Climate Change Adaptation via U.S. Land Use Transitions: A Spatial Econometric Analysis

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Abstract

Climate change, coupled with biofuels development and other factors may well be changing US land usage patterns. We use a spatial econometric approach to estimate the drivers of US land use transitions in recent years. We consider transitions between six major land uses: agricultural land, forest, grassland, water, urban, and other uses. To examine drivers, we use a two-step linearized, spatial, multinomial logit model and estimate land use transition probabilities. Our results indicate that climate change is a driver of land use change and that movements to and from agricultural land and grassland exhibit opposite responses with climate change portending a movement out of cropland into grassland. These results indicate that adaptation to climate change through land usage change is ongoing but with spatial dependence.

Introduction

Climate change influences agricultural productivity and land use (McCarl, Villavicencio and Wu 2008; Seo and Mendelsohn 2008a; Feng, Krueger and Oppenheimer 2010; Davis and Kilian 2011; Hertel 2011). Previous studies have found that land use and management changes are one potential means of farmers' adaptation to climate change. Land use transitions from crops to livestock have been found in Mu, McCarl and Wein (2013) and Seo (2010) while crop mixes changes and agricultural land movements to forest have been found by (Reilly, et al. 2003; Seo and Mendelsohn 2008b; Choi and Sohngen 2009; Langpap and Wu 2011; Souza-Rodrigues 2014). Understanding the extent to which climate is a land use and management change driver provides important insights into how climate change and farmer adaptation alters current and future agriculture. This study examines how climate plays a role as a driver of land use transitions. In particular, we inspect how land use shares including agricultural lands, grasslands, forest, and urban lands vary with climate using a discrete choice model including spatial econometric considerations along with socioeconomic, environmental, and geophysical factors.

Background on Estimation Approach

Land owners and managers are assumed to choose land uses based on profit maximization. In doing this, land owners use information on market signals as well as exogenous factors such as climate and policy.

We estimate the proportional land use share for each use as a proportion of total land area. Estimating these proportions response can be done by using a linear probability model which has a drawback that the estimated probability is not confined to the unit interval. Another possible method is a logit or logarithm transformation of the relative shares as in Wu and Brorsen (1995) and Hardie and Parks (1997) but in doing this undefined or infinite values may arise.

Some recent studies examined spatial effects on land use using spatial econometric methods which account for spatial lag or spatial error dependence. In this study, the spatial effects are the physical and economic conditions in nearby areas. The assumption implies that the propensity of land use change in an area depends on the propensity to change land uses in neighboring areas.

For the estimation, we use a two-step linearized GMM estimator. Six land uses (agriculture, forest, grass, urban, water, and other) are examined over the 48 contiguous United States at the county and 10 km square level. Preliminary results from the estimation with the county level data have insignificant results for some spatial dependences. Thus, we explicitly incorporate the spatial interactions between contiguous areas on the estimation for the major land uses at the 10 × 10 km cell level.

Following Li, Wu and Deng (2013), we assume that the expected conditional mean of allocations across parcels of land in nearby areas is affected by common factors including climate, land quality, information spillovers, technology adoption, and labor transfers.

We use a quasi-maximum likelihood method for the non-spatial discrete choice model including fractional dependent variable as done in Kala, Kurukulasuriya and Mendelsohn (2012) and suggested by Papke and Wooldridge (1996) and Murteira and Ramalho (2013). Discrete choices in fractional multinomial regression are restricted between 0 and 1 inclusive and sum to one. Then, adding spatial dependence into the conditional mean function of the fractional multinomial regression model, the equation can be expressed as:

(1) $$\mathrm{E}(s_{ijt} \mid \mathbf{x}, w) = K_j(\mathbf{x}_{it-1}, w_{im}; \boldsymbol{\beta}, \rho) = K\left(\sum_{m \neq i} \rho_{jt} w_{im} s_{mjt} + \mathbf{x}_{it-1} \boldsymbol{\beta}_{jt}\right),$$

where ρ_{jt} is a spatial lag parameter ($|\rho_{jt}| < 1$), implying the degree to which the propensity to have land use j in nearby areas. Here, $K(\cdot)$ is a known function with $0 < K(z) < 1 \quad \forall z \in \mathbb{R}$. For example, the functional forms of $K(z) \equiv \Lambda(z) \equiv \exp(z)/(1+\exp(z))$ (logistic function) or

$K(z) \equiv \Phi(z)$ (standard normal cumulative distribution function) limit the range of the predicted value. The logistic function for $K(\cdot)$ is used for this study since it allows simple estimation approaches and can be extended to a spatial multinomial logit framework. The explanatory variables $\mathbf{x}$ include geophysical and socioeconomic factors plus the lagged proportional share in time $t-1$ to control for potential endogeneity as done in Li, Wu and Deng (2013). In the above equation, w_{im} reflects the spatial relationship between land areas i and m. By construction, the spatial relation term in a single region ($w_{ii}, i = i$) is zero. The specification in $K(\cdot)$ including spatially lagged dependent variables is often referred to as a spatial lag model (LeSage 2008).

