Strategic Grasslands Conversions and Conservation Easement Acquisitions in the Dakotas: Analysis using Remotely Sensed Data

Gaurav Arora
Dept. of Economics & Center for Agricultural and Rural Development, Iowa State University
Email: gaurav88@iastate.edu

David A. Hennessy
Dept. of Agriculture, Food and Resource Economics, Michigan State University
and
Dept. of Economics & Center for Agricultural and Rural Development, Iowa State University
Email: hennes64@anr.msu.edu

Hongli Feng
Dept. of Agriculture, Food and Resource Economics, Michigan State University
and
Department of Economics, Iowa State University
Email: hennes65@anr. msu.edu

Peter T. Wolter
Dept. of Natural Resource Ecology and Management, Iowa State University
ptwolter@iastate.edu

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Abstract:

This paper analyses strategic permanent grassland conversion decisions in the Dakotas. We present a binary discrete choice model with dynamic decision-making among heterogeneous farmers to evaluate these land use changes. We also explore the role of conservation easements- a policy tool to inhibit grassland conversions. We utilize a spatially-explicit panel dataset to empirically analyze permanent grass conversions relative to the neighborhood characteristics in North Dakota during 1997-2015. A duration modelling approach is used to estimate the risk of conversion for a representative land parcel as a function of the density of grasslands in its locality, and its proximity to previously allocated easements. We find that the land parcels with higher local grass-density 'survived' relatively longer before being permanently converted to cropland. This affirms our conjecture that strategic complementarities exist. We further find that easements are a viable conservation tool as their presence in a parcel's proximity complements higher grass-density and inhibits conversion. However, most easements seem to have been misallocated in the sense that they are generally located away from conversion sites, in proximity of the areas where conversions did not occur anyway.

Background and Introduction

The U.S. Prairie Pothole Region (PPR) is a biodiversity-rich ecosystem sustained by the native mixed-prairie grasslands. These grasslands generate ecosystem services by supporting regional wetlands that provide a nesting and breeding habitat for the local waterfowl species and migratory birds. Geographically, the PPR is located within (and covers significant portions of) five U.S. states: Iowa, Minnesota, North Dakota, South Dakota, and Montana. We focus on the states of North and South Dakota where the grassland-wetland ecosystem intersects with the U.S. Western Corn Belt (WCB) east of the Missouri River, see figure 1. The river runs north-south cutting these states into western and eastern Dakotas. Eastern Dakotas contain a grass-crop frontier at the boundary of WCB. Majority land use on the west of this frontier is perennial grasses, and on the east is intensive agricultural production driven by better soils and higher precipitation relative to the western region. At the frontier, the grasslands sustain a peculiar agro-ecosystem that generates economic as well as ecological value through row crop cultivation, livestock production and ecosystem services.

Even though the native grasses are vital to the region's multiple production systems, significant conversions have replaced these grasslands towards cropping in the past two decades. Almost 670,000 net acres of grasslands were converted to corn/soy cultivation in the Dakotas' PPR between 2006 and 2011 (Wright & Wimberley 2013). Apart from threatening regional wetlands and supported species, these conversions may impact regional soil quality as increased erosion potential and loss of soil carbon may lower the region's land productivity. Grasslands are natural resources largely under private ownership in the PPR and are responsive to changing incentives, as reflected in increased cropland values, changes in policy, etc. For example, an increase in average non-irrigated cropland values in Central South Dakota from $1,187/acre in 2007 to $4,614/acre in 2014 (Janssen et al. 2014) may have incentivized these conversions.

Past studies have analyzed factors that impact grassland conversions in the PPR. Rashford *et al.* (2010) found that while higher commodity prices favor conversion, conversion probability could vary spatially with better soils posing higher risk of conversion. Stephens *et al.*'s (2008) found that higher grass cover in a parcel's neighborhood lowered the risk of conversion. However, lower enrollments and budget constraints of the Conservation Reservation Program coupled with reduced financial risks from higher crop insurance subsidies resulted in increased grassland conversions (Turner and Gates, 2014; Feng *et al.* 2013; Claassen *et al.* 2011).

The U.S. Fish and Wildlife Service (USFWS) aims at protecting grasslands through acquiring conservation easements, which is a key policy instrument for conservation. Under this policy, landowners enter a voluntary contract with the conservation agency and are incentivized in lieu of permanently ceding their right to cultivate. For over 60 years the USFWS and its partners have used funds from selling Duck Stamps to protect more than two million acres under easements, but only a third of the grassland that they wish to protect has been enrolled. Insufficient funds to protect the grasslands and higher economic incentives towards conversion calls for cost-effective conservation targeting, as Rashford *et al.* (2010) and Stephens *et al.* (2008) too assert. Polasky (2008) and Newburn *et al.* (2005) have argued the importance of incorporating human interactions with natural habitat in conservation policy planning.

The Dakotas' PPR is a focus region for grass protection as 80%, i.e. 2.2 mi. acres, of all easement acquisitions in the U.S. are located here (USFWS, 2011; Walker *et al.*, 2013). Walker *et al.* (2013) pointed towards underlying budget constraints with rising land values during 2008-

’12 that restrained total acquisitions to only about 30% of to those during 1998-2012, even though fund allocations were about the same. The study found that USFWS’s easement acquisition strategy prioritized landscapes with greatest abundance of waterfowl breeding pairs (see figure 2). Authors developed a geographic information system that identified land parcels with highest biological value with high conversion risk but low acquisition cost, thereby providing an actionable conservation targeting strategy that was more efficient.

We too analyze on the effectiveness of past allocations of Grassland Conservation Easements with a focus in the Dakotas’ PPR but examine how conservation targeting should extend beyond benefits, costs and conversion probability for individual land parcels. We conjecture that spillovers exist from the advent of more cropped land. When more cropland emerges in a locality then cropping costs may decline because more tillage equipment, tillage entrepreneurs and input suppliers enter the area. Our extension to the network effects is distinct from the spatial contiguity argument, in that connected cropland parcels will provide higher conversion incentives than the same amount of land that is spatially separated. On the other hand, judiciously placed easements could disrupt this network effect.

To the best of our knowledge, this study is first to consider the role of networks in designing grassland conservation planning through easement acquisitions. To better understand the underlying dynamics we utilize a conceptual framework that models strategic permanent grassland conversions and present analytical results on the role of easements in grassland protection. We also conduct an empirical analysis to tests for the existence, and measures the degree, of local spillovers towards the region’s land use dynamics. Our empirical strategy specifically focuses on permanent grassland conversions by implementing remote sensing tools extensively. On spatial spillovers, we evaluate how permanent conversions are impacted by neighboring grass-density and the presence of easements. We control for the parcels' soil quality, access to highways and town-centers in our regressions.

This paper is divided into several sub-sections. We first describe our data generating process utilizing remote sensing platforms ArcGIS and ERDAS, and briefly summarize the data. A conceptual model of permanent conversions and the role of easements is then discussed, following which we underline our empirical strategy. Finally, we present our estimation results and conclude with a brief discussion.

Data Preparation and Description

We use remotely sensed land use data from the 'CropScape' portal of USDA-National Agricultural Statistical Service's Cropland Data Layer (CDL) program. CDL provides raster (pixelated) data for all contiguous U.S. states with two distinct spatial resolutions, 56 m pixels for 2006-2009 and 30 m pixels for other years. The years available for CDL vary by state, i.e. for South Dakota during 2006-'15 and for North Dakota during 1997-2015. Since the focus of this study are long-term (or permanent) grassland conversions that are better studied with long time-series, we focus on eastern North Dakota for now. To that extent our analysis is preliminary.

We first condense all CDL land uses into two categories: cropland and grassland. We then characterize all possible land use combinations from one year to the next at the pixel-level during 1997-2015. For instance, between years Y1 and Y2 land use change may be crop (Y1) to crop (Y2); crop (Y1) to grass (Y2); grass (Y1) to crop (Y2); and grass (Y1) to crop (Y2). As such, within this study's entire time-window for eastern North Dakota, i.e. 19 years, there are a total 2^{19} possible combinations of land use switches between grass and crop. By employing remote-sensing tools we can conduct a spatially explicit investigation of land-use changes. For this analysis we focus on three specific land use change combinations: always crop (C); always grass (G); and permanent conversion from grass to crop (GC).

Figure 3 shows a map of land use switches C, G & GC, along with the location of conservation easements.[1] There are a total of 759,043 acres of permanent croplands mostly located on eastern parts of the study region, whereas 189,231 permanent grassland acres are located mostly in the west. Interestingly, while most GC switches happened near the always crop (C) category most easements were allocated near the always grass (G) parcels. This signifies the scope for analyzing network effects and evaluating efficiency of past easement allocations.

One other easement attributes used in this study is date of acquisition for each conservation easement in the Dakotas. Soil quality data was acquired from the Web Soil Systems portal of USDA-National Resource Conservation Service (NRCS). We retrieve tabular data for Land Capability Classification (LCC) and representative slope from the Soil Data Viewer application developed by NRCS. Briefly, LCC groups soils into eight broad classes each representing impediments for cropping, with higher class codes assigned to bigger impediments. Representative slope simply measures the average rise per unit run. We also utilize Euclidean distance of land parcels from principal highways and town centers (or cities) acquired from U.S. Census Bureau's TIGER. Variable summaries, listed in table 1, will be discussed later.

Model

We adapt the modelling framework developed by Brock and Durlauf (2001) to understand aggregate community behavior when strategic complementarities exist. We build upon the

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[1] A spatially-explicit conservation easement database is available from the National Conservation Easement Database website, see: http://www.conservationeasement.us/projects

theoretical foundations of this paper. In order to evaluate permanent grassland conversions we designate one-time conversion costs as objective function (rather than a payoff function). We extend Brock and Durlauf's (2001) one-shot simultaneous decision game with homogenous agents to incorporate temporal dynamics and heterogeneity. This is important as our interest lies in understanding scenarios where rate of conversion may differ with neighborhood's land use endowments. By incorporating agent heterogeneity we explore implications of differing private costs in a strategic environment. We first layout the baseline model for permanent grass conversions and then extend it to incorporate farmer heterogeneity and temporal dynamics.

Under the baseline model by Brock and Durlauf (2001) an individual farmer *i* in a population of *I* farmers chooses $\omega_i \in \{-1,1\}$ with $-1 \equiv$ 'stay in grass' and $1 \equiv$ 'convert to crop'. Define $\boldsymbol{\omega} = (\omega_1,...,\omega_I)$ as an *I-tuple* choice set for the population and $\boldsymbol{\omega}_{-i} = (\omega_1,...,\omega_{i-1,}\omega_{i+1,}...,\omega_I)$ as a choice set of farmers other than *i*. Assume non-cooperative behavior among farmers and express the individual cost, $C(\omega_i)$, as sum of (a) private costs ($P(\omega_i)$), (b) social costs ($S(\omega_i, E_i(\boldsymbol{\omega_{-i}}))$), and (c) a random cost component ($\varepsilon(\omega_i)$).[2]

$$C(\omega_i) = P(\omega_i) + S(\omega_i, E_i(\boldsymbol{\omega_{-i}})) + \varepsilon(\omega_i) \tag{1}$$

Here, $\varepsilon(\omega_i)$ is unknown to the analyst but fully known to the individual at the time of deciding to convert. Assume $\varepsilon(\omega_i)$ to be independently and identically distributed across agents. $E_i(\boldsymbol{\omega_{-i}})$ is *i*'s conditional expectation of the mean choice-level of farmers other than *i*. $S(\omega_i, E_i(\boldsymbol{\omega_{-i}}))$ exhibit strategic complementarity if $|S(1, E_i(\boldsymbol{\omega_{-i}})) - S(-1, E_i(\boldsymbol{\omega_{-i}}))|$ is increasing in $E_i(\boldsymbol{\omega_{-i}})$.

