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Modeling the response of land use to climate change and alternative bio-feedstock scenarios in the Upper Missouri River Basin

WAFERx Objective 1a

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Summary

This report documents a land-use/land-cover (LULC) change model developed at the University of Wyoming for the WAFERx[1] project. Using satellite imagery generated observation of land cover from 2001 to 2011 (National Land Cover Database), we estimate a parametric conditional logit model to explain LULC change as a function of economic, biophysical and climate drivers. The model produces estimates of the probability of land use conversion between four broad uses (crops, pasture/hay, grass/shrubland, and urban), and produces estimates of marginal effects, which measure how changes in the drivers affect probabilities of conversion. This report documents the data and processes used to estimate the LULC change model, the base model results, and describes how the model can be used for forecasting future land use change in response to climate, policy shocks, or combinations of these.

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Contents

1. LAND-USE/LAND-COVER CHANGE MODEL

a. General Theory and Model Specification

We develop a parametric logit model of land-use/land-cover (LULC) change to model the drivers of agricultural land-use change in the Upper Missouri River Basin (UMRB). Our parametric modeling approach closely follows the economic literature on LULC modeling (see e.g., Rashford et al. 2011; Lewis and Plantinga 2007; Lubowski et al. 2003). Following standard assumptions (e.g., utility maximizing landowners with static expectations), the probability that plot *i* converts from use *j* to use *k* in period *t* is given by

(1) $$P_{ijkt} = prob(U_{ikt} \geq U_{ilt}) \ \forall l$$

where U_{ikt} is the expected utility of having plot *i* in use *k* in year *t* (including conversion costs). Since individual landowner preferences are unknown to the researcher, utility is disaggregated into indirect utility with observable and unobservable components:

(2) $$U_{ikt} = V_{ikt} + \varepsilon_{ikt}$$

where ε_{ikt} is an unobserved random component. We further assume that indirect utility can be generally expressed as a linear function of observable variables:

(3) $$V_{ikt} = \beta_k' X_{ikt} + \varepsilon_{ikt}$$

where X_{ikt} is a vector of observable variables believed to influence the utility associated with use *k*. Then the probability that plot *i* is converted from use *j* to use *k* in period *t* can be expressed as:

(4) $$P_{ijkt} = prob(V_{ikt} \geq V_{ilt}) = prob(\beta_k' X_{ikt} - \beta_l' X_{it} \geq \varepsilon_{ilt} - \varepsilon_{ikt})$$

Finally, assuming the random error terms are distributed IID Type I extreme value results in the conditional logit model with land-use conversion probabilities given by (see Train 2009):

(5) $$P_{ijkt} = \frac{\exp(V_{ikt})}{\sum_{l=1}^{K} \exp(V_{ilt})}$$

We specify indirect utilities for each ending land use using available data believed to influence landowner's utility or conversion costs. In general, indirect utility function are specified as:

(6) $$V_{ikt} = \alpha_k + \sum_m \delta_k^m w_{ikt}^m + \sum_n \gamma_k^n z_i^n$$

where:

α_k is an alternative specific constant term;

w_{ikt}^m are *m = 1,…, M* alternative specific variables with alternative specific coefficients (i.e., variables, such as returns, that enter the indirect utility function of specific uses and have parameter estimates specific to each use); and

z_i^n are *n = 1,…,N* are location-specific variables with alternative specific coefficients (i.e., variables, such as precipitation or soil quality, that are specific to each location and do not vary by land use, but have varying effects on different land-use choices).

The coefficients of the logit model are difficult to interpret directly, so we calculate marginal effects to evaluate the effects of changes in explanatory variables on the probability of land-use conversion. Specifically, marginal effects measure the effect of small changes in explanatory variables on the probability of land-use conversion $\left(\frac{\partial P_{ijkt}}{\partial X_{ikt}}\right)$ (see Train 2009). The explicit calculation of marginal effects depends on the type of variable being examined (alternative- vs. location-specific) and on whether the variable has a direct or indirect effect on the land-use choice in question:

Alternative-specific direct marginal effects:

$$\frac{\partial P_{ijkt}}{\partial w_{ikt}^m} = \delta_k^m P_{ijkt}(1 - P_{ijkt}) \ \forall m,k$$

These marginal effects show how a small ("one-unit") change in an alternative specific variable changes the absolute probability of converting to a specific use with respect to variables in indirect utility function for that use. For example, for the probability of crops remaining in crops $(P_{i,crop,crop,t})$, if the marginal effect on crop returns $\left(\frac{\partial P_{i,crop,crop,t}}{\partial w_{crop}^{crop\ returns}}\right)$ is 0.001, then a \$1 increase in crop returns would be expected to increase the probability of cropland staying in cropland by 0.001.

Alternative-specific indirect marginal effects:

$$\frac{\partial P_{ijkt}}{\partial w_{ilt}^m} = -\delta_l^m P_{ijlt} P_{ijkt} \ \ \forall m, l \neq k$$

These marginal effects show how a small ("one-unit") change in an alternative specific variable changes the absolute probability of converting to a specific use with respect to variables in indirect utility function of other uses. For example, for the probability of crops remaining in crops $(P_{i,crop,crop,t})$, if the marginal effect on grass returns $\left(\frac{\partial P_{i,crop,crop,t}}{\partial w_{grass}^{grass\ returns}}\right)$ is -0.001, then a $1 increase in grass returns would be expected to decrease the probability of cropland staying in cropland by 0.001.

Location-specific direct marginal effects:

$$\frac{\partial P_{ijkt}}{\partial z_i^m} = P_{ijkt}(\gamma_k^m - \sum_l P_{ijlt}\gamma_l^m)\ \forall m,l,k$$

These marginal effects show how a small ("one-unit") change in a location-specific variable changes the absolute probability of converting between uses. Since these variables are location-specific, they indicate the comparative advantage (disadvantage) of one type of location (e.g., locations with a specific precipitation) for a particular use – relative to other locations. For example, if the marginal effect of precipitation on the probability of cropland remaining in cropland $\left(\frac{\partial P_{i,crop,crop,t}}{\partial z_i^{precipitation}}\right)$ is 0.005, then locations with one unit (mm) more rain would be expected to have probabilities of remaining in crops that are 0.005 larger then locations with one unit less precipitation.

b. Data Description

i. UMRB Region

Following the WAFERx project, we define the UMRB as the region upriver from the confluence of the Big Sioux and Missouri Rivers in Sioux City, Iowa (excluding the Niobrara watershed) (Figure 1). For the purposes of the LULC change model, we restrict the UMRB to the U.S. portion of this watershed as the data available to model LULC change in Canada is fundamentally different. The final region encompasses 124,103,320 acres (193,911 square miles).

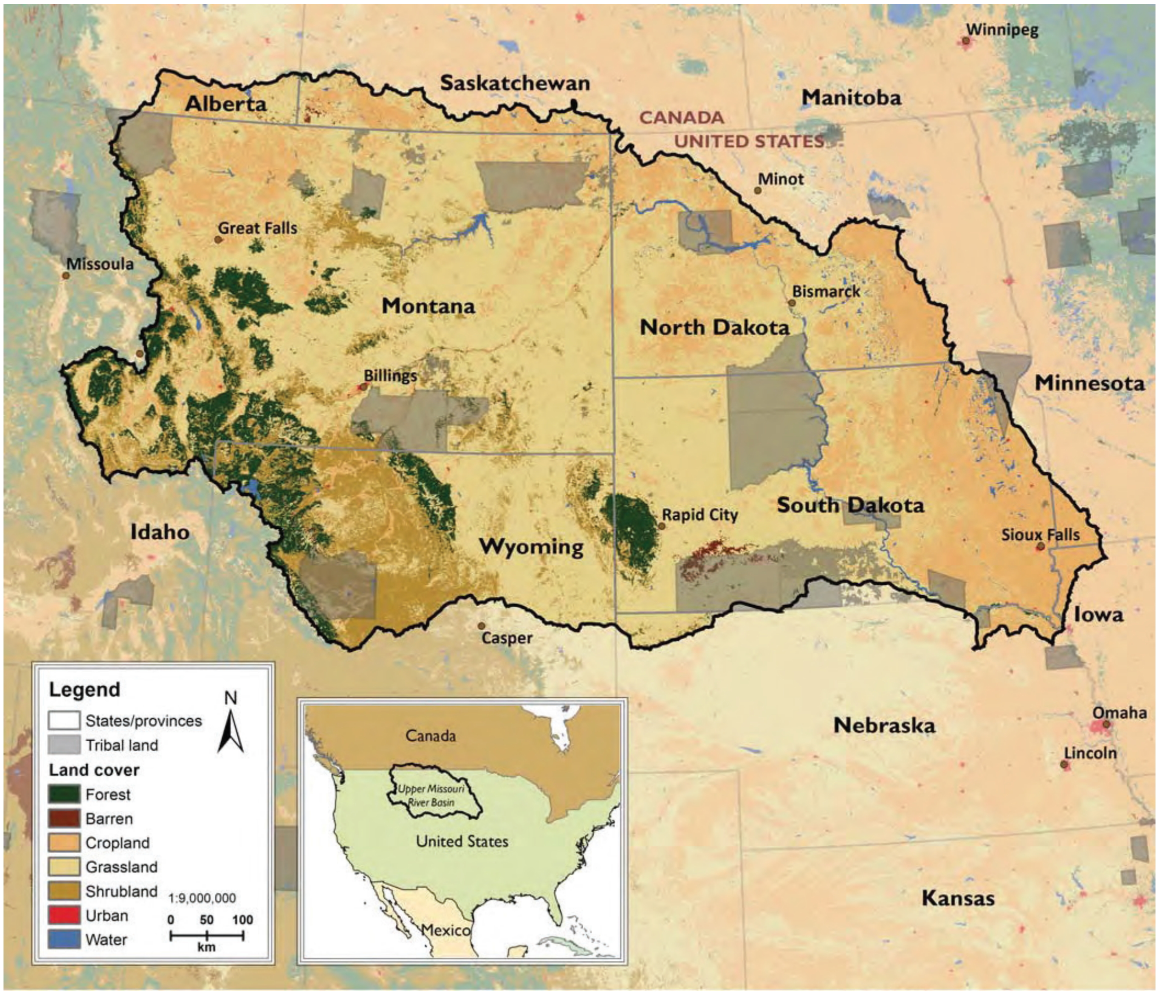


Figure 1. General map of the UMRB region and dominant land cover (source: Stoy et al., 2018).

Data available to specify the LULC model described above are provided at a variety of spatial scales. Depending on the data source (see below), we use the following spatial scales and associated definitions for the LULC change model data in the UMRB:

> Ecoregions (Omernik and Griffith 2014) define separate regions with similar ecosystems (type, quality and quantity of environmental regions). Our UMRB is composed of 5 level II ecoregions and 15 level III ecoregions (Figure 2).

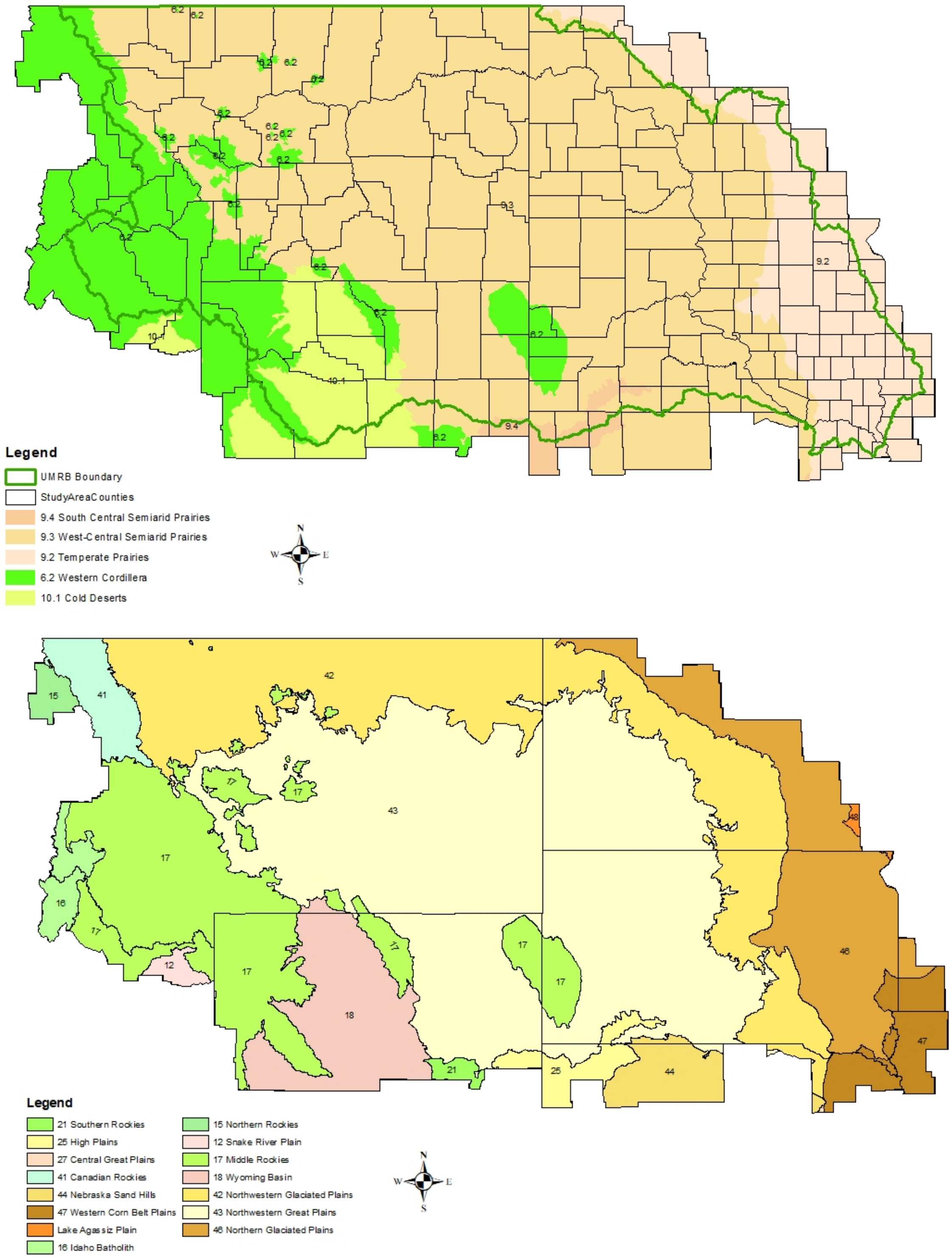


Figure 2. EPA level II (top) and level III (bottom) ecoregions in the WAFERx UMRB.

State, County, Census Tract: Our UMRB intersects 8 states, 193 counties, and 640 census tracts (see Appendix A, Table A1). For the purposes of LULC change modeling we include data from any county that intersects our UMRB boundary (Figure 3). This study area includes 640 census tracts used for the 2000 US Census. Tracts were redefined for the 2010 US Census, which reported 608 tracts in the study area (Figure 4). Census tracts are converted from 2000 to 2010 areas by 2000 tracts that were consolidated in 2010 and dividing values by two.

Figure 3. Map of the states and counties included in the UMRB study region.

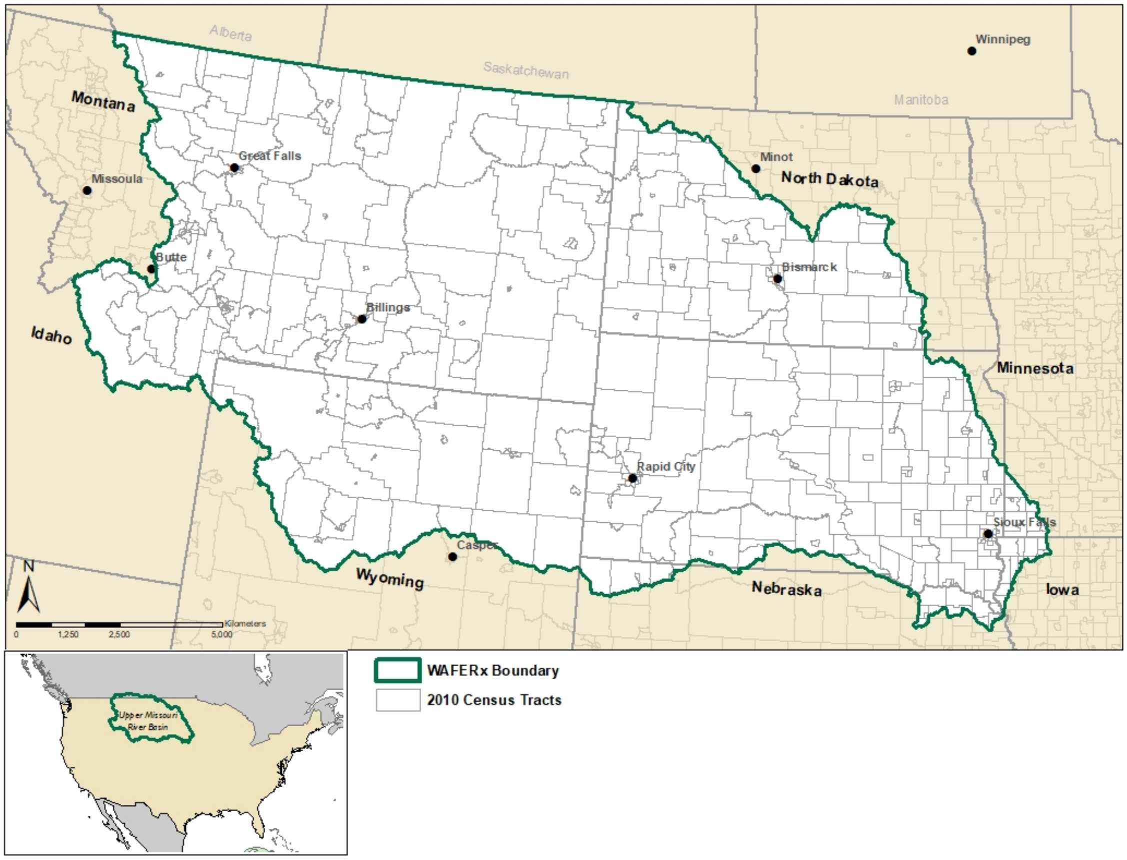


Figure 4. Map of 2010 US Census Tracts included in the UMRB study region.

Field/Plot: The "field/plot-scale" (hereafter termed "plot") serves as the primary spatial scale for the purposes of estimating the LULC change model and for projecting future LULC change. We develop our plot-scale spatial units by combining USDA common land unit data with US Census tract centroids and nearest NLCD land cover class data for respective transition years. The USDA common land unit (CLU) "is the smallest unit of land that has a permanent, contiguous boundary, a common land cover and land management, a common owner and a common producer in agricultural land associated with USDA farm programs" (USDA FSA n.d.). Thus, CLUs define distinct agricultural fields with a high level of precision. Since CLUs are defined for the primary purpose of identifying agricultural fields, they are not available for non-agricultural land uses/covers. Spatial R scrips were used to develop a contiguous layer of plot-level polygons for the UMRB. The plot-scale spatial units represent a highly disaggregated scale for LULC change modeling, which is most consistent with the scale at which landowners make land-use decisions. Our resulting plot-scale dataset includes 11,134,478 individual plots.

Finally, since the LULC change model is defined based on individual landowner optimization, the model only applies to privately owned land. We therefore mask out all non-privately owned lands in UMRB for the purposes of LULC modeling and projection. Are exclusionary mask is defined by aggregating all non-private lands, including municipal, state and federally owned lands. After masking non-private lands, the final plot-level data set for estimating and projecting LULC change in the UMRB contains 8,674,963plots.

ii. Land Cover Data

We use the USDA National Land Cover Database (NLCD) to generate observation of land use. Generated by the Multi-Resolution Land Characteristics Consortium (MRLC), a group of federal agencies coordinating to generate consistent land cover information at the national scale, the NLCD provides nationwide land cover classification at a 30mm resolutions with a 16-class legend based on a modified Andersen Level II classification system (MRLC 2019). To specify land cover and land cover change for our model, we aggregate the NLCD land use categories into four land uses: crops, grass and shrubland, pasture and hay, and urban. These four classes constitute the primary categories most affected by climate change and bioenergy policies, and encompass 87% of the total UMRB land area (NLCD 2011). All other uses/covers are not explicitly included in our model and thus are assumed to remain constant in future land use projections. The four land use categories used in the LULC model are aggregated from NLCD classifications as follows:

Crops (82) is the NLCD classification **82 Cultivated Crops** described as "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. This class also includes all land being actively tilled."

Grass and shrubland (70) combines two NLCD classifications: **71 Grassland/Herbaceous**, "areas dominated by gramanoid or herbaceous vegetation (not subject to intensive management such as tilling, but can be utilized for grazing)" and **52 Shrub/Scrub** "areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation (includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions)."

Pasture and hay (81) is the NLCD classification **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."

Urban (20) includes all developed classifications (**21 Developed, open space**; **22 Developed, low intensity**; **23 Developed medium intensity**; and **24 Developed, high intensity**.)

iii. Economic Drivers

We use a variety of data to construct variables believed to influence landowner incentives to choose to transition between the different land use categories. These variables influence the economic returns or costs borne by landowners and thus influence the utility landowners receive from choosing different land uses.

Price and cost measures are adjusted by year to normalize dollar values to a $2010 base year using a standard Bureau of Economic Analysis GDP price deflator (US BEA 2021).

Net Crop Returns measures the net returns to cropland by county, measured in 2010 dollars per acre ($2010/acre). Net crop returns are calculated using data on crop acreages, prices, costs and yields to form an aggregate net returns measure. Specifically, we construct an area-weighted county-level expected crop net returns measure according to:

$$NR_{crops,t} = \sum_i \left[\left(price_{i,t} \times yield_{i,t} \times (1 - costshare_{i,t}) \right) weight_{i,t} \right],$$

where:
i indexes the primary crops in the UMRB (barley, corn grain, oats, sorghum grain, soybeans, and wheat),
$price_{i,t}$ is a five-year lagged moving average price using USDA NASS county-level commodity price data (USDA NASS n.d.),
$yield_{i,t}$ is a five-year lagged Olympic average using USDA NASS county-level commodity yield data (USDA NASS n.d.),
$costshare_{i,t}$ is the calculated cost share of gross returns (operating costs/value of production) from ERS commodity costs and returns data (USDA ERS 2021), and
$weight_{i,t}$ is the county-level proportion of total harvested area (USDA NASS n.d.) represented by each crop.