In turn the conditional mean function is expressed in a stacked form across areas as

(2) $$\mathrm{E}(\mathbf{S}_{jt} \mid \mathbf{X}, \mathbf{W}) = K(\rho_{jt}\mathbf{W}\mathbf{S}_{jt} + \mathbf{X}_{t-1}\boldsymbol{\beta}_{jt}),$$

where $\mathbf{S}_{jt} = \left(s_{1jt}, \ldots, s_{Njt}\right)'$ and $\mathbf{X}_{t-1} = \left(\mathbf{x}_{1t-1}, \ldots, \mathbf{x}_{Nt-1}\right)'$. The reduced form of the above equation can be described as $\mathrm{E}(\mathbf{S}_{jt} \mid \mathbf{X}, \mathbf{W}) = K[(\mathbf{I}_N - \rho_{jt}\mathbf{W})^{-1}\mathbf{X}_{t-1}\boldsymbol{\beta}_{jt}]$, where $\mathbf{I}_N$ is an N -dimensional identity matrix. An important aspect of the spatial lag model is the spatial multiplier, which can be implied by expanding the inverse term in this reduced form:

(3) $$\mathrm{E}(\mathbf{S}_{jt} \mid \mathbf{X}, \mathbf{W}) = K(\mathbf{X}_{t-1}\boldsymbol{\beta}_{jt} + \rho_{jt}\mathbf{W}\mathbf{X}_{t-1}\boldsymbol{\beta}_{jt} + \rho_{jt}^2\mathbf{W}^2\mathbf{X}_{t-1}\boldsymbol{\beta}_{jt} + \ldots).$$

Thus, the value of s_{ijt} in area i relies not just on $\mathbf{x}_{it-1}$ but also on $\mathbf{x}$ at other areas ($-i$), with locations further discounted by powers of ρ_{jt}. This demonstrates the diminishing nature of the spatial multiplier effects in the spatial lag model. Specifically, if a unit change were induced in a given explanatory variable x_{it-1}^k at every location, the effect on s_{ijt} would measure $\left(1-\rho_{jt}\right)^{-1}\beta_{jt}^k$ (Kim, Phipps and Anselin 2003).

Although specification for spatial weight matrix $\mathbf{W}$ is an empirical question as discussed in LeSage (2008), we use a row-normalized first queen contiguity matrix for simple but comparable analysis as done in the previous literature including Li, Wu and Deng (2013). $\mathbf{W}$ is defined as a $N \times N$ matrix where $\sum_{m=1}^{N} w_{im} = 1$ and $w_{im} > 0$ if areas i and m share common borders or vertices; $w_{im} = 0$ otherwise. The specification captures spatial reactions between any two locations through higher powers of $\mathbf{W}$. Let $(\mathbf{I}_N - \rho_{jt}\mathbf{W}) \equiv \boldsymbol{\Psi}_{jt}$. Then the variancecovariance matrix of $\mathbf{S}_{jt}$ is proportional to $[(\Psi_{jt})'(\Psi_{jt})]^{-1}$. Let σ_{ijt}^2 be the diagonal elements of $[(\Psi_{jt})'(\Psi_{jt})]^{-1}$ matrix, and let $\mathbf{x}_{ijt-1}^{*} = \mathbf{x}_{it-1}\sigma_{ijt}^{-1}$ and $\mathbf{X}_{jt-1}^{**} = (\Psi_{jt})^{-1}\mathbf{X}_{jt-1}^{*}$. Under the assumption analogous to the maximum quasi-likelihood estimation, the share of area i can be derived as follows:

$$p_{ijt} = E(s_{ijt} \mid \mathbf{x}_{ijt-1}^{**}) = \frac{\exp\left(\mathbf{x}_{ijt-1}^{**}\boldsymbol{\beta}_{jt}\right)}{\sum_k \exp\left(\mathbf{x}_{ikt-1}^{**}\boldsymbol{\beta}_{kt}\right)}, \tag{4}$$

where changes in land use in area i between $t-1$ and t are intrinsically captured by the left-hand side variable $p_{ijt}, j = 1,..., J$ and the right-hand side vector of the land proportions at period $t-1$.