[2] The implication of non-cooperative agents is that their decisions do not involve any coordination. Rather the decisions are solely based on subjective expectations of mean-neighborhood choice level (and not on $\varepsilon(\omega_i)$).

$E_i(\boldsymbol{\omega}_{-i})$ is mean-neighborhood behavior from i's perspective and can be written as

$\overline{m}_i^e = (I-1)^{-1}\sum_{j\neq i} E_i(m_j)$ with $E_i(m_j)$ as subjective expectation of j's choices from i's perspective. We restrict our attention to proportional spillovers form of strategic complementarity such that the percent change in individual cost from a unit change in mean-neighborhood choice is constant. That is,

$$(2) \qquad \frac{\partial^2 S(\omega_i, \overline{m}_i^e)}{\partial \omega_i \partial \overline{m}_i^e} = J < 0$$

A social cost function that exhibits proportional spillovers is specified as $S(\omega_i, \overline{m}_i^e) = J\omega_i \overline{m}_i^e$ s.t. $J < 0$. Note that, J characterizes the impact of social costs on mean-community behavior. For econometric tractability of the above framework, we assume $\varepsilon(\omega_i)$ is extreme-value distributed and $\varepsilon(-1)-\varepsilon(1)$ is logistically distributed. Hence,

$$(3) \qquad \text{Prob}(\varepsilon(-1)-\varepsilon(1) \leq x) = \frac{1}{1+\exp(-\beta x)}$$

Now, farmer i will choose to convert if $C(1) < C(-1)$. So the probability of permanent conversion, $\text{Prob}(\omega_i = 1)$, is expressed as

$$\begin{aligned}
\text{Prob}(\omega_i = 1) &= \text{Prob}(C(1)-C(-1) \leq 0) \\
&= \text{Prob}(\varepsilon(-1)-\varepsilon(1) \geq [P(1)+J\cdot 1\cdot \overline{m}_i^e]-[P(-1)+J\cdot -1\cdot \overline{m}_i^e]) \\
&= 1-\text{Prob}(\varepsilon(-1)-\varepsilon(1) \leq [P(1)+J\cdot 1\cdot \overline{m}_i^e]-[P(-1)+J\cdot -1\cdot \overline{m}_i^e]) \\
&= 1-\frac{\exp(\beta(P(1)+J\cdot 1\cdot \overline{m}_i^e))}{\sum_{\nu_i\in\{-1,1\}}\exp(\beta(P(\nu_i)+J\cdot \nu_i\cdot \overline{m}_i^e))} \qquad (\because \text{eq. (3)})
\end{aligned}$$

And generally,

$$\text{(4)} \qquad \text{Prob}(\omega_i) = 1 - \frac{\exp(\beta(P(\omega_i) + J \cdot \omega_i \cdot \overline{m}_i^e))}{\sum_{\nu_i \in \{-1,1\}} \exp(\beta(P(\nu_i) + J \cdot \nu_i \cdot \overline{m}_i^e))}$$

Here β parametrizes the dependence of individual decision-making process on deterministic individual costs. If $\beta \to 0$ then $\text{Prob}(\omega_i = 1) = \text{Prob}(\omega_i = -1) \to 0.5$ regardless of the private and social costs since the decisions are now solely based on random $\varepsilon(\omega_i)$'s. If $\beta \to \infty$ then the impact of $\varepsilon(\omega_i)$'s vanishes. To evaluate the equilibrium community behavior, we write

$$\begin{aligned}
E(\omega_i) &= 1 \cdot \text{Prob}(\omega_i = 1) + (-1) \cdot \text{Prob}(\omega_i = -1) \\
&= 1 \cdot \{1 - \frac{\exp(\beta(P(1) + J \cdot 1 \cdot \overline{m}_i^e))}{\sum_{\nu_i \in \{-1,1\}} \exp(\beta(P(\nu_i) + J \cdot \nu_i \cdot \overline{m}_i^e))}\} \\
&\qquad + (-1) \cdot \{1 - \frac{\exp(\beta(P(-1) + J \cdot -1 \cdot \overline{m}_i^e))}{\sum_{\nu_i \in \{-1,1\}} \exp(\beta(P(\nu_i) + J \cdot \nu_i \cdot \overline{m}_i^e))}\} \\
&= \frac{-\exp(\beta(P(1) + J \cdot 1 \cdot \overline{m}_i^e)) + \exp(\beta(P(-1) + J \cdot -1 \cdot \overline{m}_i^e))}{\exp(\beta(P(1) + J \cdot 1 \cdot \overline{m}_i^e)) + \exp(\beta(P(-1) + J \cdot -1 \cdot \overline{m}_i^e))}
\end{aligned}$$

To characterize an equilibrium Brock and Durlauf (2001) linearize the exponential function above by specifying $P(\omega_i) = h\omega_i + k$. See that $2h = (P(1) - P(-1))$, i.e. difference between farmers' private costs across the available choices. Substituting the linearized private costs and $J = -L$ so that $L > 0$, we get:

$$\text{(5)} \qquad E(\omega_i) = \frac{-\exp(\beta(h - L \cdot \overline{m}_i^e)) + \exp(\beta(-h + L \cdot \overline{m}_i^e))}{\exp(\beta(h - L \cdot \overline{m}_i^e)) + \exp(\beta(-h + L \cdot \overline{m}_i^e))} = -\tanh(\beta(h - L \cdot \overline{m}_i^e))$$

The authors also impose rational expectations, that is $E_i(m_j) = E(m_j)\ \forall\ i, j$, and apply Brower's fixed point theorem to utilize the continuity property of tanh along with the boundedness of the *I-tuple* choice set to assert that there exists a fixed-point with respect to $E(\omega_i)$'s such that

$$(6)\qquad E(\omega_i) = -\tanh(\beta(h - L\cdot(I-1)^{-1}\sum_{\forall j\neq i} E(\omega_j)))$$

By symmetry of the system of equations in (6) we can conclude that there exists a equilibrium based on rational expectations where $E(\omega_i) = E(\omega_j) = m^*\ \forall\ i, j$. Hence, the equilibrium characterizing equation

$$(7)\qquad m^* = -\tanh(\beta(h - Lm^*))$$

We conduct graphical analyses to generate the equilibrium results of the baseline model, see Brock and Durlauf (2001) p.241. To facilitate this exercise we re-express eq. (7) as follows:

$$-m^* = \tanh(\beta(h - Lm^*)) = \frac{\exp(\beta(h - Lm^*)) - \exp(\beta(-h + Lm^*))}{\exp(\beta(h - Lm^*)) + \exp(\beta(-h + Lm^*))}$$

$$\Rightarrow -m^* = \frac{\exp(z) - \exp(-z)}{\exp(z) + \exp(-z)},\ \text{where } z = \beta(h - Lm^*)$$

$$(8)\qquad \Rightarrow \boxed{\frac{1}{2}\ln(\frac{1-m^*}{1+m^*}) = \beta h - \beta L m^*}$$

Since our analysis is built upon Brock and Durlauf's theoretical foundations we utilize specific examples to showcase results on existence of multiple/unique equilibrium.

Result 1:

(a) If $h = 0$ and $\beta L > 1$, then there exist three roots to eq. (7) – one positive, one negative and one zero.

(b) If $h \neq 0$ and $\beta L > 1$, then there exists a threshold *H*=*f*(*βL*) such that

(i) For $|\beta h| < H,$ then there exist three roots to eq. (7) – one with the same sign as *h*, and the others with opposite signs.

(ii) For $|\beta h| > H,$ then there exists a unique root to eq. (7) – with the same sign as *h.*

Figure 4 visualizes Result 1. The relative strengths of strategic complementarities (*L*) and difference between private costs towards "staying in grass" and "converting to crop" determine the nature of an equilibrium. We fix βL =2 and vary βh. Clearly, as βh increases the model projects cropping as a more expensive option compared to grass-based production and the equilibrium behaviors are found to tilt accordingly. An important interpretation of the aggregate community behavior at equilibrium is through the percentage of population that 'converts to crop' as $k^* = (1+m^*)/2$.

We now extend the above baseline model to incorporate temporal dynamics and heterogeneity among decision makers and explore the role of easements.

Case 1a.: Dynamic Strategic Grassland Conversions without Easements

Consider a time-period *t* snapshot of *I* farmers where each individual farmer *i* faces a choice set $\omega_{i,t} \in \{-1,1\}$, where $-1 \equiv$ 'stay in grass' and $1 \equiv$ 'convert to crop'. We assume a non-cooperative decision-making process among the farmers at each time-period *t.* Farmer *i*'s individual cost at time *t* is $C_t(\omega_{i,t})$ for choosing action $\omega_{i,t}$. As discussed above, $C_t(\omega_{i,t})$ is decomposed as

$$C_t(\omega_{i,t}) = P_t(\omega_{i,t}) + S_t(\omega_{i,t}, E_i(\boldsymbol{\omega}_{\textbf{-i,t}})) + \varepsilon_t(\omega_{i,t})$$

We assume that $\varepsilon(\omega_{i,t})$ is independent and identical across agents, and that Cov($\varepsilon(\omega_{i,t1})$, $\varepsilon(\omega_{i,t2})$) = 0 $\forall$ $t1$, $t2$ [3]. Again, define $E_i(\boldsymbol{\omega_{-i,t}}) \triangleq \overline{m}^{e}_{i,t} = (I-1)^{-1}\sum_{j\neq i} E_i(m_{j,t})$, which upon assuming *myopic expectations* becomes $\overline{m}^{e}_{i,t} = (I-1)^{-1}\sum_{j\neq i} \omega_{j,t-1}$, where $\omega_{j,t-1}$ is the optimal (equilibrium) decision of all farmers, *j* ≠ *i*, at time-period *t* - 1. For the social cost component to exhibit strategic complementarity, we need $\frac{\partial^2 S_t(\omega_{i,t}, \overline{m}^{e}_{i,t})}{\partial \omega_{i,t} \partial \overline{m}^{e}_{i,t}} = -L_t < 0$ (or $L_t > 0 \;\forall\; t$) .

As earlier, we specify the social cost component that imposes proportional spillovers, i.e. $S_t(\omega_{i,t}, \overline{m}^{e}_{i,t}) = -L_t \omega_{i,t} \overline{m}^{e}_{i,t}$ s.t. $L_t < 0 \;\forall\; t$. Before specifying L_t notice that we intend to model permanent grassland conversion. Therefore, effective decision-makers at time *t* are those who chose to not convert until this period. In addition, the total cropland share in a neighborhood increases incrementally as additional landowners convert every period. So, modelling farmer *i*'s conversion decision implicitly assumes that the farmer decided to 'stay-in-grasses' up until *t*. More importantly, this farmer's individual decision will depend not only on the (myopic) expectations of previous period's decisions but also on the total cropland share in his/her neighborhood leading up to *t*. This follows from the conjectural premise of our study that more cropland will potentially encourage higher conversion through reduced costs via emergence of more input suppliers and entrepreneurs enabling knowledge/skill transfer etc. (and vice-versa). We capture this effect through L_t as a function of endowed total cropland share at *t*.

[3] Cov($\varepsilon(\omega_{i,t1})$, $\varepsilon(\omega_{i,t2})$) = 0 $\forall$ $t1$, $t2$ can be viewed as a special case where these idiosyncrasies are individual-specific and do not change over time. We introduce potential temporal correlations through economy-wide shocks in private costs in a subsection.