Ethanol Production is the average annual state-level ethanol production (thousand barrels) from estimates reported by the US Energy Information Administration (US EIA 2018).

Federal Agricultural Commodity Payments is the county-level total federal payments ($2010) for all agricultural programs excluding conservation and wetlands programs measured in receipts per operation reported in the US Census of Agriculture (USDA NASS n.d.).

Gross Returns to Pasture is the gross returns to hay calculated as yield (tons/acre) times the price for hay (excluding alfalfa) ($2010/ton) reported by the US Census of Agriculture (USDA NASS n.d.).

Cattle Inventory is the county inventory of cattle including calves (head) reported in the US Census of Agriculture (USDA NASS n.d.).

Cattle Price is county price received for cattle and calves ($2010/CWT) reported by US Census of Agriculture (USDA NASS n.d.).

Average CRP Rent is county average annual rent paid on Conservation Reserve Program enrolled land ($2010/acre) reported by USDA Farm Service Agency (FSA 2016).

Federal Conservation Payments is the total county-level federal payments from Conservation Reserve, Wetlands Reserve, Farmable Wetlands, and Conservation Reserve Enhancement programs measured in receipts per ($2010/operation) reported in the US Census of Agriculture (USDA NASS n.d.).

Population Density is total census tract population divided by tract area (km2), derived from census tract level population reported by the US Census Bureau for 2000 and 2010 (US CB n.d.).

Distance to Railroad is the distance from each raster cell to the nearest railroad, measured in meters, to capture crop cost/benefits associated with access to markets.

Distance to Road is the minimum distance in meters from the boundary of each plot to the nearest primary or secondary road. Distance to serviceable roads is included to capture the effects or rural-ness on decision to convert to urban uses.

Distance to Incorporated Area is the minimum distance in meters from the boundary of each plot to the nearest incorporated place, reported by the US Census Bureau for 2000 and 2010.

iv. Climate Drivers

We use ensembles of all available historic and projected modeled climate data to represent two emissions scenarios. Modeled historic climate data (rather than actual observations) ensures that the model estimates and future projections are in model space (Sofaet, et al. XXXX).

Representative Concentration Pathways (RCPs) are defined by a cumulative measure of human GHG emissions in Watts per square meter on a pathway to the year 2100 (IPCC—RPCs; van Vuuren et al. 2011). Two RCPs are compared:

> *RCP 2.6* is a mitigation scenario, modeling assumes rapid reduction in emissions from all sources. BECCS is a crucial component of this model (van Vuuren 2011b). RCP 2.6 represents a global "peak and decline" global emissions scenario.

> *RCP 4.5* is the lower of two medium stabilization scenarios, a cost-minimizing pathway driven by changes in energy technologies and carbon capture, again relying on BECCS and afforestation to a large extent (Thompson, et al. 2011; Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009). RCP 4.5 represents global emissions stabilization without overshooting.

General Circulation Models (GCMs) are geographically and physically consistent estimates of regional climate change, required in impact analysis. GCMs depict the climate using a three dimensional grid over the globe with a resolution that is coarse relative to the scale of exposure units in most Integrated Assessment Models (University of Chicago n.d.). Climate variables used in the land use model are ensembles of all available GCMs for RCP 2.6 and RCP 4.5 (reported in Appendix B, Table B1). Each ensemble averages four precipitation and temperature measures from these modeled over the time period 1861 through 2099. The following climate measures are included in the land use model, averaged over all GCMs for each of the two RCPs:

> *Median Growing Season Temperature* is the median of median growing season temperature (degrees C) 1981 – 2011.

> *Median Winter Temperature* is the median of median winter temperature (degrees C) 1981 – 2011.

> *Variability Growing Season Temperature* is the median standard deviation of growing season temperature (degrees C) 1981 – 2011.

Variability Winter Temperature is the median standard deviation of winter temperature (degrees C) 1981 – 2011.

Mean Growing Season Precipitation is mean of mean growing season precipitation (monthly accumulation, mm)) 1981 – 2011.

Mean Winter Precipitation is mean of mean winter precipitation (monthly accumulation, mm) 1981 – 2011.

Variability Winter Precipitation is the mean standard deviation of growing season precipitation (monthly accumulation, mm) 1981 – 2011.

Variability Growing Season Precipitation is the mean standard deviation of winter precipitation (monthly accumulation, mm) 1981 – 2011.

Dryness Index is calculated from the climate data as the annual mean temperature (degrees C) divided by the annual precipitation (mm).

v. Biophysical Drivers

Soil Productivity is an index measure of soil quality for agricultural production. We developed it from the USFS Soil Productivity Index, which is an ordinal estimate of soil productivity, ranking soils from 0, least productive to 19, most productive (USFS n.d.; Schaetzl, et al. 2012). Relative to other index measures of soil quality, such as the landscape capability class form SSURGO, the soil productivity index suffers from fewer boundary issues. To create an aggregate soil measure from this index, we is aggregated into 3 classifications:

Most Productive Soil combines ratings 15 through 19;

Productive Soil combines 10 through 14; and

Least Productive Soil combines ratings 0 through 9.

Slope is calculated from the National Elevation Dataset (NED) (USGS n.d.a) as the rate of change in the NED value from one raster cell to the next, identifying the steepness of each cell of the slope raster (degrees). We measure slope as the average value across all NED cells within a land use plot.

Available Water Capacity (AWC), a measure of the amount of water in centimeters that the top meter of soil can hold multiplied by 100. AWC is an indicator of water the soil can store (Cornell University 2016). Values range from 9 to 5,876 across the UMRB study area.

Soil Organic Carbon (SOC) is a measure of soil health. Organic carbon is a source of energy for soil microorganisms, affecting plant growth and nutrient availability (Soil Quality for Environmental Health 2011). Data are from the USDA NRCS Gridded Soil Survey Geographic (gSSURGO) (USDA NRCS n.d.). SOC values are reported in kilograms per meter squared (kg/m2) and range from zero to 65,535 across the UMRB.

Compound Topographic Index (CTI), a steady state wetness index, is a function of slope and upstream flow (USGS n.d.b). CTI values are reported in meters (m). CTO values in the UMRB range from 2.8 to 30.5.

vi. Spatial and Temporal Control Variables

We also use several spatial and temporal variables to control for any spatio-temporal drivers not captured by the other continuous explanatory variables. We include a dummy variable for sample year with 2011 as the base (*SampYear2006)* to control for any policy other temporal changes not captured by our other temporal variables. We also include dummies for EPA ecoregions to control for other spatial/biophysical drivers. Specifically, we create the following aggregated ecoregion categories (Figure 5):

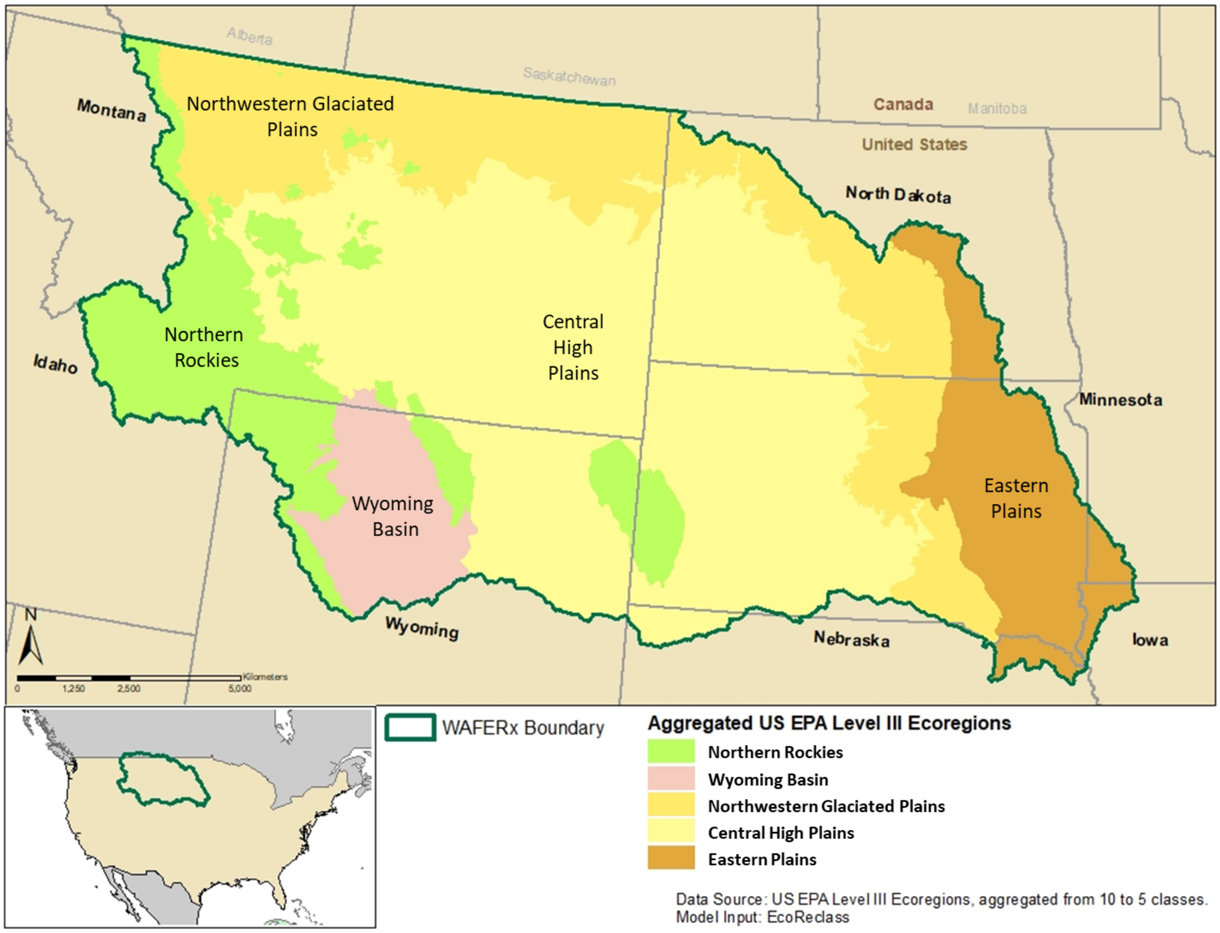


Figure 5. Aggregated EPA Level III Ecoregions.

The *Northern Rockies Region* represents an area aggregating EPA Level III ecoregions 16 - Idaho Batholith, 17 - Middle Rockies, and 41 – Canadian Rockies. The area encompasses the Rocky Mountains in western Montana and eastern Idaho as well as isolated mountains including the Bighorns in northcentral Wyoming and the Black Hills, which span the border between Wyoming and South Dakota. The Northern Rockies Region contains forested mountainous areas as well as mixed forest and shrub-covered intermountain plateaus and valleys.

The *Wyoming Basin Region* represents a single Level III ecoregion with the same designation and name. The area encompasses central Wyoming, crossing into southern Montana between the Rocky and Bighorn Mountains. It is described as a broad intermountain basin interrupted by hills and low mountains and dominated by arid grasslands and shrublands.

The *Northwestern Glaciated Plains Region* represents a single Level III ecoregion with the same designation and name. This region follows the northern border of Montana, then curving south through central North and South Dakota, roughly coinciding with the limits of glaciation and encompassing seasonal wetlands of the Prairie Potholes.

Three Level III ecoregions are aggregated to define the *Central High Plains Region* within the UMRB: 25 – High Plains, 43 – Northwestern Great Plains, and 44 – Nebraska Sandhills. This region includes most of the central UMRB. It is characterized by smooth to slightly irregular plains with a high percentage of cropland in the northern High Plains portion, transitioning to mostly unglaciated buttes and badlands in the central UMRB. The region also includes the Sandhills of northwestern Nebraska, a distinct area of grass-stabilized dunes.

Two Level II ecoregions, 46 – Northern Glaciated Plains and 47 – Western Corn Belt Plains, are combined to form the *Eastern Plains Region,* which follows the eastern edge of the UMRB, across central North Dakota and eastern South Dakota. Within the UMRB the region is typified by rolling plains composed of glacial drift with seasonal wetlands in the northern portion transitioning to fertile croplands on the westernmost portion of the Midwest Corn Belt.

c. Bootstrap Procedure

d. Data Cleaning

Plots with observed land use transitions (e.g., a plot changing from grass to urban) were visually checked using satellite imagery corresponding to the observation time period (sample year 2001 or 2006) to ensure reasonable NLCD coding. Rejected plots were replaced in the stratified sample using re-sampled, visually checked plots.

e. Final Model Specification and Estimation Procedure

The final model specified with the data described above is estimated across four land uses: crops (*c*), grass and shrubland (*g*), pasture and hay (*p*), and urban (*u*). Indirect utility functions for each use are specified according to (6) with the following variables (also denoted in Table 1 below):

V_c = *f(Intercept, Sample Year 2006, Wyoming Basin Region, Glaciated Plains Region, Central High Plains Region, Eastern Plains Region, Available Water Capacity, Soil Organic Carbon, Slope, Compound Topographic Index, Median Growing Season Temperature, Median Winter Temperature, Variability Growing Season Temperature, Variability Winter Temperature, Mean Growing Season Precipitation,* *Mean Winter Precipitation, Variability Winter Precipitation, Variability Growing Season Precipitation, Dryness Index, Distance to Railroad, Distance to Road, Net Crop Returns, Ethanol Production, Federal Agricultural Commodity Payments)*

V_g = *f(Intercept, Sample Year 2006, Wyoming Basin Region, Glaciated Plains Region, Central High Plains Region, Eastern Plains Region, Available Water Capacity, Soil Organic Carbon, Slope, Compound Topographic Index, Median Growing Season Temperature, Median Winter Temperature, Variability Growing Season Temperature, Variability Winter Temperature, Mean Growing Season Precipitation, Mean Winter Precipitation, Variability Winter Precipitation, Variability Growing Season Precipitation, Dryness Index, Cattle Price, Cattle Inventory, Average CRP Rent, Federal Conservation Payments)*

V_p = *f(Intercept, Sample Year 2006, Wyoming Basin Region, Glaciated Plains Region, Central High Plains Region, Eastern Plains Region, Available Water Capacity, Soil Organic Carbon, Slope, Compound Topographic Index, Median Growing Season Temperature, Median Winter Temperature, Variability Growing Season Temperature, Variability Winter Temperature, Mean Growing Season Precipitation, Mean Winter Precipitation, Variability Winter Precipitation, Variability Growing Season Precipitation, Dryness Index, Gross Returns to Pasture, Cattle Price, Cattle Inventory)*

V_u = *f(Population Density, Distance to Incorporated Area, Distance to Road)*

Table 1. Variables by Land Use Indirect Utility

Variables	**Land Use**			
	Crops	**Grass and shrubland**	**Pasture and hay**	**Urban**
Location-specific Variables				
(Intercept)	X	X	X	
Sample Year 2001 (base)	X	X	X	
Sample Year 2006	X	X	X	
Northern Rockies Region (base)	X	X	X	
Wyoming Basin Region	X	X	X	
Glaciated Plains Region	X	X	X	
Central High Plains Region	X	X	X	
Eastern Plains Region	X	X	X	
Available Water Capacity	X	X	X	
Soil Organic Carbon	X	X	X	
Slope	X	X	X	
Compound Topographic Index	X	X	X	
Median Growing Season Temperature	X	X	X	
Median Winter Temperature	X	X	X	
Variability Growing Season Temperature	X	X	X	
Variability Winter Temperature	X	X	X	
Mean Growing Season Precipitation	X	X	X	
Mean Winter Precipitation	X	X	X	
Variability Winter Precipitation	X	X	X	
Variability Growing Season Precipitation	X	X	X	
Dryness Index	X	X	X	
Use-specific Variables				
Crops (Vc)				
Distance to Railroad	X			
Distance to Road	X			
Net Crop Returns | Most Productive Soil (base)	X			
Net Crop Returns | Productive Soil	X			
Net Crop Returns | Least Productive Soil	X			
Ethanol Production	X			
Federal Agricultural Commodity Payments	X			
Grass and Shrubland (Vg)				
Cattle Price		X		
Cattle Inventory		X		
Average CRP Rent		X		
Federal Conservation Payments		X		
Pasture and Hay (Vp)				
Gross Returns to Pasture | Most Productive Soil (base)			X	
Gross Returns to Pasture | Productive Soil			X	
Gross Returns to Pasture | Least Productive Soil			X	
Cattle Price			X	
Cattle Inventory			X	
Urban (Vu)				
Population Density				X
Distance to Incorporated Area				X
Distance to Road				X

In the final specifications, we interact crop and hay returns with Soil Productivity (defined above) to allow the effect of returns on land use choices to vary with soil quality.

Using these specifications, we estimate separate logit models by starting use using stratified random samples from the observed NLCD transitions between 2001 and 2006, and 2006 and 2011. We do not estimate an explicit model for plots starting in urban, since urban uses are irreversible – thus, any other use can convert to urban, but once a plot is in urban it does not convert back to any other uses.

Pooling the data across the two transition periods, there are a total of 74,294,544 observations starting in crops, 154,062,928 observations starting in grassland/shrubland, and 17,102,970 observations starting pasture/hay. After stratified random sampling, the resulting estimation data sets contain 548,702 observations starting in crops, 761,262 observations starting in grass and shrubland, and 153,143 observations starting in pasture and hay.

f. Basic Estimation Results

i. Parameter Estimates and Marginal Effects

The logit LULC model fits the data well and parameter estimates generally conform to *a-priori* expectations. Raw parameter estimates are provide in the Appendix C, Tables C1-4; however, since they difficult to interpret directly, we focus here on briefly describing some of the key marginal effects from the model. The signs and magnitude of marginal effects generally conform to economic theory and *a-priori* expectations. Own marginal effects on returns measures generally indicate, as expected, that higher returns increase the probability of remaining in, or converting to, that use (marginal effect on returns > 0). Furthermore, the effect of higher returns is moderated by plot-level soil quality such that the effect generally diminishes on lower quality lands (returns-soil quality interactions < 0).

ii. LULC Change Probabilities

As expected, the model generally predicts that most lands remain in their starting use with mean probabilities for remaining in the starting use are all greater than 98% (Table 2). Reported means are across all sampled plots conditional on starting use and explanatory variable values from 2011.

Table 2. Mean predicted conversion probabilities by starting use for 2011

Starting use	**Ending use**			
	Crop	**Grass and shrubland**	**Pasture and hay**	**Urban**
Crop	0.994995	0.004653	0.000131	0.000221
Grass and shrubland	0.003010	0.995939	0.000416	0.000635
Pasture and hay	0.012309	0.004044	0.983502	0.000145
Urban	0	0	0	1

2. Projecting Future LULC Change

a. General Projection Methods

Given the model and resulting parameter estimates described above, transition probabilities can be calculated according to (5). Transition probabilities can be calculated for any five-year transition period starting in 2011, and for any scenario (where scenarios are defined by changing the value of variable used to calculate indirect utilities). Specifically, for a given transition period ending in year *t'* and scenario ($X_{t'}^{S1}$):

$$P_{ijkt'} = \frac{\exp\left(V_{ikt'}(X_{t'}^{S1})\right)}{\sum_{l=1}^{K}\exp\left(V_{ilt'}(X_{t'}^{S1})\right)} \tag{7}$$

where S1 denotes a specific scenario (e.g., setting all climate variables to a specific future climate). Following (7), probabilities can be calculated for each plot (CLU) for any node along the land use change transition tree (Figure 6).

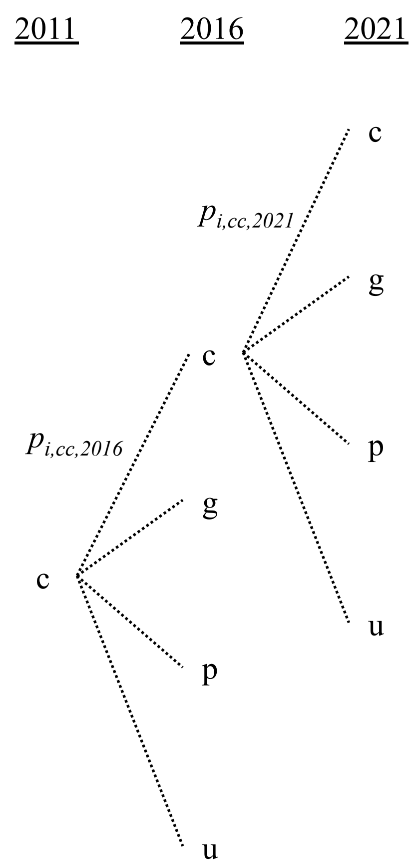


Figure 6. Land Use Transition Tree for Four Uses and Two Transition Periods.

In each transition period, there are 16 transition probabilities based on the four possible starting and ending uses. The probability that a parcel ends in a specific use in any future period then becomes a function of all the transition paths it could follow and their associated probabilities. Thus, the probability that the parcel in Figure 6 ends in crop (*c*) in 2021 is:

$$
\begin{aligned}
p_{i,c-c,2011-2021} = & \; p_{i,cc,2011-2016} \times p_{i,cc,2016-2021} \\
& + p_{i,cg,2011-2016} \times p_{i,gc,2016-2021} \\
& + p_{i,cp,2011-2016} \times p_{i,pc,2016-2021} \\
& + p_{i,cu,2011-2016} \times p_{i,uc,2016-2021}
\end{aligned}
$$

More generally, the transition probabilities for all beginning and ending uses in any transition period can be expressed as:

$$P_{i,j,k,1-T} = P_{ijk1} \times P_{ijk2} \times \ldots \times P_{ijkT}$$

Transition probabilities can be viewed as a start/end use matrix (Figure 7). For each starting use, probabilities sum to 1 across all potential ending uses. Viewed in this context, irreversibility of urban use is described by setting Puu = 1.