This estimation approach is similar to the fractional multinomial logit via quasi-maximum likelihood estimation discussed in Papke and Wooldridge (1996) and Kala, Kurukulasuriya and Mendelsohn (2012). However, the fractional multinomial logit model with integration of spatial effects can be computationally challenging, especially in a large sample. Thus, we use a linearized spatial logit approach for the spatial general method of moments estimator as suggested by Li, Wu and Deng (2013) and Klier and McMillen (2008). The approach involves a two-step estimation. The first step is to estimate the model by standard multinomial logit in setting $\rho = 0$ to linearize the model around a reasonable starting point. Then the initial estimates of $\boldsymbol{\beta}$ (coefficients), $u = s - p$ (generalized residual), $\mathbf{g}_{ijt}^{\beta} = \partial p_{ijt} / \partial \boldsymbol{\beta}_{kt}$ (gradient terms for β), and $g_{ijt}^{\rho} = \partial p_{ijt} / \partial \rho_{kt}$ (gradient terms for ρ). Based on $\mathbf{g}_{ijt} = (\mathbf{g}_{ijt}^{\beta\prime}, g_{ijt}^{\rho})'$, calculate $u_{ijt}^1 \equiv u_{ijt}^0 + \mathbf{g}_{ijt}^{\beta}\boldsymbol{\beta}_t^0 + \mathbf{g}_{ijt}^{\rho} \cdot \mathbf{0}$ which are used for the following two-stage least squares since $u_{ijt}^0 + \mathbf{g}_{ijt}^{\beta}\boldsymbol{\beta}_t^0 + \mathbf{g}_{ijt}^{\rho} \cdot \mathbf{0} \approx u_{ijt} + \mathbf{g}_{ijt}^{\beta}\boldsymbol{\beta}_t + \mathbf{g}_{ijt}^{\rho} \cdot \boldsymbol{\rho}_t$. In the second step, regress $\mathbf{G}_{jt} = (\mathbf{g}_{1jt}', ..., \mathbf{g}_{Njt}')'$ on instruments $\mathbf{Z} = (\mathbf{X}, \mathbf{WX}, \mathbf{W}^2\mathbf{X}, ..., \mathbf{W}^5\mathbf{X})$ and then regress the calculated terms $[u_{11t}^1, ..., u_{NJ-1t}^1]'$ on $(\hat{\mathbf{G}}_{1t}', ..., \hat{\mathbf{G}}_{J-1t}')'$ by using two-stage least squares. The estimated coefficients $\hat{\boldsymbol{\beta}}$ and $\hat{\rho}$ are the spatial multinomial logit estimates.

Note that the coefficients from the spatial econometric models are not directly interpreted because the model is nonlinear. That is due to the fact that the explanatory variables are not independently determined by the equation but depend on interactions through the weight matrix.

Thus, following Li, Wu and Deng (2013), the marginal effects of covariates with respect to the expected share of land uses are estimated as:

(5) $$\frac{\partial p_{ijt}}{\partial \mathbf{x}_{it-1}} = p_{ijt}\left(\boldsymbol{\beta}_{jt} / \sigma_{ijt} \odot \left(\mathbf{I}_N - \rho_{jt}\mathbf{W}\right)^{-1} - \sum_k \boldsymbol{\beta}_{kt} p_{ikt} / \sigma_{ikt} \odot \left(\mathbf{I}_N - \rho_{kt}\mathbf{W}\right)^{-1}\right),$$

where $\odot$ is an element-by-element product operator.

The marginal effects of each independent factor on land use are direct marginal effects as shown in LeSage and Pace (2009). We can estimate the indirect marginal effects that are formed from the total marginal effects (the row sum or column sum of marginal effects) minus direct marginal effects. This can be viewed as spillover effects or indirect effects as termed in LeSage and Pace (2009).

Empirical model specification

Table 1 describes land shares and explanatory variables. The dependent variable is a vector of proportions, $\mathbf{s} = (s_1, s_2, ..., s_J)'$ of land use shares across the J mutually exclusive usages. The other (barren) land use is indexed by J and is used for the base reference in the fractional multinomial logit and spatial multinomial logit.

US land use transitions data among the major categories were obtained from National Land Cover Database (NLCD) and contains 30 × 30 m level remote sensing data in 2001 (Homer, et al. 2007), in 2006 (Fry, et al. 2011), and in 2011 (Jin, et al. 2013). The NLCD land covers are classified into water, developed, barren, forest, shrubland, herbaceous, planted/cultivated, and wetlands. This study classifies them into six categories - agriculture, developed, forest, grassland, water, and others. The matches between classifications are shown in table 2.

The number of national land parcel cells is approximately 16.8 trillion, which makes it hard to compute so we use a larger scale of aggregation. Also all of the other data we have are more highly aggregated. We use 10 × 10 km cells as a spatial unit. Although this will prevent capturing heterogeneity within the cells, it allows us to capture the interaction between cells.

Major recent year land use transitions in the US are shown in table 3. In the period 2002-2012, the land areas for agriculture and forest decreased while the amount in the urban lands, grasslands, and water lands increased. The largest transitions out of agricultural lands were movements into urban lands during 2002-2012. Also note that there was a net movement from forest to grasslands. Major movements of grasslands involved conversion to forest in the 2002-2012 period. Most agricultural land remained in agriculture with 99.3% unchanged during the period. Likely the higher recent prices influenced this greater retention. The remote sensing data show that urban land does not generally convert back once it is developed.