Let $L_t = f(C_{t-1} - 0.5) > 0,$ where $C_{t-1} \in [0,1]$ is the cropland share at the end of $t-1$. Assume $f'(.) > 0$ and $f''(.) < 0$. This signifies that marginally higher cropland share at the beginning of t reduces conversion costs but at a decreasing rate. Why decreasing rate? To allow for a diminishing marginal social valuation of either land-use type.

Now, specify $L_t = f(C_{t-1} - 0.5) = f([C_{t-2} - \{\frac{1+m_{t-1}}{2}\}G_{t-2}] - 0.5) = f([C_{t-2} - \{\frac{1+m_{t-1}}{2}\}G_{t-2}] - 0.5)$,

i.e. $L_t = f([C_{t-2} + m_{t-1}G_{t-2}])$, where $m_{t-1} \in [-1,+1]$ is the mean community behavior that signifies new conversions among effective decision-makers at t-1. We specify $L_t = C_{t-2} + |m_{t-1}|^p\ G_{t-2}]$ s.t $0 < p < 1$. While designating $p \in (\mathbf{0},\ \mathbf{1})$ implies diminishing marginal social valuation of crop/grass in the neighborhood, $|m_{t-1}|$ imposes symmetry on L_t due to higher crop/grass shares at t-1[4]. In addition, this specification of L_t can also characterize the role of past cropland shares and private costs to determine current-period's mean community behavior.

Now, assuming extreme-value distribution for the random component of conversion costs and linearized private cost component $P_t(\omega_{i,t}) = h_t\omega_{i,t} + k_t$ s.t. $2h_t = P_t(1) - P_t(-1)$, we have

$$\begin{aligned} E(\omega_{i,t}) &= 1 \cdot \text{Prob}(\omega_{i,t} = 1) + (-1) \cdot \text{Prob}(\omega_{i,t} = -1) \\ &= \frac{-\exp(\beta(h_t - L_t \cdot \overline{m}_i^e)) + \exp(\beta(-h_t + L_t \cdot \overline{m}_i^e))}{\exp(\beta(h_t - L_t \cdot \overline{m}_i^e)) + \exp(\beta(-h_t + L_t \cdot \overline{m}_i^e))} \\ &= -\tanh(\beta(h_t - L_t \cdot (I-1)^{-1} \textstyle\sum_{j \neq i} \omega_{j,t-1})) \qquad (\because \text{myopic expectations}) \end{aligned}$$

Therefore, the self-consistent equilibrium choice-level at time-period t will satisfy

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[4] $|C_{t-1} - 0.5|^p$ is an alternative specification of L_t but with asymmetric social cost for positive and negative $m_{t-1}(\in [-1,+1])$.

(9) $$m_t = -\tanh(\beta(h_t - [C_{t-2} + |m_{t-1}|^p G_{t-2}].m_{t-1}))\ ,\ 0 < p < 1$$

We re-write equation (9) to facilitate a graphical analysis of dynamic equilibrium choice-levels:

(10) $$\frac{1}{2}\ln(\frac{1-m_t}{1+m_t}) = \beta h_t - \beta \cdot [C_{t-2} + |m_{t-1}|^p G_{t-2}].m_{t-1}$$

We first investigate a scenario where $h_t = 0\ \forall\ t$, i.e. private costs of 'staying-in-grass' and 'converting to crop' are the same, to analyze the role of *p* and C_{t-2} before characterizing the equilibria. Hence, $\frac{1}{2}\ln(\frac{1-m_t}{1+m_t}) = -\beta \cdot [C_{t-2} + |m_{t-1}|^p G_{t-2}].m_{t-1}$.

(i) See that the dependence factor *p*, of L_t on m_{t-1}, is a proportional to the elasticity of L_t w.r.t. m_{t-1}[5]. So, as *p*→0 the R.H.S. of equation (10) is near-linear in m_{t-1} and as *p*→1 the R.H.S. is convex in $|m_{t-1}|$, with degree of convexity increasing with *p*. An example with $C_{t-2} = 0$ and for two extreme values of *p* is presented in figure 5.

(ii) C_{t-2} is the endowed the neighborhood land-use profile in the beginning of time-period *t*-1 which feeds into period t's equilibrium choices through an interaction with prior period's mean choice level m_{t-1}. To understand its role, we fix *p* = 0.8 and vary C_{t-2}, see figure 6..

Thus the land-use endowments affect how much social costs depend upon m_{t-1}. The degree of dependence decreases with higher endowed crop share. This is justified since within the context of permanent conversions less grass (to begin with) means lower scope of conversion. Further,

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[5] ($p = (\partial L_t / \partial |m_{t-1}|) \cdot (|m_{t-1}| / L_t) \cdot (L_t / L_t - C_{t-2})$). *p* would overstate the elasticity of L_t w.r.t. m_{t-1} as the share of land-use mix at the beginning of t-1 tilts towards higher copping, but still remain directly proportional to this elasticity.

established pro-crop infrastructure would incentivize cropping even when $m_{t-1} < 0$. Note here that β is chosen such that Slope[R.H.S.] ≤ Slope[L.H.S.] for some $m \in (-1, +1)$. If this condition is not satisfied then the only stable equilibrium mean choice-level is $m^* = 0$.

To analyze the scenario where $h_t \neq 0$ such that $h_t < (>) 0$ means the private cost of converting to crop is lower (higher) than that of staying in grass. For a graphical analysis, we consider the case where cropping is less costly, i.e. $h_t < 0$ and prior-year behavior is relevant to the strength of social costs of conversion (L_t) with p = 0.8 and C_{t-2} = 0. The graphs are presented in figure 7. We provide the results for this scenario followed by the one where $h_t = 0 \ \forall \ t$ below.

Case 1a Results: (characterizing equilibria that solve equation (10))

(i) If $h_t = 0 \ \forall \ t$ and $-\beta L'(m) < (m - m^{-1})^{-1}$ for some $m \in (-1, +1)$ [6] then there exist five roots to equation (10).

→When $m_{t-1} < (>) 0$ then there are three possible equilibria m_t : one is equal to zero and two others are the same sign as m_{t-1}. However, not all of these roots are stable.

→When $m_{t-1} = 0$ then m_t =0 is the unique root.

For the case when $m_{t-1} < 0$, there are three potential roots $m_t^0 = 0,\ m_t^1 < 0,$ and $m_t^2 < 0$ with $m_t^2 < m_t^1$. Then, m_t^0 and m_t^2 (larger negative) roots are stable. The dynamic system will either move to m_t^0 if $m_t^1 < m_{t-1} < 0$ or to m_t^2 if $m_{t-1} < m_t^1$. The dynamics move in a similar fashion in the case when $m_{t-1} > 0$.

[6] $(m - m^{-1})^{-1}$ is Slope of (L.H.S) in equation (2).

(ii) If $h_t < (>) 0$ and $-\beta L'(m) < (m - m^{-1})^{-1}$ for some $m \in (-1, +1)$ [7], then there exists a threshold, *T*, which characterizes the roots to equation (10) at *t*. Clearly, the threshold, *T*, is a function of β and L_t. Note that T = -0.1212 for the example in figure 7.

→When $|h_t| > |T|$, there is a unique equilibrium that is stable and is of opposite sign to that of h_t.

→When $|h_t| < |T|$, there are multiple equilibria: (a) one that is of opposite sign to that of h_t, which is stable; (b) two equilibria with the same sign as that of h_t but only the one with a higher absolute value is stable.

The equilibrium dynamics when $|h_t| < |T|$ depends on the absolute size of m_{t-1} relative to that of that of the unstable root of equation (2), say m^U. If $|m_{t-1}|$ <(>) m^U then the neighborhood dynamics will lead to the root of equation (2) which is of the same (opposite) sign as h_t.

An interesting property of the time-varying private costs towards grassland conversions:

If the private opportunity cost of conversion is assumed to be a random walk process, i.e. $h_t = h_{t-1} + v_t$ where if h_{t-1} is small then the equilibrium mean choice-levels may be reverted due present-day exogenous shocks like higher commodity prices, better technology, etc. To visualize the mean-reverting property of dynamic private costs that follow a random walk process, see figure 8. In a scenario when m_{t-1} = -0.5, then with no new shocks we know that the equilibrium dynamics will lead to $m_t < -0.5$ until it reaches the stable equilibrium of -1 (no one converts). However, a large negative shock at time *t* due to advent of a technology that makes conversions significantly inexpensive will lead m_{t-1} = -0.5 to $m_t > -0.5$ until the system reaches a state

[7] $(m - m^{-1})^{-1}$ is Slope of (L.H.S) in equation (10).

where 'everyone converts'. Similarly, an opposite large shock can lead the system to a state where 'everyone will stay in grass' irrespective of m_{t-1}. Such shocks may be referred to as a mean-reverting.

A more sophisticated scenario would be that of '***sustained shocks***' where, say, a pro-crop v_t is not as large and one-time as above but is a combination of many small, sustained, uni-directional shocks that (at least theoretically) the system first decelerates the tendency to 'stay in grass' and then reverts it to the point where 'everyone converts to crop'. This case of sustained shocks can be useful to understand the role of shocks in commodity prices from 2005 to ~2011 in shifting community behavior which remained in native grasslands before 2006.

Case 1b.: Dynamic Strategic Grassland Conversions with Easements

Given the extreme-value distribution for the independently and identically distributed random cost component for each individual farmer, we know that the farmer *i*'s choice-level at period *t* solves $E(\omega_{i,t}) = -\tanh(\beta(h_t - L_t \cdot (I-1)^{-1}\sum_{j\neq i} E_i\omega_{j,t}))$. Further, myopic expectations imply $E_i\omega_{j,t} = \omega_{j,t-1} \forall j \neq i$, so the term $(I-1)^{-1}\sum_{j\neq i} E_i\omega_{j,t}$ is a function of the share of grassland-owners who decided to convert at period *t*-1. However, if e_t% of remaining grasslands at the beginning of period *t* (, or end of period *t*-1) were eased then the expected choice-level at time *t* will be restricted to a maximum value of $(1\text{- } 2e_t.100^{-1}) \triangleq 1 - E_t$ [8]. Define the new expected mean

---

[8] Let the percent grasslands remaining at the beginning of period *t* (or end *t*-1) be denoted as G_t. If e_t% of G_t is eased then maximum conversion at *t*, that is everyone else decided to convert, would be restricted to $G_t(1\text{- } e_t.100^{-1})$. We know that the proportion of grassland-owners who decide to convert (*C*) and the mean choice-level (*m*) are related as $C = (1+m)/2$. By that, if *C* is restricted to a maximum value of $(1\text{- } e_t.100^{-1})$ then *m* is restricted to $(1\text{- } 2.e_t.100^{-1})$.

choice level at t as $m_{t-1} = \min(m_{t-1}, 1-E_{t-1})$ so that we have $m_{t-1} \in [-1, 1-E_t]$. The equilibrium characterizing equation is rewritten as

$$
\begin{aligned}
& m_t = -\tanh(\beta(h_t - L_t.\min(m_{t-1}, 1-E_t))) \\
& \Rightarrow \frac{1}{2}\ln\frac{1-m_t}{1+m_t} = \beta.h_t - \beta.L_t.\min(m_{t-1}, 1-E_t)
\end{aligned}
\qquad (11)
$$

See that the restriction placed on maximum land-use conversion due to the advent of easements does not have direct implications on the strength of social component of conversion costs as per our choice of functional specifications. However, it can be seen from equation (11) that beyond $1-E_t$ the curvature of R.H.S. of this equation will experience a reduced degree of convexity. This feature of the impact of advent of easements in a neighborhood may be interpreted as weakened pro-crop societal perceptions due to past levels of conversions through hindrances towards future conversion or higher level of consciousness towards conservation. A graphical analysis is presented in figures 9 and 10.