		Ending Use:				
		Crops	**Pasture/Hay**	**Grass/Shrub**	Urban	
Starting Use:	**Crops**	**Pcc**	Pcp	Pcg	Pcu	Pc*j* ∑ 1
	Pasture/Hay	Ppc	**Ppp**	Ppg	Ppu	Pp*j* ∑ 1
	Grass/Shrub	Pgc	Pgp	**Pgg**	Pgu	Pg*j* ∑ 1
	Urban	Puc = 0	Pup = 0	Pug = 0	**Puu = 1**	Pu*j* ∑ 1

Figure 7. Transition Probability Start/end Use Matrix.

i. Projecting LULC Change Probabilities

b. Defining and Projecting Future Land Use Scenarios

As described previously, the estimated LULC change model can be used to project future land use for any scenario that can be described by changes in the explanatory variables (drivers) of the parametric logit model. We consider a range of climate and biofeedstock scenarios meant to bound the possible land use futures resulting in the UMRB basin given different broad assumptions about how global and national policies could move towards a more carbon friendly energy and agricultural system. Each land-use scenario requires assumptions about future climate conditions (i.e., what global climate scenario or RCP is realized) and about relative prices/returns to different land uses. The scenarios described here focus on the assumptions needed to project land use change. The broader WAFERx scenarios require additional assumptions related to how various policy/economic systems could emerge that are consistent with the land-use scenario assumptions (e.g., what are the downstream uses/processing systems that would lead to a specific relative price assumption for cellulosic biofeedstocks).

i. Dynamic IPCC Climate Scenarios

For all of our scenarios we consider two dynamic IPCC climate futures – RCP 2.6 and RCP 4.5 (IPCC 2019). The RCPs result from a set of broad global assumptions about the pace at which the world develops and moves towards reduced carbon technologies. RCP 2.6 and 4.5 are both negative emissions pathways that rely on aggressive bioenergy with carbon capture and storage (BECCS) to reach negative CO_2 – a world where more CO_2 is taken out of the atmosphere than is added to it. Each of these scenarios includes the assumption of an "aggressive" carbon tax, which would increase incentives for low or negative carbon approaches, such as BECCS. The RCPs, however, do not provide explicit assumptions about specific technologies or policies in specific locations – they do not, for example, make explicit assumptions about prices for biofeedstocks in the UMRB. Thus our future scenarios are meant to capture a range of possibilities that would be consistent with futures along either RCP, and where the UMRB contributes by adopting different forms of BECCS technologies to varying degrees. Note, however, that our scenarios and modeling are not necessarily implying that the UMRB itself must achieve net negative CO_2.

For our land-use projections, the RCPs provide a forecasted climate consistent with the assumptions of each RCP. To incorporate the forecasted future climate conditions into our projections, we use the climate data from each RCP to generate the land-use model climate variables using the same approach we used for modeling. In summary, we use the projected climate data to generate ensemble plot-level 30-year normal for each five-year transition period. Thus, the climate data used to project conversion probabilities in each future 5-year transition period are normals representing the 30 years preceding the start of each transition period averaged across GCMs.

Compared to historic averages, under both mitigation assumptions, regional projected winter and growing season precipitation and precipitation variability increase over time. Generally, this change is greater in later time periods with less GHG mitigation (RCP 4.5), with a few exceptions. Likewise, winter and growing season temperature increase over time, while variability in winter temperatures drops over time.

ii. Static/Status Quo Scenarios

The static or status quo climate scenario assumes that the rest of the world advances as necessary to achieve a given climate pathway but that policies affecting incentives for alternative land uses remain unchanged in the UMRB. This status quo describes how land use would respond as landowners adapt to changing climate conditions assuming that the relative returns/incentives for alternative land uses stay constant[2]. This is an admittedly naïve scenario – imagining that the world adopted policies to achieve a negative CO_2 pathway without affecting relative prices for agricultural commodities in the UMRB. It does, however, provide a necessary within-model space comparison of alternative land-use futures from which to evaluate ecological and economic tradeoffs. We produce a status quo/climate only projection for RCP 2.6 and 4.5. These results will allow us to compare the projected outcomes from other policy-related scenarios to two reference points:

1) Current land use – comparing future projections to current land (i.e., land use according to the 2011 NLCD) use allows us to understand how climate and alternative BECCS scenarios impose tradeoffs relative to present conditions (or alternatively to how the future would look if neither climate nor policy changed); and

2) Static/Status Quo – comparing future policy projection to the climate only status quo allows us to isolate the effects of policy vs climate induced changes in land use.

iii. 1st Generation Biofeedstock Scenarios

First generation biofeedstocks refer to conventional biofuels produced from oils, sugars and starches originating in food crops (Dahiya 2015; Nagler and Gerace 2020). The primary 1st generation biofeedstocks in the UMRB are corn for bio-ethanol and oilseeds for bio-diesel. Though many global scenarios for achieving RCP 2.6 and 4.5 assume that the US capacity for first generation biofuels is already saturated, we consider a scenario of 1st generation expansion to understand the tradeoffs that could arise if policies adjusted to incentivize the expansion and intensification of 1st generation biofeedstocks.

---

[2] Note that the assumption of "relative returns staying constant" does not imply, for example, that agricultural prices cannot change. Only relative changes in the drivers of land use matter in projecting land sue change. Thus agricultural prices can all increase at the same rate without any change to relative prices (e.g., if crop and hay returns both double, then there is no change in relative returns and no change in the incentives for landowners to convert between crop and pasture/hay).

Specifically, we assume two alternative positive price shocks: 1) a 5% increase in the relative returns to 1st generation crops, and 2) a 30% increase in the relative returns to 1st generation crops. Previous studies indicate that for each additional billion gallons of ethanol produced in the US, corn prices increase 5 to 10% (Condon et al. 2015). Similarly, the 2007 Renewable Fuels Standard, which requires a minimum annual quantity of biofuel content in motor fuel, has been shown to increase the long-run price of corn by 31% (Carter et al. 2015). US production is currently meeting the RFS, with ethanol production ranging between 14 and 16 billion gallons between 2001 and 2016 (US EIA 2021b). Thus, our scenarios of a 5% and 30% increase in relative returns to 1st generation crops are consistent with a quite modest increase in biofuel demand on the low end, and an extremely aggressive expansion of biofuel demand on the high end.

First-generation biofeedstock scenarios are implemented as follows: A 5% increase in crop returns is implemented starting in 2016. A 30% increase in crop returns increases linearly from zero in 2011 to 30% by 2051. Policy costs are calculated as a proportion of average regional $2010 net crop returns per acre (Figure 8).

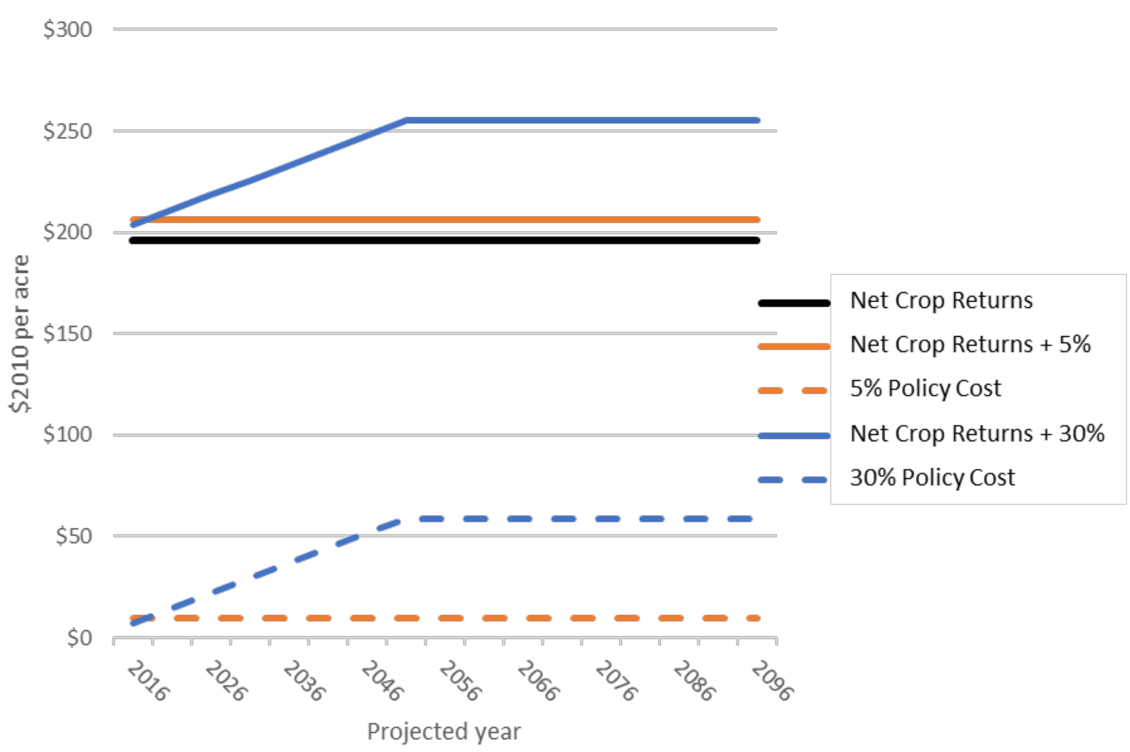


Figure 8. First-generation biofeedstock scenario policy implementation.

iv. 2nd Generation Biofeedstock Scenarios

Second generation biofeedstocks are sourced from non-food biomass, such as perennial grasses, that are dedicated to bioenergy production (Nagler and Gerace 2020). As of 2021 there is no commercial-scale biofuel production in the US.

We build are 2nd generation scenarios around assumptions consistent with switchgrass (*Panicum virgatum*); however, from a land use change perspective, the results would be consistent with any 2nd generation feedstock that had similar price and production characteristics. We model 1st generation expansion by changing the relative returns to hay, the land use in our model most consistent with switchgrass. Similar to the 2016 Billion Ton Report, we assume a range of potential farmgate prices for cellulosic biofeedstocks and assume that yields will improve through time as varieties and production practice adjust to this new land use. Specifically, we assume a low price scenario of $40/ton and a high price $80/ton. With both price assumptions, we assume new cellulosic feedstocks will initially achieve yields equal to the current county-level average yields on all new pasture and hay will increase at 1% per year from reported county-level 2011 grass hay yields (NASS n.d.). A one percent annual yield increase is consistent with the lowest assumption used in the Billion Ton Report (DOE 2016). This approach to yield assumptions ensures that the spatial heterogeneity currently observed across the UMRB is maintained.

Using these price and yield assumptions, we can generate a range of scenarios by making different assumptions to restrict (or not) where cellulosic feedstocks are allowed to expand on the landscape. These alternative scenarios include:

1) Low price 2nd Generation - $40/ton feedstock prices with 1% annual yield increase and no restrictions on production practices or location;
2) High price 2nd Generation - $80/ton feedstock prices with 1% annual yield increase and no restrictions on production practices or location

Second-generation biofeedstock scenarios are implemented as follows: Both a $40/ton and $80/ton price incentives are implemented starting in 2016. Likewise, both second-generation policy scenarios implement an annual 1% yield increase from 2011 base hay yields starting in 2016. Per-acre policy costs are relative to $2010 base hay returns (Figure 9).

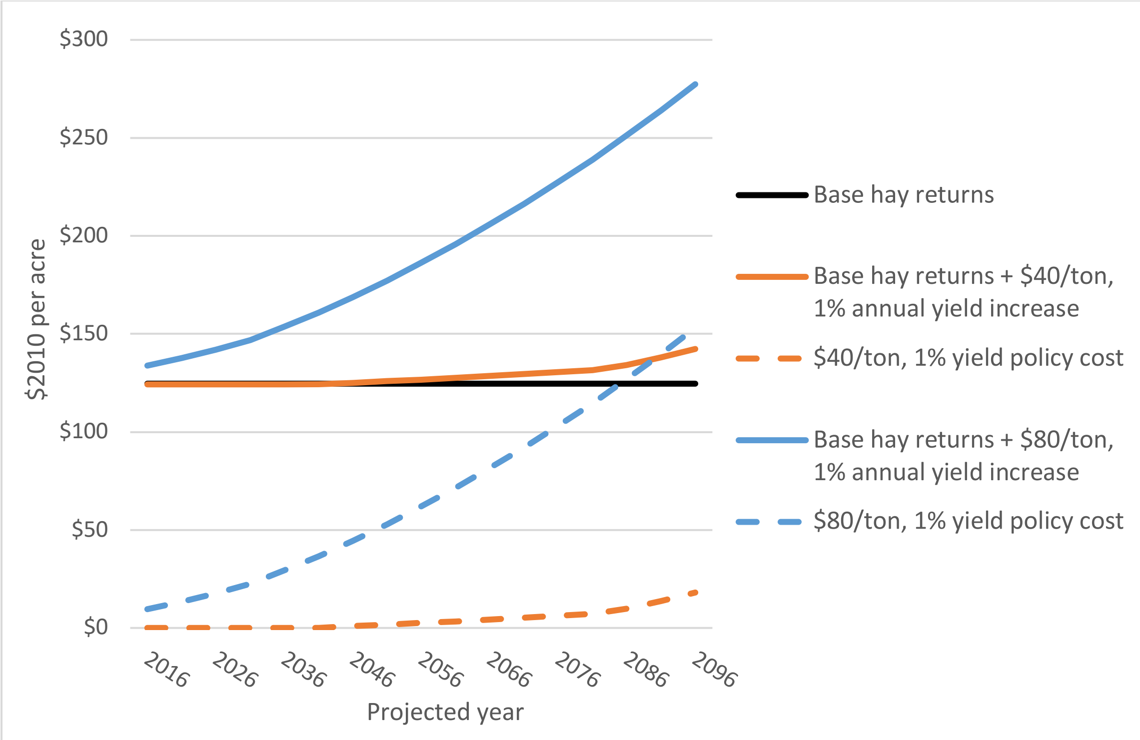


Figure 9. Second-generation biofeedstock scenario policy implementation.

v. Combining climate and biofeedstock policy scenarios

Climate and biofeedstock policies are combined in twelve modeled scenarios (Table 3).

Table 3. Modeled biofeedstock policy/climate scenarios

	Biofeedstock policy	Climate model	RCP
	Base		
1	No-policy	Dynamic	2.6
2	No-policy	Dynamic	4.5
3	No-policy	Static	2.6
4	No-policy	Static	4.5
	First-generation biofeedstock incentives - Crop area		
5	Crop returns + 5%	Dynamic	2.6
6	Crop returns + 5%	Dynamic	4.5
7	Crop returns + 30%	Dynamic	2.6
8	Crop returns + 30%	Dynamic	4.5
	Second-generation biofeedstock incentives - Pasture and hay area		
9	$40/ton, 1% annual yield increase	Dynamic	2.6
10	$40/ton, 1% annual yield increase	Dynamic	4.5
11	$80/ton, 1% annual yield increase	Dynamic	2.6
12	$80/ton, 1% annual yield increase	Dynamic	4.5

c. Translating Land Use Change into Bioenergy Potential

We interpret changes in crop and pasture/hay area resulting from incentive policies in terms of first- and second-generation bioenergy feedstock production. Resulting estimates can be used to calculate feedstock production in terms of energy. Assumptions, conversion factors, and calculations used to quantify current and projected regional bioenergy potential are detailed in Appendix D: Bioenergy Conversion Calculations.

3. Results Narratives

LULC model outputs are presented in the context of five land-use change narratives. The first focuses on how projecting climate affects regional land-use mix relative to static climate assumptions. Using the projected climate as a base, we then consider the impact of policy scenarios to incentivize first-generation bioenergy expansion and then second-generation bioenergy expansion. A fourth narrative considers both first- and second-generation bioenergy expansion in terms of relative energy production and policy costs. Finally, we focus on grass and shrubland projections under different climate and policy scenarios with implications for native habitat and ecosystem services.

a. How does projected climate affect the land-use mix across the UMRB region over time?

The LULC model is estimated using both static historic climate averages and a projected dynamic climate under two climate change mitigation assumptions, allowing a comparison of how projected climate assumptions impact land use mix across the UMRB.

Over the UMRB region, the climate "forecast" relative to the historic average is for increasing rain and snow alongside increasing variability in precipitation (Appendix B, Figure B1), and warmer growing season and winter temperatures, but less variability in winter temperatures (Appendix B, Figure B2) Increasing precipitation and temperatures combine to an overall increase in annual dryness across the region (Appendix B, Figure B3).

In some areas, an overall increase in precipitation may benefit agriculture, however, increasing variability make rain and snow events both unpredictable and unusable as precipitation patterns oscillate more between drought and flood. Warmer, more stable winter temperatures paired with more precipitation could create favorable conditions for some crop diseases while increasing growing days that could make other crops easier to grow.

i. Land use area projection

Projected cumulative ending land use areas describe a regional decrease in crop area and a corresponding increase in grass and shrubland. Pasture and hay as well as urban area response is largely dependent on climate assumptions (Figure 10).

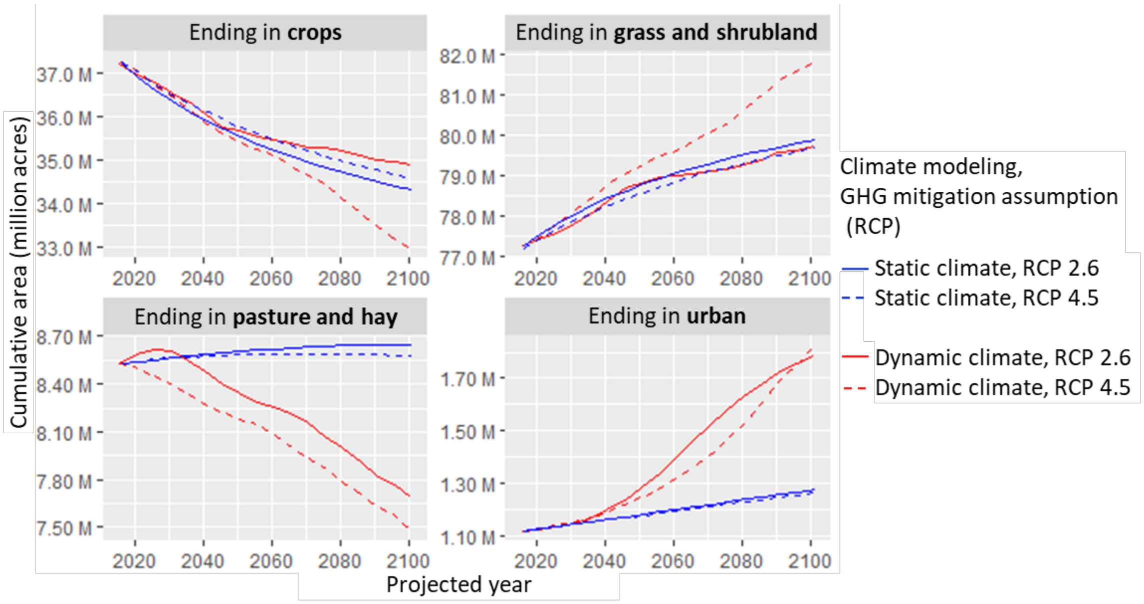


Figure 10. Cumulative land use area (acres) for historic and projected climate scenarios.

With more GHG mitigation in Rcp 2.6 (solid lines) **crop area** with projected climate (red) decreases at a slower rate relative to a static climate where global mitigation is not implemented regionally (blue). This effect is reversed with less mitigation in Rcp 4.5 (dashed lines).

Grass and shrub area increases over time, mirroring crop area decline. The largest relative increase in grass and shrubland is seen with climate projected under a low GHG emissions assumption (RCP 4.5).

With static regional climate GHG mitigation, total area ending in **pasture and hay area** is relatively stable over time regardless of RCP. Dynamic climate with most GHG mitigation (RCP 2.6) results in pasture and hay area initially climbing then dropping off; least mitigation (RCP 4.5) has it decreasing over time.

Regardless of the mitigation assumption (RCP), **urban area** increases more rapidly with projected climate relative to a static climate after 2050.

Several measures of regional land-use area change quantify the impact of modeling a static climate based on historic averages compared to projected changing climate under two GHG mitigation assumptions over the projected timeframe (2016 to 2101) (Table 4).

Table 4. Land use area change (2016 to 2101) modeled with static and dynamic climate under different GHG mitigation assumptions

RCP **Climate scenario** Ending land use	Ending area (acres) 2101	Area change (acres) 2101 - 2016	Area change, difference from static climate base	Ending use as % of total UMRB area	Area change as % of total UMRB area	Area change as % of total UMRB area, difference from static climate base
RCP 4.5 - less GHG mitigation						
Static climate						
Crops	34,586,961	-2,677,369	0	27.9%	-2.2%	0
Grass and shrub	79,679,361	2,484,313	0	64.2%	2.0%	0
Pasture and hay	8,575,054	47,396	0	6.9%	0.0%	0
Urban	1,261,944	145,660	0	1.0%	0.1%	0
Sum	*124,103,320*	*0*		*1*	*0*	
Dynamic climate						
Crops	32,970,872	-4,293,458	-1,616,088	26.6%	-3.5%	-1.3%
Grass and shrub	81,827,534	4,632,487	2,148,174	65.9%	3.7%	1.7%
Pasture and hay	7,475,362	-1,052,297	-1,099,693	6.0%	-0.8%	-0.9%
Urban	1,829,551	713,267	567,607	1.5%	0.6%	0.5%
Sum	*124,103,320*	*0*	*0*	*1*	*0*	*0*
RCP 2.6 - more GHG mitigation						
Static climate						
Crops	34,310,045	-2,901,619	0	27.6%	-2.3%	0
Grass and shrub	79,868,773	2,617,641	0	64.4%	2.1%	0
Pasture and hay	8,649,568	125,324	0	7.0%	0.1%	0
Urban	1,274,936	158,654	0	1.0%	0.1%	0
Sum	*124,103,320*	*0*		*1*	*0*	
Dynamic climate						
Crops	34,902,084	-2,309,580	592,039	28.1%	-1.9%	0.5%
Grass and shrub	79,725,163	2,474,031	-143,610	64.2%	2.0%	-0.1%
Pasture and hay	7,692,246	-831,997	-957,322	6.2%	-0.7%	-0.8%
Urban	1,783,827	667,546	508,892	1.4%	0.5%	0.4%
Sum	*124,103,320*	*0*	*0*	*1*	*0*	*0*

Crop area decreases over the modeled timeframe under all climate assumptions and scenarios. This decline in crop area is greatest when climate is modeled as dynamic with less GHG mitigation in RCP 4.5 (-4,293,458acres); the lowest crop area decline is projected with a dynamic climate assuming more GHG mitigation in RCP 2.5 (-1,980,042 acres). Relative to static, including dynamic climate modeling results in relatively more crop decline in RCP 4.5 and somewhat less in RCP 2.6 (Table 4).