Census data for economic and social factors were obtained for 2002, 2007, and 2012 from the Census of Agriculture and the general U.S. Census. These data include cropland asset value, pastureland asset value, median housing value of owner-occupied units, farm proprietor income, non-farm proprietor income, and population. When the data for a specific year are not available, the data from a succeeding or preceding year were used. Irrigation rate for agricultural land, asset values of crop land and pasture land data were drawn from National Agricultural Statistics Service, United States Department of Agriculture (USDA NASS) QuickStats[1] on a county basis.

The time-invariant land characteristics data are obtained from the soils data base SSURGO[2] data (Soil Survey Staff 2014) of the Natural Resources Conservation Service (USDA-NRCS). This includes data on land capability classes (LCC) which for ease of interpretation were reversed so that 1 is the least desirable for agriculture and 8 the most. This is named soil quality in the estimation results and is assumed continuous.

The base county and state maps (*tl_2008_us_county00* and *tl_2008_us_state00*) were obtained from the TIGER products of the US Census Bureau for 2008. The 10 × 10 km map was based on the TIGER maps and gridded by using `fishnet` function in the ArcGIS software. We provide more detailed information on data sources and definitions in the Appendix.

Climate variables such as annual mean temperature, annual mean of monthly minimum temperature, annual mean of monthly maximum temperature, and annual total precipitation were obtained from United States Historical Climatology Network (USHCN). The variables are spatially interpolated between weather stations for the finer scale data.

[1] For the detailed information, see the website (http://quickstats.nass.usda.gov/).
[2] For detailed information, refer to http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627 (accessed May 27, 2014).

Estimation results

We estimate land use transitions at the 10 × 10 km cell level. As shown in table 1, many of the non-physical data used are at the county level data.

We present results from the fractional multinomial logit and the spatial multinomial logit in table 4 for 2002-2007 and table 5 for 2007-2012. The results show that the coefficients are not much different between the spatial and non-spatial models. However, the spatial model lag parameter estimates are all positive and significant at the 1% level. It implies that the estimates without spatial lag terms can lead to a misspecification error and thus the estimates can be biased (Pace and LeSage 2010).

The spatial dependence estimates are summarized in table 6. Comparing the period 2002-2007 with the period 2007-2012, the share of grassland and forest is becoming more dependent on land use patterns in the nearby areas over time with the agricultural and urban lands less dependent. The spatial dependences are mostly stable over time but the negative growth rate of the dependence is most significant in urban lands and water. Decreasing spatial dependence in urban areas might be because the allocation of US lands has been highly stable so that the changes have become less sensitive to the spatial interactions with nearby areas or that once a parcel goes to urban lands and almost never comes back to other land usage.

Table 7 contains estimates of the average marginal effects from the spatial multinomial logit for the years 2002-2007 and 2007-2012. We find the marginal effects of the explanatory variables are consistent across time on most land use transitions. Namely:

- Higher temperatures lead to a decrease in the share of land in agriculture with the effects growing over the years. Increases in precipitation leads to an increase in the agricultural land share but over time this is declining. Also, larger variations in temperature and precipitation generally decrease in the agricultural land use share, implying that higher volatility appears to reduce the agricultural land share.
- Higher temperatures lead to an increase in the share of land in grassland but the effect is declining over time. Increases in precipitation lead to less land in grasslands with the effect increasing over the years.
- Soil quality does not significantly affect shares of agricultural land and grassland. This may indicate that agricultural and grazing lands are less dependent on the land or soil quality as technology advances.

- Irrigation rates have positive impacts on allocating lands to grasslands with negative impacts on forest and urban lands. This implies that irrigated crops may push marginal dry land over to pastureland.
- Higher asset values for cropland have negative impacts on agricultural land use share. This indicates that the agricultural land with high asset values is likely near urban areas and may be converted to other uses as discussed in Nickerson, et al. (2012).
- Farm income per acre does not have consistent impacts on the land allocations but increases in non-farm income has negative impacts on land use for agriculture and urban areas and positive impacts on grasslands and forest. It is noted that the non-farm income is defined the total income minus the farm income by county so it is reasonable that the agricultural land decreases due to the higher non-farm incomes. Allocating urban lands and grasslands from other land uses are possibly affected by the specific type of non-farm incomes so the overall incomes might not separate the effects. This may also reflect a greater demand for environmental amenities as income grows.
- Higher median housing values decrease the probability of allocating lands to agriculture and urban uses but increases the probability of allocation lands to forest. It implies that the high-valued housing units are likely to be placed out of agricultural or urban lands.
- More populated areas increase the land allocation for agriculture and urban lands. This implies that as population grows, grassland and forest may be converted to agricultural or urban lands. This also indicates the agricultural and urban lands may be placed nearby for the agricultural land to be urbanized in the future.
- Land share in the previous period affects land usage of the current period. In specific, increases in the previous forest share have negative impacts on land share for agriculture and grass in the current period and vice versa. This may imply that agricultural and grass lands are competing with forest lands in allocating land shares. Also we find that when any land shares in the previous period increases, the urban land share in the current period still increases. This indicates that urban lands are likely to be developed from any lands in the previous period as well as the previous urban lands.