Case 1b. Results:

(1) An easement reduces rate of conversion to cropland by restricting the land available for conversion, thereby potentially delaying conversion rates.

→ The reduction in rate of conversion is achieved by introducing asymmetric social costs through less convex R.H.S in equation (3) when $m > 1$.

→ However, such a reduction in the rate of conversion is only experienced when proportion eased exceeds the previous period's share of converted grasslands.

(2) There exists a threshold proportion of existing grasslands in a neighborhood (which is a function of p, β, h_t and C_{t-2}) beyond which the maximum conversion will be restricted to 50% instantaneously.

→ The threshold increases as C_{t-2} increases.

→The threshold increases as h_t decreases. However, if h_t decreases beyond $-\boldsymbol{T}$ then easements still reduce the rate of conversion but only up to a minimum of greater than 50% every period.

(3) Easement allocations cannot achieve zero conversion if $m_{t-1} > 0.5$. Conversely, easements can only achieve zero conversion due to social effects only in neighborhoods where an average farmer preferred to 'stay in grass' over 'converting to crop' in the previous period.

Case 2a.: Static grassland conversions with group-level heterogeneity and no easements.

We introduce heterogeneity in the linear specification of private cost function, i.e. $P_i(\omega_i) = h_i\omega_i + k$. Again, the degree of strategic complementarity is L and $\varepsilon(\omega_i)$ is assumed to be extreme-value distributed. Hence, the system of equilibrium characterizing equations are:

(12)

$$E(\omega_i) = 1 \cdot \text{Prob}(\omega_i = 1) + (-1) \cdot \text{Prob}(\omega_i = -1)$$
$$= \frac{-\exp(\beta(P(1) - L \cdot 1 \cdot (I-1)^{-1} \sum_{j \neq i} E(\omega_j)) + \exp(\beta(P(-1) - L \cdot -1 \cdot (I-1)^{-1} \sum_j E(\omega_{j \neq i})))}{\exp(\beta(P(1) - L \cdot 1 \cdot (I-1)^{-1} \sum_{j \neq i} E(\omega_j))) + \exp(\beta(P(-1) - L \cdot -1 \cdot (I-1)^{-1} \sum_j E(\omega_{j \neq i})))} \quad \forall\ i, j$$

If $h_i \sim F_h$ then under rational expectations, that is $E_i(m_j) = E(m_j)\ \forall\ i, j$, a self-consistent equilibrium that solves equation (12) can be specified as

(13) $$m^* = \int_h -\tanh(\beta(h_i - Lm^*))dF_h$$

($\because$ integrate both sides w.r.t. dF_h)

In order to understand the implications of agent-specific private costs of conversion, consider two types of agents, A and B and denote their respective private costs as h^A and h^B. Assume α proportion of type A agents and ($1-\alpha$) type B agents. Equation (13) is re-written as

$$m^* = -\left\{\alpha \cdot \tanh(\beta(h^A - Lm^*)) + (1-\alpha)\cdot \tanh(\beta(h^B - Lm^*))\right\}$$

Denote $x(\#) = \beta(h^\# - Lm^*)$,

(14) $$\Rightarrow m^* = -\left\{\tanh(x(B)) + \alpha \cdot [\tanh(x(A)) - \tanh(x(B))]\right\}$$

$$\Rightarrow m^* = -\left\{\tanh(x(B)) + \alpha \cdot \tanh(x(A) - x(B)) \cdot (1 - \tanh(x(A)) \cdot \tanh(x(B)))\right\}$$

$$\Rightarrow m^* = -\left\{\alpha \cdot \tanh(h^A - h^B) + \tanh(x(B)) \cdot (1 - \alpha \cdot \tanh(h^A - h^B) \cdot \tanh(x(A)))\right\}$$

First we focus on the role of $\alpha \cdot\ (h^A - h^B) = C(\alpha, h^A - h^B)$, which is a constant conditional on α and $(h^A - h^B)$, on equilibrium level of conversion. See that the variance of private costs in the neighborhood, $V(h_i) = \int_h h_i^2 dF_h = \sum\ h_i^2 \Pr(h) = h_B^2 + (h_A + h_B)\cdot[\alpha(h^A - h^B)]$, is monotonously increasing in C. Hence, C can be interpreted as the degree of neighborhood-level heterogeneity that is near-zero for a largely homogenous neighborhood and close to 1 for a very heterogeneous neighborhood. A neighborhood may be heterogeneous when its agents are either highly differentiated due to their private cost of conversion, i.e. significant $(h^A - h^B)$, or just because there is enough density mass under each type, i.e. $0 \ll \alpha \gg 1$, or both. Also that α and $(h^A - h^B)$ may vary across neighborhoods meaning that equation (14) is no longer interchangeable between any subset of a population and the population itself. Specifically, in a finite set of neighborhoods N that make up the population I, such that $N \in \{1, 2, ..., n\}$, we have:

$$
(15) \qquad \begin{aligned} & m_n^* = -\left\{C + \tanh(\beta(h^B - Lm_n^*)) \cdot (1 - C \cdot \tanh(\beta(h^A - Lm_n^*)))\right\} \\ & \Rightarrow \frac{1}{2}\ln\left(\frac{1-m_n^*}{1+m_n^*}\right) = \text{Arctanh}\left\{C + \tanh(\beta(h^B - Lm_n^*)) \cdot (1 - C \cdot \tanh(\beta(h^A - Lm_n^*)))\right\} \end{aligned}
$$

To understand the implications of heterogeneity we conduct a graphical analysis presented in figure (11).

We first interpret the impact of the degree of heterogeneity on permanent conversions from figure 11 (a) and (b). Assuming, without loss of generality, $h^A > h^B$ we examine the case when a neighborhood is homogeneously populated with type B agents. The two stable equilibriums are $m^* = -0.97, +0.93$, i.e. the average community behavior is characterized by two equilibria where either 98.5% choose to 'stay in grass' or only 3% choose to 'stay in grass'. Contrast that with another neighborhood with a higher degree of heterogeneity such that it is composed of 50% type B agents who share the neighborhood with 50% type A agents for whom cropping is costly. The two stable equilibria in this new neighborhood are $m^* = -0.98, +0.80$, i.e. the average community behavior is characterized by two equilibria where either 99% choose to 'stay in grass' or only 10% choose to 'stay in grass'. Note that heterogeneity reduced the overall conversions and there is a threshold α above which 100% of the neighborhood opts to 'stay in grass'. A similar graph can be achieved if we increase $|h^A - h^B|$ while keeping α fixed. Therefore, heterogeneity (as speficied) has exactly the same implications as would the level of private costs as in Result 1(b) of the baseline model earlier. Hence, the results:

Case 2a. Results:

Given the strength of strategic complementarity in a neighborhood (L) and parameter β, there exists a threshold value of neighborhood degree of heterogeneity, $\overline{C}$, such that

(a) If $|C| < \overline{C}$, then neighborhood average choice will be characterized by three equilibria: one that is of the sign opposite of C and two of the sign same as C.

i. As C increases, the mean equilibrium behavior of the society tilts towards the unique equilibria that has an opposite sign of C.

(b) If $|C| > \overline{C}$, then neighborhood average choice will be characterized by a unique equilibrium that is of the sign opposite of C.

Case 2b.: Role of easements among heterogeneous farmers (intuition)**:**

We know that easements reduce conversion rates by restricting the scope of conversion, thereby weakening strategic complementarity. In that, this effect is similar to (but not the same as) a heterogeneous neighborhood with enough proportion of agents with high costs of conversion. Consider a population with neighborhood-level heterogeneity and many agents with high private costs but not high enough to negate $m^* > 0$. The effects of easements coupled with that of heterogeneity among private conversion costs can yield a unique equilibrium where all 'stay in grass'. The amount of land that is needed to be eased in order to achieve 'no conversions' is lower in the case of 'pro-grass heterogeneity' as compared to the homogeneous neighborhood even with relatively lower average costs in the homogeneous case.

Empirical Strategy and Econometric Considerations

We employ a duration modelling approach to analyze permanent grassland conversions with the number of years for parcels to be converted to crop or the duration-to-convert is our dependent variable. This strategy is appropriate provided that the remote-sensing tools allowed generating spatially-explicit data on permanent conversions, i.e. the GC sequence discussed earlier. The details of our approach that ultimately estimates risk of conversion are discussed next.

Specifically, the duration to covert, T, is assumed to be distributed with a differentiable C.D.F., $F(T)$ and $F'(T) = f(T)$. $F(T)$ is the probability that a representative land parcel will be converted by T years. Hence, the probability of surviving conversion until T years is written as $S(T) \equiv 1 - F(T)$. Further, the instantaneous risk of conversion or the hazard rate, $\lambda_{GC}(T)$, is defined as $\lambda_{GC}(T) = f(T)/S(T)$. In order to estimate the hazard rate we assume that T is directly proportional to the difference in total cost of individual action discrete choice set $\omega_i \in \{-1,1\}$, i.e. $T = k(C(1) - C(-1))$, where k is a constant. This makes sense because the costlier it is to convert the longer farmers are expected to stay in grass-based production. A reduced form regression model for difference in is:

(16) $$C_{i,t}(1) - C_{i,t}(-1) = a + bX_i + cY_n - Lm_{n,t-1} + \alpha_n + (\varepsilon_{i,t}(1) - \varepsilon_{i,t}(-1)) \text{ s.t. } L \geq 0$$

Equation (16) models choice-level $\omega_{i,t}$ as a function the explanatory variables in a non-linear fashion. The explanatory variables are observed and unobserved individual characteristics (X_i and $\varepsilon_{i,t}(.)$ resp.), observed and unobserved neighborhood characteristics (Y_n and α_n resp.), and *i*'s subjective expectation of community behavior in the previous period ($m_{n,t-1}$, assuming myopic expectations). Manski (1993) pointed out that social interactions' parameter *L* is difficult to identify because $m_{n,t-1}$ is likely to be functionally dependent on Y_n, an issue popularly known as the 'reflection' problem. Brock and Durlauf (2007), who proposed the utility function equivalent of equation (16), showed that the non-linearity due to modelling difference in costs between choice levels (rather than the choice itself) implies that parameters *a*, *b*, *c* and *L*, are identified. Since the duration to convert is assumed to be directly proportional to the cost difference in (16) these parameters will be identified for our study as well. However, the conditions that need to hold for identification are random assignment of land parcels to their neighborhood and no unobserved neighborhood-level effects, i.e. $\alpha_n = 0$. We assume these conditions hold, although they have not been tested and so our results are preliminary.

Variable *spell* is defined as the duration to convert and we estimate non-parametric Kaplan-Meier survival probabilities based on each parcel's duration of permanent conversion in our sample. Figure 12 presents the results. Large proportion of the sample, more than 90%, contains parcels in the always grass category (G). Among the ones that did convert, i.e. the (GC) category, more than 85% converted in just one year. A highly skewed sample is a caveat of this analysis and warrants future work that reconciles this issue. Table 1 shows that among the converted parcels average spell was about 2.6 years. We utilize a semi-parametric specification, also known as the Cox-proportional hazard model, $\lambda_{GC}(T \mid X; \beta) = \lambda_o(T)\exp(X'\beta)$, to model conversion risk due to covariate vector X. Here, $\lambda_o(T)$ is the baseline hazard that represents heterogeneity among land parcels (Greene, 2003, p. 799). A coefficient, β, to a particular independent variable translates into $100(\exp(\beta)-1)\%$ change in hazard rate due to unit increase in that variable.