Grass and shrub area increases over time under all climate assumptions and scenarios. Compared to a static climate, dynamic climate modeling results in a relative increase in grass and shrub area (+2,148,174acres) when less GHG mitigation is assumed (RCP 4.5) and a small relative decrease in grass and shrub area (-143,610acres) with more GHG mitigation modeled under RCP 2.6 (Table 4).

Pasture and hay area increases overall with a static climate and declines when a dynamic climate is projected in both RCPs. Compared to static, there is a larger relative decline in pasture and hay when less GHG mitigation is assumed in RCP 4.5 (-1,099,693 acres) and a smaller relative decline with more mitigation in RCP 2.6 (-957,322 acres) with dynamic climate modeling (Table 4).

Urban area increases from 2016 to 2101 under all climate assumptions and scenarios. Relative to a static climate, urban area increases more with dynamic climate modeling. This relative increase is similar across RCP 4.5 and 2.6 (+567,607 and +508,892 acres, respectively) (Table 4).

Overall, grass and shrubland make up the largest proportion of modeled land area in the UMRB, followed by cropland, pasture and hay, and urban areas. Viewed as a percent of total modeled UMRB area (124 M acres), the largest regional changes are seen in crop decrease (-3.5%) and grass and shrub area increase (+3.7%) with a dynamic climate assuming less GHG mitigation (RCP 4.5), pointing to more change in regional climactic growing conditions when land change incorporates a dynamic climate model. Relative to a static climate, this crop area decrease is 1.3% of the study area and grass and shrub area increase is 1.7% of the total UMRB modeling this low GHG mitigation assumption (Table 4).

Given different climate modeling and mitigation assumptions, what transition patterns of start and ending land use result? Table 5 presents area change (acres) over the projected timeframe (2016 to 2101) modeling climate as static and dynamic under two GHG mitigation assumptions as a start/end land use grid. A second row reports the percent of each starting use area that transitions to each of the other use categories. (Note that end use area columns sum to area change 2101 - 2016 reported in Table 4 above, that is, 2101 ending area minus the 2016 starting area.)

Table 5. Start/end land use change grid, area (acres) and percent of start use area transitioning from each starting use to ending use modeled with static and dynamic climate under different GHG mitigation assumptions

Starting use	**End Land Use Area (acres, % starting use area)** to Crops	to Grass and shrub	to Pasture and hay	to Urban	*Sum*
RCP 4.5 - less GHG mitigation					
Static climate					
Crops	-4,617,100	4,527,741	68,100	21,258	0
		98.1%	1.5%	0.5%	100.0%
Grass and shrub	1,879,704	-3,155,536	1,161,369	114,464	0
	59.6%		36.8%	3.6%	100.0%
Pasture and hay	60,027	1,112,108	-1,182,073	9,938	0
	5.1%	94.1%		0.8%	100.0%
End use sum (area change 2101-2016)	-2,677,369	2,484,313	47,396	145,660	0
Dynamic climate					
Crops	-5,766,925	5,613,319	17,320	136,286	0
		97.3%	0.3%	2.4%	100.0%
Grass and shrub	1,393,070	-2,061,323	147,543	520,710	0
	67.6%		7.2%	25.3%	100.0%
Pasture and hay	80,397	1,080,491	-1,217,159	56,271	0
	6.6%	88.8%		4.6%	100.0%
End use sum (area change 2101-2016)	-4,293,458	4,632,487	-1,052,297	713,267	0
RCP 2.6 - more GHG mitigation					
Static climate					
Crops	-4,840,885	4,765,596	49,594	25,696	0
		98.4%	1.0%	0.5%	100.0%
Grass and shrub	1,884,258	-3,267,924	1,261,767	121,899	0
	57.7%		38.6%	3.7%	100.0%
Pasture and hay	55,008	1,119,969	-1,186,037	11,059	0
	4.6%	94.4%		0.9%	100.0%
End use sum (area change 2101-2016)	-2,901,619	2,617,641	125,324	158,654	0
Dynamic climate					
Crops	-4,454,219	4,320,634	27,957	105,628	0
		97.0%	0.6%	2.4%	100.0%
Grass and shrub	1,988,634	-3,020,275	524,629	507,012	0
	65.8%		17.4%	16.8%	100.0%
Pasture and hay	156,004	1,173,672	-1,384,583	54,906	0
	11.3%	84.8%		4.0%	100.0%
End use sum (area change 2101-2016)	-2,309,580	2,474,031	-831,997	667,546	0

Area moving out of **crop** use, described in Table 4 above, mainly transitions to grass and shrubland across all climate scenarios and assumptions (Table 5). With a dynamic climate, crop area transitions are impacted by GHG mitigation assumptions. With dynamic climate modeling, assuming less mitigation in RCP 4.5, 97.3% of area transitioning out of crops ends in grass and shrubland, 0.3% in pasture and hay, and 2.5% transitions from crop to urban by 2101. Compared to the RCP 4.5 climate modeled as a static historic average, crop area is less likely to transition to grass/shrub and pasture/hay and more likely to end in urban in RCP 4.5. This general pattern of crop area transitions also holds for RCP 2.6, which assumes more GHG mitigation, lessoning climate change.

Grass and shrub area increases across all climate scenarios and assumptions (Table 4). The majority of area transiting to grass and shrub comes from crops (80%) with the remainder (20%) from pasture/hay (Table 5).

Over the projected timeframe, **pasture and hay** area increases with climate modeled as static and decreases with a dynamic climate model in both RCPs (Table 4). The majority of area transitioning into pasture and hay in all climate combinations transitions from grass and shrubland (Table 5).

New **urban** area is most likely to transition out of grass and shrubland, followed by crop and pasture/hay (Table 5). With a dynamic climate, especially in RCP 4.5 with the least GHG mitigation, a relatively larger new urban area is even more likely to transition out of grass and shrub.

ii. Spatial distribution

Mapping parcel-level land use change probabilities provides further information about the spatial distribution of changes in response to climate modeling. As reported above (Table 4), regional crop area decreases over the study period, especially with a dynamic climate assuming less GHG mitigation (and therefore greater climate changes) in RCP 4.5. Under this climate scenario, decreases in the cumulative probability that a parcel will end in crop area over the study period (2016 to 2101) are more likely across Montana (lighter areas) while the probability that a parcel will end in crop area increases in some parcels east of the Missouri River in North Dakota and South Dakota (darker areas) Figure 11, top). The inverse is true for change in the likelihood that a parcel will end in grassland or shrubland (

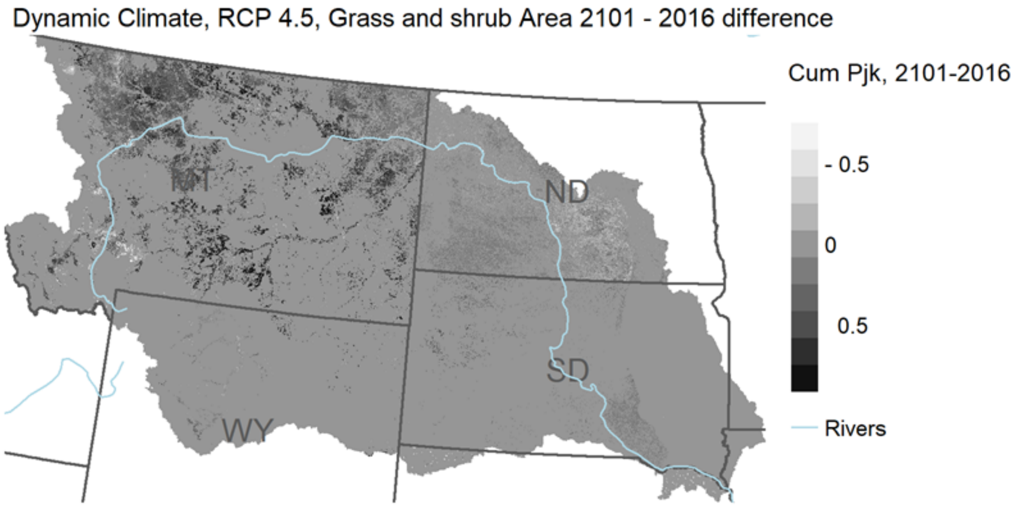
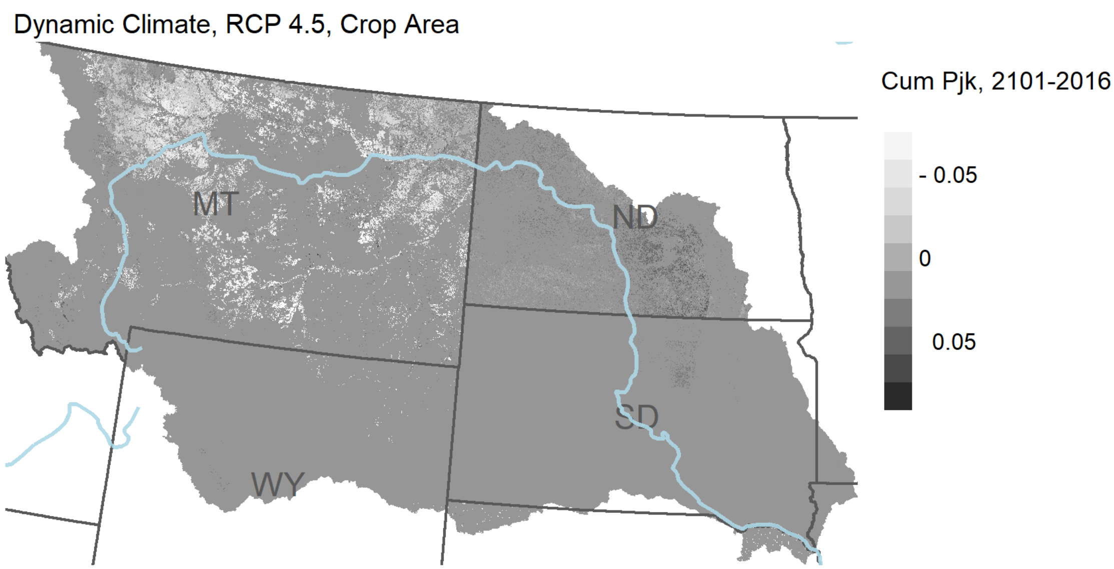


Figure 11, bottom). This follows regional averages indicating that most new grassland and shrubland transitions out of crop areas (Table 5 above).



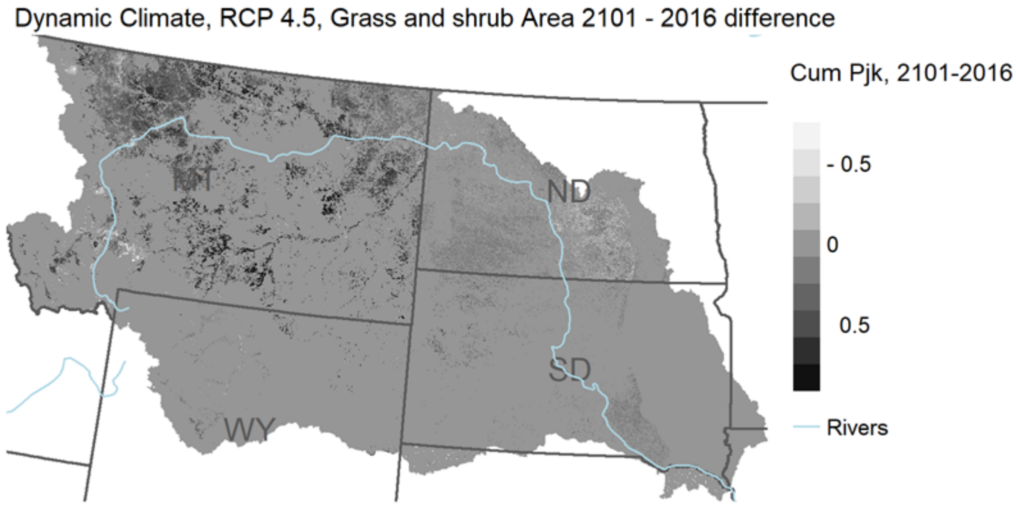


Figure 11. Spatial distribution of the difference in cumulative probability of parcels ending in crop (top) and grassland and shrubland area (bottom) over the study period (2016 to 2101).

iii. Bioenergy implications

What are the climate implications for future agricultural biofuel production across the region? Changes in crop area can be interpreted in terms of first-generation bioenergy feedstock production. We translate crop area into biofuel production using 2016 yield and fuel use proportions for corn and soy (see Appendix D: Bioenergy Conversion Calculations). (Since there is no second-generation bioenergy production on base no-policy pasture/hay acres, all climate implications are in terms of first-generation biofuel.) Potential first-generation bioenergy production can be described in terms of production land area, gallons of biofuel, as well as total energy content (Table 6).

Table 6. First-generation bioenergy potential

RCP **Climate scenario** Year	Total crop area (acres)	First-gen biofuel prod. area (acres)	Corn ethanol potential (gal)	Soy biodiesel potential (gal)	First-gen energy potential (trillion BTU)
RCP 4.5 - less GHG mitigation					
Static climate					
2016	34,014,166	4,343,609	1,142,037,860	20,877,895	98
2101	31,698,524	4,047,901	1,064,289,343	19,456,554	91
Change (2101 - 2016)	-2,315,642 -6.8%	-295,707	-77,748,517	-1,421,341	-7
Dynamic climate					
2016	34,014,166	4,343,609	1,142,037,860	20,877,895	98
2101	30,251,951	3,863,174	1,015,720,139	18,568,647	87
Change (2101 - 2016)	-3,762,215 -11.1%	-480,435	-126,317,722	-2,309,248	-11

RCP 2.6 - more GHG mitigation					
Static climate					
2016	33,965,617	4,337,409	1,140,407,824	20,848,096	98
2101	31,419,588	4,012,281	1,054,923,980	19,285,343	90
Change (2101 - 2016)	-2,546,029 -7.5%	-325,128	-85,483,844	-1,562,753	-8
Dynamic climate					
2016	33,965,617	4,337,409	1,140,407,824	20,848,096	98
2101	31,985,575	4,084,558	1,073,927,198	19,632,746	92
Change (2101 - 2016)	-1,980,042 -5.8%	-252,851	-66,480,626	-1,215,350	-6

Keeping biofuel crop proportions, yields, and harvest fuel use constant, decreasing crop area across all climate modeling and assumptions translates into less potential first-generation energy production. With a dynamic climate model assuming less GHG mitigation, an 11% decrease in crop area equates to an annual decrease of 11 trillion BTUs from 2016. For some perspective, total US biofuel production was 2,328 trillion BTU in 2019 (EIA 2021b). The spatial distribution of land use change probabilities over the study period (

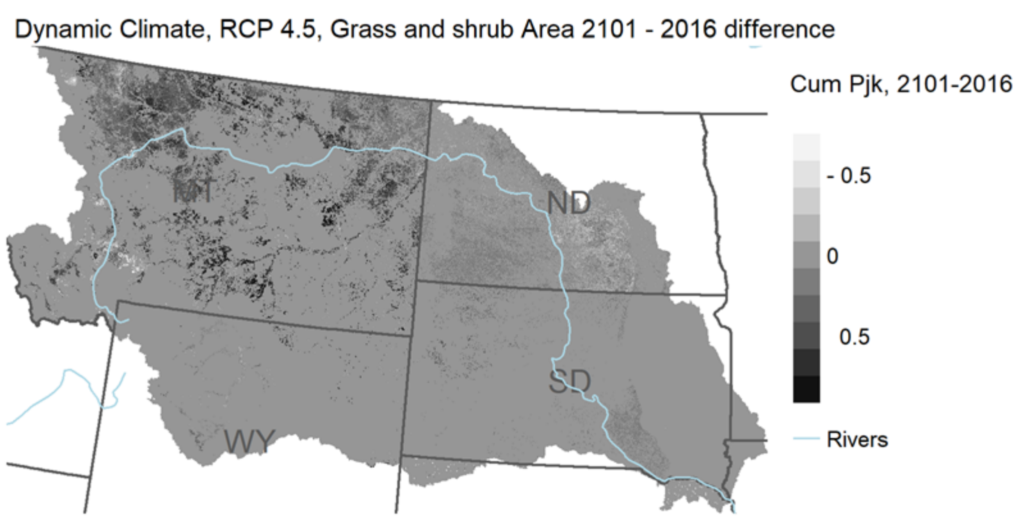


Figure 11 above) inform where area transitioning out of or into crop production with historic links to first-generation bioenergy production are likely to occur.

b. How does an expansion of first-generation bioenergy through different crop price incentives affect land use mix across the UMRB over time?

Two first-generation bioenergy feedstock-incentive policy scenarios investigate land use implications from the expansion of conventional biofuel bioenergy (corn ethanol and soy biodiesel) in the UMRB region. These are implemented as a 5% and 30% increase in relative returns to first-generation crops, as described above in section 2.b.iii.*1st Generation Biofeedstock Scenarios*. We consider policy impacts relative to a dynamic climate under RCP 4.5. This climate pathway is an intermediate stabilizing scenario that assumes a range of technologies for reducing GHG emissions (described above in section 2.b.i.Dynamic IPCC Climate Scenarios).

As a regional county-level average, the per-acre policy cost of a 5% increase in relative returns to crop area is $10 (with a range of $3 to $21). After a 30% increase in relative returns, implemented over 40 years, is reached in 2051, the average per-acre policy cost is $59 (with a range of $20 to $129) (Figure 12, top).

i. Land use area projection

First-generation biofeedstock incentives moderate some of the crop area loss observed in the dynamic climate base (RCP 4.5) (Figure 12, center). With a 5% increase in relative returns to first-generation biofeedstocks, regional crop area in 2101 is 30.4 and with a 30% increase in relative biofeedstock returns crop area is 31.0 million acres—relative to 30.3 million acres observed in the no-policy base (Table 7, column 1, Figure 12, center).

Viewed as a difference from land use changes under the no-policy base, a 5% increase in relative returns to first-generation biofeedstock results in an additional 116,219 acres of crop area over the projected timeframe with corresponding decreases in grass and shrubland (-102,986 acres), pasture and hay (-11,856 acres), and urban area (-1,374 acres). With a 30% incentive policy crop area increases by 739,663 acres by 2101, with corresponding decreases in grass and shrubland (-619,962 acres) and to a lesser extent pasture and hay area (-112,194), as well as some urban area (-7,508 acres) (Figure 12, bottom; Table 7, column 3).

As a percentage of total modeled land area across the UMRB region, these land use area changes are modest. The highest bump in crop area, resulting from a 30% incentive, results in less than 1% increase in crop area relative to an overall 3.5% decrease in crop area observed in the no-policy base (Table 7, columns 5 and 6).