Overall, temperature and precipitation are found to have the largest effects on use of agricultural land and grassland. Generally, increasing temperature affects an increase in grassland share and a decrease in agricultural land but increasing precipitation leads to declining share of agricultural land and increasing share of grasslands. Given the most areas are expected to experience higher temperatures, the agricultural land is likely to decline but the grassland is likely to increase in the next decades.

Concluding remarks

This study examines major land use change in the US. We employ a linearized multinomial logit considering spatial dependence with the 10 × 10 km cell level data. The results show that that climate significantly affects land use transitions. This study also finds that the climate change adaptation has significantly spatial dependence on the nearby area. In major land transitions, agricultural land and grassland have opposite responses to changing temperature and precipitation with cropland declining as temperatures increase.

This study can be further developed by using the prediction under climate scenarios by regions. Also the predicted share of major land uses would be drawn as a map for the difference between the periods, say, from 2020 to 2100. It is however needed to use longer period data for a reliable prediction of land use change in the next decades.

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Table 1 Descriptions and sources of variables for major land use change

Variables	Description	Aggregation	Source
% Agriculture	Share of agricultural land (%)	10×10km	MRLC[a]
% Grass	Share of grasslands (%)	10×10km	MRLC[a]
% Forest	Share of forest (%)	10×10km	MRLC[a]
% Urban	Share of urban land (%)	10×10km	MRLC[a]
% Water	Share of water/ice (%)	10×10km	MRLC[a]
% Other	Share of other lands (%)	10×10km	MRLC[a]
Temperature	5-year average of annual mean temperature (degrees Celsius)	10×10km	USHCN[b]
Precipitation	5-year average of annual total precipitation (100mm)	10×10km	USHCN[b]
Temperature Std.Dev.	Standard deviation of Temperature	10×10km	USHCN[b]
Precipitation Std.Dev.	Standard deviation of Precipitation	10×10km	USHCN[b]
Drought index	Palmer drought severity index (Index)	10×10km	SSURGO[c]
Altitude	Altitude from the sea level (100m)	10×10km	SSURGO[c]
Slope	Slope of land (degrees)	10×10km	SSURGO[c]
Soil quality	Soil quality based on land capability classification (Index)	10×10km	SSURGO[c]
Irrigation rate	Irrigation rate of crop land (%)	County	USDA NASS[d]
Cropland asset value	Logarithm of cropland asset value ($/acre)	County	USDA NASS[d]
Pastureland asset value	Logarithm of pastureland asset value ($/acre)	County	USDA NASS[d]
Farm income	Farm income (1000$/ha)	County	CENSTAT[e]
Non-farm income	Non-farm income (1000$/ha)	County	CENSTAT[e]
Housing value	Logarithm of Median value of owner housing ($)	County	CENSTAT[e]
Log(Population density)	Logarithm of population density (persons in an acre)	County	CENSTAT[e]

Note: USHCN and NASS data are averaged with the current and past four years at the year (t-1). MRLC and CENSTAT data are used at the year (t-1).

[a] Multi-Resolution Land Characteristics (Environmental Protection Agency, National Oceanic and Atmospheric Administration, United States Forest Service, United States Geological Survey, Bureau of Land Management, National Park Service, National Aeronautics and Space Administration, U.S. Fish and Wildlife Service, National Agricultural Statistics Service, U.S. Army Corps of Engineers, and United States of Department of Agriculture)

[b] United States Historical Climatology Network, National Climatic Data Center, National Oceanic and Atmospheric Administration

[c] Soil Survey Geographic Database, Natural Resources Conservation Service, United States of Department of Agriculture

[d] National Agricultural Statistics Service, United States of Department of Agriculture

[e] United States Census Bureau

Table 2 Matched land use classifications

Classification for this study		NLCD 2001–2011 Classification
Agriculture	82	Cultivated Crops
	81	Pasture/Hay
Developed	24	Developed, High Intensity
	22	Developed, Low Intensity
	23	Developed, Medium Intensity
	21	Developed, Open Space
Forest	41	Deciduous Forest
	42	Evergreen Forest
	43	Mixed Forest
Grassland	71	Grassland/Herbaceous
	52	Shrub/Scrub
Water	11	Open Water
	12	Perennial Ice/Snow
Other	31	Barren Land
	95	Emergent Herbaceous Wetlands
	90	Woody Wetlands

Note: Detailed descriptions of each classification are provided in the Appendix.