To capture strategic decisions, we control for grass-density within each parcel's 0.5km, 1km, and 2km outer-rings. If an easement was established before permanent conversion, we assign proportion of eased area within each outer-ring and deduct this from grass proportion of the ring. This arrangement can be easily visualized in figure 13. By including both, the proportion of grasses as well as easements, we evaluate the interaction between eased acres and grass acres. We also control for each parcel's soil quality, and the Euclidean distance to the nearest highway and a city. Soil quality is measured as weighted slope of a parcel and percent land with Land

Capability Classes (LCC) less than or two.[9] Proximity to highways and town-centers (or cities) forms a proxy for a network of infrastructure may prompt farmers to convert to crops through efficient supply chain and logistics. Polasky (2008) has underlined the importance of the interactions of human population and ecological systems towards conservation planning.

Note that equation (16) also includes neighborhood-level regressors Y_n that may impact conversion decisions. For this study, Y_n would be the soil quality variables within the outer rings. However, table 2 shows that parcel-level attributes are highly correlated with their neighborhood-level counterparts. Therefore, we include parcel-level land quality for an amenable interpretation towards conversion decisions.

Estimation Results

Since the number of observations in category G are much greater than that in GC, we conduct our analysis for GC category separately in order to document relevant difference in results. Table 1 shows that the parcels that never convert during the period of this study (1997-2015) have, at an average, higher slopes, poorer soils for cropping (or higher LCC), and are more distant to the highways and the nearest city center as compared the ones that do convert. The difference in average values of the soil quality parameters' are significant even though the respective standard deviations are high, see table 3.

The hazard regression estimates for the 'full' sample are listed in Table 4 and the corresponding hazard rates are listed in Table 5. We find that a unit increase in the proportion of grasses within a representative parcel's 0.5km neighborhood would decreases the conversion risk

[9] LCC is a system of categorizing soils such that each higher category has incrementally higher impediments towards cropping. LCCs less than or equal to two are among the most productive croplands.

by 99%. Correspondingly, higher grass density within larger neighborhoods of 1km and 2km decrease the hazard rate by 97% and 94% respectively. This suggests a monotonically decreasing strategic response function for change in hazard rates due to increasing size/expanse of the neighborhood. Such high impacts of neighborhood grass density is driven by the fact that permanent conversions are all concentrated in areas that were historically highly cropped. We find that the easements reduce hazard rates by a 100% meaning that the advent of an easement completely halts conversion. This result is driven by the fact that in the past easements were allocated away from the converted parcels and near regions with high concentration of grasslands. So the easements seem to have been allocated on lands that would not have converted anyway. Further, higher slopes, and more distant cities and highways also reduced the conversion risks. Finally, a higher percentage of land under LCC categories I and II reduced conversion risk while we had expected otherwise.

To fully understand the strategic interactions and the role of easements, we estimate hazard rates within the GC category as well. These results are listed in tables 6 and 7. Briefly, higher grass density as well as more eased acres are related to reduced hazard rates, although the impact of easements if insignificant. This result is explained by easements rarely allocated in the neighborhood of converted parcels, see in table 1, which is the empirical evidence for Case 1b's result #2 above. However, it is interesting that the impact of an extra easement acre is stronger than that of a grass acre in reducing conversion risk. This result potentially suggests an educational impact that enhanced environmental conscience due to the presence of near-by easements, beyond cost complementarity through higher proportion of the grasslands.

Discussion

This paper analyzes grassland conversions in North and South Dakota, while also exploring the role of conservation easements in protecting grasslands. The region of study experienced extensive land-use transitions in the past decade where cropland expanded by replacing grasslands. Grassland losses threaten the regional natural ecosystem since many species depend on them in sustaining their habitat by supporting wetlands. Since this region is a critical habitat for native and migratory birds in North America, the U.S. Fish and Wildlife Service actively engages in buying out perpetual easements to conserve grasslands. A past study has suggested that easement acquisitions must account for economic costs apart from ecological benfits that have been used to prioritize acquisitions by USFWS and its partners. This paper investigates the role of network effects towards efficient easement allocations. We argue (and empirically test) that strategic cost complementarities are driving making conversion decisions, and can be disrupted if easements are strategically allocated.

We present a conceptual dynamic model of permanent grassland conversions with strategic cost complementarity and heterogeneous agents. We also analyze the role of easements in the model. Briefly, our analysis suggests that in presence of strategic complementarities easements could reduce the rate of conversion over a certain threshold. This threshold level of easement acreage varies with the neighborhood-level land-use endowments and is higher when local crop density increases. We capture this effect in our empirical analysis as well. An important fact that comes out of this analysis is that permanent croplands and permanent grasslands individually emerge as large, nearly continuous tracts, but spatially separated from each other. Permanent conversions, on the other hand, are small islands within the crop-intensive areas. Even though easement are found to inhibit permanent conversions, they have been placed in areas that would not have converted anyway. This study reinforces the idea that easement allocations must account for overall costs as not only biological benefits.

Our study has caveats that warrant future work. First, we need to reconcile a highly skewed distribution of our sample that contains more than 90% parcels in permanent grassland category. Second, our empirical exercise assumes that permanent conversions were randomly placed, which needs to be tested. Third, in order to evaluate long-term grasses we need to incorporate historical grass acreage that will be accomplished through a separate exercise of processing raw satellite imagery.

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TABLES

Table 1: Variable Summaries

Variable	N	Mean	Median	Std Dev	Minimum	Maximum
PERMANENT CONVERSIONS						
Parcel Characteristics						
Spell	972	2.59	1.00	3.99	0.00	18.00
Acres	972	12.76	8.23	13.08	5.12	142.55
WSLP	972	3.25	2.80	1.87	1.00	11.30
WLCC	972	2.41	2.00	0.77	2.00	7.00
%LCC ≤ 2	972	72	100	44	0.00	100
Highway (km)	972	4.49	3.87	3.49	0.00	16.60
City (km)	972	7.57	7.11	3.70	0.52	21.09
Neighborhood-level Characteristics						
%Eased (0.5 km)	972	0.00	0.00	0.90	0.00	20.00
%Eased (1 km)	972	0.10	0.00	2.30	0.00	46.00
%Eased (2 km)	972	0.20	0.00	1.60	0.00	30.00
%Grass (0.5 km)	972	31.00	28.00	17.00	0.00	94.00
%Grass (1 km)	972	26.00	23.00	15.00	0.00	95.00
%Grass (2 km)	972	24.00	21.00	14.00	0.00	97.00
NEVER CONVERT						
Parcel Characteristics						
Spell	12420	19.00	19.00	0.00	19.00	19.00
Acres	12420	16.98	9.34	21.98	5.12	199.49
WSLP	12419	7.68	7.00	3.60	1.10	29.00
WLCC	12419	3.07	2.00	1.69	1.82	7.00
%LCC ≤ 2	12420	65	100	47	0.00	100
Highway (km)	12420	6.22	5.63	4.37	0.00	27.14
City (km)	12420	10.15	9.67	4.60	0.26	25.21
Neighborhood-level Characteristics						
%Eased (0.5 km)	12420	1.50	0.00	0.082	0.00	100
%Eased (1 km)	12420	1.40	0.00	0.063	0.00	87.30
%Eased (2 km)	12420	1.40	0.00	0.046	0.00	71.80
%Grass (0.5 km)	12420	67.00	69.00	24.00	0.00	100.00
%Grass (1 km)	12420	56.00	57.00	26.00	0.00	100.00
%Grass (2 km)	12420	49.00	48.00	26.00	0.00	100.00

Table 2: Person's Correlation Coefficient among parcel-level land quality variables and their respective neighborhoods characterized as outer-rings.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
WSLP	0.97	0.93	0.86
WLCC	0.97	0.93	0.86
%LCC ≤ 2	0.97	0.94	0.88

Table 3: A t-test with unequal variance to compare mean of land quality variables among G- and GC-sequences. Null hypothesis is that this difference is zero.

Variable	Difference ($M_{GC} – M_{G}$)	t-value	p-value
WSLP	-4.43	-64.87	<0.0001
WLCC	-0.66	-22.63	<0.0001
%LCC ≤ 2	7.61	5.12	<0.0001

Table 4: Cox-Proportional Hazard Regression Estimates. Dependent Variable: **spell**.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion (0.5km)	-4.31***		
Eased Proportion (0.5km)	-14.53***		
Grass Proportion (1km)		-3.56***	
Eased Proportion (1km)		-11.74***	
Grass Proportion (2km)			-2.83***
Eased Proportion (2km)			-19.08***
WSLP	-0.53***	-0.60***	-0.63***
%LCC ≤ 2	-0.37***	-0.38***	-0.33***
Highway (km)	-0.03***	-0.04***	-0.05***
City (km)	-0.02**	-0.02**	-0.02**
-2LogL	15230.30	15538.45	15691.51
AIC	15242.30	15550.45	15703.51

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$

Table 5: Cox-proportional hazard rates.

Variable	0.5km Outer Ring	1km Outer Ring	2km Outer Ring
Grass Proportion (0.5km)	0.01		
Eased Proportion (0.5km)	0.00		
Grass Proportion (1km)		0.03	
Eased Proportion (1km)		0.00	
Grass Proportion (2km)			0.06
Eased Proportion (2km)			0.00
WSLP	0.53	0.55	0.53
%LCC ≤ 2	0.69	0.68	0.72
Highway (km)	0.97	0.96	0.96
City (km)	0.98	0.98	0.98

Table 6: Cox-Proportional Hazard Regression Estimates for only the GC sequence. Dependent Variable: **spell**

Variable	**0.5km Outer Ring**	**1km Outer Ring**	**2km Outer Ring**
Grass Proportion (0.5km)	-1.33***		
Eased Proportion (0.5km)	-0.30		
Grass Proportion (1km)		-1.27***	
Eased Proportion (1km)		-0.81	
Grass Proportion (2km)			-1.34***
Eased Proportion (2km)			-0.54
WSLP	-0.10***	-0.11***	-0.09***
%LCC ≤ 2	-0.13*	-0.12	-0.12
Highway (km)	-0.000	-0.003	-0.004
City (km)	-0.01	-0.004	-0.005
-2LogL	12113.13	12126.56	12128.10
AIC	12125.13	12138.56	12140.10

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$

Table 7: Cox-proportional hazard rates for the GC sequence.