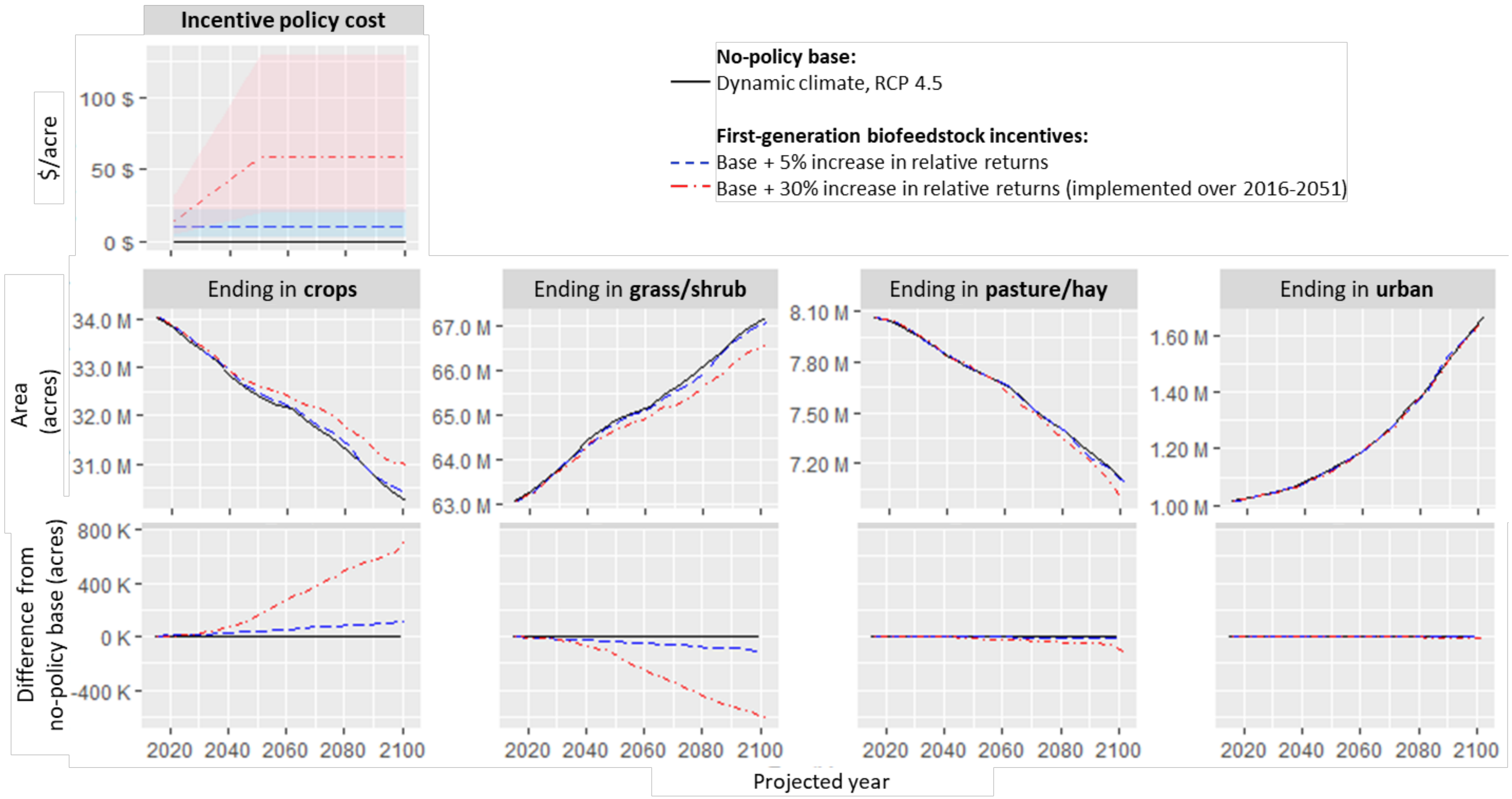


Figure 12. First-generation policy incentive cost (mean, min, max), projected cumulative land use area, and area difference from no-policy base (dynamic climate, RCP 4.5)

Table 7. Land use area change (2016 to 2101) no-policy base (dynamic climate, RCP 4.5) plus first-generation policy scenarios

	1	2	3	4	5	6
RCP **Climate, policy scenario** Ending land use	Ending area (acres) 2101	Area change (acres) 2101 - 2016	Area change, difference from no-policy base	Ending use as % of total UMRB area	Area change as % of total UMRB area	Area change as % of total UMRB area, difference from static climate base
RCP 4.5 - less GHG mitigation						
Dynamic climate, no-policy base						
Crops	32,970,872	-4,293,458	0	26.6%	-3.5%	0
Grass and shrub	81,827,534	4,632,487	0	65.9%	3.7%	0
Pasture and hay	7,475,362	-1,052,297	0	6.0%	-0.8%	0
Urban	1,829,551	713,267	0	1.5%	0.6%	0
Sum	124,103,320	0	*0*	*1*	*0*	*0*
Dynamic climate, 5% first-generation biofeedstock price incentive						
Crops	33,097,099	-4,167,232	126,226	26.7%	-3.4%	0.1%
Grass and shrub	81,714,946	4,519,898	-112,589	65.8%	3.6%	-0.1%
Pasture and hay	7,463,128	-1,064,531	-12,234	6.0%	-0.9%	0.0%
Urban	1,828,148	711,864	-1,403	1.5%	0.6%	0.0%
Sum	*124,103,320*	*0*	*0*	*1*	*0*	*0*
Dynamic climate, 30% first-generation biofeedstock price incentive						
Crops	33,771,641	-3,492,690	800,768	27.2%	-2.8%	0.6%
Grass and shrub	81,149,891	3,954,843	-677,644	65.4%	3.2%	-0.5%
Pasture and hay	7,359,937	-1,167,722	-115,425	5.9%	-0.9%	-0.1%
Urban	1,821,852	705,568	-7,699	1.5%	0.6%	0.0%
Sum	*124,103,320*	*0*	*0*	*1*	*0*	*0*

ii. Spatial distribution

Where is new crop area resulting from a 30% first-generation biofeedstock price incentive likely to be located on the landscape? Parcel-level cumulative probability of ending in crop in 2101 relative to the base scenario (dynamic climate, RCP 4.5) shows the probability of ending in crop increases for some parcels east of the Missouri River in North and South Dakota as well as parts of Montana (Figure 13).

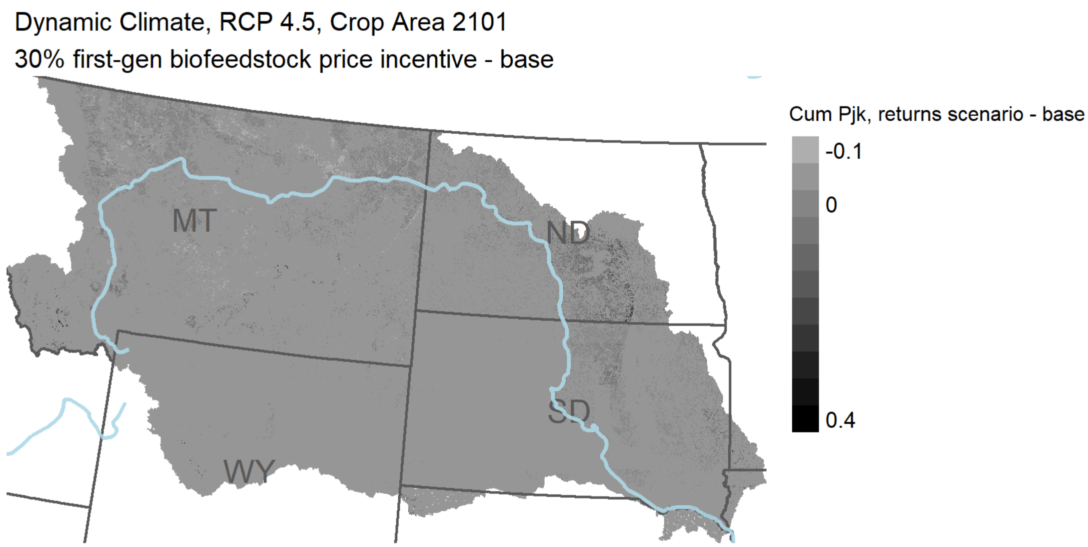


Figure 13. Spatial distribution of the impact of a 30% first-generation biofeedstock price incentive relative to the no-policy base on cumulative probability of parcels ending in crop by 2101

iii. Bioenergy implications

Assumptions used for translating projected changes in pasture/hay area into associated with first-generation bioenergy policy scenarios into bioenergy production are as follows:

> All new crop area in policy scenarios designed to promote first-generation bioenergy crops (e.g., 30% and 5% crop returns incentives) is harvested and used for corn ethanol or soy biodiesel biofuel production following regional historic crop yields and national crop bioenergy use proportions.

Relative to the no-policy base, the increase in crop area in the 30% crop returns incentive scenario indicates a cumulative increase of just under a million acres (800,768) in RCP 4.5 over the projected time period (2016 – 2101) (Table 7). This represents new crop area gained under this policy scenario allocated to new potential first-generation biofuel production. Based on historic regional yields and standard biofuel conversion assumptions (described in Appendix D: Bioenergy Conversion Calculations), this new crop area could produce 83,593,798 bushels of corn, yielding 234,062,635 gallons of

E100 ethanol or 20 trillion BTUs of energy annually. Alternatively, this new crop area could be used to grow 27,118,017 bushels of soybeans, yielding 40,677,025 gallons of biodiesel or 5 trillion BTUs of energy annually.

In the no-policy base scenario, under all climate modeling and mitigation assumptions, crop area decreases over the projected timeframe. In this context, new crop area resulting from first-generation bioenergy incentives mitigates a portion of overall crop area loss. From the no-policy base Dynamic Climate, RCP 4.5, total crop area, including the portion of crops historically allocated to first-generation bioenergy, decrease by 4,293,458 acres, or 3.5% of the total UMRB study area (Table 4, Figure 14). Introducing 30% increase in crop returns by 2051 results in additional 800,768 acres transitioning into crops by 2101, mitigating just under 20% of crop area loss (Figure 14).

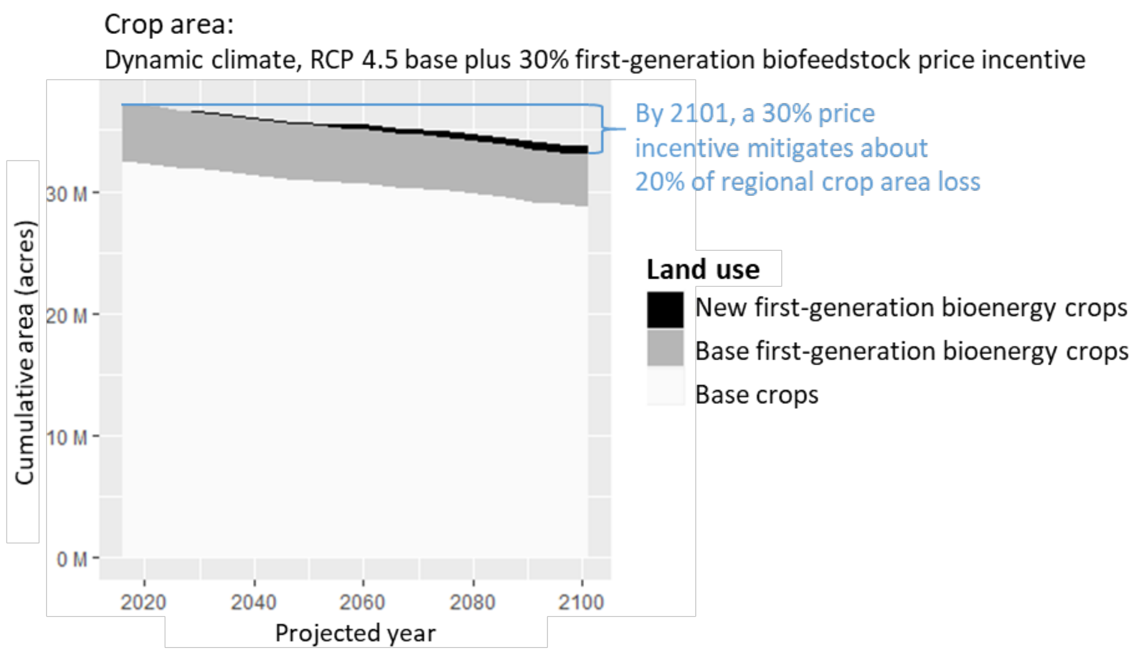


Figure 14. Projected conventional and bioenergy crop area for no-policy base (Dynamic Climate, RCP 4.5) and 30% first-generation biofeedstock incentive policy scenarios

c. How does an expansion of second-generation bioenergy through different pasture/hay price incentives affect land use mix across the UMRB over time?

Two second-generation bioenergy feedstock incentive policy scenarios investigate land use implications from the expansion of dedicated biomass crops (such as switchgrass) in the UMRB region. The policies are implemented as $40 and $80/ton biomass farmgate base prices, assuming annual yield increases of 1%, as described in section 2.b.iv. *2nd Generation Biofeedstock Scenarios***Error! Reference source not found.**. We consider policy impacts relative to a dynamic climate under RCP 4.5. This climate pathway is an intermediate stabilizing scenario that assumes a range of technologies for reducing GHG emissions (as described in section 2.b.i.Dynamic IPCC Climate Scenarios**Error! Reference source not found.**).

As a regional county-level average over the projected timeframe, the policy cost for the $40/ton scenario is $4 per acre of pasture and hay (with a range of $0 to $20); mean per-acre policy cost for the $80/ton scenario is $59 ($17, $114) (Figure 15, top).

i. *Land use area projection*

As seen with first-generation biofeedstock incentives and crop area, second-generation feedstock price incentives moderate pasture and hay area loss observed in the dynamic climate base (described here for RCP 4.5) (Figure 15, center). Under the $40/ton scenario, regional pasture and hay area in 2101 is 7,479,389 acres; with the $80/ton scenario in place 2101 pasture and hay area is 7,770,094 acres—relative to 7,475,362 acres observed in the no-policy base (Table 8, column 1; Figure 14, center).

Viewed as a difference from land use changes under the no-policy base, a $40/ton biomass price incentive results in an additional 4,027 pasture and hay acres over the projected timeframe with corresponding decreases in grass and shrubland (-2,881 acres), crops (-1,135 acres), as well as a small urban area (-10 acres). With the $80/ton scenario, relative to the no-policy base, pasture and hay area increases by 294,732 acres with corresponding decreases in grass and shrubland (-253,093 acres), crops (-26,404 acres), as well as some urban area (-15,234 acres) (Figure 15, bottom; Table 8, column 3).

As a percentage of total regional modeled land area, land use changes associated with $40/ton and $80/ton biomass base price incentives are modest. The highest bump in pasture and hay area, resulting from a $80/ton base price incentive, results in less than a quarter percent increase in pasture and hay area relative to an overall 0.8% decrease in pasture and hay area observed in the no-policy base (Table 8, columns 5 and 6)

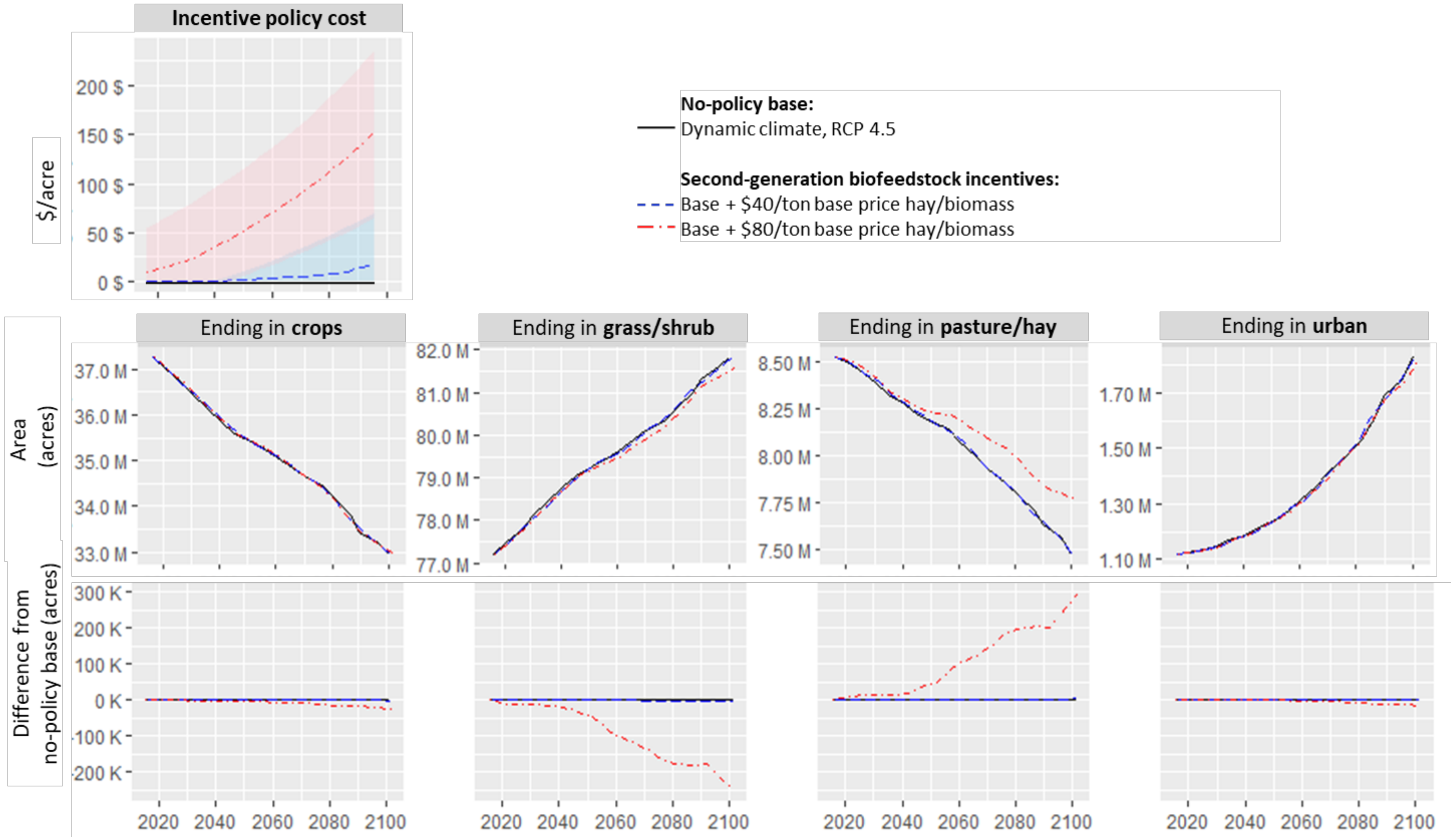


Figure 15. Second-generation policy incentive: cost (min, mean, max) (top), projected cumulative land use area (center), and area difference from no-policy base (dynamic climate, RCP 4.5) (bottom)

Table 8. Land use area change (2016 to 2101) no-policy base (dynamic climate, RCP 4.5) plus second-generation policy scenarios

	1	2	3	4	5	6
RCP **Climate, policy scenario** Ending land use	Ending area (acres) 2101	Area change (acres) 2101 - 2016	Area change, difference from no-policy base	Ending use as % of total UMRB area	Area change as % of total UMRB area	Area change as % of total UMRB area, difference from static climate base
RCP 4.5 - less GHG mitigation						
Dynamic climate, no-policy base						
Crops	32,970,872	-4,293,458	0	26.6%	-3.5%	0
Grass and shrub	81,827,534	4,632,487	0	65.9%	3.7%	0
Pasture and hay	**7,475,362**	-1,052,297	0	6.0%	-0.8%	0
Urban	1,829,551	713,267	0	1.5%	0.6%	0
Sum	124,103,320	0	*0*	*1*	*0*	*0*
Dynamic climate, $40/ton second-generation biofeedstock base price						
Crops	32,969,737	-4,294,593	-1,135	26.6%	-3.5%	-0.001%
Grass and shrub	81,824,653	4,629,606	-2,881	65.9%	3.7%	-0.002%
Pasture and hay	**7,479,389**	-1,048,270	4,027	6.0%	-0.8%	0.003%
Urban	1,829,541	713,257	-10	1.5%	0.6%	0.000%
Sum	*124,103,320*	*0*	*0*	*1*	*0*	*0*
Dynamic climate, $80/ton second-generation biofeedstock base price						
Crops	32,944,468	-4,319,862	-26,404	26.5%	-3.5%	-0.021%
Grass and shrub	81,574,441	4,379,394	-253,093	65.7%	3.5%	-0.204%
Pasture and hay	**7,770,094**	-757,565	294,732	6.3%	-0.6%	0.237%
Urban	1,814,317	698,033	-15,234	1.5%	0.6%	-0.012%
Sum	*124,103,320*	*0*	*0*	*1*	*0*	*0*

ii. Spatial distribution

Parcel-level cumulative probability of ending in pasture and hay in 2101 with a second-generation policy scenario relative to the base no-policy scenario (dynamic climate, RCP 4.5) allows mapping of where on the landscape new dedicated bioenergy is likely to be grown. Second-generation high price incentive ($80/ton) incentivizes new pasture and hay in areas of southeastern Montana (Figure 16).

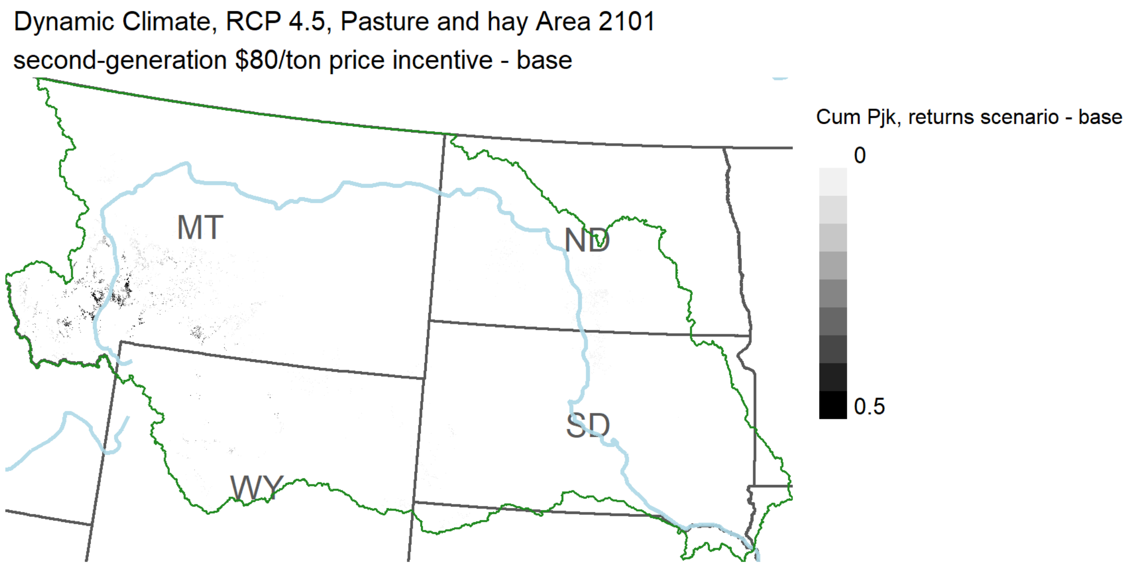


Figure 16. Spatial distribution of the impact of a $80/ton second-generation biomass base price incentive relative to the no-policy base on cumulative probability of parcels ending in pasture and hay by 2101

iii. Bioenergy implications

Assumptions used for translating projected changes in pasture/hay area into associated with second-generation bioenergy policy scenarios into bioenergy production are as follows:

> All new pasture/hay area in policy scenarios designed to promote second-generation bioenergy crops (e.g., base price Hay $80/ton, Hay $40/ton) is harvested and used for bioenergy production–either for cellulosic ethanol or converted into electricity.

Relative to the no-policy base (dynamic climate, RCP 4.5) pasture and hay area with the $80/ton second-generation incentive scenario results in a cumulative increase of 294,732 acres over the projected time period (2016 – 2101) (Table 8). This represents new area gained under this policy scenario allocated to second-generation bioenergy production. Based on regional yield estimates for switchgrass and standard second-generation bioenergy conversion assumptions (described in Appendix D: Bioenergy Conversion Calculations), by 2101 this new pasture and hay area could produce

1,136,782 tons of biomass, yielding 113,678,154 gallons of cellulosic E100 ethanol or 10 trillion BTUs of energy annually. Alternatively, used to produce biomass electricity at current best energy conversion rates this new pasture and hay area could produce 5 trillion BTUs of energy annually.