Table 3 Land use transitions between 2002 and 2012 (million acres)

	To 2012						
From 2002	Agriculture	Developed	Forest	Grass	Water	Other	2002 Total
Agriculture	439.161	2.108	1.058	1.771	0.371	0.771	445.240
Developed	0.000	107.234	0.001	0.004	0.001	0.002	107.242
Forest	0.566	1.279	478.866	22.088	0.108	0.904	503.813
Grass	2.274	1.159	7.153	696.907	0.404	1.238	709.134
Water	0.140	0.024	0.028	0.266	102.684	0.919	104.061
Other	0.301	0.444	0.243	1.152	0.907	123.895	126.941
2012 Total	442.442	112.248	487.349	722.189	104.475	127.728	1996.431

Table 4 Estimates of land use transitions (2002-2007)

	Land share 2007									
	Fractional Multinomial Logit					Spatial Multinomial Logit				
Variables	Agriculture	Grass	Forest	Urban	Water	Agriculture	Grass	Forest	Urban	Water
Temperature	–0.0159***	0.0371***	0.0141***	0.0118***	–0.0246***	–0.0108***	0.0303***	0.0158***	0.0110***	–0.0100***
Precipitation	–0.0360***	–0.0806***	–0.0117***	–0.0331***	–0.0062	–0.0369***	–0.0731***	–0.0231***	–0.0310***	0.0098**
Temperature Std.Dev.	–0.9392***	–0.9701***	–0.0713**	–0.8349***	–0.3709***	–0.8408***	–0.8527***	–0.1659***	–0.7113***	–0.3445***
Precipitation Std.Dev.	–0.0769***	0.1052***	–0.0365***	–0.0173*	–0.0298**	–0.0547***	0.0885***	–0.0243***	–0.0141***	–0.0488***
Drought index	–0.0119**	–0.0067	0.0022	0.0347***	0.1282***	–0.0150***	–0.0029	0.0105***	0.0151***	0.1377***
Altitude	–0.0373***	–0.0150***	0.0128***	–0.0245***	–0.0380***	–0.0333***	–0.0150***	0.0096***	–0.0235***	–0.0136***
Slope	0.0008*	0.0059***	0.0061***	0.0021***	0.0073***	0.0020***	0.0055***	0.0057***	0.0018***	0.0075***
Soil quality	0.0091***	0.0053**	0.0150***	0.0017	–0.0040	0.0085***	0.0071***	0.0131***	0.0011	–0.0018
Irrigation rate	–0.3650***	–0.2355***	–0.5452***	–0.5276***	0.1704**	–0.3475***	–0.2373***	–0.5194***	–0.4908***	0.1932***
Cropland value	–0.3905***	–0.2102***	–0.0561***	–0.1203***	–0.2513***	–0.3334***	–0.1849***	–0.0640***	–0.1220***	–0.0837***
Pastureland value	0.3079***	–0.1431***	0.0288**	0.1247***	0.0220	0.2641***	–0.1114***	0.0270***	0.1236***	–0.1253***
Farm income	–0.2594***	0.0068***	0.0004	0.0050**	0.0004	–0.1282**	0.0069**	–0.0041	0.0054	–0.0364
Non-farm income	–0.0436***	0.0360***	0.0211*	–0.0602***	–0.0026	–0.0388***	0.0436***	0.0109**	–0.0542***	0.0109
Housing value	–0.2950***	0.0747***	0.0954***	–0.1243***	–0.0361	–0.2313***	0.0493***	0.0643***	–0.0639***	–0.1414***
Population density	0.0878***	–0.0108**	0.0172***	0.1661***	0.0202*	0.0702***	0.0005	0.0242***	0.1330***	0.0190**
Share of agriculture (t-1)	10.4758***	5.9894***	5.9293***	7.7345***	3.4863***	9.9833***	5.7423***	5.6226***	7.5663***	3.4307***
Share of grass (t-1)	6.8717***	9.4467***	5.9550***	6.8361***	3.2547***	6.5493***	9.0185***	5.5876***	6.6946***	3.1317***
Share of forest (t-1)	6.6336***	6.9065***	10.1943***	7.0432***	3.8575***	6.4556***	6.6018***	9.7045***	6.9171***	3.7726***
Share of urban (t-1)	6.6711***	4.7791***	6.0791***	11.8321***	5.3293***	6.3484***	4.4151***	5.7371***	11.6010***	5.2048***
Share of water (t-1)	4.3341***	3.4364***	4.2196***	5.8379***	9.5803***	4.1268***	2.8975***	3.6998***	5.7642***	9.3479***
Constant	–0.8444***	–3.0259***	–6.4293***	–5.2857***	–1.9385***	–1.5572***	–2.9721***	–5.5918***	–5.7561***	–1.2416***
Spatial lag (WX)						0.0680***	0.0707***	0.0513***	0.0456***	0.0528***
Number of observations			67539					67539		

Note: *, **, and *** indicate statistical significance at the levels 10%, 5%, and 1%, respectively. (t-1) and t indicate 2002 and 2007 in this estimation.