Variable	**0.5km Outer Ring**	**1km Outer Ring**	**2km Outer Ring**
Grass Proportion (0.5km)	0.26		
Eased Proportion (0.5km)	1.35		
Grass Proportion (1km)		0.28	
Eased Proportion (1km)		0.44	
Grass Proportion (2km)			0.26
Eased Proportion (2km)			0.59
WSLP	0.90	0.90	0.92
%LCC ≤ 2	0.88	0.89	0.89
Highway (km)	1.00	1.00	0.97
City (km)	0.99	1.00	0.99

FIGURES

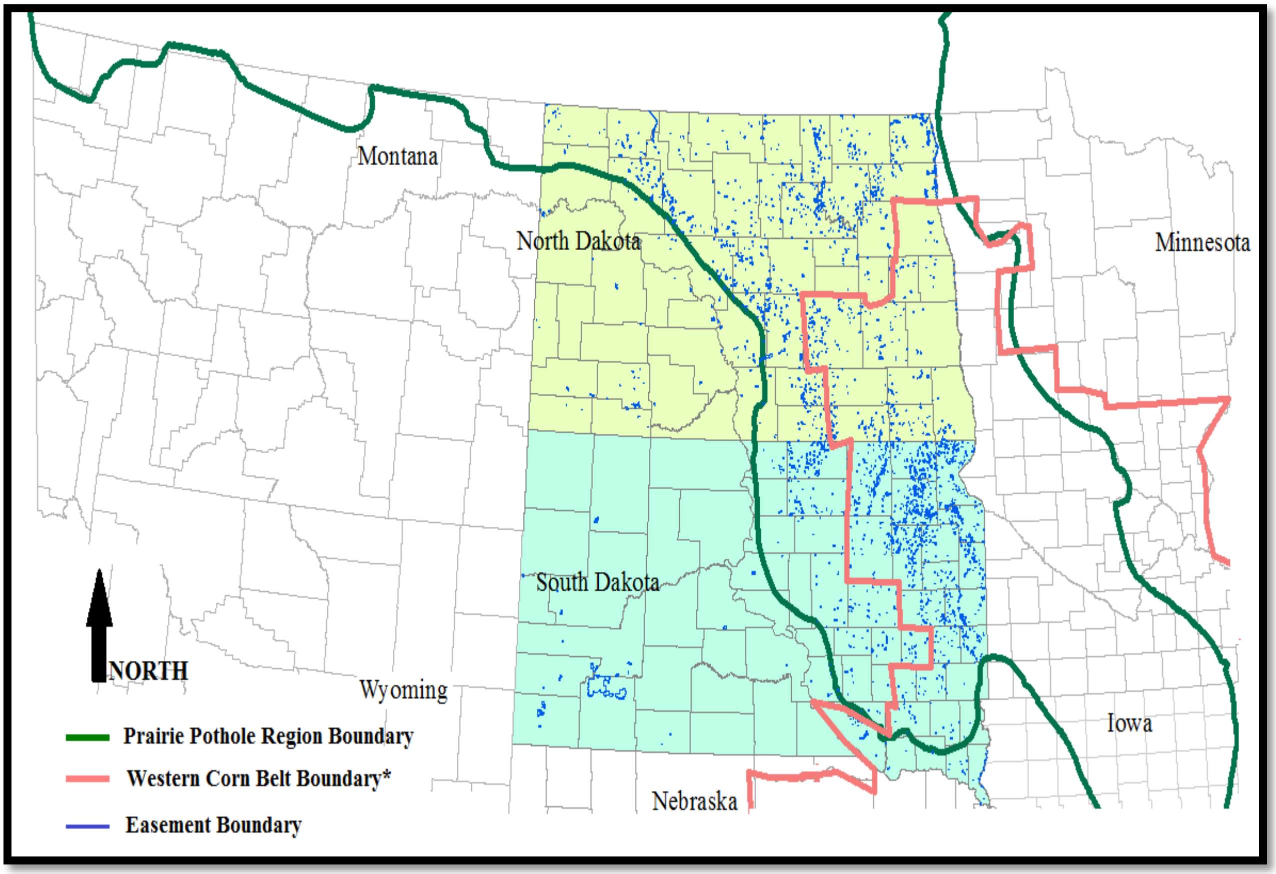


Figure 1: The U.S. Prairie Pothole Region, Western Corn Belt frontier and easement allocations in North and South Dakota. Not to scale.

*Notes: The representation of the Western Corn Belt frontier is approximate and manually built with the 2010 county-level map of the United States Department of Agriculture-National Agricultural Statistics Service's as a reference. Downloadable from: https://www.nass.usda.gov/Charts_and_Maps/Crops_County/.

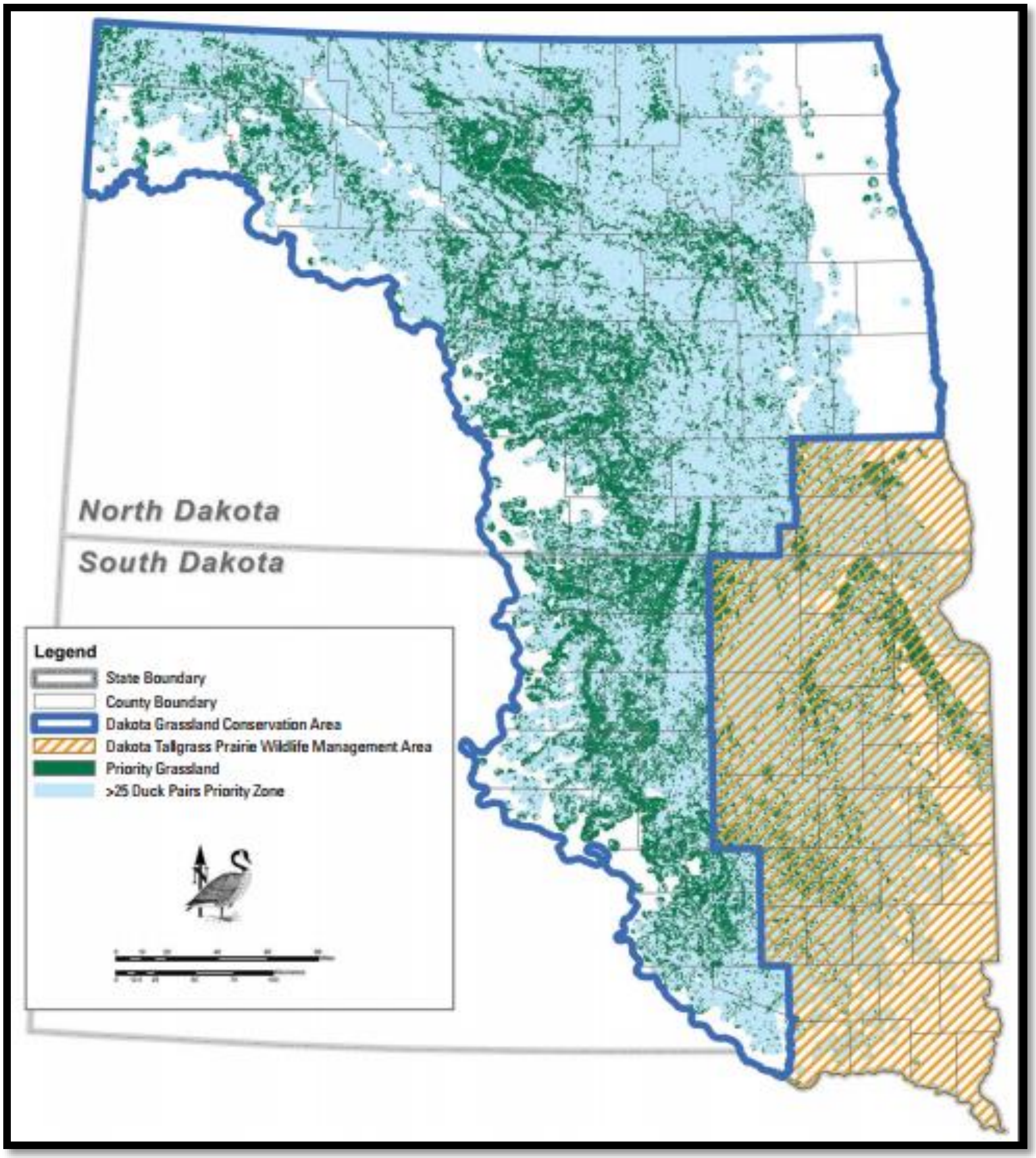


Figure 2: Waterfowl breeding density and USFWS Priority Conservation Acres. The figure has been taken from USFWS Land Protection Plan, 2011 p. 4. Source: *https://www.fws.gov/mountain-prairie/planning/lpp/nd/dkg/documents/dkg_lpp_final_all.pdf*

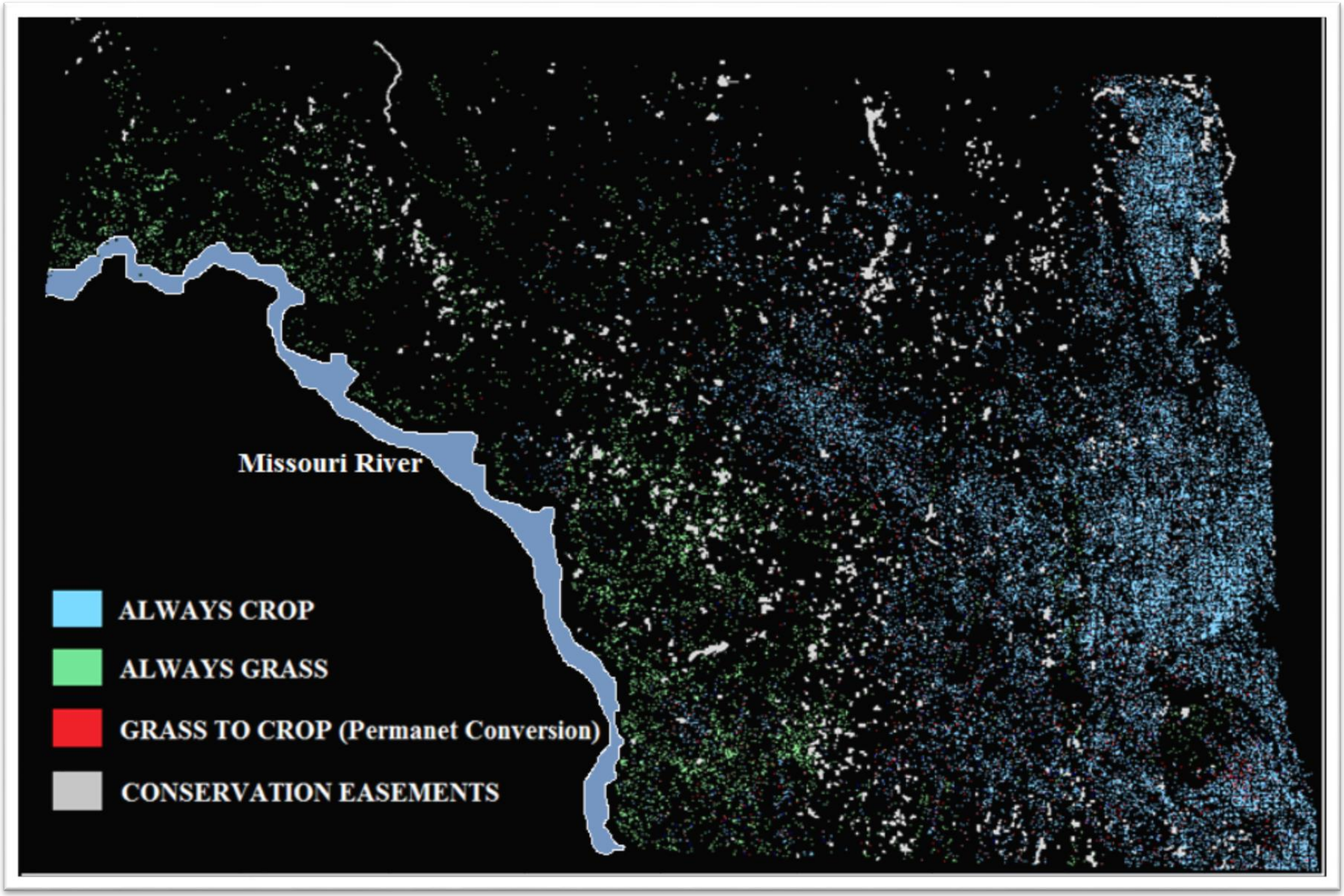
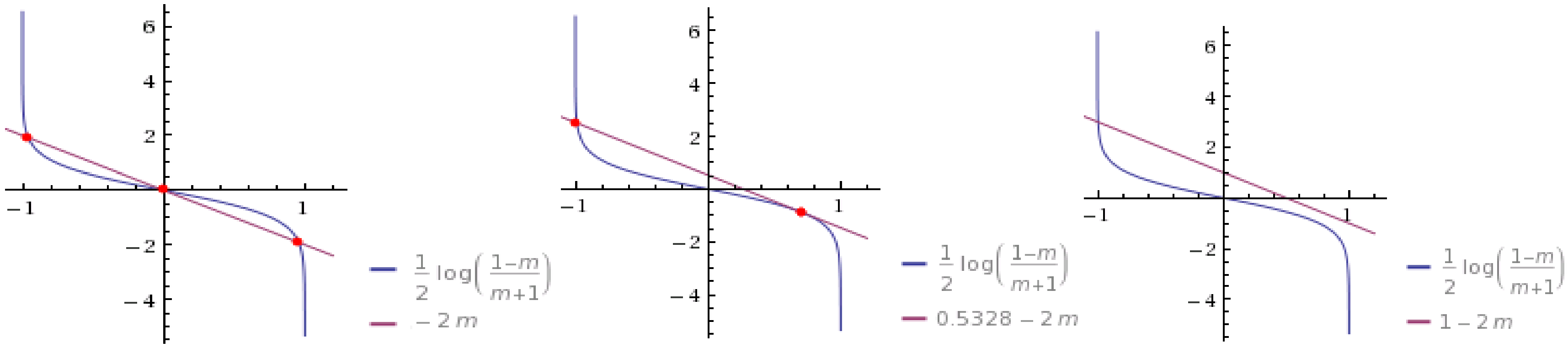
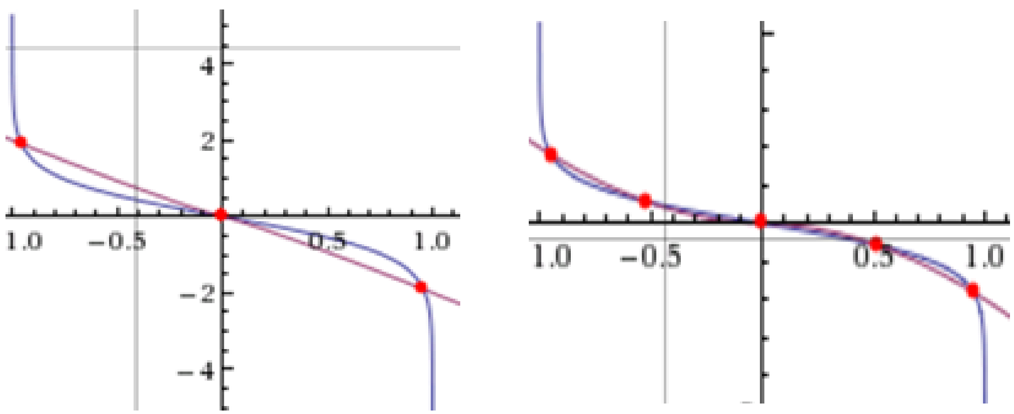