In all no-policy base scenarios (dynamic and static climate modeling under RCP 2.6 and 4.5), regional pasture and hay area declines over the projected time period (2016-2101). In this context, new pasture and hay area resulting from second-generation bioenergy incentives mitigates a portion of overall pasture and hay area loss. From the no-policy base Dynamic Climate, RCP 4.5, total pasture and hay area decreases by -1,052,297 acres, or 0.8% of the total UMRB study area (Table 8, Figure 15). Introducing an $80/ton biomass incentive along with a 1% increase in dedicated bioenergy crop yields results in an additional 294,732 acres transitioning into pasture and hay by 2021, mitigating 28% of regional pasture and hay area loss under the no-policy base (Figure 17).

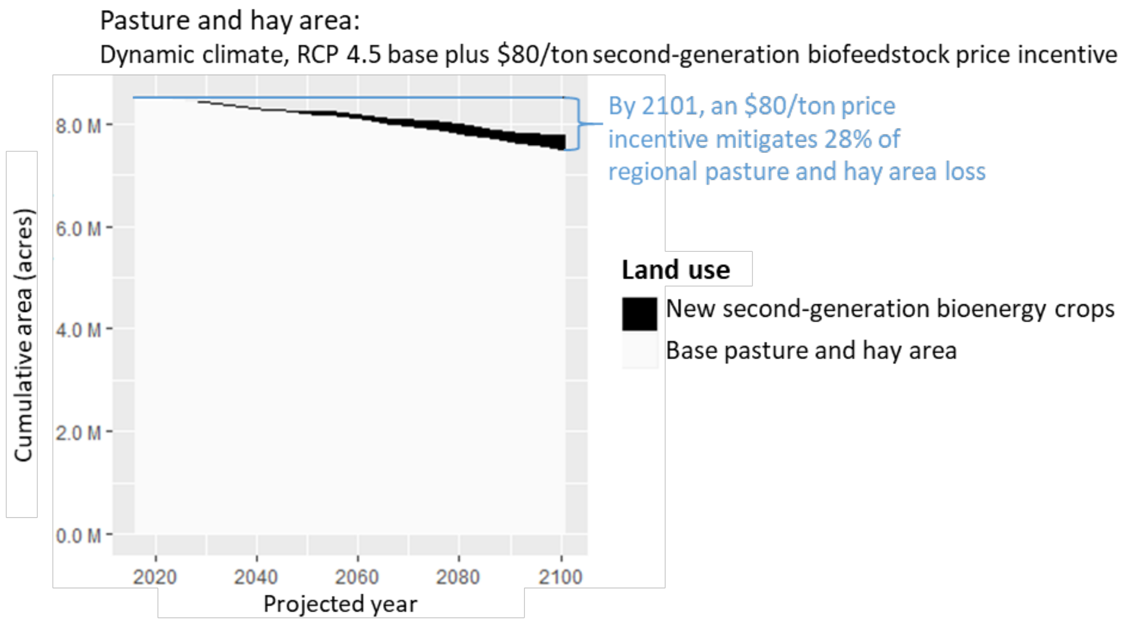


Figure 17. Projected pasture and hay area for no-policy base (Dynamic Climate, RCP 4.5) and $80/ton second-generation biofeedstock incentive policy scenarios

d. How do first- and second-generation bioenergy incentives compare in terms of energy production and policy cost?

i. Converting New Bioenergy Production Area to Biofeedstock and Bioenergy

Following historic regional crop mix and yields, national domestic crop use for fuel (versus feed/food), and standard energy conversion rates (detailed in detailed in

Appendix D: Bioenergy Conversion Calculations), changes in crop and pasture/hay area can be converted to first- and second-generation bioenergy potential, respectively. Energy measures are gross energy after feedstock conversion to biofuel or biopower, they do not net out energy used in agricultural production or transportation.

On a per-acre basis, in terms of gross energy production, new crop and pasture acres used for corn and cellulosic ethanol production are the most efficient, followed by using pasture for biomass electric production (Figure 18).

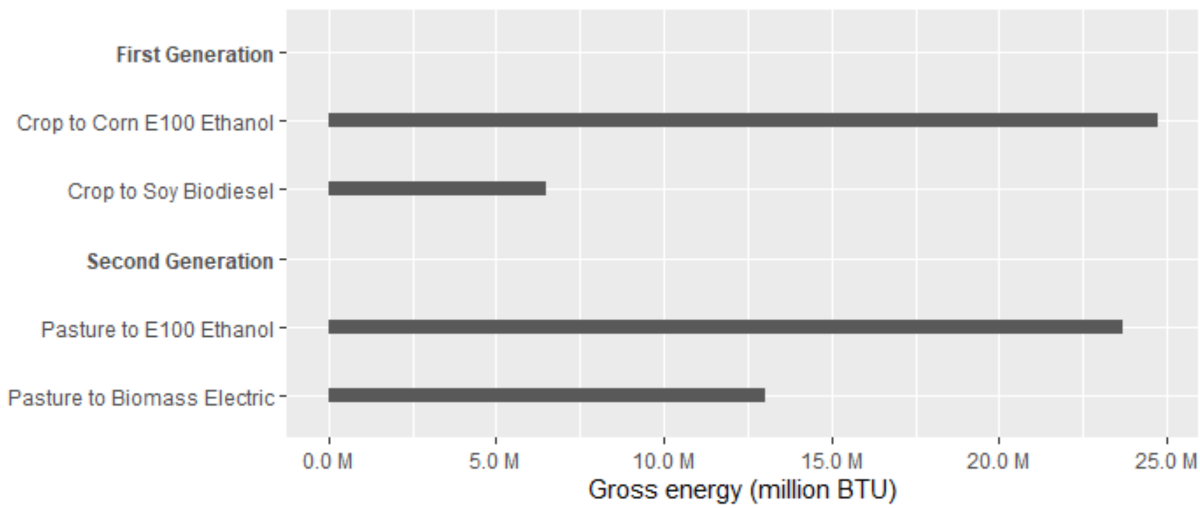


Figure 18. Bioenergy potential per acre of UMRB crop and pasture/hay land based on historic crop proportion, yield, fuel use, and standard energy conversions

Both first-generation corn and second-generation biomass converted to ethanol biofuel have the potential to produce just under 25 million BTUs per acre. In addition, corn ethanol produces important byproducts used in animal feed that are not accounted for here.

First-generation soybeans converted to biodiesel are far less productive in terms of energy conversion both because of lower regional average yields per acre (104 BU/Acre for corn and 34 BU/Acre for soybeans) as well as lower biofuel conversion rates per bushel (2.8 gal E100 ethanol/BU corn; 1.5 gal biodiesel/BU soybeans). Soy diesel has a low per-acre productivity as only a portion of the harvest (soy oil) is used for energy, with soy meal going primarily to animal feed.

The gap between second-generation biomass converted to ethanol biofuel versus electricity is the result of conversion efficiency. Using current technology for biomass-to-electricity conversion is at best 30% efficient.

e. What are the projections for grass and shrublands (native habitats that have ecosystem service implications) associated with different climate and policy assumptions?

Grass and shrubland projections under different climate and policy scenarios with implications for native habitat and ecosystem services.

The LULC model projects plot-level changes in land transitioning into and out of grass and shrubland under different climate and biofeedstock policy assumptions.

i. Climate projection impacts

The LULC model is estimated using both static historic climate averages and a projected dynamic climate under two climate change mitigation assumptions, allowing a comparison of how projected climate assumptions impact land use mix across the UMRB, focusing on native grass and shrubland.

Grass and shrub area increases across the UMRB region under all climate models and assumptions (see Figure 10 above). Over the region, grass and shrub area increase generally mirrors crop area decline. This trend is most pronounced when climate is modeled as dynamic under RCP 4.5. Compared to relatively more GHG emission mitigation in RCP 2.6, X new acres of grass and shrublands have transitioned out of crop, pasture, and urban area by 2101 in RCP 4.5 (add reference to this data). This suggests that changes in projected climate that are more pronounced under RCP 4.5, including increasing winter precipitation and winter precipitation variability, increasing growing season and winter temperatures, and increasing dryness (annual mean temperature/precipitation) (Appendix B, Figures B1 and B2) favor grass and shrubland cover and use.

Add description of (Table 9).

Table 9. Starting land uses ending in grass/shrub (acres, 2101) modeled with static and dynamic climate under different GHG mitigation assumptions

Starting use	**Ending in Grass and shrub** Ending area, 2101 (acres)	Area change (2016 - 2101)	% area change	Area change as % of total UMRB area
RCP 4.5 - less GHG mitigation				
Static climate				
Crops	5,007,866	4,527,741	6%	4%
Grass and shrub	73,450,482	-3,155,536	92%	-3%
Pasture and hay	1,221,013	1,112,108	2%	1%
Urban	0	0	0%	0%
End use sum	*79,679,361*	*2,484,313*	*100%*	*2%*
Dynamic climate				
Crops	6,093,444	5,613,319	7%	5%
Grass and shrub	74,544,695	-2,061,323	91%	-2%
Pasture and hay	1,189,396	1,080,491	1%	1%
Urban	0	0	0%	0%
End use sum	*81,827,534*	*4,632,487*	*100%*	*4%*
RCP 2.6 - more GHG mitigation				
Static climate				
Crops	5,300,083	4,765,596	7%	4%
Grass and shrub	73,340,648	-3,267,924	92%	-3%
Pasture and hay	1,228,042	1,119,969	2%	1%
Urban	0	0	0%	0%
End use sum	*79,868,773*	*2,617,641*	*100%*	*2%*
Dynamic climate				
Crops	4,855,121	4,320,634	6%	3%
Grass and shrub	73,588,297	-3,020,275	92%	-2%
Pasture and hay	1,281,745	1,173,672	2%	1%
Urban	0	0	0%	0%
End use sum	*79,725,163*	*2,474,031*	*100%*	*2%*

The spatial distribution of the probability of area transitioning into our out of native grass and shrubland area mapped at the plot level over the study period (2016 to 2101 difference) for the dynamic, RCP 4.5 climate scenario where the most grass/shrub area increase is seen regionally indicates that transitions into grass and shrub (darker areas) are more likely to occur in northwestern portions of the UMRB region (Figure 19. Spatial distribution of the difference in cumulative probability of parcels ending in grassland and shrubland area over the study period (2016 to 2101) with dynamic climate modeling under GHG mitigation assumptions RCP 4.5, top). Moderate grass and shrubland losses (lighter areas) are more likely to occur east of the Missouri river in North Dakota (Figure 19). A dynamic climate under RCP 2.6, where the least grass and shrubland area increase is observed regionally, shows a similar pattern of spatial distribution.

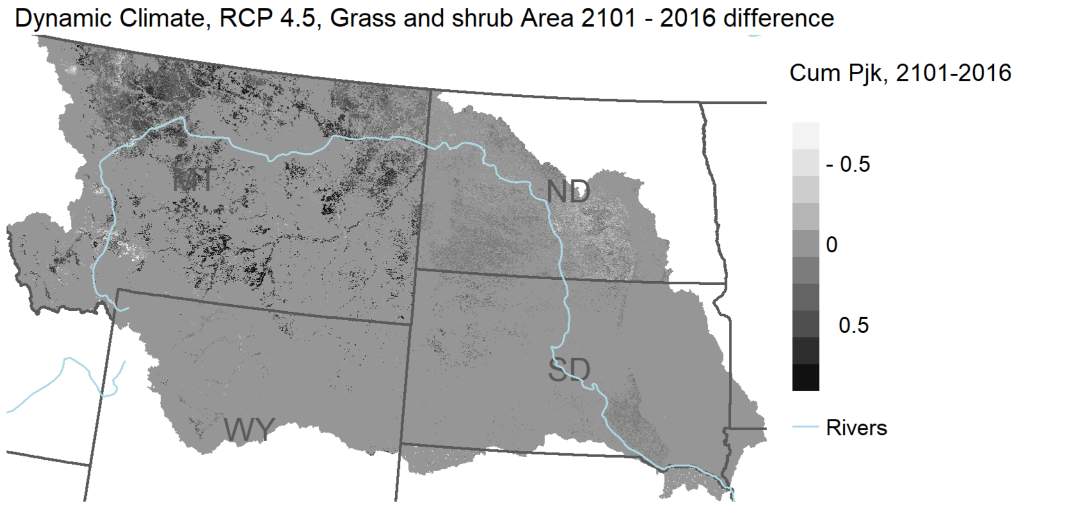


Figure 19. Spatial distribution of the difference in cumulative probability of parcels ending in grassland and shrubland area over the study period (2016 to 2101) with dynamic climate modeling under GHG mitigation assumptions RCP 4.5

Add description of figs. 20 and 21.

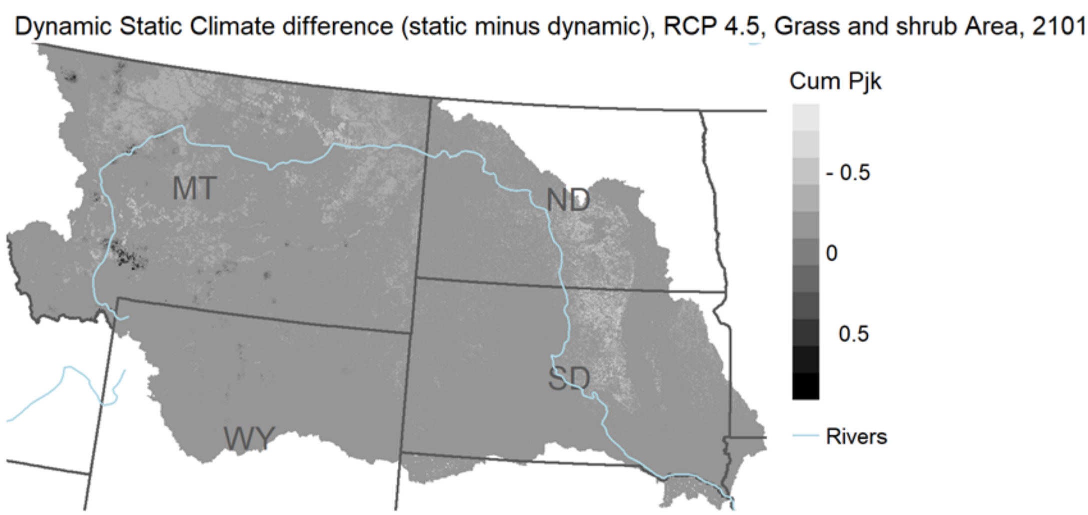


Figure 20. Spatial distribution of grass and shrubland area cumulative probabilities showing the impact of climate modeling. Relative to static, a dynamic climate results in less grass and shrub area east and north of the Missouri River (lighter areas) and relatively more grass and shrub (darker areas) in areas of western Montana.

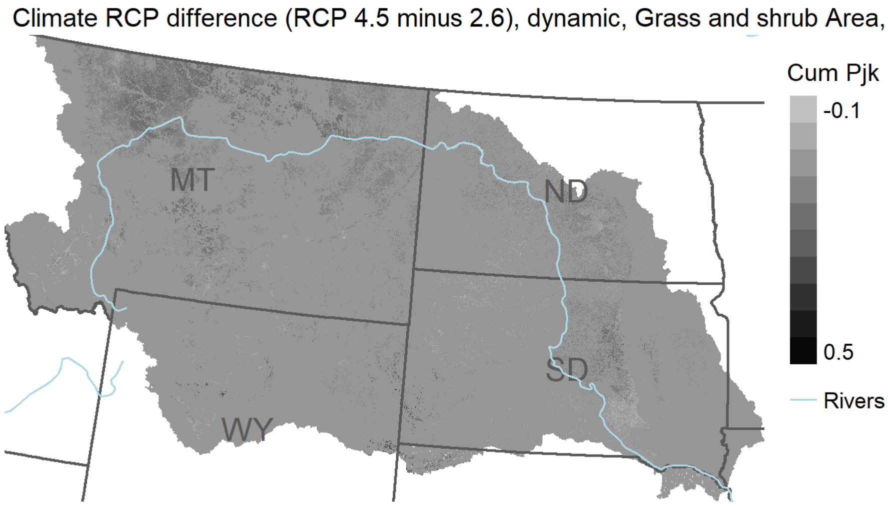


Figure 21. Spatial distribution of grass and shrub—difference between RCP 4.5 and 2.6.

ii. Biofeedstock policy scenario impacts

What is the impact of biofeedstock production incentives on native grass and shrublands in the UMRB region relative to a no-policy base that projects land use responses to climate? As above, we use dynamic climate, RCP 4.5 as the no-policy base, both because this climate scenario results in the greatest increase in grass and shrubland and because the RCP 4.5 is a more realistic GHG mitigation pathway. Further, we consider each of the higher first- and second-generation biofeedstock incentive scenarios: 30% increase in crop returns and $80/ton biomass with 1% annual yield, respectively.

Relative to the no-policy base, as expected, the first-generation biofeedstock incentive results in less area ending in grass and shrubland overall (-677,644 acres by 2101, accounting for 0.6% of the total UMRB area) The second-generation biofeedstock incentive results in 253,093 fewer grass and shrub acres in 2101 relative to the no-policy base, 0.2% of total UMRB area. (

Table 10).

Table 10. Starting land uses ending in grass/shrub (acres, 2101), no-policy base (dynamic climate, RCP 4.5) and first-and second-generation biofeedstock incentives

	Ending in grass and shrub			
Starting use	Ending area, 2101 (acres)	Area change (2016 - 2101)	Difference from no-policy base	Difference as % of total UMRB region
RCP 4.5 - less GHG mitigation				
Dynamic climate - no-policy base				
Crops	6,093,444	5,613,319	0	0%
Grass and shrub	74,544,695	-2,061,323	0	0%
Pasture and hay	1,189,396	1,080,491	0	0%
Urban	0	0	0	0%
End use sum	*81,827,534*	*4,632,487*	*0*	*0*
First-generation biofeedstock incentive: 30% increase in crop returns				
Crops	5,989,019	4,765,596	-104,425	-0.08%
Grass and shrub	73,987,743	-3,267,924	-556,952	-0.45%
Pasture and hay	1,173,130	1,119,969	-16,266	-0.01%
Urban	0	0	0	0.00%
End use sum	*81,149,891*	*2,617,641*	*-677,644*	*-0.55%*
Second-generation biofeedstock incentive: $80/ton biomass price + 1% yield increase				
Crops	6,078,939	4,320,634	-14,504	-0.01%
Grass and shrub	74,342,204	-3,020,275	-202,490	-0.16%
Pasture and hay	1,153,297	1,173,672	-36,099	-0.03%
Urban	0	0	0	0.00%
End use sum	*81,574,441*	*2,474,031*	*-253,093*	*-0.20%*

Add description of spatial distribution (Figure 22, top). (Figure 22, bottom).

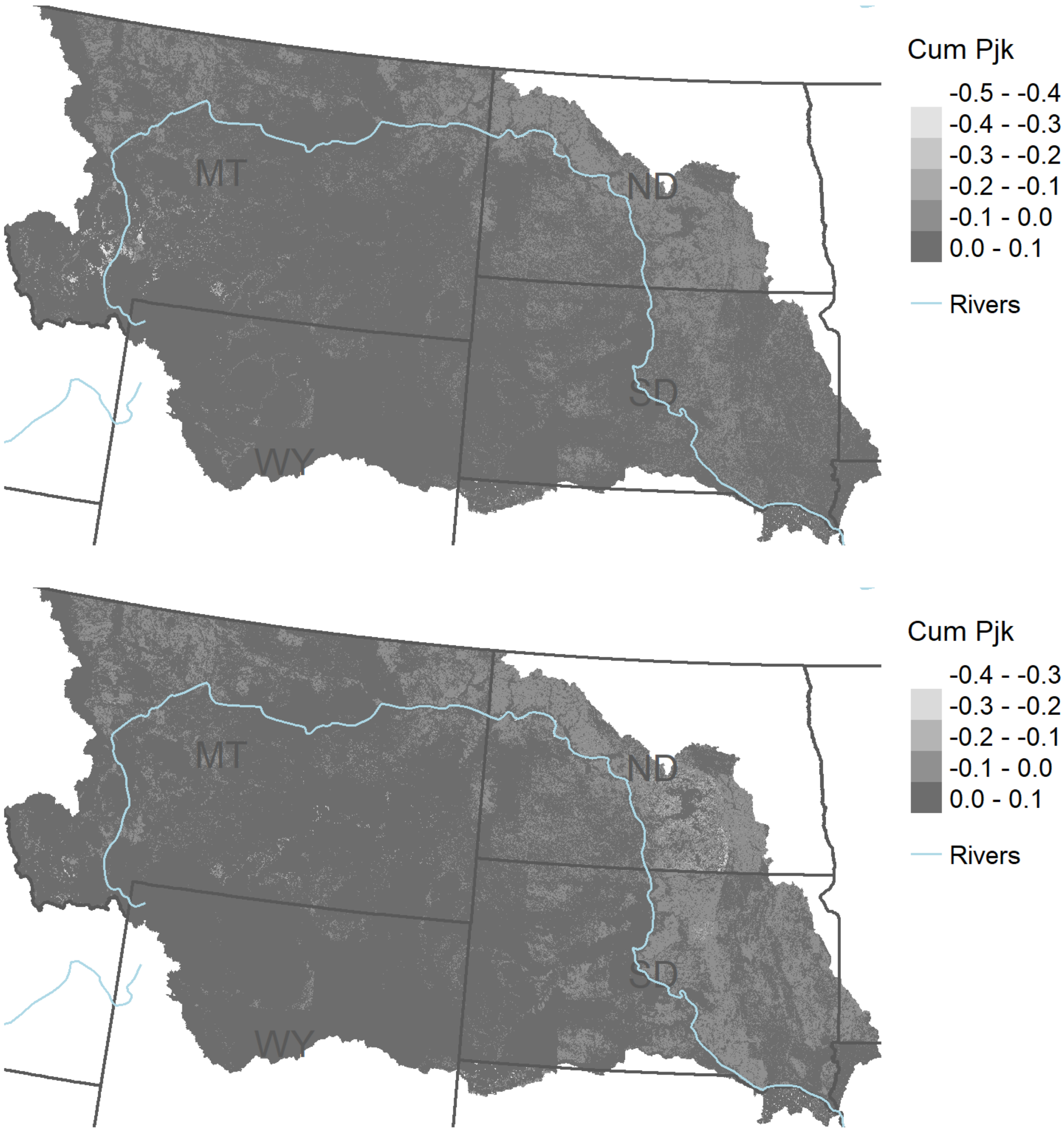


Figure 22. Spatial distribution of the impact of a first-generation 30% increase in crop returns incentive (top) and second-generation $80/ton plus 1% yield incentive (bottom) relative to the no-policy base on cumulative probability of parcels ending in grass and shrub by 2101