Table 5 Estimates of land use transitions (2007-2012)

	Land share 2012									
	Fractional Multinomial Logit					Spatial Multinomial Logit				
Variables	Agriculture	Grass	Forest	Urban	Water	Agriculture	Grass	Forest	Urban	Water
Temperature	–0.0084***	0.0422***	0.0218***	0.0234***	–0.0278***	–0.0021**	0.0342***	0.0213***	0.0224***	–0.0095***
Precipitation	–0.0302***	–0.0583***	–0.0184***	–0.0173***	–0.0359***	–0.0245***	–0.0508***	–0.0254***	–0.0162***	–0.0314***
Temperature Std.Dev.	–0.3571***	–0.2650***	0.3906***	0.0603	0.0918	–0.2748***	–0.1824***	0.3438***	0.0685***	0.2796***
Precipitation Std.Dev.	0.0120*	0.1003***	0.0278***	0.0488***	0.1458***	0.0118***	0.0788***	0.0311***	0.0438***	0.1511***
Drought index	0.1124***	0.0707***	0.0285***	0.1396***	0.1254***	0.0993***	0.0697***	0.0334***	0.1311***	0.1372***
Altitude	–0.0209***	0.0036***	0.0235***	–0.0065***	–0.0334***	–0.0139***	0.0017***	0.0197***	–0.0054***	–0.0125***
Slope	0.0014***	0.0063***	0.0067***	0.0031***	0.0073***	0.0027***	0.0060***	0.0063***	0.0030***	0.0069***
Soil quality	0.0097***	0.0062***	0.0149***	0.0028	–0.0003	0.0092***	0.0080***	0.0140***	0.0027**	–0.0008
Irrigation rate	–0.4401***	–0.2828***	–0.7364***	–0.5305***	–0.0202	–0.4302***	–0.2875***	–0.6677***	–0.5075***	0.1045
Cropland value	–0.2545***	–0.1085***	–0.0015	0.0180	–0.0872***	–0.1998***	–0.0818***	–0.0049	0.0178*	0.0830***
Pastureland value	0.1868***	–0.1922***	0.0013	–0.0364***	–0.2433***	0.1389***	–0.1581***	–0.0131**	–0.0217***	–0.3857***
Farm income	–0.2900***	0.0363***	0.0227**	0.0286***	0.0122	–0.0713	0.0445***	0.0184*	0.0375***	–0.0590*
Non-farm income	–0.0330***	0.0278***	0.0053	–0.0528***	0.0046	–0.0287***	0.0317***	0.0015	–0.0487***	0.0138*
Housing value	–0.2746***	0.0948***	0.0947***	–0.0571***	–0.0326	–0.2026***	0.0632***	0.0745***	–0.0343***	–0.1358***
Population density	0.0698***	–0.0315***	0.0253***	0.1280***	–0.0162	0.0524***	–0.0154***	0.0245***	0.1087***	–0.0159*
Share of agriculture (t-1)	10.5914***	6.0222***	5.8766***	7.6855***	3.2876***	10.0609***	5.7205***	5.4880***	7.5748***	3.2380***
Share of grass (t-1)	6.9677***	9.4895***	5.8959***	6.7394***	2.7490***	6.5914***	8.9769***	5.4309***	6.6621***	2.6932***
Share of forest (t-1)	6.6811***	6.8743***	10.1374***	6.8566***	3.5141***	6.4693***	6.5207***	9.5038***	6.8031***	3.4910***
Share of urban (t-1)	6.9069***	5.0075***	6.0530***	11.7552***	5.1685***	6.5413***	4.5860***	5.6374***	11.6039***	5.1059***
Share of water (t-1)	4.6921***	3.4636***	4.3390***	6.0388***	9.6295***	4.2210***	2.7707***	3.6738***	6.0072***	9.5102***
Constant	–1.8878***	–4.1543***	–7.0376***	–6.6635***	–1.0407***	–2.6532***	–4.0046***	–6.1790***	–6.8676***	–0.4867*
Spatial lag (WX)						0.0652***	0.0838***	0.0635***	0.0311***	0.0323***
Number of observations			67539					67539		

Note: *, **, and *** indicate statistical significance at the levels 10%, 5%, and 1%, respectively. (t-1) and t indicate 2007 and 2012 in this estimation.

Table 6 Estimated spatial lag parameter to the final land usage

	Agriculture	Grass	Forest	Urban	Water
2002-2007	0.0680***	0.0707***	0.0513***	0.0456***	0.0528***
2007-2012	0.0652***	0.0838***	0.0635***	0.0311***	0.0323***

