5.374*	6.357**
NaturalLand2000	0.031***	−0.041***	−0.146**	−0.115*	0.029***	−0.045***	−0.137**	−0.108**
LandSuitability	−0.013	−0.554***	−1.988**	−2.000**	−0.036	−0.578***	−1.759**	−1.795**
Elevation	−2.371**	1.078***	3.866	1.495	−2.868**	1.745***	5.314	2.447

Notes: The effects are computed using the trace created by powering sparse matrix of distance weights. The tests for the impacts are based on 5000 times of simulations from a Multivariate Normal Distribution (MND). *W* represents the threshold distance for the spatial weights matrix. ***, **, and * denote significance at 1%, 5%, and 10% level, respectively.

Table A8. Equality test of direct and indirect effects for the EMR and CRP

	$ADE_{EMR} - ADE_{CRP}$	$AIE_{EMR} - AIE_{CRP}$
Income	13.249***	−29.705***
PopulationGrowth	−0.093***	−1.213***
RoadDensity	−0.602***	−2.081***
NaturalLand2000	0.002***	0.110***
LandSuitability	−0.012***	1.522***
Elevation	2.548***	−0.030***

Note: *** denotes a significance level of 1% for the t-test against the null hypothesis that there is no difference in the marginal effect between the two regions.

References

Addae M and Oppelt N (2019) Land-use/land-cover change analysis and urban growth modelling in the Greater Accra Metropolitan Area (GAMA), Ghana. *Urban Science* **3**, 26.

Aljoufie M, Zuidgeest M, Brussel M and van Maarseveen M (2013) Spatial–temporal analysis of urban growth and transportation in Jeddah City, Saudi Arabia. *Cities* **31**, 57–68.

Busch J and Ferretti-Gallon K (2017) What drives deforestation and what stops it? A meta-analysis. *Review of Environmental Economics and Policy* **11**, 3–23.

CRPB (Calgary Regional Partnership Board) (2014) Calgary Metropolitan Plan. Available at https://prism.ucalgary.ca/bitstream/handle/1880/107153/Calgary_Metropolitan_Plan.pdf?sequence=1&isAllowed=y.

Deng X, Huang J, Rozelle S and Uchida E (2010) Economic growth and the expansion of urban land in China. *Urban Studies* **47**, 813–843.

Efron B (1978) Regression and ANOVA with zero-one data: measures of residual variation. *Journal of the American Statistical Association* **73**, 113–121.

EMRB (Edmonton Metropolitan Region Board) (2017) Edmonton Metropolitan Region Growth Plan. Available at http://emrb.ca/Website/media/PDF/Publications/EMRGP-Interactive.pdf.

Irwin EG, Jeanty PW and Partridge MD (2014) Amenity values versus land constraints: the spatial effects of natural landscape features on housing values. *Land Economics* **90**, 61–78.

Kivell P (1993) *Land and the City: Patterns and Processes of Urban Change*. Psychology Press.

Liu Y, Yue W and Fan P (2011) Spatial determinants of urban land conversion in large Chinese cities: a case of Hangzhou. *Environment and Planning B: Planning and Design* **38**, 706–725.

Pfaff AS (1999) What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management* **37**, 26–43.

Seto KC, Fragkias M, Güneralp B and Reilly MK (2011) A meta-analysis of global urban land expansion. *PloS One* **6**, e23777.

Statistics Canada (2021) Census Datasets. Available at https://www12.statcan.gc.ca/datasets/index-eng.cfm?Temporal=2016

Tong Q and Qiu F (2020) Population growth and land development: investigating the bi-directional interactions. *Ecological Economics* **169**, 106505.

Uusivuori J, Lehto E and Palo M (2002) Population, income and ecological conditions as determinants of forest area variation in the tropics. *Global Environmental Change* **12**, 313–323.