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APPENDIX A: GEOGRAPHIC DIVISIONS

Table A1. Federal Information Processing Standards Codes for LULC Change Modeling in the Upper Missouri River Basin

State Name	County Name	FIPS
IOWA	LYON	19119
IOWA	O BRIEN	19141
IOWA	OSCEOLA	19143
IOWA	PLYMOUTH	19149
IOWA	SIOUX	19167
IOWA	WOODBURY	19193
IDAHO	CLARK	16033
IDAHO	FREMONT	16043
IDAHO	LEMHI	16059
MINNESOTA	LINCOLN	27081
MINNESOTA	MURRAY	27101
MINNESOTA	NOBLES	27105
MINNESOTA	PIPESTONE	27117
MINNESOTA	ROCK	27133
MONTANA	BEAVERHEAD	30001
MONTANA	BIG HORN	30003
MONTANA	BLAINE	30005
MONTANA	BROADWATER	30007
MONTANA	CARBON	30009
MONTANA	CARTER	30011
MONTANA	CASCADE	30013
MONTANA	CHOUTEAU	30015
MONTANA	CUSTER	30017
MONTANA	DANIELS	30019
MONTANA	DAWSON	30021
MONTANA	DEER LODGE	30023
MONTANA	FALLON	30025
MONTANA	FERGUS	30027
MONTANA	FLATHEAD	30029
MONTANA	GALLATIN	30031
MONTANA	GARFIELD	30033
MONTANA	GLACIER	30035
MONTANA	GOLDEN VALLEY	30037
MONTANA	GRANITE	30039
MONTANA	HILL	30041
MONTANA	JEFFERSON	30043
MONTANA	JUDITH BASIN	30045

State Name	County Name	FIPS
MONTANA	LEWIS AND CLARK	30049
MONTANA	LIBERTY	30051
MONTANA	MADISON	30057
MONTANA	MCCONE	30055
MONTANA	MEAGHER	30059
MONTANA	MUSSELSHELL	30065
MONTANA	PARK	30067
MONTANA	PETROLEUM	30069
MONTANA	PHILLIPS	30071
MONTANA	PONDERA	30073
MONTANA	POWDER RIVER	30075
MONTANA	POWELL	30077
MONTANA	PRAIRIE	30079
MONTANA	RAVALLI	30081
MONTANA	RICHLAND	30083
MONTANA	ROOSEVELT	30085
MONTANA	ROSEBUD	30087
MONTANA	SHERIDAN	30091
MONTANA	SILVER BOW	30093
MONTANA	STILLWATER	30095
MONTANA	SWEET GRASS	30097
MONTANA	TETON	30099
MONTANA	TOOLE	30101
MONTANA	TREASURE	30103
MONTANA	VALLEY	30105
MONTANA	WHEATLAND	30107
MONTANA	WIBAUX	30109
MONTANA	YELLOWSTONE	30111
N. DAKOTA	ADAMS	38001
N. DAKOTA	BARNES	38003
N. DAKOTA	BILLINGS	38007
N. DAKOTA	BOWMAN	38011
N. DAKOTA	BURKE	38013
N. DAKOTA	BURLEIGH	38015
N. DAKOTA	DICKEY	38021
N. DAKOTA	DIVIDE	38023
N. DAKOTA	DUNN	38025

State Name	County Name	FIPS
N. DAKOTA	EDDY	38027
N. DAKOTA	EMMONS	38029
N. DAKOTA	FOSTER	38031
N. DAKOTA	GOLDEN VALLEY	38033
N. DAKOTA	GRANT	38037
N. DAKOTA	HETTINGER	38041
N. DAKOTA	KIDDER	38043
N. DAKOTA	LA MOURE	38045
N. DAKOTA	LOGAN	38047
N. DAKOTA	MCHENRY	38049
N. DAKOTA	MCINTOSH	38051
N. DAKOTA	MCKENZIE	38053
N. DAKOTA	MCLEAN	38055
N. DAKOTA	MERCER	38057
N. DAKOTA	MORTON	38059
N. DAKOTA	MOUNTRAIL	38061
N. DAKOTA	OLIVER	38065
N. DAKOTA	RANSOM	38073
N. DAKOTA	SARGENT	38081
N. DAKOTA	SHERIDAN	38083
N. DAKOTA	SIOUX	38085
N. DAKOTA	SLOPE	38087
N. DAKOTA	STARK	38089
N. DAKOTA	STUTSMAN	38093
N. DAKOTA	WARD	38101
N. DAKOTA	WELLS	38103
N. DAKOTA	WILLIAMS	38105
NEBRASKA	ANTELOPE	31003
NEBRASKA	BOYD	31015
NEBRASKA	CEDAR	31027
NEBRASKA	CHERRY	31031
NEBRASKA	DAKOTA	31043
NEBRASKA	DAWES	31045
NEBRASKA	DIXON	31051
NEBRASKA	KNOX	31107
NEBRASKA	PIERCE	31139
NEBRASKA	SHERIDAN	31161
NEBRASKA	SIOUX	31165
S. DAKOTA	AURORA	46003
S. DAKOTA	BEADLE	46005
S. DAKOTA	BENNETT	46007

State Name	County Name	FIPS
S. DAKOTA	BON HOMME	46009
S. DAKOTA	BROOKINGS	46011
S. DAKOTA	BROWN	46013
S. DAKOTA	BRULE	46015
S. DAKOTA	BUFFALO	46017
S. DAKOTA	BUTTE	46019
S. DAKOTA	CAMPBELL	46021
S. DAKOTA	CHARLES MIX	46023
S. DAKOTA	CLARK	46025
S. DAKOTA	CLAY	46027
S. DAKOTA	CODINGTON	46029
S. DAKOTA	CORSON	46031
S. DAKOTA	CUSTER	46033
S. DAKOTA	DAVISON	46035
S. DAKOTA	DAY	46037
S. DAKOTA	DEUEL	46039
S. DAKOTA	DEWEY	46041
S. DAKOTA	DOUGLAS	46043
S. DAKOTA	EDMUNDS	46045
S. DAKOTA	FALL RIVER	46047
S. DAKOTA	FAULK	46049
S. DAKOTA	GRANT	46051
S. DAKOTA	GREGORY	46053
S. DAKOTA	HAAKON	46055
S. DAKOTA	HAMLIN	46057
S. DAKOTA	HAND	46059
S. DAKOTA	HANSON	46061
S. DAKOTA	HARDING	46063
S. DAKOTA	HUGHES	46065
S. DAKOTA	HUTCHINSON	46067
S. DAKOTA	HYDE	46069
S. DAKOTA	JACKSON	46071
S. DAKOTA	JERAULD	46073
S. DAKOTA	JONES	46075
S. DAKOTA	KINGSBURY	46077
S. DAKOTA	LAKE	46079
S. DAKOTA	LAWRENCE	46081
S. DAKOTA	LINCOLN	46083
S. DAKOTA	LYMAN	46085
S. DAKOTA	MARSHALL	46091
S. DAKOTA	MCCOOK	46087
S. DAKOTA	MCPHERSON	46089

State Name	County Name	FIPS
S. DAKOTA	MEADE	46093
S. DAKOTA	MELLETTE	46095
S. DAKOTA	MINER	46097
S. DAKOTA	MINNEHAHA	46099
S. DAKOTA	MOODY	46101
S. DAKOTA	OGLALLAKOTA[a]	46102
S. DAKOTA	PENNINGTON	46103
S. DAKOTA	PERKINS	46105
S. DAKOTA	POTTER	46107
S. DAKOTA	ROBERTS	46109
S. DAKOTA	SANBORN	46111
S. DAKOTA	SPINK	46115
S. DAKOTA	STANLEY	46117
S. DAKOTA	SULLY	46119
S. DAKOTA	TODD	46121
S. DAKOTA	TRIPP	46123
S. DAKOTA	TURNER	46125
S. DAKOTA	UNION	46127
S. DAKOTA	WALWORTH	46129
S. DAKOTA	YANKTON	46135
S. DAKOTA	ZIEBACH	46137
WYOMING	BIG HORN	56003
WYOMING	CAMPBELL	56005
WYOMING	CONVERSE	56009
WYOMING	CROOK	56011
WYOMING	FREMONT	56013
WYOMING	HOT SPRINGS	56017
WYOMING	JOHNSON	56019
WYOMING	NATRONA	56025
WYOMING	NIOBRARA	56027
WYOMING	PARK	56029
WYOMING	SHERIDAN	56033
WYOMING	SUBLETTE	56035
WYOMING	TETON	56039
WYOMING	WASHAKIE	56043
WYOMING	WESTON	56045

[a] Oglala Lakota County, SD is listed as Shannon County prior to 2016.

APPENDIX B: CLIMATE DRIVERS

Table B1. GCMs included in climate ensembles

RCP 2.6			
HadGEM2-AO	MPI-ESM-LR	BNU-ESM	FIO-ESM
HadGEM2-ES	MPI-ESM-MR	CanESM2	GFDL-CM3
IPSL-CM5A-LR	MRI-CGCM3	CESM1-CAM5	GISS-E2-H
IPSL-CM5A-MR	NorESM1-M	CNRM-CM5	GISS-E2-R
MIROC5	NorESM1-ME	CSIRO-Mk3-6-0	
MIROC-ESM	bcc-csm1-1	EC-EARTH	
MIROC-ESM-CHEM	bcc-csm1-1m	FGOALS-g2	
RCP 4.5			
ACCESS1-0	CMCC-CM	GISS-E2-H-CC	IPSL-CM5A-MR
ACCESS1-3	CMCC-CMS	GISS-E2-R	IPSL-CM5B-LR
bcc-csm1-1	CNRM-CM5	GISS-E2-R-CC	MIROC5
bcc-csm1-1-m	CSIRO-Mk3-6-0	HadCM3	MIROC-ESM
BNU-ESM	CSIRO-Mk3L-1-2	HadGEM2-AO	MIROC-ESM-CHEM
CanESM2	EC-EARTH	HadGEM2-CC	MPI-ESM-LR
CCSM4	FGOALS-g2	HadGEM2-ES	MPI-ESM-MR
CESM1-BGC	FIO-ESM	inmcm4	MRI-CGCM3
CESM1-CAM5	GISS-E2-H	IPSL-CM5A-LR	

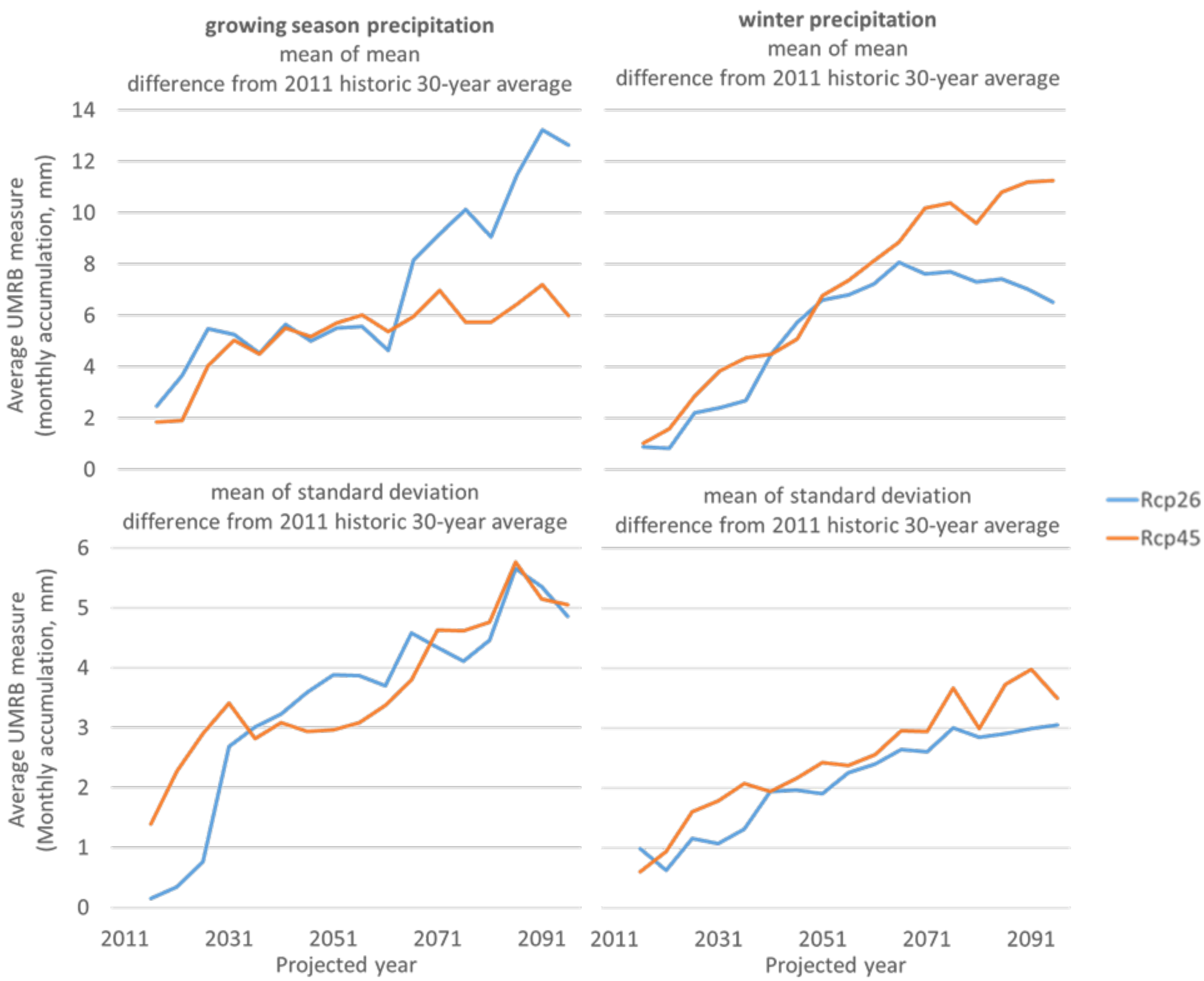

Figure B1. Projected UMRB precipitation measures.

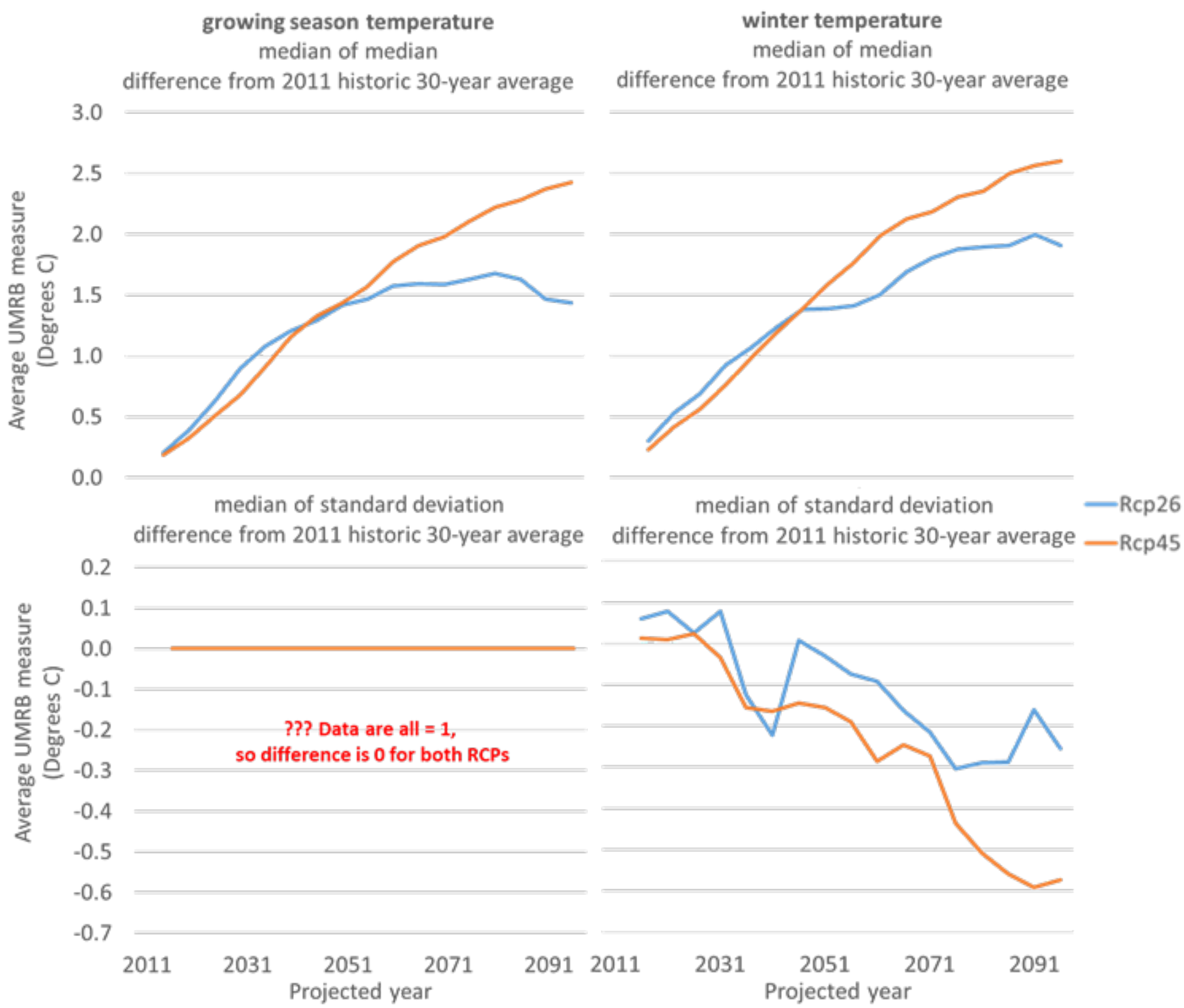

Figure B2. Projected UMRB temperature measures.

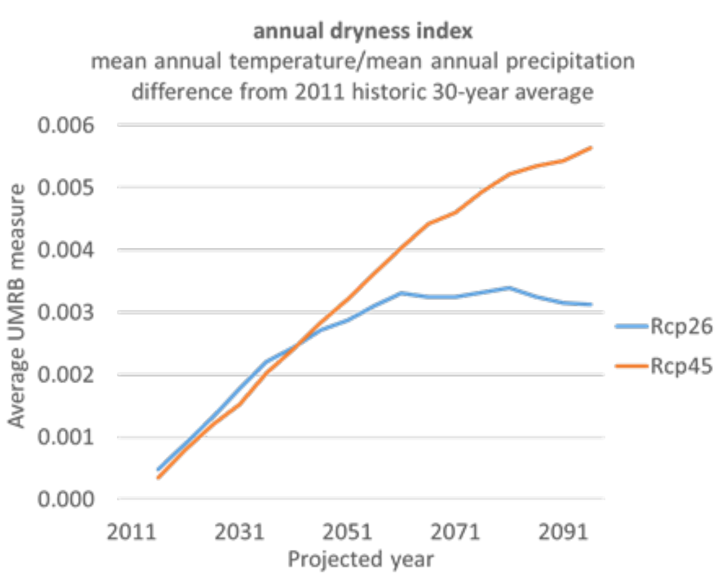

Figure B3. Projected UMRB measure of dryness.