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

Table 7 Marginal effects on land use transitions in spatial multinomial logit

	Agriculture	Grass	Forest	Urban	Water
From 2002 to 2007					
Temperature	–0.0028***	0.0028***	0.0005***	0.0002***	–0.0003***
Precipitation	0.0003	–0.0051***	0.0024***	0.0002***	0.0007***
Temperature Std.Dev.	–0.0327***	–0.0446***	0.0564***	–0.0061***	0.0024**
Precipitation Std.Dev.	–0.0074***	0.0128***	–0.0044***	–0.0003	–0.0007***
Drought index	–0.0024***	–0.0008***	0.0009***	0.0005***	0.0021***
Altitude	–0.0025***	–0.0005***	0.0030***	–0.0004***	0.0000
Slope	–0.0002***	0.0002***	0.0002***	–0.0001***	0.0001***
Soil quality	0.0002	–0.0002	0.0008***	–0.0003***	–0.0001***
Irrigation rate	–0.0023	0.0149***	–0.0271***	–0.0073***	0.0079***
Cropland value	–0.0212***	–0.0032***	0.0136***	0.0026***	0.0010**
Pastureland value	0.0273***	–0.0236***	–0.0012	0.0022***	–0.0029***
Farm income	–0.0124**	0.0057***	0.0032*	0.0022**	–0.0001
Non-farm income	–0.0049***	0.0061***	0.0009	–0.0023***	0.0002
Housing value	–0.0246***	0.0120***	0.0127***	–0.0002	–0.0016***
Population density	0.0039***	–0.0050***	–0.0013***	0.0042***	–0.0003**
Share of agriculture (t-1)	0.4532***	–0.0910***	–0.0864***	0.0376***	–0.0372***
Share of grass (t-1)	0.0175***	0.3959***	–0.1211***	0.0217***	–0.0381***
Share of forest (t-1)	–0.0337***	–0.0475***	0.4069***	0.0070***	–0.0367***
Share of urban (t-1)	0.0810***	–0.1497***	0.0412***	0.2699***	–0.0002
Share of water (t-1)	0.0578***	–0.0946***	0.0199**	0.0902***	0.0955***
From 2007 to 2012					
Temperature	–0.0024***	0.0027***	0.0005***	0.0004***	–0.0004***
Precipitation	0.0007***	–0.0032***	0.0008***	0.0006***	–0.0001**
Temperature Std.Dev.	–0.0322***	–0.0273***	0.0503***	0.0044***	0.0046***
Precipitation Std.Dev.	–0.0040***	0.0058***	–0.0019***	0.0002	0.0019***
Drought index	0.0035***	0.0006	–0.0048***	0.0027***	0.0012***
Altitude	–0.0019***	–0.0001	0.0025***	–0.0002***	–0.0002***
Slope	–0.0002***	0.0002***	0.0002***	–0.0001***	0.0000***
Soil quality	0.0001	–0.0001	0.0008***	–0.0003***	–0.0001**
Irrigation rate	–0.0035	0.0202***	–0.0372***	–0.0045***	0.0077***
Cropland value	–0.0167***	–0.0017***	0.0087***	0.0045***	0.0023***
Pastureland value	0.0215***	–0.0204***	0.0035***	–0.0006	–0.0059***
Farm income	–0.0095	0.0065*	0.0018	0.0021	–0.0010
Non-farm income	–0.0033***	0.0049***	0.0001	–0.0020***	0.0003**
Housing value	–0.0232***	0.0119***	0.0118***	0.0004	–0.0018***
Population density	0.0033***	–0.0058***	0.0005	0.0037***	–0.0007***
Share of agriculture (t-1)	0.4674***	–0.0908***	–0.1005***	0.0394***	–0.0411***
Share of grass (t-1)	0.0273***	0.4104***	–0.1402***	0.0224***	–0.0461***
Share of forest (t-1)	–0.0198***	–0.0472***	0.3925***	0.0064***	–0.0407***
Share of urban (t-1)	0.0965***	–0.1375***	0.0190***	0.2696***	–0.0031***
Share of water (t-1)	0.0679***	–0.1174***	0.0179*	0.1011***	0.0990***

Note: *, **, and *** indicate statistical significance at the levels 10%, 5%, and 1%, respectively, based on the standard errors using the delta method.

Appendix

Table A-1 National Land Cover Database (NLCD) 2011 Legend

Class\ Value		Classification Description
Water		
	11	**Open Water** - areas of open water, generally with less than 25% cover of vegetation or soil.
	12	**Perennial Ice/Snow** - areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed		
	21	**Developed, Open Space** - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
	22	**Developed, Low Intensity** - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
	23	**Developed, Medium Intensity** – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
	24	**Developed High Intensity** -highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren		
	31	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest		
	41	**Deciduous Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
	42	**Evergreen Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
	43	**Mixed Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland		
	51	**Dwarf Scrub** - Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
	52	**Shrub/Scrub** - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.

Class\ Value		Classification Description
Herbaceous		
	71	**Grassland/Herbaceous** - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	72	**Sedge/Herbaceous** - Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
	73	**Lichens** - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
	74	**Moss** - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated		
	81	**Pasture/Hay** – areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
	82	**Cultivated Crops** – areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands		
	90	**Woody Wetlands** - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
	95	**Emergent Herbaceous Wetlands** - Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Source: NLCD 2011 Product Legend. MRLC-USDA. http://www.mrlc.gov/nlcd11_leg.php (accessed August 24, 2014).