Figure 3: Land use change combinations in eastern North Dakota and relative allocations of conservation easements.



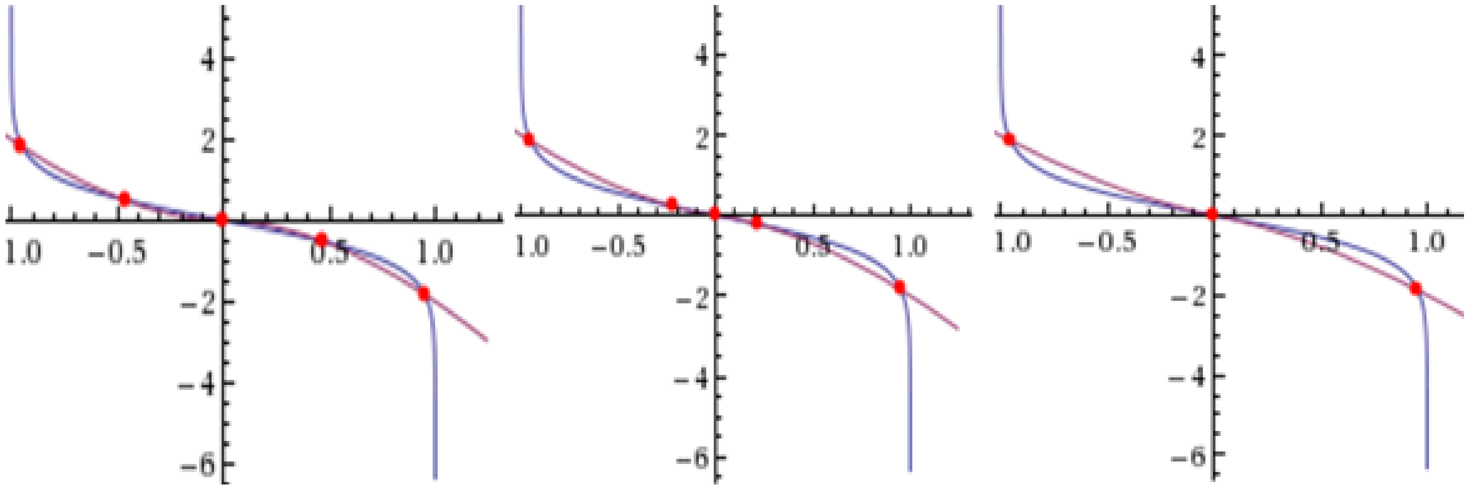
(a) βL =2 and βh =0 (b) βL =2 and βh =0.5328 (c) βL =2 and βh =1

Figure 4: Specific examples that generate unique and multiple equilibria in a static environment with homogeneous farmers. The nature of equilibrium depends upon the relative strengths of strategic complementarities (L) and difference between private costs towards "staying in grass" and "converting to crop".
Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-m)%2F(1%2Bm))%3D0-2m



(a) $C_{t-2} = 0$, p = 0.1 and βh =0 (b) $C_{t-2} = 0$, p = 0.1 and βh =0

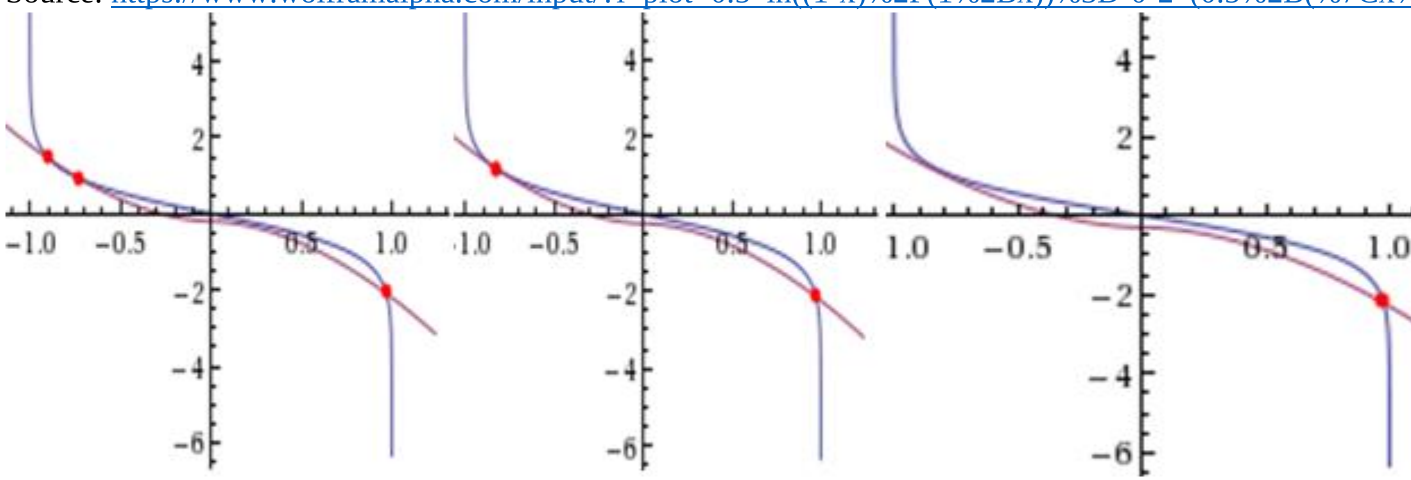
Figure 5: Temporal dynamics with specific examples portraying the role of p while $C_{t-2} = 0$ when βh =0 holds.
Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-x)%2F(1%2Bx))%3D-0-2*(0.0%2B(%7Cx%7C%5E.9)*1)*x



(a) $\boldsymbol{C}_{t-2} = 0$, p = 0.8 and βh=0 (b) $\boldsymbol{C}_{t-2} = 0.3$, p = 0.8 and βh=0 (c) $\boldsymbol{C}_{t-2} = 0.5$, p = 0.8 and βh=0.

Figure 6: Temporal dynamics with specific examples portraying the role of C_{t-2} while $p = 0.8$ when βh=0 holds.

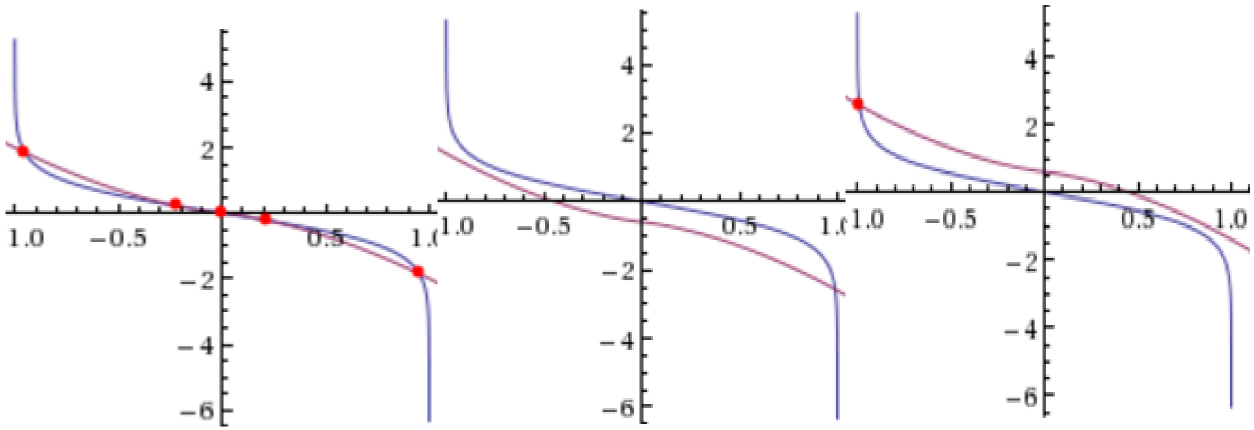
Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-x)%2F(1%2Bx))%3D-0-2*(0.5%2B(%7Cx%7C%5E.8)*.5)*x



(a) $h_t = -0.1;\ \beta = 2,\ C_{t-2} = 0$ b) $h_t = -0.1212;\ \beta = 2,\ C_{t-2} = 0$ (c) $h_t = -0.15;\ \beta = 2,\ C_{t-2} = 0$

Figure 7: Temporal dynamics with specific examples in the scenario where when $\beta h \neq 0$ and $p = 0.8$.