APPENDIX C: PARAMETER ESTIMATES

Note: Tables C1:XC4 are not updated with the most recent (7.2.2021) full sample results

Table C1. Parameter Estimates by Starting Land Use from the Conditional Logit Land Use Change Model

Starting use: Crops								
	Ending use							
Variable	**Crops**		**Grass and shrubland**		**Pasture and hay**		**Urban**	
	estimate [a]	**SE**	**estimate [a]**	**SE**	**estimate [a]**	**SE**	**estimate [a]**	**SE**
(Intercept)	12.014***	1.372	1.859	1.484	-6.325	6.304		
Northern Rockies region	3.641***	0.853	4.927***	0.902	-8.709	2013.600		
Wyoming Basin region	0.038	0.441	-0.933*	0.476	-2.145	1.395		
Central High Plains region	1.213**	0.424	0.668	0.455	-0.252	1.389		
Eastern Plains region	-0.924.	0.549	-2.856***	0.585	-5.741***	1.461		
Base year (2006)	-1.886***	0.155	-2.148***	0.162	-0.1	0.317		
Median growing season temperature	0.732***	0.109	1.074***	0.118	2.016***	0.408		
Median winter temperature	-0.208*	0.085	-0.128	0.093	-0.404	0.345		
Mean growing season precipitation	0.045***	0.006	0.037***	0.007	0.13***	0.023		
Mean winter precipitation	-0.011	0.007	0.024**	0.007	-0.064**	0.020		
Growing season precip. std. dev.	-0.324***	0.030	-0.332***	0.033	-0.702***	0.107		
Dryness index	-366.220***	57.118	-429.080***	62.294	-915.870***	274.880		
Slope	-0.013	0.038	0.057	0.041	-0.083	0.110		
Distance to railroad	$-4.7X10^{-6}$**	$1.5X10^{-6}$						
Net crop returns	0.005**	0.002						
Net crop returns, productive soil	-0.001	0.001						
Net crop returns, moderate soil	-0.004***	0.001						
Net crop returns, least productive soil	-0.005	0.003						
Average ethanol production	$2.6X10^{-4}$***	$2.4x10^{-5}$						
Federal ag commodity payments	$2.2X10^{-8}$**	$8.0X10^{-9}$						
Cattle inventory, grass			$5.1X10^{-6}$***	$9.7X10^{-7}$				
Federal conservation payments			$3.7X10^{-5}$***	$4.2X10^{-6}$				
Grass returns					0.010	0.010		
Grass returns, productive soil					-0.004	0.003		
Grass returns, moderate soil					0.010*	0.005		
Grass returns, least productive soil					-0.236	33.390		
Cattle inventory, pasture					0.000	$3.3X10^{-6}$		
Median home value							$1.4X10^{-5}$***	$2.1X10^{-6}$
Population							$2.1X10^{-4}$***	$3.4X10^{-5}$
Population density							0.004***	$3.3X10^{-4}$
Distance to road							$-6.3X10^{-5}$***	$8.6X10^{-6}$

[a] Significance: * p<0.05; ** p <0.01; ***p<0.001

Starting use: Grass and shrubland

Variable	Ending use							
	Crops		Grass and shrubland		Pasture and hay		Urban	
	estimate [a]	SE	estimate [a]	SE	estimate [a]	SE	estimate [a]	SE
(Intercept)	-4.751***	0.895	5.899***	0.791	-1.517	1.212		
Northern Rockies region	-2.449***	0.441	-0.33	0.295	-1.171**	0.376		
Wyoming Basin region	-1.908***	0.240	-1.697***	0.202	-2.552***	0.290		
Central High Plains region	-0.309	0.224	-0.207	0.188	-0.891***	0.233		
Eastern Plains region	-1.162**	0.357	-0.590	0.324	-1.463**	0.447		
Base year (2006)	-0.644***	0.098	-1.446***	0.091	-2.058***	0.125		
Median growing season temperature	0.195**	0.060	0.092.	0.052	0.266***	0.077		
Median winter temperature	-0.898***	0.054	-0.463***	0.047	-0.774***	0.070		
Mean growing season precipitation	0.029***	0.004	0.009*	0.004	0.078***	0.006		
Mean winter precipitation	0.002	0.003	0.007*	0.003	-0.016***	0.004		
Growing season precip. std. dev.	-0.120***	0.019	-0.045**	0.017	-0.385***	0.031		
Dryness index	151.300***	36.078	27.758	31.154	3.439	38.929		
Slope	-0.196***	0.017	0.139***	0.014	-0.226***	0.027		
Distance to railroad	$8.51X10^{-6}$***	$8.9X10^{-7}$						
Net crop returns	0.006***	0.001						
Net crop returns, productive soil	-0.005***	0.001						
Net crop returns, moderate soil	-0.010***	0.001						
Net crop returns, least productive soil	-0.020***	0.003						
Average ethanol production	$-1.0X10^{-4}$***	$1.4\ X10^{-5}$						
Federal ag commodity payments	$-1.4X10^{-8}$*	$5.9\ X10^{-9}$						
Cattle inventory, grass			$1.7X10^{-6}$**	$6.4\ X10^{-7}$				
Federal conservation payments			$-1.0X10^{-5}$***	$2.1\ X10^{-6}$				
Grass returns					0.016***	0.002		
Grass returns, productive soil					-0.004***	0.001		
Grass returns, moderate soil					-0.006***	0.001		
Grass returns, least productive soil					-0.005*	0.002		
Cattle inventory, pasture					$-5.1X10^{-6}$**	$1.8\ X10^{-6}$		
Median home value							$4.3X10^{-6}$***	$1.2\ X10^{-6}$
Population							$2.5X10^{-4}$***	$2.2\ X10^{-5}$
Population density							0.006***	$3.2\ X10^{-4}$
Distance to road							$-5.1X10^{-5}$***	$5.5\ X10^{-6}$

[a] Significance: * $p<0.05$; ** $p<0.01$; *** $p<0.001$

Starting use: Pasture and hay

Variable	Ending use							
	Crops		Grass and shrubland		Pasture and hay		Urban	
	estimate [a]	SE	estimate [a]	SE	estimate [a]	SE	estimate [a]	SE
(Intercept)	-12.487***	2.550	0.373	2.034	2.959	1.914		
Northern Rockies region	1.240	0.755	-0.465	0.582	-0.323	0.520		
Wyoming Basin region	-3.084***	0.929	0.033	0.559	-0.993.	0.537		
Central High Plains region	-1.035	0.850	1.353**	0.438	0.656	0.424		
Eastern Plains region	-3.962***	0.973	-3.899***	0.676	-1.298*	0.598		
Base year (2006)	1.805***	0.322	-3.02***	0.262	-0.938***	0.241		
Median growing season temperature	0.547**	0.211	0.113	0.167	0.100	0.159		
Median winter temperature	-1.163***	0.154	-0.373**	0.133	-0.545***	0.124		
Mean growing season precipitation	0.046**	0.016	0.044***	0.013	0.038**	0.012		
Mean winter precipitation	-0.033**	0.010	0.007	0.008	-0.009	0.008		
Growing season precip. std. dev.	-0.135	0.086	-0.217***	0.065	-0.140*	0.064		
Dryness index	77.755	74.599	-5.145	74.972	88.765	67.747		
Slope	-0.002	0.091	0.156*	0.079	0.063	0.077		
Distance to railroad	$1.2X10^{-5}$*	$4.9X10^{-6}$						
Net crop returns	0.006	0.005						
Net crop returns, productive soil	-0.001	0.002						
Net crop returns, moderate soil	-0.001	0.003						
Net crop returns, least productive soil	-0.009	0.008						
Average ethanol production	$-3.2X10^{-4}$***	$6.3\ X10^{-5}$						
Federal ag commodity payments	$3.9X10^{-9}$	$1.6\ X10^{-8}$						
Cattle inventory, grass			$-1.5X10^{-6}$	$2.4\ X10^{-6}$				
Federal conservation payments			$5.8X10^{-5}$***	$5.8\ X10^{-6}$				
Grass returns					0.006***	0.002		
Grass returns, productive soil					-0.002*	0.001		
Grass returns, moderate soil					-0.002*	0.001		
Grass returns, least productive soil					0.001	0.003		
Cattle inventory, pasture					$-8.5X10^{-6}$***	$2.\ X10^{-6}$		
Median home value							$9.2X10^{-6}$**	$2.9\ X10^{-6}$
Population							$2.7X10^{-4}$***	$5.1\ X10^{-5}$
Population density							0.004***	$4.8\ X10^{-4}$
Distance to road							$-3.2X10^{-4}$***	$5.8\ X10^{-5}$

[a] Significance: * p<0.05; ** p <0.01; ***p<0.001

Table C2. Starting use in crops: Model own marginal effects mean and 95% confidence interval (CI 95) by initial land use in the parametric logit model of land-use change in the Upper Missouri River Basin

Starting use: Crops

Variable	**Ending use**							
	Crops		**Grass and shrubland**		**Pasture and hay**		**Urban**	
	mean	**CI 95**	**mean**	**CI 95**	**mean**	**CI 95**	**mean**	**CI 95**
(Intercept)	0.052	0.008	-0.047	0.008	-0.002	0.001		
Wyoming Basin region	-0.004	0.001	0.006	0.001	-0.002	$4.6X10^{-4}$		
Glaciated Plains region	0.005	0.001	-0.004	0.001	$-2.8X10^{-4}$	$8.2X10^{-5}$		
Central High Plains region	0.003	$4.0X10^{-4}$	-0.003	$4.3X10^{-4}$	$-1.9X10^{-4}$	$5.5X10_{-5}$		
Eastern Plains region	0.009	0.002	-0.009	0.002	-0.001	$1.8X10^{-4}$		
Base year (2006)	0.001	$2.7X10^{-4}$	-0.001	$2.0X10^{-4}$	$2.3X10^{-4}$	$6.7X10^{-5}$		
Median growing season temperature	-0.002	$2.8X10^{-4}$	0.002	$2.7X10^{-4}$	$1.6X10^{-4}$	$4.8X10^{-5}$		
Median winter temperature	$-3.8X10^{-4}$	$6.1X10^{-5}$	$3.6X10^{-4}$	$6.3X10^{-5}$	$-2.5X10_{-5}$	$7.4X10^{-6}$		
Mean growing season precipitation	$3.9X10^{-5}$	$7.3X10^{-6}$	$-4.0X10^{-5}$	$6.9X10^{-6}$	$1.1X10^{-5}$	$3.2X10^{-6}$		
Mean winter precipitation	$-1.5X10^{-4}$	$2.8X10^{-5}$	$1.6X10^{-4}$	$2.7X10^{-5}$	$-6.9X10^{-6}$	$2.0X10^{-6}$		
Growing season precip. std. dev.	$1.4X10^{-5}$	$2.1X10^{-5}$	$-3.6X10^{-5}$	$6.3X10^{-6}$	$-4.9X10^{-5}$	$1.4X10^{-5}$		
Dryness index	0.281	0.060	-0.289	0.050	-0.072	0.021		
Slope	$-3.1X10^{-4}$	$5.5X10^{-5}$	$3.2X10^{-4}$	$5.5X10^{-5}$	$-9.1X10^{-6}$	$2.6X10^{-6}$		
Distance to railroad	$-2.3X10^{-8}$	NA						
Net crop returns	$2.4X10^{-5}$	NA						
Net crop returns, productive soil	$-6.8X10^{-6}$	NA						
Net crop returns, moderate soil	$-2.2X10^{-5}$	NA						
Net crop returns, least productive soil	$-2.3X10^{-5}$	NA						
Average ethanol production	$1.3X10^{-6}$	NA						
Federal ag commodity payments	$1.1X10^{10}$	NA						
Cattle inventory, grass			$2.3X10^{-8}$	NA				
Federal conservation payments			$1.7X10^{-7}$	NA				
Grass returns					$1.3X10^{-6}$	NA		
Grass returns, productive soil					$-4.7X10^{-7}$	NA		
Grass returns, moderate soil					$1.2X10^{-6}$	NA		
Grass returns, least productive soil					$-3.1X10^{-5}$	NA		
Cattle inventory, pasture					$4.3X10^{10}$	NA		
Median home value							$3.2X10^{-9}$	NA
Population							$4.6X10^{-8}$	NA
Population density							$8.9X10^{-7}$	NA
Distance to road							$-1.4X10^{-8}$	NA

Table C3. Starting use in grass and shrubland: Model own marginal effects mean and 95% confidence interval (CI 95) by initial land use in the parametric logit model of land-use change in the Upper Missouri River Basin

Starting use: Grass and shrubland								
	Ending use							
Variable	**Crops**		**Grass and shrubland**		**Pasture and hay**		**Urban**	
	mean	**CI 95**	**mean**	**CI 95**	**mean**	**CI 95**	**mean**	**CI 95**
(Intercept)	-0.032	0.003	0.039	0.003	-0.003	$2.5X10^{-4}$		
Wyoming Basin region	-0.006	0.001	0.006	0.001	$-3.2X10^{-4}$	$2.8X10^{-5}$		
Glaciated Plains region	-0.001	$6.2X10^{-5}$	$2.0X10^{-4}$	$1.8X10^{-4}$	$-3.3X10^{-4}$	$2.9X10^{-5}$		
Central High Plains region	$-2.6X10^{-4}$	$3.0X10^{-5}$	$4.0X10^{-4}$	$4.3X10^{-5}$	$-2.6X10^{-4}$	$2.3X10^{-5}$		
Eastern Plains region	-0.002	$1.6X10^{-4}$	0.002	$1.6X10^{-4}$	$-3.3X10^{-4}$	$2.9X10^{-5}$		
Base year (2006)	0.002	$2.3X10^{-4}$	-0.003	$3.3X10^{-4}$	$-2.3X10^{-4}$	$2.0X10^{-5}$		
Median growing season temperature	0.000	$3.0X10^{-5}$	$-3.0X10^{-4}$	$2.9X10^{-5}$	$6.7X10^{-5}$	$5.9X10^{-6}$		
Median winter temperature	-0.001	$1.2X10^{-4}$	0.001	$1.1X10^{-4}$	$-1.2X10^{-4}$	$1.0X10^{-5}$		
Mean growing season precipitation	$5.4X10^{-5}$	$6.0X10^{-6}$	$-7.X10^{-5}$	$6.3X10^{-6}$	$2.6X10^{-5}$	$2.3X10^{-6}$		
Mean winter precipitation	$-1.2X10^{-5}$	$1.3X10^{-6}$	$2.6X10^{-5}$	$1.7X10^{-6}$	$-8.9X10^{-6}$	$7.8X10^{-7}$		
Growing season precip. std. dev.	$-1.9X10^{-4}$	$2.2X10^{-5}$	$3.1X10^{-4}$	$2.4X10^{-5}$	$-1.3X10^{-4}$	$1.1X10^{-5}$		
Dryness index	0.370	0.036	-0.342	0.035	-0.010	0.001		
Slope	-0.001	$9.8X10_{-5}$	0.001	$1.0X10^{-4}$	$-1.4X10^{-4}$	$1.2X10^{-5}$		
Distance to railroad	$2.2X10^{-8}$	NA						
Net crop returns	$1.5X10^{-5}$	NA						
Net crop returns, productive soil	$-1.2X10^{-5}$	NA						
Net crop returns, moderate soil	$-2.6X10^{-5}$	NA						
Net crop returns, least productive soil	$-5.3X10^{-5}$	NA						
Average ethanol production	$-2.8X10^{-7}$	NA						
Federal ag commodity payments	$-3.7X10^{11}$	NA						
Cattle inventory, grass			$5.9X10^{-9}$	NA				
Federal conservation payments			$-3.6X10^{-8}$	NA				
Grass returns					$6.2X10^{-6}$	NA		
Grass returns, productive soil					$-1.5X10^{-6}$	NA		
Grass returns, moderate soil					$-2.5X10^{-6}$	NA		
Grass returns, least productive soil					$-2.0X10^{-6}$	NA		
Cattle inventory, pasture					$-2.0X10^{-9}$	NA		
Median home value							$2.3X10^{-9}$	NA
Population							$1.3X10_{-7}$	NA
Population density							$2.9X10^{-6}$	NA
Distance to road							$-2.7X10^{-8}$	NA

Table C4. Starting use in pasture and hay: Model own marginal effects mean and 95% confidence interval (CI 95) by initial land use in the parametric logit model of land-use change in the Upper Missouri River Basin

Starting use: Pasture and hay								
	Ending use							
Variable	**Crops**		**Grass and shrubland**		**Pasture and hay**		**Urban**	
	mean	**CI 95**	**mean**	**CI 95**	**mean**	**CI 95**	**mean**	**CI 95**
(Intercept)	-0.177	0.056	-0.010	0.002	0.188	0.056		
Wyoming Basin region	0.018	0.006	-0.001	1.0X10-4	-0.017	0.006		
Glaciated Plains region	-0.024	0.008	0.004	0.001	0.020	0.008		
Central High Plains region	-0.019	0.006	0.003	0.001	0.017	0.006		
Eastern Plains region	-0.031	0.010	-0.010	0.002	0.041	0.009		
Base year (2006)	0.032	0.010	-0.008	0.002	-0.023	0.011		
Median growing season temperature	0.005	0.002	$1.8X10^{-5}$	9.7X10-6	-0.005	0.002		
Median winter temperature	-0.007	0.002	0.001	1.2X10-4	0.006	0.002		
Mean growing season precipitation	$1.6X10^{-5}$	$3.0X10^{-5}$	$9.5X10^{-6}$	4.3X10-6	$-5.2X10^{-5}$	$2.9X10^{-5}$		
Mean winter precipitation	$-4.7X10^{-5}$	$9.0X10^{-5}$	$2.4X10^{-5}$	1.1X10-5	$3.0X10^{-5}$	$9.4X10^{-5}$		
Growing season precip. std. dev.	$9.1X10^{-6}$	$1.7X10^{-5}$	$-1.2X10^{-4}$	5.6X10-5	$8.4X10^{-5}$	$6.5X10^{-5}$		
Dryness index	-0.125	0.040	-0.376	0.069	0.514	0.067		
Slope	-0.001	$2.3X10^{-4}$	$1.5X10^{-4}$	6.7X10-5	$-7.8X10^{-6}$	0.000		
Distance to railroad	$1.1X10^{-5}$	NA						
Net crop returns	$-2.6X10^{-6}$	NA						
Net crop returns, productive soil	$-1.5X10^{-6}$	NA						
Net crop returns, moderate soil	$-1.6X10^{-5}$	NA						
Net crop returns, least productive soil	$-6.3X10^{-7}$	NA						
Average ethanol production	$7.5X10^{12}$	NA						
Federal ag commodity payments	$-2.4X10^{-9}$	NA						
Cattle inventory, grass			$9.4X10^{-8}$	NA				
Federal conservation payments			$5.3X10^{-5}$	NA				
Grass returns					$-1.3X10^{-5}$	NA		
Grass returns, productive soil					$-1.5X10^{-5}$	NA		
Grass returns, moderate soil					$7.1X10^{-6}$	NA		
Grass returns, least productive soil					$-7.3X10^{-8}$	NA		
Cattle inventory, pasture					$1.0X10^{-9}$	NA		
Median home value							$3.1X10^{-8}$	NA
Population							$4.4X10^{-7}$	NA
Population density							$-3.7X10^{-8}$	NA
Distance to road							$2.4X10^{-8}$	NA

APPENDIX D: BIOENERGY CONVERSION CALCULATIONS

Land Use Area to Bioenergy Crop Production

Proportion of regional cropland dedicated to 1st Generation bioenergy production

To convert crop area into a measure of biofuel production we first multiply a change in crop area by a regional percentage of crop area planted in corn and soy. Since only a portion of these crops are currently processed into fuel, we then multiply the resulting corn/soy area by a national proportion of these crops going to fuel use (vs feed or food).

In our UMRB study area, 26.2% of crop area was harvested for corn, 27.2% for soybeans (NASS 2016); nationally, 44.0% of US corn is used for ethanol (ERS 2017) and 4.6% of the US soybean crop is used processed into oil and used as a biodiesel feedstock (ASA 2019; RFA n.d.; FAO 2012).

Following these crop area and use proportions, we estimate proportion of base crop area used for corn ethanol (corn crop area * corn crop fuel use) as 0.115, and the area used for soy biodiesel (soy crop area * soy crop fuel use) as 0.013. Combining these results in an estimate of the proportion of base crop area used for first-generation feedstock as 0.128. These historic harvest and use proportions are used to convert baseline crop area into biofuel feedstock production.

We consider all new crop area resulting from bioenergy incentive policy scenarios used for bioenergy feedstock following historic corn/soy proportions. That is, all new crop area is assumed to be harvested for soy or corn at 2017 proportions (0.49 corn, 0.51 soy) with the entire harvest used as biofuel feedstock. (Note that this may not be realistic for soybeans, since only soy oil—18% of the crop—and not meal is currently used as a biodiesel feedstock.)

Proportion of regional pasture/hay land dedicated to 2nd Generation bioenergy production

Interpreting baseline second-generation biofuel production in terms of changes in pasture and hay area is a bit more straightforward, since functionally no switchgrass or hay crop is currently used as a cellulosic feedstock. Conversely, we assume all new pasture/hay area is harvested and used for bioenergy production—either as cellulosic ethanol or converted into electricity.

All other land uses

All grass and shrubland and urban areas are allocated to non-bioenergy use in historic, base, and crop and grass returns scenarios.

Table D1 combines the per-acre multipliers described above that are used to convert historic and projected land use area into bioenergy feedstock production for base and bioenergy policy scenarios.

Table D1. Land use area bioenergy feedstock production multipliers

Area dedicated to bioenergy production/use:		Per acre multipliers			
		Historic	**ClimateOnly Base**	**Crop Returns Scenarios (difference from base)**	**Grass Returns Scenarios (difference from base)**
NLCD EndUse	**bioenergy use**	2001, 2006, 2011	2016 - 2101	2016 - 2101	2016 - 2101
To_Crop	corn ethanol	0.11528	0.11528	0.49	0.11528
	soy biodiesel	0.01238	0.01238	0.51	0.01238
	1st gen bioenergy use	**0.12770**	**0.12770**	**1**	**0.12770**
	All other crops/uses	1 - 0.12770	1 - 0.12770	0	1 - 0.12770
To_PastureHay	switchgrass electricity/ethanol	0	0	0	1
	2nd gen bioenergy use	**0**	**0**	**0**	**1**
	All other uses	1	1	1	0
To_GrassShrub	Bioenergy use	0	0	0	0
	All other	1	1	1	1
To_Urban	Bioenergy use	0	0	0	0
	All other	1	1	1	1

Bioenergy crop to feedstock yield and energy conversion

1st Generation crop acres to biofeedstock, biofuel, and energy yield

Crop area allocated to first-generation bioenergy production is converted to feedstock yield using regional Olympic average corn and soybean yields over observed years (2001, 2006, 2011) (NASS 2016): 104.4 BU/Acre for corn and 33.8 BU/Acre for soybeans.

First-generation crop yields are converted into biofuel following reported conversion rates: 2.8 gallons E100 ethanol/BU corn (PU Ex 2006, RFA/UA Ex n.d.) and 1.5 gallons B100 biodiesel/BU soybeans (AFDC, RFA/UA Ex n.d.).

Standard energy conversions are used to convert first-generation feedstock into energy: 84,530 BTU/gallon E100 ethanol (AFDC 2021) and 1.5 gallons of Biodiesel/BU Soybeans (AFDC 2021, RFA/UA Ex n.d.).

Following these conversions, one acre of corn dedicated to ethanol production has a potential to produce 24.7 million gross BTUs of energy and one acre of soybeans dedicated to biodiesel production has a potential to produce 6.5 million gross BTUs.

2nd Generation pasture/hay acres to biofeedstock and bioenergy yield

Pasture/hay area allocated to new second-generation bioenergy production is converted to feedstock using regional switchgrass yields and biomass energy conversion rates. Regional switchgrass yields are estimated at 2.8 tons per acre (Gu, et al. 2015; Omojeso 2020). One dry ton of cellulosic biomass produces about 100 gallons of E100 ethanol (AFDC 2021). One dry ton of biomass can be converted into 100 gallons of E100 ethanol (Haque and Epplin 2010, EP 2010). Following these estimates, one new acre of dedicated switchgrass has a potential to produce 2.4 million gross BTUs of energy from E100 ethanol.

One dry ton of switchgrass contains 7,750 BTUs of energy (USFS FVC 2004). Biomass electrical production with current technology has a conversion efficiency of 30% (DOE BTO 2011). Following these estimates, one new acre of dedicated switchgrass has a potential to produce 1.3 million BTUs of energy from electricity.