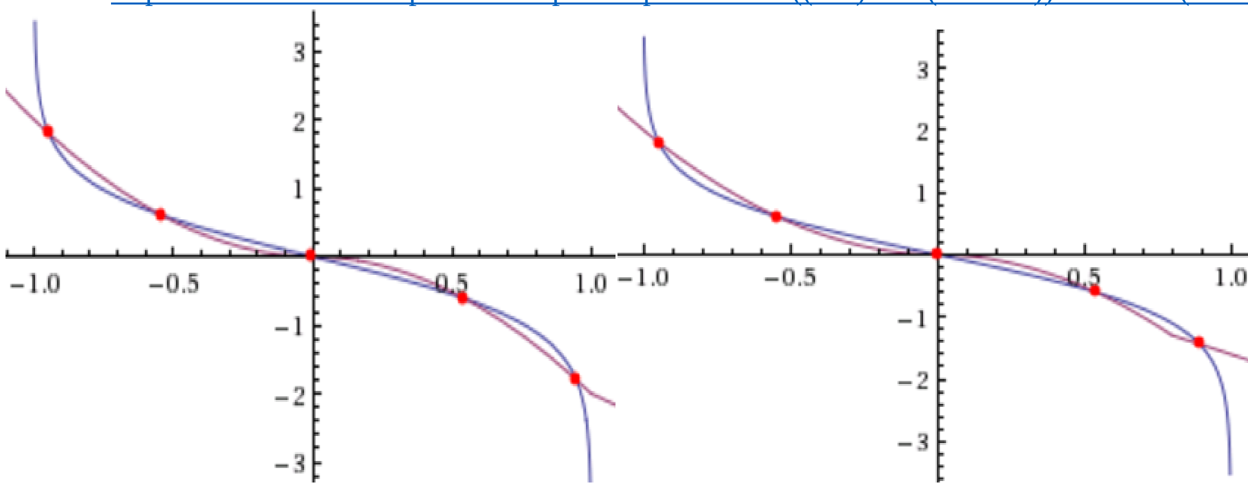
Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-x)%2F(1%2Bx))%3D-0.3-2*(0.0%2B(%7Cx%7C%5E.8)*1)*x



(a) $v_t = 0$ **(b)** $v_t \ll 0$ **(c)** $v_t \gg 0$

Figure 8: Exploring the role of potential mean-reverting shocks when $h_{t-1} = 0$, $\beta = 2$, $C_{t-2} = 0.3$, $p = 0.8$

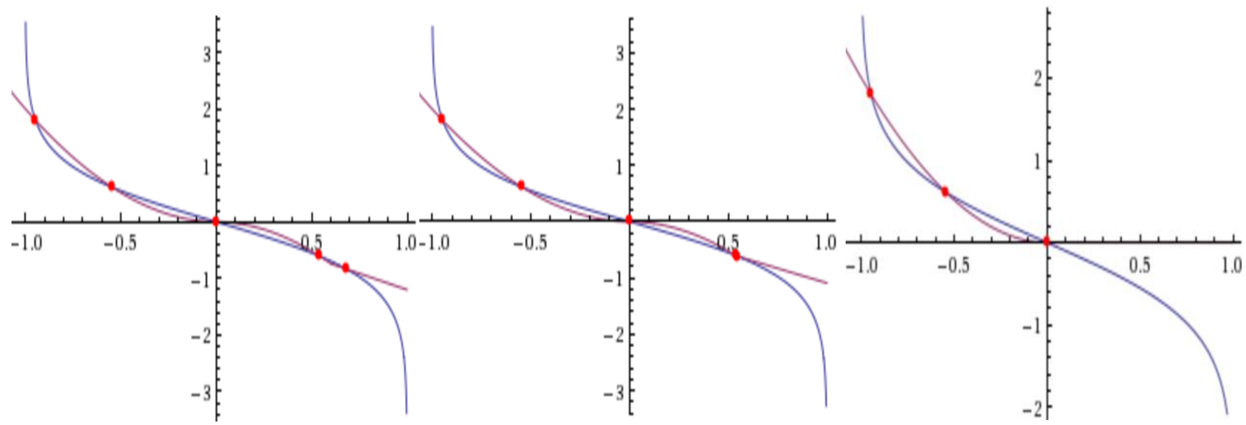
Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-x)%2F(1%2Bx))%3D1-2*(0.3%2B(%7Cx%7C%5E.8)*0.7)*x



(a) $e_t = 0\% \Rightarrow E_t = 0$ (b) $e_t = 10\% \Rightarrow E_t = 0.2$

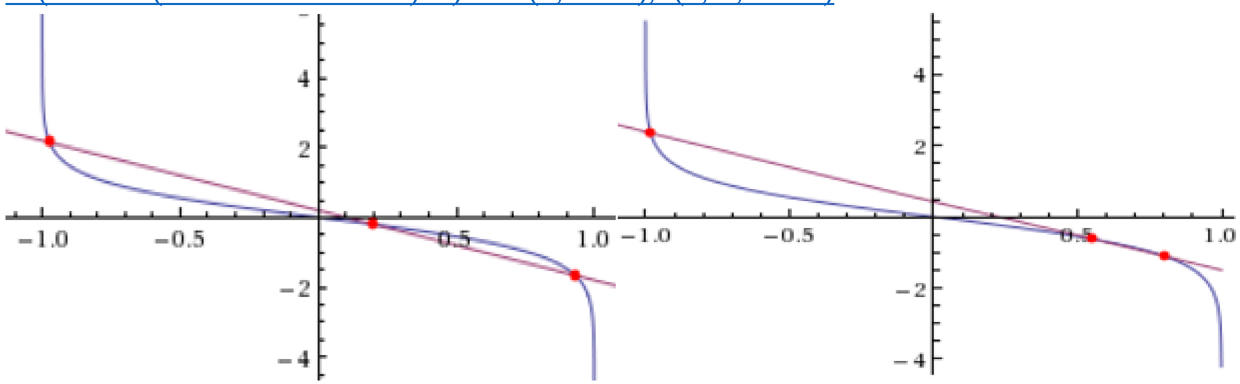
Figure 9: Role of easements in case of temporal dynamics. An example with $h_t = 0$, $\beta = 2$, $C_{t-2} = 0$, $p = 0.95$

Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-x)%2F(1%2Bx))%3D-0.3-2*(0.0%2B(%7Cx%7C%5E.95)*1)*min(x,+0.20),+(x,-1,%2B1)



(c) $e_t = 20\% \Rightarrow E_t = 0.4$ (d) $e_t \approx 22.25\% \Rightarrow E_t \approx 0.465$ (c) $e_t = 100\% \Rightarrow E_t = 0.0$

Figure 10: Existence of threshold easement level that curtails conversion rate in a decision environment with temporal dynamics. Source: https://www.wolframalpha.com/input/?i=plot+0.5*ln((1-x)%2F(1%2Bx))%3D-0.3-2*(0.0%2B(%7Cx%7C%5E.95)*1)*min(x,+0.20),+(x,-1,%2B1)



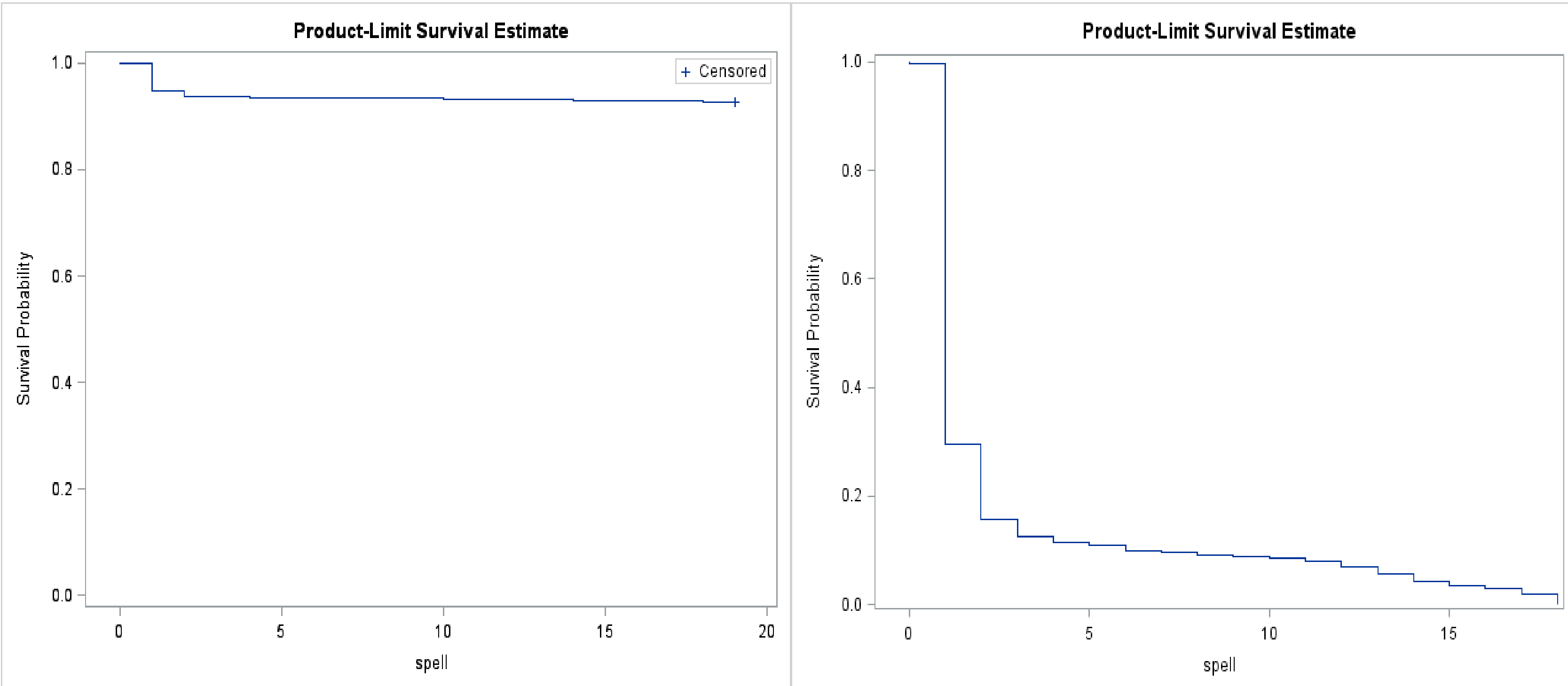
$\beta h^B = 0.2, \beta h^A - \beta h^B = 0.5$, $\alpha = 0$; $m^* \in \{-0.97, 0.20, 0.93\}$

(a)

$\beta h^B = 0.2, \beta h^A - \beta h^B = 0.5, \alpha = 0.5$; $m^* \in \{-0.98, 0.56, 0.80\}$

(b)

Figure 11: Static equilibrium with agent-level heterogeneity in private conversion cost component where βL =2.



(a) (b)

Figure 12: Kaplan-Meijer Survival Probability Estimates. Panel (a) signifies that more than 90% of the sample is permanent grasslands. Panel (b) zooms into the converted parcels in our sample and presents corresponding estimates for survival probability.

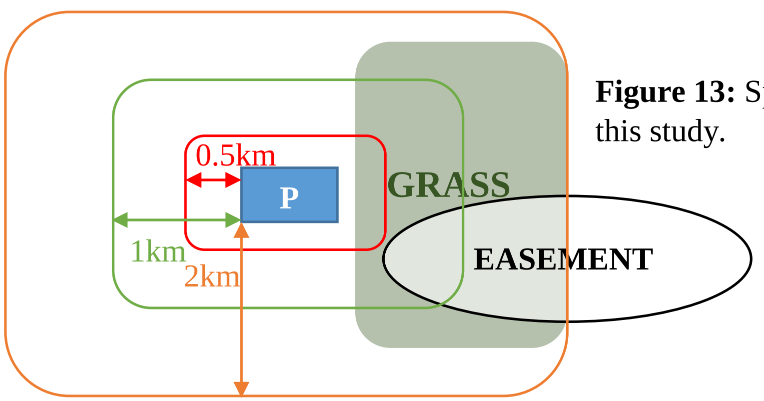


Figure 13: Spatial schematics of the outer-rings and easement allocations coverage for this study.